Analyzing the Interactions Between Dynamic Vehicle Loads and Highway Pavements

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Mechanistic models to predict structural performance and deterioration have been developed for both flexible and rigid pavements. However, many of these models retain a simplified and idealized depiction of tire loads, and none really incorporates a true representation of a moving, dynamic force along the pavement surface. Thus, attempts to model the impacts to pavements of new types of heavy vehicles have at best been approximate and have often had to be supplemented by empirical data. In this paper we develop analytic models to study the interactions between moving, dynamic loads and highway pavements. One set of models simulates the dynamic behavior of heavy vehicles, including their body configuration and mass distribution, axle spacing and configuration, nonlinear suspension characteristics, and nonlinear tire behavior. The second set of models simulates the primary responses (stresses, strains, etc.) of pavements to vehicle forces, and translates primary responses into pavement damage. Existing mechanistic models are modified specifically to treat moving, dynamic loads for both flexible and rigid pavements. This paper presents examples of results (in terms of both dynamic forces and pavement damage) for rigid pavements, although the concepts apply as well to flexible surfaces. A parametric study is summarized, considering variations in both vehicle and pavement characteristics. Those characteristics most important to dynamic loading include vehicle suspension type and characteristics, speed, height of pavement faults, and joint spacing. Other factors (such as tire pressure) contribute smaller effects (although tire pressures are more important on flexible pavements). Results indicate that under certain conditions, dynamic loads are 40 percent higher than static loads and affect the mid-region of PCC slabs most significantly.

Current models of vehicle-pavement interaction employ simplified models of vehicle loading, such as static or pseudo-moving loads. However, instantaneous dynamic vehicle loads may be considerably higher than static loads (*1*, *2*); thus, dynamic loading can have a considerable impact on pavement performance (*3*). Current models cannot account for this effect. The prediction of pavement deterioration and serviceability under dynamic vehicle loading becomes particularly important when pavement design and analysis methods must be extended to encompass changing vehicle and pavement technology responding to new road design, construction, and regulatory practices. The purpose of this paper is to describe and illustrate a general methodology to analyze pavement responses to moving, dynamic vehicle loads, which may be used to predict pavement performance.

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DYNAMIC VEHICLE-PAVEMENT INTERACTIONS

The interaction between vehicle loads and pavement responses is frequently characterized as a one-way interaction, wherein the vehicle loads influence pavement responses but not vice versa. In reality, a mutually sustaining process occurs. The roughness of the pavement surface excites dynamic forces within the vehicle. These dynamic tire forces induce primary responses (stresses, strains, deflections) within the pavement, which affect the amount of distress produced by the vehicle, which in turn affects the dynamic tire forces experienced by subsequent vehicles, and so on in a two-way interaction between vehicles and pavements.

Analysis by Simulation Models

The study of this two-directional interaction between vehicles and pavements is a fundamental tenet of the research project described in this paper. The objective of this study is to assess the impacts of moving, dynamic vehicle loads on both flexible and rigid surfaces. Furthermore, an underlying premise is to generalize the problem description and analytic procedures so that, for example, new axle configurations, new tire designs, variations in tire pressures, as well as changes in pavement design and construction may be analyzed simultaneously. To do this, the study employs two sets of simulation models.

One set of models simulates the behavior of several commercial vehicles, including their configuration and mass distribution, axle spacing and configuration, suspension characteristics, and tire behavior. Each of these models simulates the movement of a given vehicle along a pavement profile;

any roughness inherent in the profile excites the dynamic elements of the simulated vehicle, as a function of the amplitude and frequency of the surface irregularities, the vehicle characteristics described above, and vehicle speed. The result of this simulation is a vehicle force profile containing digitized values of tire forces over distance (or time), representing the combined effects of all dynamic motions simulated. (Vehicle motions are simulated in a vertical plane through the vehicle's longitudinal axis (a "bicycle model"). The models therefore simulate bounce and pitch of the vehicle body, suspension, and tires, but not roll from side to side.)

The second set of models simulates the response of a pavement to the dynamic force profile of a moving vehicle developed above. The models used have been selected from the available mechanistic models for flexible and rigid pavements and adapted specifically to handle moving, dynamic loads. The objective was not to improve the modeling of pavement responses per se, but rather to build in the coupling with the vehicle force profile and to modify the response calculations to account for axle groupings (tandems, tridems, etc.). A requirement placed on the models selected was that they predict both primary responses (stresses, strains, and deflections), as well as ultimate responses: both distress (cracking, rutting, spalling, faulting, etc.) and serviceability. Since distress accumulates with the number of load repetitions and is also influenced by the magnitude, duration, and configuration of loading, as well as environmental and time-dependent conditions, the behavioral response predicted by these models should also be time- and temperature-dependent.

Separate analyses have been conducted for flexible and rigid pavements to account for inherent differences in mechanistic behavior, boundary conditions, and design characteristics. For flexible pavements, a modified version of Federal Highway Administration (FHWA) VESYS system has been used to represent pavement responses to moving, dynamic vehicle loads; for rigid pavements, a modified version of PMARP (also developed for FHWA) has been used. For purposes of illustration, this paper examines a case study of rigid pavements; the modifications to the PMARP pavement model are described in a subsequent section.

General Analytic Approach

Although separate models are used to simulate flexible and rigid pavements, the general approach is the same in each case. The force profile generated by the vehicle models simulates a moving, dynamic load along the pavement. At one or more points of measurement in the pavement, these dynamic forces are translated into primary responses and the maximum response computed. Where axle groups are encountered, appropriate superposition of responses is performed, and the maximum total response is identified. The maximum response is then translated into the appropriate components of pavement distress. Increments of distress are accumulated through repeated vehicle passes and the results compiled. Thus, the result of this simulation is a progression of damage in the pavement as a function of the pavement surface roughness (which increases over time as a function of the thickness and materials properties of the pavement layers, subgrade strength, environmental factors, etc.), vehicle characteristics (as represented by the dynamic tire force profile), and vehicle speed.

In theory, the two analytic steps above should be performed in an iterative process in which vehicle forces are generated and applied to a pavement, the increment in pavement damage (specifically, roughness) due to this force profile computed, that new force profile applied to the pavement, the new increment in roughness computed, and so forth. Since this procedure would be extremely expensive in computer time, a close approximation is employed: vehicle force profiles are computed in the vehicle simulation for several discrete levels of pavement roughness. These results are interpolated for any other levels of roughness encountered in the subsequent simulations of pavement deterioration.

Dynamic Vehicle Behavior

Models to simulate the behavior of moving vehicles have been developed for several commercial trucks and buses and are described by O'Connell, Abbo, and Hedrick (*4*); Hedrick, Cho, Gibson, et al. (*5*); Hedrick, Markow, Brademeyer et al. (*6*); and Abbo (*7*). These models represent analytically the dynamic behavior of the component rigid bodies, axle suspensions, and tires as the vehicle moves along a pavement of specified roughness at a specified speed. The result is a force vs. time or force vs. distance profile, again as a function of (assumed constant) speed and pavement roughness. Separate force profiles are produced for each axle of the vehicle, for each speed and roughness. These force profiles are used as inputs to the models of pavement response.

Influence Functions to Reflect Moving Loads

For vehicle speeds of interest, the dynamic effect on pavement mass or inertia is negligible, as shown by Delatte (*8*). There-

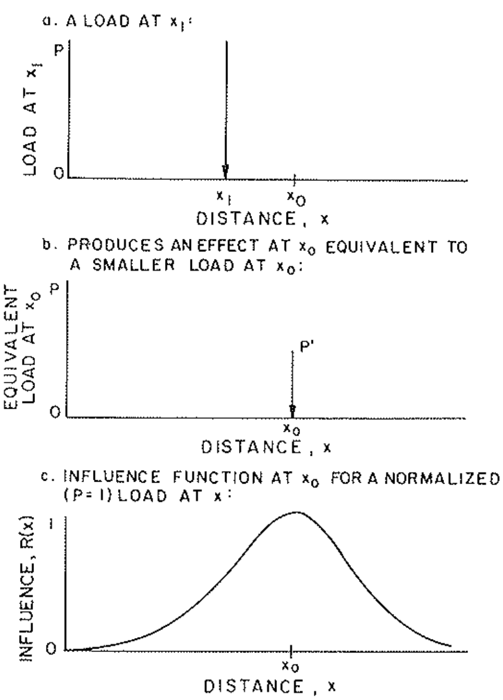

FIGURE 1 Load influence.

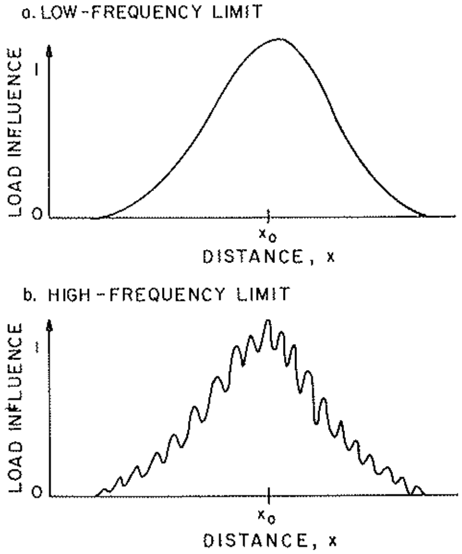

FIGURE 2 Variation of load influence with dynamic loads.

fore, one may represent the pavement response to a moving vehicle load as a quasi-static phenomenon, as shown in figure 1 (where pavement response refers to stress, strain, or deflection at a point in the pavement structure). Given this premise, the pavement response to a load P at a distance $x = x_0 - x_1$ is assumed to be equivalent to the response to a lesser load ($P' < P$) placed directly above the point of interest (x_0). This effect can be captured by influence functions relating the effect at x_0 of a load P at x_1. For a unit load ($P = 1$), the primary response at x_0 due to the load P at x_1 is characterized by the instantaneous static (or elastic) response $I(x_0 - x_1)$, where the function $I(x_0 - x_1)$ is the influence function. As an arbitrary load traverses the pavement, the response at x_0, $R(x_0)$, due to the force $F(x)$ imposed by this load at an arbitrary location x is given by the response function:

$$R(x_0) = I(x_0 - x)\,F(x) \tag{1}$$

The influence function in figure 1 is appropriate for a load of constant (unit) magnitude traversing the pavement. In the general case, however, the load will fluctuate, reflecting the dynamic vehicle forces discussed above. Thus, a dynamically varying component will be superimposed on the influence function in figure 1. The result of this superposition is illustrated in figure 2 (at the low-frequency and high-frequency limits). Therefore, the maximum influence a moving load can exert in the vertical plane at x_0 is a function of both the shape of the basic influence function in figure 1 and the dynamic effects superimposed on the basic function, as shown in figure 2. It is this maximum influence (or, if appropriate, the mean and variance of the maximum influence) that is used as the basis of pavement damage prediction.

Observe that the maximum influence a moving, dynamic load may have on x_0 does not necessarily occur when the load is directly above x_0. First, because of viscoelastic behavior, pavement responses may exhibit a delay in relation to the moving load. Second, the dynamic effects illustrated in figure 2 may shift the peak influence some distance from x_0. The magnitude of this distance depends on the frequency of the dynamic load variation.

Pavement Damage

Different response functions (equation 1) may be defined for stress, strain, strain-energy, or deflection and are obtained from the particular mechanistic model used in the analysis. For purposes of illustration, rigid pavements have been selected as examples in this paper. Solutions yielding the primary responses in portland cement concrete pavements that have joints or cracks have been developed over the past ten years. These solutions rely on finite element methods to treat the rigid behavior of the slab and the discontinuities (joints) between slabs. Several candidate models were available for consideration for this project, as reviewed by Abbo (*7*). The one selected for this project was the PMARP program (*9*).

In its original form, the PMARP program computes stresses and strains due to a static point load at a critical slab location. Miner's hypothesis is used to determine fatigue cracking at the individual nodes of the slab. Although the Miner's Law calculation is retained in the version used in this research, several changes were made to PMARP to improve its simulation of a moving, dynamic load. First, influence functions were introduced to model the travel of the load along the slab. Second, new equations were included (and some corrections made to existing equations in the model) to improve its predictions of pavement damage. A summary of the major additions is given below.

Joint Faulting Model

The joint faulting model used is the one adapted from PCA research for use in the EAROMAR-2 program developed for Federal Highway Administration (*10*). This model considers jointing as a function of traffic, pavement age, joint spacing, subgrade drainage, and type of subbase. For undoweled pavements the equation for jointing is as follows:

$$JF = 0.0403 + \frac{1.53(DTN{\cdot}A^2)^{0.465}}{H^{3.9}}\,S^{0.61}\,(J - 13.5)^b \tag{2}$$

where

JF = joint fault magnitude (in.),
DTN = daily traffic number, or the number of vehicle passes per day,
A = age of pavement (yrs),
H = slab thickness (in.),
S = subgrade type (good = 1, poor = 2),
J = joint spacing (ft.), and
b = factor depending upon subbase characteristics, equaling 0.241 for granular subbases and 0.037 for stabilized subbases.

The faulting model for doweled pavements is

$$JF_{LTD} = \frac{1}{(1 + A)^{1/2}}\,JF \tag{3}$$

Thermal Gradient in the Slab

A difference in temperature between the top and bottom of the slab introduces thermal stresses that are superimposed on (either constructively or in opposition to) the stresses caused by traffic loads. The thermal gradient in the slab may be represented in the finite element model as an equivalent moment applied along the edge of the slab. The resulting stress may be represented as follows:

$$M^* = \frac{\alpha g E t^3}{12} \tag{4}$$

where

M^* = equivalent moment induced by thermal stresses (psi),
α = coefficient of thermal expansion (in./in./deg-F),
g = thermal gradient (deg-F/in.),
E = Young's Modulus of Elasticity of concrete (psi), and
t = thickness of the slab (in.).

Additional Assumptions

In applying the modified PMARP model to the analysis of dynamic loads, the following assumptions were made to simplify the computations and reduce computer time:

- The elastic modulus of concrete and the modulus of rupture were assumed to remain constant over the life of the pavement and were taken as average values.
- Subgrade weakening due to pumping was neglected.
- The major contribution to roughness was taken to be the faults at joints, rather than surface roughness in the interior of the pavement slab.

RESULTS

Parametric Studies

These procedures were applied in a set of parametric studies, in which the following parameters were varied:

1. Suspension Type:
   - Single-Leaf
   - Four-Leaf Tandem
   - Walking-Beam Tandem
2. Suspension Stiffness, k
3. β-parameter for Leaf-Springs
4. Vehicle Speed
5. Tire Pressure
6. Axle Load Sharing Coefficient
7. Tandem Axle Spacing
8. Pavement Roughness (i.e., Fault Height)
9. Joint Spacing
10. Slab Warping
11. Slab Interior Roughness

The results of these studies are summarized below, with a more complete presentation by Abbo (7).

Effects of Pavement Characteristics on Dynamic Loads

First it is useful to understand the pattern of dynamic loading and how that pattern is influenced by pavement characteristics. To do so we have used a base case comprising a jointed, undoweled pavement having a slab length of 30 feet. Undoweled pavements have been simulated because they exhibit greater faulting and permit a fuller study of the effects of faults on vehicle dynamics. For the base case, a uniform fault height of 0.5 inch has been assumed. (Doweled pavement joints generally maintain faulting within 0.2 inch over the pavement service life, according to the faulting model used in equation 3. At these relatively small fault heights, less than 0.25 inch, there is no significant variation in vehicle dynamics with respect to the parameters tested. This will be illustrated in the results below.) The vehicle used in testing the sensitivity to pavement parameters is a 2S1 combination with single-leaf spring suspensions, travelling at 35 mph.

Loading and Responses Due to Multiple Axles

Although the outputs of the vehicle and pavement models permit detailed analyses by axle, more aggregate and concise measures of results make it easier to display the sensitivity of dynamic loading to pavement and vehicle parameters. These measures embody the effects of the vehicle overall, rather than of any given axle combination. One such measure pertains to the force imposed by the vehicle, the second to the pavement response. To compute these measures, the pavement slab is divided into equal-size sections sufficiently small to enable resolution of the peak forces up to the highest frequencies of interest. The aggregate force at a particular point K is defined by:

$$F_K = \sum_{j=1}^{N_a} P_{jk} \quad \text{for } k = 1, 2, 3, \ldots, N_s \tag{5}$$

where

N_a = number of vehicle axles j,
P_{jk} = force imposed by axle j at slab location k, and
N_s = total number of stations k along the slab length.

The mean aggregate load is determined by averaging the aggregate load in equation 5 over several slabs (typically 20) to suppress any transient dynamic effects. The mean aggregate load is then normalized by the vehicle static load, and it is this value that is displayed in the results below. It is important to bear in mind that the aggregate force at a point depends on the cumulative effect of all vehicle axles that pass over it. Therefore, the maximum aggregate force will not necessarily occur at the same location as the maximum force generated by any individual axle. Analogously, the aggregate response of the pavement $R_T(x)$ at some point x is the sum of the responses due to the individual vehicle axles:

$$R_T(x) = \sum_{j=1}^{N_a} R_j(x) \tag{6}$$

where $R_j(x)$ is the response function at x due to axle j (as computed in equation 1). In applying equations 5 and 6, account is taken of the proper spacing of the axles on a vehicle.

Effect of Slab Length

Four slab lengths, ranging from 10 feet to 45 feet, were investigated. The vehicle behavior due to these varying intervals between faults was investigated (for example, by changes in the power spectral density functions of the vehicles, as documented in (7)), as well as the effects on dynamic loads. A summary of these results follows.

The vehicle simulated in these examples has a steer-to-drive wheelbase of about 11.5 feet and a drive-to-rear wheelbase of 19.5 feet. Therefore, the 10-ft joint spacing results in almost simultaneous excitation of each of the three axles, stimulating primarily the vehicle bounce mode. For a joint spacing of 20 feet, there is a small time delay between inputs to the drive and rear axles, which excites the trailer bounce and tractor pitch modes, resulting in the largest pavement loads observed in this study. The 30-ft and 45-ft joint spacings do not excite the out-of-phase tractor-trailer pitch motions as much.

The effects of this behavior on aggregate vehicle load along the length of the slab can be seen in figure 3 for three of the joint spacings (20, 30, and 45 feet). A joint spacing of 20 feet produces a 12 percent increase in aggregate loading, with the peak load occurring roughly 10 feet after the faulted joint. Note, however, that the load imposed on the subsequent slab just after the joint is 20 percent lower for the 20-ft slab length than it is for the other slab lengths.

Effect of Height of Joint Fault

For the base case used (30-ft joint spacing, 35-mph vehicle speed) the height of joint faults did not affect the location of peak loads but did affect their magnitude. For example, considering just the drive axle of the vehicle, the normalized dynamic load (dynamic force divided by static force) measured at the peak load location 10 feet past the slab joint increased from about 1.05 for a 0.1-in fault to over 1.25 for a 0.75-in fault.

On an aggregate vehicle basis the impacts of joint faults can be seen in figure 4. There is a very small (about 3 percent) difference in the pattern and magnitude of loads for joint faults less than 0.25 inch. However, there is up to a 20 percent increase for a change in fault height from 0.25 inch to 0.75 inch. This illustrates the point mentioned above: relatively small fault heights (as might be expected on new pavements or those with good load transfer devices) result in insignificant changes in dynamic loadings. The increase in dynamic force that does take place when faulting becomes substantial supports the earlier contention that the two-way interaction between vehicles and pavements does indeed result in an accelerating, progressive cycle of vehicle load and pavement damage.

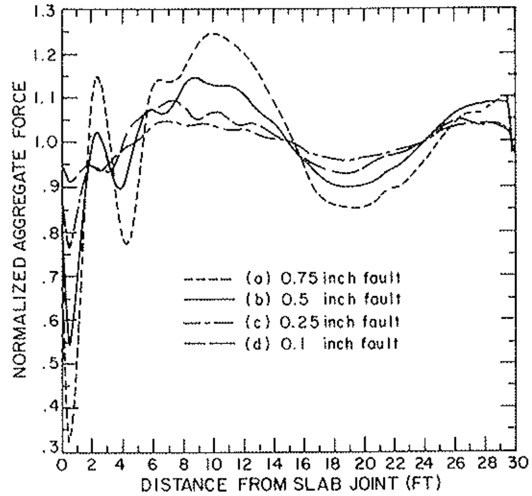

FIGURE 4 Effect of fault height on aggregate load.

Effect of Slab Warping

For a vehicle speed of 35 mph and a slab length of 30 feet, the warping of the slab corresponds to an input to the vehicle of 1.7 Hz. This frequency coincides with the natural frequency of the tractor bounce and pitch modes, which influences the changes in dynamic loading observed in figure 5. Specifically, the peak load regions of all the axles shift further away from the slab joint as the slab warping increases. The heaviest

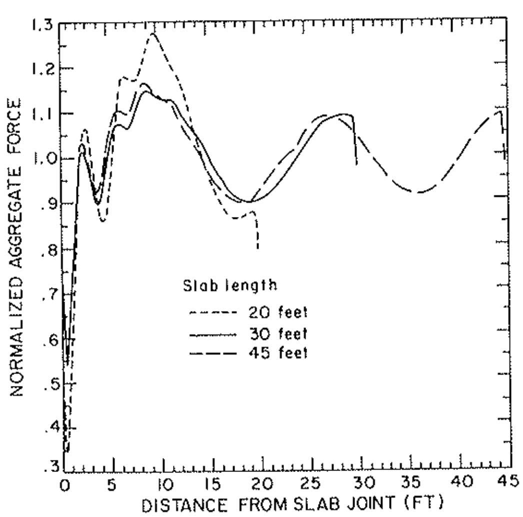

FIGURE 3 Effect of slab length on aggregate load.

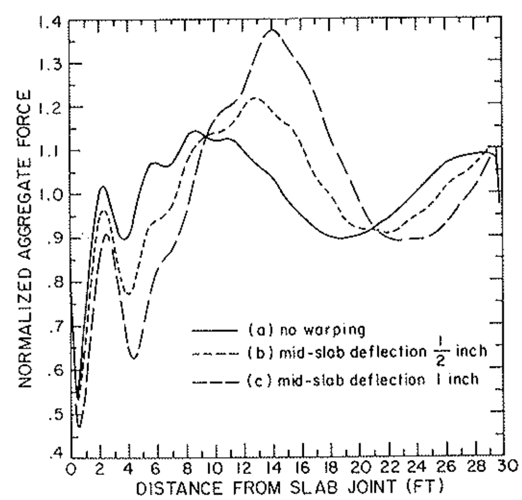

FIGURE 5 Effect of slab warping on aggregate load.

loading is sustained in the middle third of the slab, due to the excitation of the lower frequency body modes. This increase in aggregate loading is up to 25 percent for a slab radius of curvature of 1350 feet (equivalent to a 1-in deflection at the center of a 30-ft slab).

Effect of Slab Roughness

The interior roughness of the slab was varied by adjusting the assumed slope variance between 1.7×10^{-6} and 22×10^{-6} in.^{2}. Changes in the magnitudes of the resulting peak forces were no more than 4 percent and were judged to be insignificant over the range of roughnesses typically associated with rigid pavements. The primary excitation of vehicle dynamics was, therefore, taken to be the faults at rigid pavement joints.

Effects of Vehicle Parameters on Pavement Damage

The effects of vehicle parameters were also investigated. Although the results could again be expressed in terms of aggregate load, we now take them one step further to use the modified PMARP model (including equations 2 through 4) to consider the impacts on pavement damage. In these runs, damage has been limited to fatigue cracking, which is presented in two ways: (1) as a probability of occurrence over time, taken as a weighted average of the Miner's Law calculations for all nodes in the slab, and (2) as the amount of damage (in square inches) occurring by region of the slab. (Five regions have been defined, where the load traverses the slab from region 1 to region 5.)

Static Versus Dynamic Moving Load

Damage due to dynamic loading was compared to the simulated case of a moving constant load for the reference vehicle (a 2S1 tractor-semi-trailer) and the base case pavement conditions (30-ft slab length, 0.5-in fault height, 35-mph vehicle speed). The results are illustrated in figures 6 and 7.

The moving dynamic load produces approximately 38 percent greater fatigue cracking damage than the static moving case after 15 years of pavement service, as shown in figure 6. This indicates the importance of considering vehicle dynamic loading when assessing pavement performance. A somewhat unexpected result is that the rate of additional damage accumulation is linear, rather than accelerating as had been hypothesized. This result may be due to some of the simplifying assumptions made earlier, in particular the constant values of the concrete elastic modulus. (Note that these results differ from those discussed for faults earlier.)

Figure 7 illustrates the distribution of cracking along the slab length for the constant and dynamic moving load cases. For constant (or moving static) loads we obtain a symmetrical distribution of cracking over the slab, with the most severe cracking occurring in the regions close to the joints. Comparing this to the dynamically moving load, we note that there is a 15 percent decrease in the cracking that occurs in the regions close to the joints. Furthermore, there is a large increase in the cracking in the mid-slab regions, which is

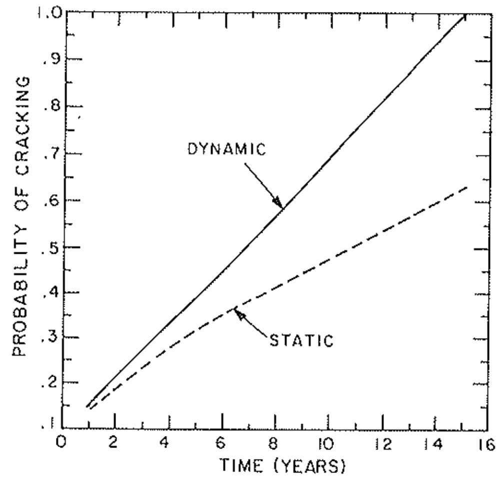

FIGURE 6 Growth in the probability of fatigue damage: moving dynamic load vs. moving constant load.

attributable directly to the body mode contribution to the tire force. The importance of the body mode contribution to total dynamic loading on rigid pavements has already been alluded to in the discussion of the role of pavement faults and joint spacing in exciting this mode; this finding will be reinforced in the analysis of vehicle characteristics below.

Single Leaf-Spring Suspension (2S1)

Effect of Leaf-Spring Stiffness The effect of increasing the leaf-spring stiffness is to reduce the wheel mode and increase the body mode contribution to the tire force on the pavement. (Wheel-mode forces are of higher frequency, about 10–15 Hz; body-mode forces are of lower frequency, about 2–3 Hz.) The resulting effect on pavement cracking over a 15-yr simulated period is a 10 percent reduction in the cracking damage when the leaf-spring stiffness is halved. Furthermore, mid-slab cracking is lowered by a reduction in the leaf-spring stiff-

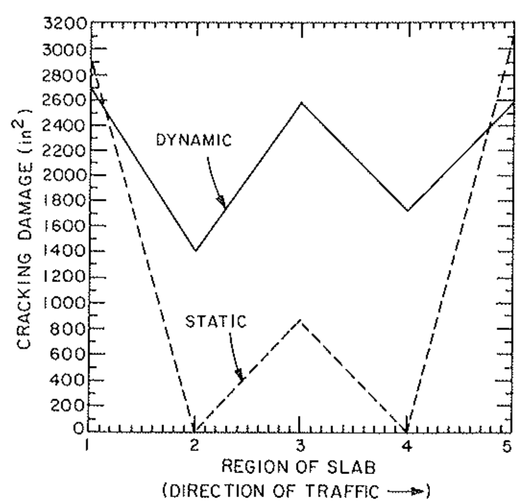

FIGURE 7 Cracking damage (in.^{2}) along slab length: moving dynamic load vs. moving constant load.

ness. However, these savings are somewhat offset by the increase in cracking in the region close to the joint, due to an increase in the wheel mode contribution to the tire force with the softer suspension.

Effect of β-Parameter β is a friction parameter that describes the hysteretic nature of the leaf-spring. The nominal (base-case) value of β is 4×10^{-3} feet. The effect of decreasing the leaf-spring damping (increasing β) is to increase the wheel mode contribution and reduce the body mode contribution. The reduction in the cracking occurs in the mid-slab region, similar to the case described above for suspension stiffness. The results show that a larger value of β, or reduction in leaf-spring damping, produces a reduction in cracking (approximately 12 percent) over the entire slab, due to the reduction in the body mode contribution.

Effect of Speed Vehicle loading was simulated at three different speeds: 35, 55, and 70 mph. For the particular vehicle and pavement characteristics used, 55 mph was determined to be the speed at which tire forces are maximum (in other words, the speed at which vehicle dynamics are reinforced by the pavement characteristics). At speeds other than this critical value the excitation of dynamic forces is reduced. For vehicle speeds of about 35 mph the effect of dynamics become less important, and the damage distribution resembles that of a static moving load. When speed is increased from 55 to 70 mph, pavement damage is reduced over most of the slab, but is increased in the latter part of the slab (where the vehicle leaves the slab).

Due to the coincidence of (1) the dimensions of the vehicle wheelbases, and (2) the slab length simulated, the vehicle experiences simultaneous inputs to the steer and rear axles. On an actual pavement, the frequency at which the vehicle experiences these inputs should be adjusted so it is not in the range of the body mode frequency. The adjustment can be made either by regulating vehicle speed or by changing the slab length.

Walking-Beam Tandem Suspension (3S2)

Analyses of the walking-beam suspension were conducted in a way similar to that described for the single leaf-spring suspension described above. Of the three speeds tested (35, 55, and 70 mph), 55 mph was the most critical (as it was for single axles) because of the excitation of the lightly damped out-of-phase axle pitch mode (approximately 10 Hz). Damage at 55 mph can be mitigated by reducing the tandem axle spacing from the standard of 52 inches simulated in these runs. However, the walking-beam suspension performs better than the single-axle suspension at low speeds, since it has the ability to filter out the faults in the pavement. This filtering occurs without excessively exciting the axle pitching mode at low speeds.

Four-Leaf Tandem Suspension (3S2)

In comparison to other axle groups, the four-leaf tandem does damage equivalent to the walking-beam (and more than the single-axle) at the slab joints, but it does no more damage than the single-axle suspension (and much less than the walking-beam) in the mid-slab regions. The reason that the four-leaf suspension does less damage than the walking-beam overall is that the out-of-phase pitching mode of the suspension is more restricted by the inherent coulomb friction in the leaf springs.

Effect of β-Parameter

The amount of cracking simulated is relatively sensitive to the β parameter. There is an optimal value of leaf-spring damping around $\beta = 4 \times 10^{-3}$ ft. (Recall that for single-axle suspensions, however, higher values of β were preferable.) The difference in response to β between these two axle groups is due to the coupling of the tandem axles (through the short-rocker). A lower value of β in the single-axle suspension translates to a larger contribution of the body mode, resulting in greater cracking damage (refer to the discussion of the single leaf-spring axle). In the tandem-axle case a very low value of β (high coulomb friction) results in increasing the contribution of the body mode to the tire force, thereby increasing the damage. On the other hand, too high a value of β excites the axle out-of-phase pitching mode, also increasing damage. Therefore, there exists an optimum value of β for the four-leaf tandem, lying between these extremes.

Effect of Tire Pressure

The effects of tire pressures were investigated for all the suspension types; the results for the four-leaf tandem will illustrate the trends observed. Tire pressure has some effect on vehicle dynamics, since lower pressures filter the input to the leaf-spring suspension, thereby attenuating the wheel mode contribution to the tire force. Also, lowering the tire pressure leads to a larger surface contact area, reducing the primary response (for example, stress) of the pavement. This would reduce the rate of crack initiation and propagation through the slab.

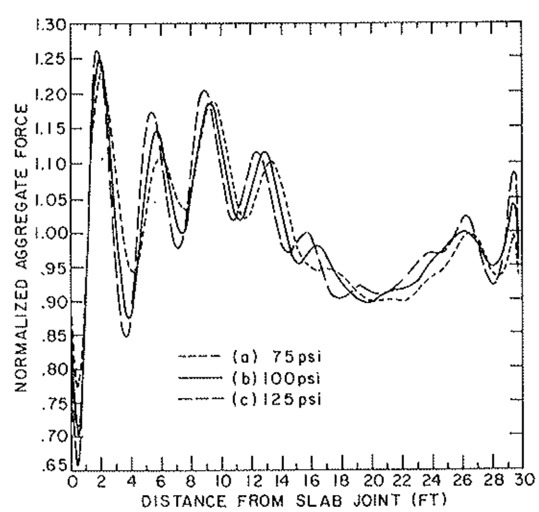

FIGURE 8 Effect of tire pressure, four-leaf tandem axle.

The analysis of tire pressure effects are shown in figure 8, where the aggregate dynamic force is shown for tire pressures of 75, 100, and 125 psi. These plots show that the greatest effect of tire pressure occurs at the second peak load, where a 5.5 percent increase in load magnitude is attained by raising the tire pressure from 75 to 125 psi. Tire pressure thus appears to have a small effect on vehicle dynamics and, therefore, a small effect on rigid pavement damage for the conditions tested in this study. This result differs from that observed for flexible pavements, where the influence functions tend to be narrower or tighter (the rigidness of the PCC slab renders it less sensitive to greater stress that may result from higher tire pressures).

Other Impacts

Other impacts are summarized below, with additional details in Reference 7:

- Increasing the leaf-spring stiffness by 50 percent produces a 6 percent reduction in the overall damage produced. This trend is the opposite of that for the single-axle leaf-spring, where softer suspensions are more favorable.
- Reducing the axle spacing from 52 to 40 inches increases the pavement damage by 9 percent. This is opposite to the effect produced in the walking-beam suspension, where the higher stress produced by bringing the axles together is far out-weighed by the reduced dynamics.
- Changing the load sharing coefficient (LSC) from perfect load sharing (LSC = 1.0) to LSC = 0.9 does not result in a significant change in damage overall but does redistribute damage somewhat, increasing the amount of cracking near the approach joint.

CONCLUSION

New analytic procedures have been developed to study in a very general way the interaction between vehicle dynamic loads and pavement damage. Detailed simulation programs of heavy truck dynamics have been created, and an existing rigid pavement program (PMARP) has been modified to account for dynamic tire loads on PCC slabs. To date, single and tandem axles have been investigated, with the following results:

- The static load case indicates that the mid-slab region has lower fatigue damage than the transverse joint regions. For the dynamic loading case, however, the mid-slab and transverse joint regions have similar fatigue damage values. Furthermore, fatigue damage due to dynamic moving loads in particular slab locations is up to 40 percent greater than that due to static loads.
- The mid-slab regions are more sensitive to dynamics than are the transverse joint regions. This results from the finding that the body mode contribution to the tire mode is more detrimental to cracking damage than the wheel mode contribution.
- For the particular combination of factors that was tested, the walking-beam suspension produces the most damage at highway speeds, followed by the four-leaf tandem and the single-axle suspension as the least damaging. These results may vary for other combinations of pavement and vehicle characteristics.

The factors that have been shown to be most critical in affecting dynamic loads on rigid pavements are

- Vehicle and axle configuration, and vehicle load,
- Suspension characteristics (stiffness, hysteresis),
- Vehicle speed, and
- Pavement roughness, faults, joint spacing, and slab warping.

Other factors are also important, although they were not specifically tested in the parametric study (for example, pavement design and environmental conditions, which affect the rate of pavement faulting and deterioration). Weakening of the pavement subgrade due to pavement pumping was not included in this set of analyses, and its inclusion might alter the conclusions obtained above. Tire pressure was investigated but not found significant in affecting dynamic loads; this conclusion is different from that obtained in earlier simulation of flexible pavements.

An important implication of these findings is the importance of the vehicle itself in influencing dynamic loads, implying that future policies governing the maintenance and rehabilitation of highway infrastructure may need to look at the vehicle as well as the pavement (and bridges). Furthermore, regulating heavy vehicles simply by gross weight and axle load may not be sufficient; the dynamic loads actually imposed by different axle configurations, suspensions, and tires may need to be accounted for. Finally, pavement management should be coordinated with the evolution in vehicle technology, since dynamic loads arise through the interaction of factors such as slab length, vehicle wheelbase, fault height, suspension damping, and axle spacing.

ACKNOWLEDGMENTS

This work has been supported by the U.S. Department of Transportation, Office of University Research. Technical supervision has been performed by the Federal Highway Administration. The authors wish to thank particularly William J. Kenis, Jr., who has served as Technical Monitor for this research and has provided very helpful suggestions and guidance.

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Publication of this paper sponsored by the Committee on Strength and Deformation Characteristics of Pavement.