Truck factors affecting dynamic loads and road damage

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Computer simulation offers a convenient means to examine the mechanisms of truck-pavement interaction leading to pavement damage. Wheel load interactions from a family of truck configurations were studied on rigid and flexible pavements to estimate the fatigue and rutting damage caused by each, with the objective of identifying the truck characteristics that most directly affect damage.

The potential for fatigue damage was found to have a first-order relationship to truck axle loads and is consistent across a range of pavement designs. Closely-spaced tandem axles have a beneficial interaction that reduces fatigue damage on rigid pavements. On flexible pavements, the tire properties of size, configuration (single vs. dual), and inflation pressure are important to both fatigue and rutting damage. Truck dynamic loads, which are affected by suspension properties, road roughness, and operating speed, act to increase pavement fatigue damage. The road damage performance of several generic truck suspension designs is compared.

1.0 INTRODUCTION

Even with the construction of the first paved roadways by the Romans, the potential for pavement damage from vehicles became evident with the rutting produced by chariot wheels [1].* In modern highway transportation systems the continuing concern with this problem is reflected in the need to regulate the trucks allowed to use the roads. In the United States the regulations are contained in Road Use Laws published by the Federal and state governments [2]. In order to control rutting and cracking damage of the road structure, limits on truck gross weights, axle weights and tire dimensions are specified. In the European community, consideration is also being given to discrimination among types of suspensions in the regulation of truck loads [3].

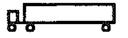
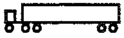
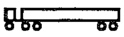
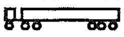
Historically, truck load regulations have been based on empirical data gathered from controlled experiments, such as the 1958 AASHO Road Tests [4], or from analytical models by which pavement stresses and strains can be predicted under load [5]. Experimental methods are expensive, subject to random errors, and difficult to extrapolate to other truck configurations and loads. Analytical methods have shortcomings in their ability to handle the complexities of truck dynamics and the moving load conditions.

With the engineer's access to high performance computers in recent years, it has become practical to simulate the dynamic performance of trucks with reasonable fidelity [6], as well as the response in a pavement structure to moving, dynamic loads [7, 8]. The National Academy of Sciences through the National Cooperative Highway Research Program recently sponsored a study, "Effects of Heavy Vehicle Characteristics on Pavement Response and Performance," with the objective of using simulation methods to systematically investigate the relationship between truck properties and pavement damage [9]. This paper summarizes key findings from that study with respect to truck-pavement interactions.

2.0 RESEARCH APPROACH

The generalized approach to modeling truck-pavement interaction is illustrated in Figure 1. Pitch-plane models of the 13 basic truck configurations listed in Table 1 were developed. The trucks were "run" on roads with generalized roughness properties designed to represent the characteristic spectral content of each type of road [10], with the amplitude varied. In the case of rigid pavements, the random roughness was augmented with periodic components representing typical failure mechanisms of faulting and slab-tilt (correlated with the pavement being modeled). The dynamic loads along the pavement were calculated for each axle of the combination and stored in such a way that they could be simultaneously applied to the pavement in their respective positions.

Table 1. Truck matrix

No.	Truck Configuration	Name	GCW (kips)	Axle Loads (kips)
1		Straight Truck	32	12/20
2		Straight Truck	46	12/34
3		Refuse Hauler	64	20/44
4		Conc. Mixer	68	18/38/12
5		Tractor-Semi.	52	12/20/20
6		Tractor-Semi.	66	12/20/34
7		Tractor-Semi.	80	12/34/34
8		5 Axle Tanker	80	12/34/34
9		6 Axle Tanker	85	12/34/39
10		5 Axle Doubles	80	10/18/17/18/17
11		7 Axle Doubles	120	12/34/34/20/20
12		9 Axle Doubles	140	12/32/32/32/32
13		Turner Doubles	114	10/26/26/26/26

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* Bracketed numbers refer to bibliographic references at end.

Heavy vehicles and roads: technology, safety and policy. Thomas Telford, London, 1992.

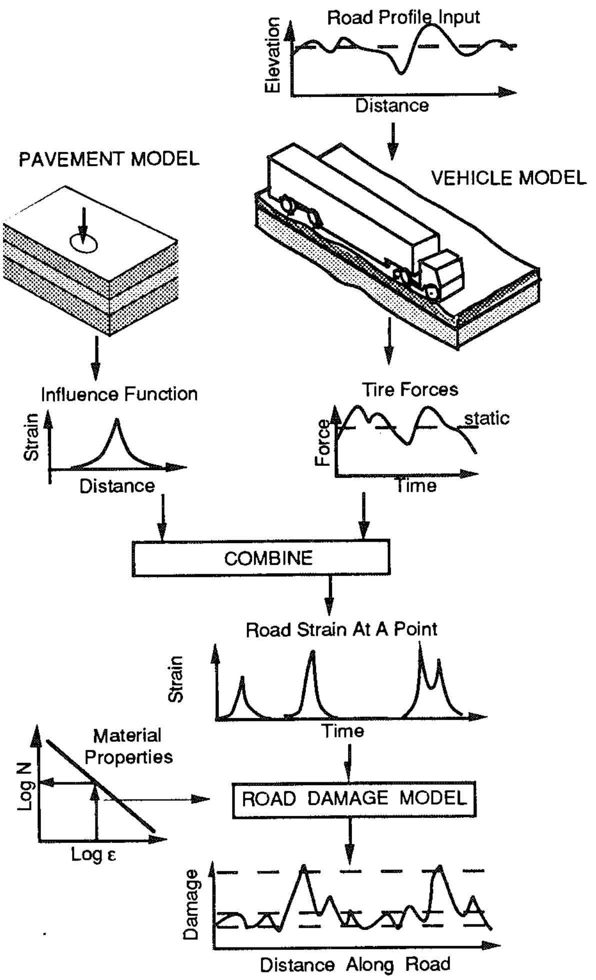


Fig. 1. Analytical approach to simulating truck-pavement interaction.

The pavements were analyzed from pavement structural models by computing influence functions for the response at each point to a unit load imposed anywhere else on the pavement. The rigid pavement model for Portland Cement Concrete roads was ILLI-SLAB, which is a finite element slab on an elastic base with provisions for different joint properties [11]. Eighteen rigid pavement designs were analyzed. The flexible (asphalt) pavement model was derived from VESYSDYN, which is a multi-layer elastic model [12]. Examples of influence functions are shown in Figure 2.

By combining the dynamic loads from the truck simulations with the influence functions, the time-varying stresses and strains could be calculated at points along the wheel path due to the combined loads of all wheels of the truck as it passed by. The time history of stress was evaluated at each point using the most-commonly accepted models to estimate the cumulative damage from passage of the truck. For estimating fatigue damage (which results in cracking) a power law relationship was used, with failure limits appropriate to the material properties of the road structure. For rutting damage, permanent deformation in each layer was computed using a visco-elastic model.

Computations were made over road sections approximately 400 m in length to allow a statistical analysis of the responses at incremental distances along the roadway. The statistics were compiled to yield the average damage from each truck, along with the 95% damage (representative of the damage imposed on the worst 5% of the pavement).

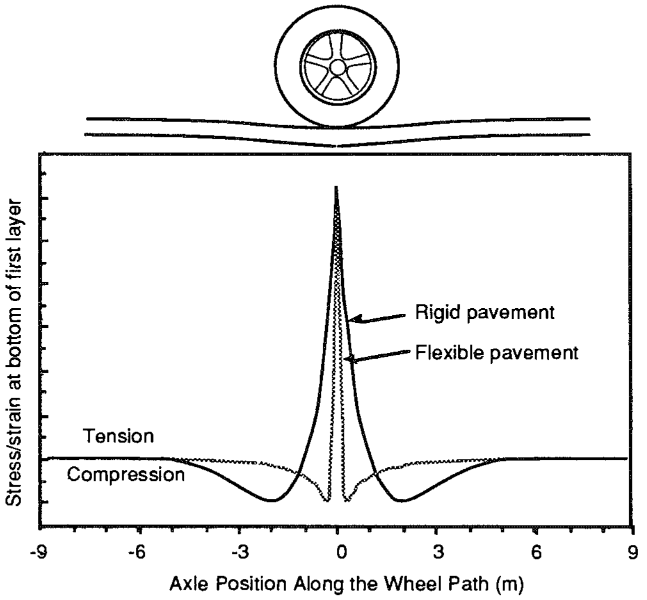


Fig. 2. Examples of influence functions for rigid and flexible pavements.

3.0 TRUCK FACTORS AFFECTING DAMAGE

The various truck-pavement combinations were analyzed to determine the systematic relationships between truck properties and pavement damage. An overview of the fatigue damage arising from the static loads on the axles of the 13 basic truck configurations is shown in Figures 3 and 4 for rigid and flexible pavements, respectively.

The immediate observation from the figures is that the damage variation among the pavement types is much broader than among the trucks. From the weakest, low-volume roads to the high-strength primary roads, damage varies by over three orders of magnitude. On the other hand, on any individual road the damage of the "worst" truck is less than an order of magnitude greater than that of the most road-friendly truck.

On many of the roads the vehicle passes to failure is theoretically above 10^8, which is effectively infinite life. The fact that roads do not last indefinitely infers inaccuracies in modeling the mechanics of truck-road interaction, inaccuracies in modeling failure mechanisms, or unrealistic failure criteria. It is likely that all of these factors contribute to the shortcomings of the theoretical predictions when environmental deterioration of the pavement structure is taken into account. Unfortunately, these mechanics are too complex to duplicate with current models.

3.1 Static Load Distribution

The truck property with the strongest direct influence on fatigue damage of the pavement structure is the static load(s) on the most heavily loaded axles. The strength of the relationship arises from the fact that fatigue is generally related to load by a power law. Whereas front axles on loaded trucks may operate at 4.5 t (10 kips), rear axles may be loaded to 10 t (22 kips). With a 4th power damage law, the variation in damage over the range of axle loads is more than 20 to 1.

The cumulative damage for a total vehicle depends on the static load "footprint" imposed on the roadway–reflected in the number of axles and the load on each axle in the combination. The total damage from the static axle loads of a

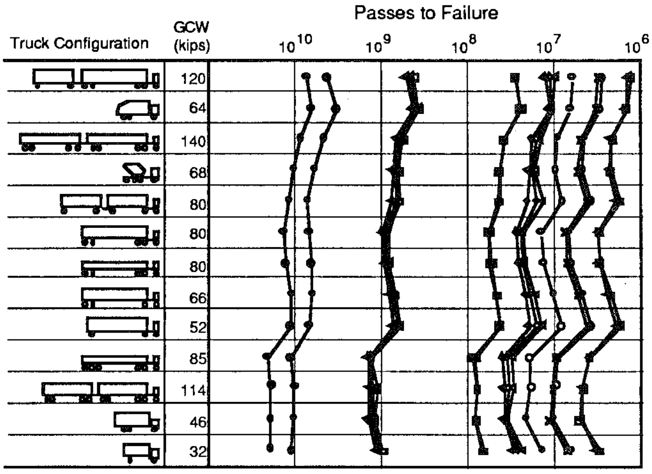


Fig. 3. Fatigue damage caused by various trucks at their static loads on a mix of rigid pavement designs.

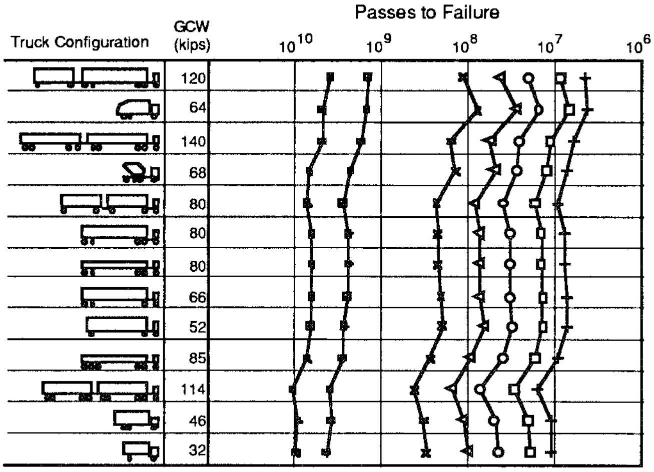


Fig. 4. Fatigue damage caused by various trucks at their static loads on a mix of flexible pavement designs.

truck can be quantified by expressing it in terms of equivalent passes of a reference axle. In the United States that reference is an 8.2 t (18 kip) load carried on a single axle with dual tires. Relative damage is expressed as Equivalent Single Axle Loads (ESALs). For a total vehicle the first estimate of the relative damage from its static load footprint is obtained by summing the damage over all axles, where the damage for individual axles is computed from the load normalized by 8.2 t (18 kip) raised to the power of the failure law. That is:

$$\text{Damage (ESALs)} = \sum_{i=1}^{n} (W_i/18)^e \qquad (1a)$$

where

W_i = Load on axle "i" (thousands of pounds)
i = Axle number
n = Number of axles
e = Exponent in the failure power law

Accordingly, the damage is expressed in metric units as:

$$\text{Damage (ESALs)} = \sum_{i=1}^{n} (W_i/8.16)^e \qquad (1b)$$

where

W_i = Load on axle "i" (metric tonnes)

The exponent, e, in the power law has been assigned a wide range of values; from 2 - 6 for flexible pavements, 1.3 - 4.1 for composite pavements, and 8 - 33 for rigid pavements [9]. For purposes of discussion a numerical value of 4 will be assumed. Higher values, of course, place greater importance on the most heavily loaded axles and dynamic effects, and lower values diminish their importance.

The first order influence of axle loads is seen by comparing the theoretical damage computed for the 13 basic truck configurations presented in Figures 3 and 4, where the trucks are ordered in accordance with equation (1).

On rigid pavements the trucks order similarly despite the variations in truck and pavement design. Deviations from the order are primarily the result of beneficial load interactions between closely-spaced tandem axles which makes trucks with such axles better than predicted by equation (1). Differences in tire types have little influence on rigid pavements.

On flexible pavements the deviations in damage are primarily the result of differences in the loads carried on front axles, which have single tires. Trucks with wide-base singles (the second and fourth trucks) are more damaging because of the high front axle load. Those with light front axle loads (fifth and eleventh trucks) are less damaging relative to other vehicles.

Overall, the axle loads and load distributions in the truck loading footprint result in variations in the theoretical fatigue damage among vehicle configurations that span a range of 5 to 1. Although the truck gross weights vary over a comparable range, the most damaging trucks are not necessarily the heaviest trucks. This argues for the importance of distributing the load equally among individual axles on a truck, and making efforts to ensure that multiple-axle suspensions achieve good load sharing performance.

Rutting in the asphalt concrete layer is proportional to load with some minor deviations dependent on tire type.

3.1.1 Static load sharing on multiple-axle suspensions: Static load sharing within a multiple-axle suspension group influences fatigue of rigid and flexible pavements moderately as a result of the higher load on one axle when sharing is not equal. Increasing the load on one axle of a tandem set disproportionately increases the fatigue from that axle because of the power-law relationship between load and fatigue. The reduced load on the other axle reduces its contribution to fatigue, but does not fully offset the increase from the heavy axle. Figure 5 shows the relative fatigue damage on flexible pavements from variations in load sharing coefficient. The load sharing coefficient is defined as the load on the heaviest axle divided by the average load.

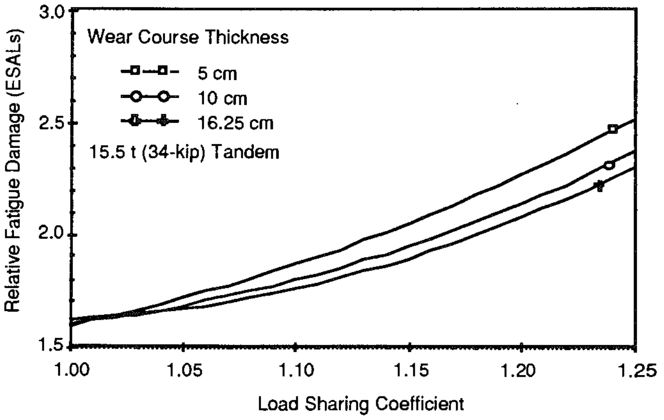


Fig. 5. Influence of load sharing coefficient on flexible pavement fatigue damage.

If the individual loads of a multiple-axle group are held to within 5% of the mean load for the group, very little additional fatigue will result. Load disparities as high as 25% have been observed [13], which increase fatigue damage as much as 60%. Static load sharing has no influence on rutting by virtue of the linear relationship between rutting and axle load.

3.2 Truck Dynamic Behavior

The significance of loads and load-distribution factors in the truck static load footprint discussed above is not directly linked to the dynamic behavior of trucks. The dynamic component of axle loads can elevate the damage experienced by a pavement above that induced by static axle loads. The dynamic effects are directly evident in the damage influences from the interacting effects of road roughness, operating speed, and truck suspension characteristics.

3.2.1 Speed and roughness: Although the roughness of a road is defined at a reference speed [14], the roughness experienced by a motor vehicle is dependent on the operating speed. Given that the road has deviations in its elevation profile, the accelerations experienced by the wheel as it follows the profile increase with speed, yielding a concurrent increase in the dynamic wheel force. Adding to the complexity of the mechanics are the dynamic properties of the vehicle, largely concentrated in the resonances of the rigid body(ies) and suspension systems, which may tune to certain wavelengths in the road. On roads which have a uniform spectral content over the relevant wavelength range, the apparent roughness increases monotonically with speed. The dynamic loads may be expected to increase accordingly, except as altered by:

- Periodic components in the roughness spectrum (e.g., joint roughness in concrete pavements) which may tune to vehicle resonances,
- Nonlinearities in the suspension which cause the effective stiffness and damping to change with excitation level,
- Tuning of vehicle pitch motion resonance due to wheelbase filtering [15],
- Resonances of multiple-axle suspensions through the load-sharing mechanisms.

The effect of a vehicle tuning to road roughness is illustrated by the dynamic load coefficients for two axles of a 3-axle tractor semi-trailer shown in Figure 6. The predominant manifestation of tuning occurs on the trailer axle at 80 kph, which is the result of rigid body bounce at the rear of the trailer.

On rigid pavements damage generally increases with speed on roads of all roughness levels. Because of the tuning it may be nonlinear with speed, and over a narrow speed range it may even decrease as a dynamic mode passes out of resonance [13].

On flexible pavements damage increases more slowly with speed as a result of the visco-elastic nature of the asphalt materials. The shorter duration of the load application time at high speed gives the pavement less time to respond. This phenomena helps to counteract the increasing damage potential from higher dynamic loads. Consequently, damage may change little with speed, particularly on smoother pavements.

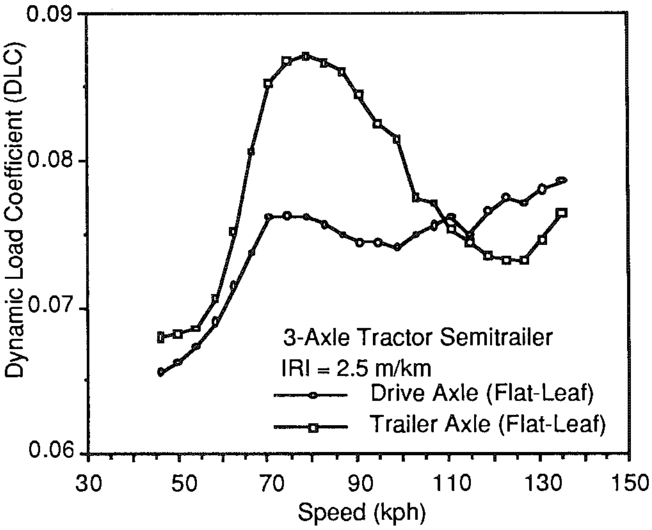


Fig. 6. Example of a vehicle "tuning" to a road.

3.2.2 Single-axle suspensions: The relative performance of different suspensions can be compared by examining how damage changes with road roughness when speed is held constant. Figure 7 shows the 95% fatigue damage on flexible pavements for the most common single-axle suspensions. The parameters for characterizing the air-spring suspension were obtained from dynamic tests on a hydraulic road simulator. Those for the leaf-spring suspensions were obtained from experimental measurements of force-displacement properties of typical suspension systems.

The value of low spring rate in minimizing road damage is evident in the performance of the air-spring suspension, which incorporates the lowest spring rate practical for a truck with passive suspensions. Equally important are the damping properties, which were not optimal on the actual suspension measured. In order to provide a reference for the best possible dynamic load performance, the "optimal air-spring suspension" shown in the figure was formulated by adjusting the linear damping coefficient to achieve minimum dynamic load and damage.

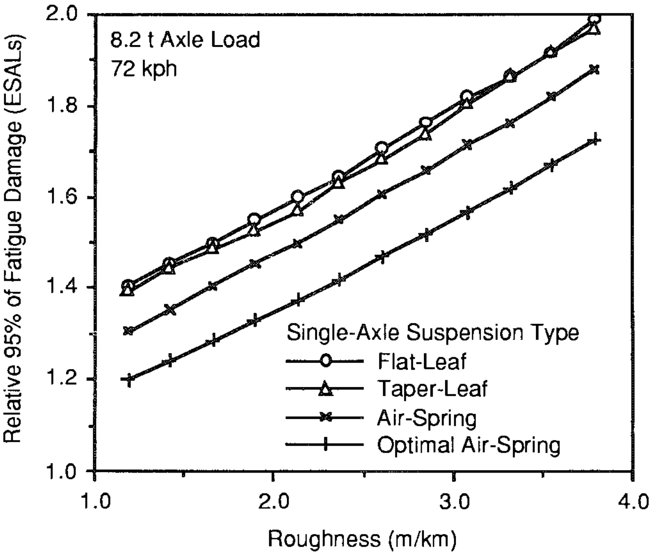


Fig. 7. Influence of single-axle suspension type on flexible pavement fatigue.

The actual air-spring suspension is nominally 10% more damaging than the optimal over the roughness range. The performance of both the flat- and taper-leaf suspensions is nominally 15% worse than the optimal air spring across the range of roughness values.

3.2.3 Tandem-axle suspensions: Tandem-axle suspensions have the potential for behavior that increases damage via dynamic interaction through the load-equalization mechanism. This behavior is most evident in the "tandem-hop" mode of vibration characteristic of walking-beam suspensions [16]. Figure 8 shows the relative damage from the most common suspension types when speed is held constant. Parameters to characterize the dynamic behavior for the air-spring and 4-spring suspension types were obtained from road simulator tests on these truck suspensions. The parameters for the walking-beam were obtained from on-road tests. However, it should be noted that only one suspension was tested in each case, so the representativeness of these curves for each suspension type is not known at this time.

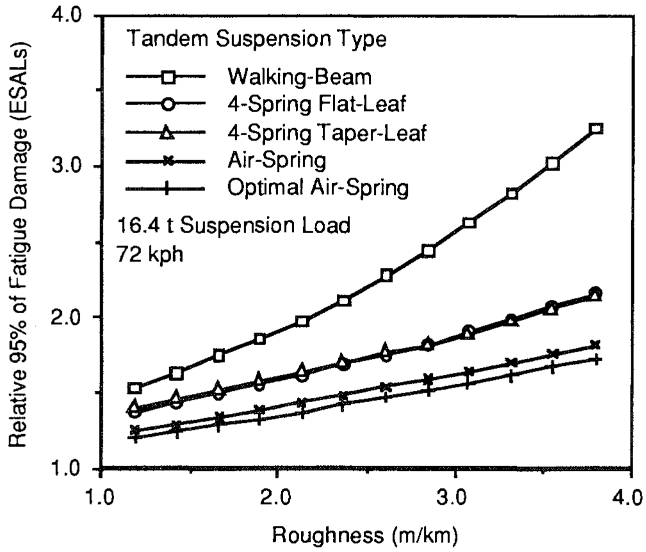


Fig. 8. Influence of tandem suspension type on flexible pavement fatigue damage per axle.

As before, the optimal air-spring suspension serves as a reference for judging performance of other suspensions. The air-spring tandem suspension is again about 10% worse than the optimal design. The 4-spring (flat and taper) suspensions are about 25% more damaging than the optimal at all levels of roughness. The poor dynamic performance of the walking-beam results in damage that is up to 90% greater than that achieved by the optimal air-spring suspension. The elevated damage of the walking-beam is caused by tandem-hop vibration, which tunes to the roughness at the speed assumed in the calculations. At other speeds the relative damage will vary from that shown.

3.3 Tire Factors

Variations in the size of the tire-pavement contact patch and the intensity of loading are responsible for the wide variation in the pavement damaging potential of different tires and tire configurations.

3.3.1 Configuration: The configuration of tires as duals, singles, wide-base singles, and low-aspect-ratio singles affects the distribution of normal stresses on the pavement surface when operated at rated load.

Flexible pavement fatigue is highly sensitive to variations in size of the tire contact area over which the load is distributed. Single tires are so damaging relative to duals that an axle loaded to 5.4 t (12 kips) with single tires (typical of a steer axle) is often more damaging than an axle with dual tires loaded to 9.0 t (20 kips). Figure 9 shows the relative damage equivalence factors for a variety of tires on flexible pavements. The damage potential for each tire configuration is sensitive to pavement design factors, so a nominal range is shown for each. The comparison in this case is an axle loaded to 8.2 t (18 kip) outfitted with conventional dual tires of the common 11R22.5 size.

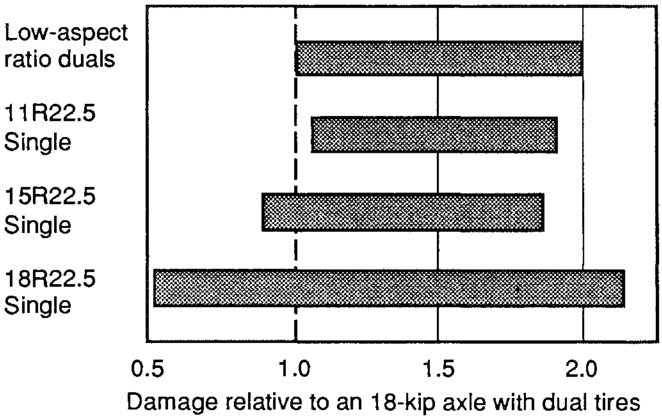


Fig. 9. Flexible pavement fatigue damage equivalence factors for different tire configurations at their rated load.

The low-aspect ratio tires (even though limited to 7.7 t (17 kip) load in the duals configuration) are at least as damaging as the conventional arrangement, and nearly twice as damaging on thinner pavements.

An axle with 11R22.5 single tires, rated to carry 10.9 t (12 kip) and typical of steering axle applications, is generally more damaging than the 16.3 t (18 kip) drive or trailer axle.

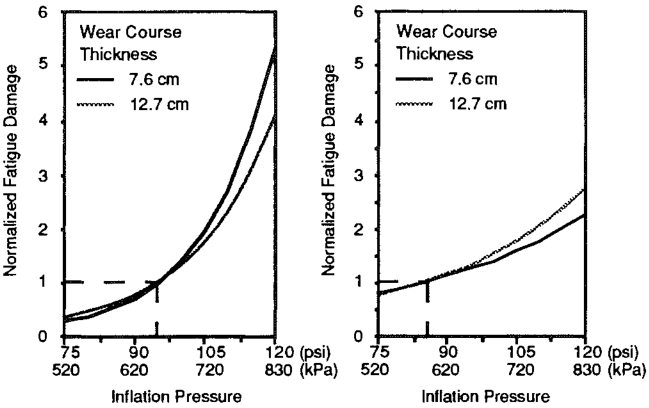
The wide-base single tires vary in their relative damage level. On most pavements they are worse than the 16.3 t (18 kip) standard axle. In order to preclude higher damage, wide-base single tires need to be operated at less than their rated load.

Rigid pavement fatigue is not as sensitive to tire contact conditions. Thus, axles with single tires are less damaging than those with duals, except for the largest wide-base single tires which are rated to carry loads above that of axles with conventional dual tires.

Rutting is dependent on load and contact area. For a given load, rut *depth* is higher when it is carried on single tires, although the rut *volume* differs little between single and dual tires.

3.3.2 Inflation pressure: Variations in tire inflation pressure affect pavement damage primarily through the change in size of the contact patch. Inflation pressure has only a moderate impact on rigid pavement fatigue, because rigid pavement response is dependent on tire load, rather than contact area.

On the other hand, flexible pavement fatigue is strongly affected by inflation pressure as shown in Figure 10. In the case of wide-base single tires, damage may increase by more than 100% with a 70 kPa (10 psi) increase in pressure.



(a) 15R22.5 at 3640 kg (b) 11R22.5 duals at 4550 kg

Fig. 10. Flexible pavement fatigue damage as a function of inflation pressure for wide-base single and dual tires.

Rutting was found to increase moderately with inflation pressure.

Overall, changes in tire dimensions and inflation pressures that will reduce contact pressures can reduce road damage, particularly on flexible pavements. This translates into use of tires with the widest available tread and largest diameters. The competitive pressure for truck operators to adopt small, low-aspect tires to their fleets carries with it the potential for even more road damage from trucks in the future.

3.3.3 Construction type: Tire construction type (radial vs. bias-ply) has little direct effect on fatigue of rigid or flexible pavements. The differences in vertical stiffness and contact patch size are second-order in magnitude and may not be systematic between tire types.

However, the different camber and cornering properties of radial and bias-ply tires will affect wheel tracking behavior and consequently the rutting damage. Rear axles on trucks with radial-ply tires will tend to track more precisely in the path of front axles. In addition, the low camber stiffness of radial-ply tires makes it easier for tires to track in existing pavement ruts.

Figure 11 shows the forces acting on a truck tire operating on a cross-sloped surface. Tracking behavior depends on the balance between the gravitational force component trying to push the tire down the slope and the camber thrust opposing it. If the camber coefficient (camber thrust per unit load per degree of inclination) is greater than 0.0175 kgf/kgf/deg, a tire will tend to run up the slope, whereas it will run down if the coefficient is below that value.

From the sparse amount of data available on these properties of radial and bias-ply tires (see Figure 12 from [17]), it appears that radial tires generally have insufficient camber thrust to climb out of a rut, while bias-ply tires do. Thus, trucks with bias-ply tires will tend to climb out of ruts, thereby distributing rutting damage over the width of the wheeltrack. Those with radial tires will tend to run in the rut once one has formed, thereby accelerating fatigue and rutting damage, and concentrating it in a narrow wheeltrack. This factor may be one of the primary causes for the frequent incidence of dual-wheel ruts appearing on flexible pavement roadways (sometimes known as "sudden early rutting"), which has coincided with the transition to radial-ply tires in the trucking industry.

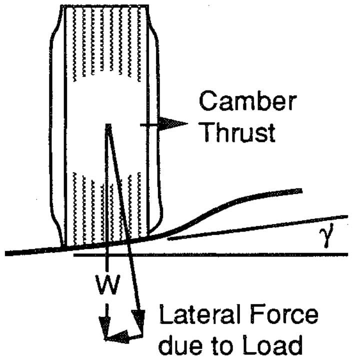


Fig. 11. Forces acting on a tire on a cross-slope surface.

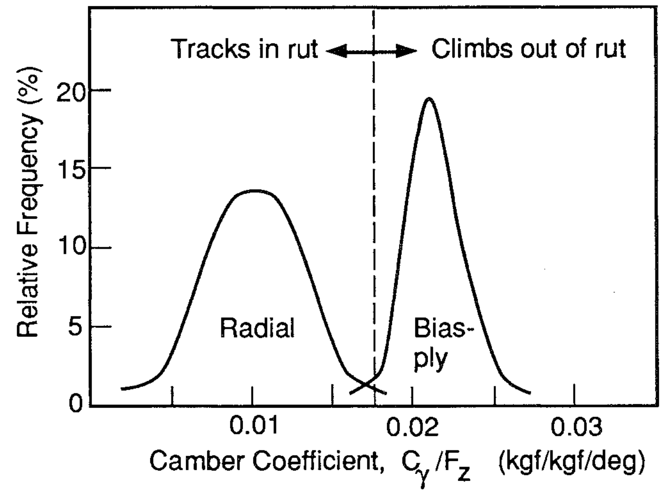


Fig. 12. Frequency distribution of camber coefficient for radial and bias-ply passenger car tires.

4.0 CONCLUSIONS

Road damage from heavy truck loads is dependent on many factors--the strength of the road being one of the most important. However, given that trucks must use the existing road system, it is advantageous to favor trucks with characteristics that impose the least damage.

The most critical property affecting fatigue damage on any type of road is the maximum load on the axles. Distributing load to achieve uniformity among axles and equal loads on tires (of comparable size) is essential to minimizing road damage. This requires attention to loading practices, as well as selection of multiple-axle suspensions with good load equalization performance. Similarly, the use of the largest practical tire size helps to minimize fatigue damage of flexible pavements. Wide-base singles operated at their rated loads are more damaging than dual tires. On all tires, inflation pressures in excess of the rated pressure will increase damage.

The dynamic motions of trucks caused by road roughness adds to the damage in regions of high dynamic load, increasing the localized damage by factors of two or more on rough roads. Air-spring suspensions have the potential for near optimal performance (among passive suspensions) with regard to minimizing road damage, if the damping is properly chosen. Typical leaf-spring suspensions appear to be about 15% - 25% more damaging than an optimal passive suspension. Walking-beam tandem suspensions may be nearly twice as damaging as the optimal suspension as a result of poorly-damped "tandem-hop" vibrations.

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