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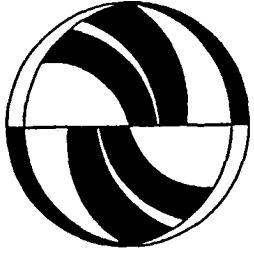
Lysmer, J.

Sousa, J.

et al.

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**Truck Pavement Interactions:
Requisite Research**

C.L. Monismith
J. Lysmer
J. Sousa
J.K. Hedrick

Department of Civil Engineering
University of California at Berkeley
Berkeley, CA 94720-1850

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Truck Pavement Interactions — Requisite Research

C. L. Monismith, J. Lysmer, J. Sousa, and J. K. Hedrick
University of California at Berkeley

ABSTRACT

A framework for consideration of the effects of dynamic loads on pavement performance is presented. The paper discusses requisite research which will permit both the pavement engineer and the truck designer to effectively utilize such a framework to arrive at optimal solutions which will result in overall savings to the agencies responsible for design, construction, maintenance, and rehabilitation of pavement facilities and to the users of the facilities as well.

Included is a discussion of needed research to evaluate: the dynamic response of jointed portland cement concrete pavements to load, the influence of dynamic loads on the development of rutting in asphalt concrete pavements, and the development of new suspension concepts to reduce dynamic load variations with pavement roughness.

Also included are recommendations for field measurement procedures to truly identify dynamic load spectra, methods to identify pavement profiles to reflect the effects of such profiles on truck suspension performance, and measurements to evaluate the methodology developed within the proposed framework.

IN FIG. 1 IS SHOWN A FRAMEWORK for consideration of the effects of dynamic vehicle loads on pavement performance.

Input to the process includes estimates of the proportion of different classes of vehicles which will use the specific facility over some prescribed time period. In addition, estimates of pavement profiles in some form will be required and possibly may be obtained from historic records, e.g., some organizations determine the roughness characteristics of their systems on a periodic basis. This information, together with a truck simulation model, will permit an estimate of dynamic loads to be made.

Estimates of the environmental influences at a particular site (particularly moisture and temperature effects) will permit determination of the dynamic material properties of the various pavement components by means of laboratory tests using some form of dynamic testing equipment.

This information, together with the dynamic loadings obtained from the truck simulation model, permits estimates to be made of stresses, strains, and deformations in each of the pavement layers.

For specific pavement types, it is important to decide which modes of distress contribute to pavement deterioration and therefore to a reduction in pavement serviceability. For asphalt pavements, currently the major modes of distress associated with the load are fatigue (alligator) cracking and rutting.

For portland cement concrete (p.c.c.) pavements, step faulting at the joints (in undoweled pavements) and fatigue cracking appear to be the major causes of loss in serviceability due to traffic loadings.

As seen in Fig. 1, analysis of a specific pavement section involves determining if the section under consideration will be able to sustain the anticipated loadings; if not, a new section must be selected and checked.

To illustrate the process, consider the analysis for fatigue. Results of research on the fatigue response of asphalt concrete indicate that the following expression is a reasonable damage determinant.

$$N = K(1/\epsilon_t)^n (1/S_{mix})^b \quad (1)$$

where:

- N = number of load applications to some extent of cracking,
- ϵ_t = tensile strain (resulting from load) repeatedly applied.
- S_{mix} = dynamic stiffness modulus of the asphalt bound layer,

K, n, b = experimentally determined coefficients.

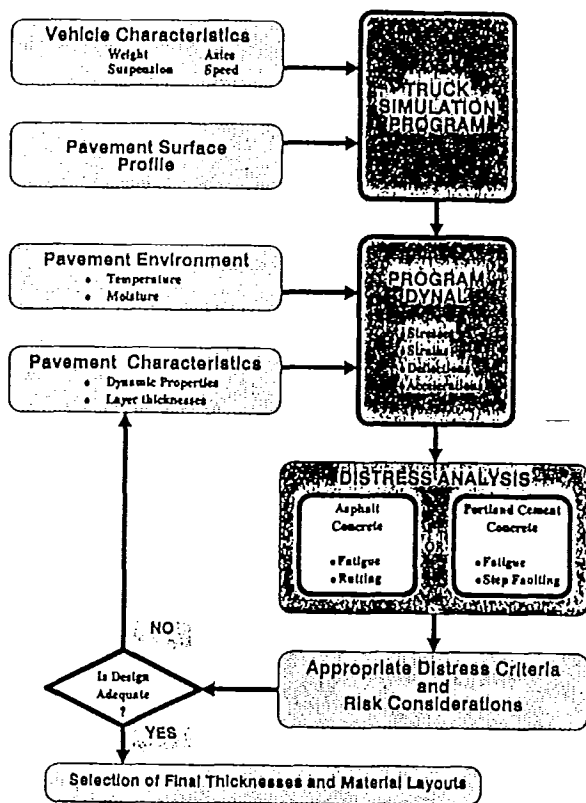


Fig. 1 - Design Framework to Consider Dynamic vehicle loads.

With the DYNAL program (PAVEMENT model), strains resulting from the anticipated dynamic loads can be ascertained. For a particular strain level there is, according to the above expression, some number of load repetitions, N, which can be sustained before cracking takes place. In all probability, this number of repetitions to cause failure will exceed the number anticipated at the associated load level. Since there will be a range in loads and thus a range in strains, the cumulative effects of the various strain levels must be considered. This can be done by using the linear summation of cycle ratios cumulative damage hypothesis:

$$\sum_{i=1}^n (n_i/N_i) \geq 1 \quad (2)$$

where:

- n_i = actual number of load repetitions at strain level i ,
- N_i = allowable number of load repetitions at strain level i (from equation (1)).

When the linear sum of the cycle ratios reaches unity in this expression, the pavement is no longer considered serviceable and

rehabilitation is required.

Similar types of analyses using the estimated stress, strain, or deflection parameters can be performed to estimate the propensity for other distress modes.

The objective of the design process is to find a suitable combination of materials which will permit the anticipated loads to be carried for some prescribed time period.

As seen from the above discussion and illustrated in Fig. 1, there are essentially four steps in the process to define representative interactions between a vehicle (truck) and the pavement. These are:

1. Definition of vehicle characteristics through direct measurement of response, e.g., through the use of a shaking table or a simulator like that developed by PACCAR (1) or by means of analyses using truck simulation programs.
2. Definition of representative pavement profiles.
3. Definition of the pavement response to the loads generated from (1) and (2).
4. Definition of adequate distress analyses and distress criteria for representative pavement materials.

It should be emphasized that new concepts in truck suspensions, axle configurations, and truck trailer combinations could be evaluated by this methodology. For such studies it would be necessary for the organization interested in introducing a new vehicle to go through the same steps. That is, it would be necessary to define the vehicle characteristics by means of a shaking table or similar study to define the necessary truck characteristics for use in the truck simulation program. With this information and a range in pavement profiles representative of those existing, dynamic loads could be generated. Using the DYNAL program and representative pavement sections, estimates of pavement damage could then be ascertained for representative dynamic stiffness characteristics of paving materials. With the strains, etc., generated, the influence of the proposed truck system on pavement life could be compared with the effects generated by existing vehicles using the system. Longer pavement lives resulting from the new designs would give the manufacturer sufficient evidence to proceed with the design and to encourage agencies to use the new design.

So that the design process of Fig. 1 or the vehicle evaluation procedure described above can be accomplished, research is required. The following sections describe some of the requisite research.

Finally, it must be emphasized that while the title of this paper refers to the interaction between the truck and the pavement, the proposed research will not completely define this interaction. To illustrate this point, at a particular stage in time the pavement

will exhibit a specific degree of roughness. This will in turn excite a particular truck suspension resulting in loads which may develop damage which in turn will lead to increased roughness, etc. To define interactions at this level is not considered practical from an engineering standpoint. Accordingly, damage development resulting from dynamic loads associated with specific truck suspensions will be based on different levels of pavement roughness. By examining such effects, both the engineers responsible for the pavement system and the truck designers are in a position to define an optimal economic solution to the transport of goods by trucks on our pavement network.

PAVEMENT RESPONSE ANALYSES

Practical procedures are required for determining the dynamic response of asphalt concrete and portland cement concrete to given traffic loads. In such procedures the traffic loads are assumed to be specified in terms of time histories of one or more set of moving wheel loads; each set corresponding to a single truck. It is anticipated that these sets of loads can be produced by truck models such as those identified herein.

The required response data consist of time histories of stress, strain, and acceleration at a specified point of the pavement. The stresses and strains are required for distress analyses while the acceleration time histories, which may be integrated to produce velocities and displacements, provide a means of validation of the analytical procedure in that the computed motions can be compared with observational data obtained from the field experiments, a necessary part of the requisite research.

SIMPLIFIED DYNAMIC ANALYSIS - To be practical for routine design, the analytical procedures which are developed should be as simple as possible. This precludes a complete state-of-the-art dynamic analysis which would be anything but simple and would require analytically-trained engineers and the use of computer codes which can only be executed on main frame computers. A compromise between practicability, economy, and completeness is therefore in order. We believe that in today's world any procedure which cannot be executed on a micro-computer will probably be considered too complicated and expensive by most highway engineers. Thus a method of analysis and associated interactive computer program(s) should be produced which can be executed on an IBM/AT type personal computer. This can only be achieved by the introduction of simplifying assumptions.

Recent research by the authors and described in another paper to this conference has shown that for asphalt concrete pavements it is in fact unnecessary to perform a complete dynamic analysis. Inertia effects can be ignored and the local dynamic response can thus be determined by an essentially static method

which assumes that at any given instant of time the local response of a pavement can be determined by static analysis using materials properties which are compatible with the rate of loading.

It is anticipated that the simplified procedure could also be used for p.c.c. pavements; otherwise a microcomputer design procedure may not be within reach. Nevertheless, ignoring inertia effects is a sweeping assumption and the errors introduced by using the assumption must be evaluated before the procedure is finally adopted for both asphalt concrete and p.c.c. pavements.

The forces which traffic exert on a pavement can be described as a system of moving time-dependent loads. It is recommended that the dynamic effects of such a system of loading can be considered in two parts, one which relates to the dynamics of moving loads of constant magnitude and another which relates to stationary time-dependent loads.

Effects of Traffic Velocity - The basic dynamic problem of traffic velocity is that of a point load moving with constant velocity over the surface of a layered elastic system. No solutions appear to have been published for this complicated three-dimensional problem.

Chen's results (2) computed for a moving line load on asphalt concrete pavements, Fig. 2, indicated that for velocities as high as 60 mph the increase in stress due to velocity is only of the order of 10 percent. This small difference between static and dynamic results would not appear to justify consideration of traffic velocity in dynamic stress analysis, at least at speeds associated with highway vehicles.

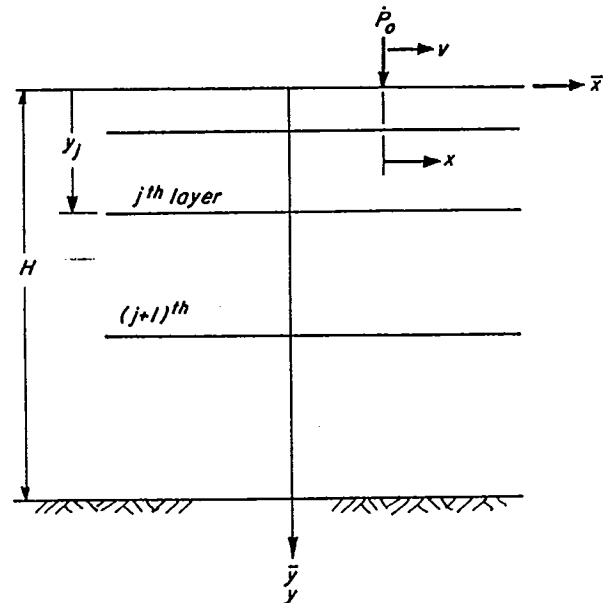


Fig. 2 - Model for Pavement-Subgrade System Subjected to Moving Loads.

It is to be expected that the above will hold not only for the two-dimensional case but also for cases involving moving point loads

and p.c.c. pavements. Except for the possible local influence of joints and edges, p.c.c. pavements should be able to distribute dynamic loads even faster than flexible pavements. To prove the point, however, an analysis should be made of moving line loads of constant magnitude using a two-dimensional finite element computational model which includes a joint in the pavement. This will involve the use of a main frame computer and also a considerable programming effort since no existing finite element computer programs can handle moving loads.

Effects of Stationary Dynamic Loads - For the above study, constant loads were assumed. However, the actual wheel loads are strongly time-dependent and this will produce dynamic stress amplification in pavements over and above that due to the moving nature of the loads. This additional amplification can be evaluated by considering the dynamic effects of a stationary time-dependent load. Results of the program, SAPSI (2), which provides an essentially exact solution for the dynamic stress and displacement field caused by a set of stationary transient load on the surface of a layered viscoelastic system, indicates that for realistic time histories of loading very little dynamic amplification occurs in flexible pavements and that for practical purposes the stress, strain, and displacement time histories can be determined by static analysis at each instant of time.

The inertia effects for this case of time-varying stationary loads on flexible pavements appear to be smaller than or of the same order of magnitude as those observed for constant moving loads. The reason for these small differences is again to be found in the ability of the pavement to almost immediately distribute the load over a large volume of the pavement. There is no reason to believe that the behavior of rigid pavement is significantly different from that of flexible pavements in this respect. Joints and edges may cause some local effects which do not follow the above trend and adjustments may have to be made for this.

Pseudo-static Computer Program - It would thus appear that the errors induced by neglecting all inertia effects in pavement analysis are of the order 10 percent - 15 percent and, thus, that the arguments for a simplified pseudo-static method of analysis have a sound foundation. The above errors can be ignored or adjusted for. They certainly do not justify an order of magnitude increase in cost and effort.

Thus, it would seem propitious to develop an interactive IBM/AT-PC based computer code for stress and displacement analysis of pavements. The code should be able to develop time histories of stress, strain, and acceleration which reflect both the moving nature of the traffic loads and the time-variation of the wheel loads as determined from the truck model.

The basic analytical element of the code could be an axisymmetric model of a layered elastic system loaded by a circular surface load of unit amplitude. The layered system

could be modeled as a semi-infinite continuum in the horizontal direction and as a finite element system over a halfspace in the vertical direction. This basic element has already been shown to be feasible. By repeated application of the laws of superposition in both time and space, the computer program could combine solutions obtained using this element to form complete solutions at arbitrary points for any combination of wheel loads moving over the surface of the pavement.

Probabilistic Considerations for Truck Traffic - The distribution of truck loads and suspension types may not necessarily be deterministic for a specific highway section. Consideration must therefore be given to handling traffic loading in a probabilistic manner recognizing the statistical distribution of truck loadings in both time and space. Such considerations would permit the estimation of confidence limits on the stresses, strains, and deformations calculated at specific points in representative pavement sections. Such an approach would appear to have more merit than estimating the same parameters based on considerations of random vibrations.

Effects of Tire Contact Area. For the sake of simplicity, the above code assumes that the contact area of each wheel load remains constant in time and that the load is distributed uniformly over the contact area at all instants of time. In actuality, both the radius of the contact area and the load distribution change in time as the tire deforms under the varying wheel load. Accordingly, estimates should be made as to how changes in contact area may affect the stresses in and deformations of typical pavements using, in all likelihood, finite element idealizations.

Effects of Braking Forces. The above analytical procedures consider only vertical interaction between wheels and pavement. Horizontal forces should be considered; this unfortunately would greatly increase the theoretical and computational effort required, not only for the pavement analysis phase, but also for truck and suspension analyses. Furthermore, additional major field experiments would be required to obtain data on braking forces and to verify the analytical procedures. Nevertheless, it would seem appropriate to make a simple evaluation of whether or not braking forces are important for design purposes.

Local Effects at Joints and Edges. Joints, corners, and edges are a special problem in the design of p.c.c. pavements. The local effects created by these discontinuities cannot be investigated by the analytical procedures used in the above-mentioned pseudo-static program which assumes a layered system which extends to infinity. At the current state of the art of stress analysis, the only reliable method of analysis of a problem involving a wheel load near an edge or joint would be some form of three-dimensional finite analysis. In view of the arguments made and results presented above regarding the pseudo-static behavior of pave-

ments, it would probably be accurate enough to study the edge and joint problem by static methods. Even with this simplification, however, a three-dimensional stress analysis is a major undertaking -- much too complicated to be an acceptable part of a routine procedure for pavement design.

The edge and joint problem will probably be handled by the introduction of safety or correction factors, the magnitude of these factors to be determined from experience and/or analyses of typical pavements and geometries.

RUTTING ANALYSIS FOR ASPHALT CONCRETE - None of the currently used pavement models are capable of predicting and modelling the shear deformations at constant volume, a phenomenon which occurs during the formation of a rut in an asphalt concrete layer. Thus, it is important to develop an analytical procedure to predict permanent deformation in asphalt concrete pavements. A finite element computer program to determine stresses, strains, and permanent deformations throughout the pavement section would appear to hold the most promise. Such a program has the potential to predict rutting evolution (not only rut depth but also change in pavement cross section elevations) as a function of:

- i) Tire contact pressure (uniform and nonuniform).
- ii) Temperature, frequency of loading and stress dependent material properties (elastic, viscous and plastic) obtained from laboratory data from repetitive, cyclic and creep shear tests.
- iii) Pavement structure.
- iv) Number and level of load repetitions (moving vehicles) or time of loading (stationary).

Such a program could involve a four-stage iterative procedure:

1. Compute stresses and strains within the pavement section caused by the wheel loads within the pavement section using the finite element computer program.
2. Perform laboratory tests to determine the response of the materials (elastic, viscous, and plastic), at the same stress, strain, and temperature conditions obtained in the previous step and as a function of the number of load cycles (for moving loads) or time of loading (stationary).
3. Compare the computed stresses with the laboratory determined response curves and estimate the potential strains in the elements of the pavement.
4. From the knowledge of strain potentials within the elements, evaluate the overall deformation and stability of the pavement section assuming that plastic deformations

occur due to plastic shear flow at constant volume.

Iterating through these steps with sufficiently small increments in the number of load repetitions (moving loads) or time of loading (stationary loads) will lead to the prediction of the evolution of the surface elevation of the pavement cross section.

A similar approach was successfully adopted by Serf, Seed, Makdisi, and Chang (3) in the prediction of permanent deformations caused by earthquakes on earth dams.

To validate the model, a two-step approach would appear propitious:

- 1) A 2D plain strain model could be simulated in the laboratory by applying cyclic loads to a beam. The program should be able to very accurately predict the evolution of the surface elevations. This type of test could be run at different temperatures and with different uniform and nonuniform contact areas until full confidence has been obtained in this new code.
- 2) For a selected pavement section, where the appropriate material properties can be obtained and traffic histories are accurately known, a full analysis could be carried out and the results compared with the field data.

The capability of predicting the evolution of the pavement surface caused by non-uniform tire contact is an urgently needed tool for highway engineers. Recent studies have shown that tire contact pressures can be in certain cases up to 180 percent of the tire pressures. Other studies have reported measured tire pressures of 140 psi. With the development of such an analysis procedure, contribution of these tire influences to the rutting potential can be reasonably assessed.

As with the earlier developments, this analysis procedure should then be simplified for design purposes so that it can be solved using a microcomputer.

VEHICLE CHARACTERISTICS

TRUCK SIMULATION MODELS - There are various truck simulation models which have been developed. As an example, the model developed at the PACCAR Technical Center (4) has been utilized to study tractor-semitrailer dynamics in the pitch plane. The program output includes time histories of all accelerations of the rigid bodies and each axle, with modification, can include time histories of tire forces for each of the axles as output.

Several suspension models have been incorporated into the simulation program. These models include nonlinear leaf spring behavior, dynamic change in the spring rate of air springs, and the load equalizing mechanism of walking beam suspensions.

The fifth wheel connection between the tractor and the trailer is modeled to kine-

matically constrain the bodies in vertical translation. This provides accurate representation of the dynamic interaction of the motion of the tractor and trailer.

The simulation program is written in a general fashion to accommodate a wide range of vehicle configurations. Provision is included for parametric variation of suspensions characteristics (spring rates, suspension type, and damping coefficients), axle configuration (singles, tandems, and tridem groupings), axle spacing, wheelbase, fifth wheel position, and load distribution.

An extensive database of vehicle parameters for use with the simulation is on file at the PACCAR Technical Center. Included in this data base are measured values for various suspension parameters for commonly used suspensions (leaf spring, air spring, walking beam, and torsion bars), tires (bias ply, radial ply, and wide-based singles), damping characteristics of commercially available shock absorbers, and geometric and inertial properties of a wide range of tractors and trailers.

Validation of the models for various truck configurations and suspension components is continuing, using the PACCAR Center Road Simulator (1).

Additional research is required to define the influence of various tire types on the dynamic forces applied to the pavement surface. In addition, the effects of acceleration and deceleration requires investigation. To do

this, however, greatly complicates the simulation model since consideration of these influences adds a number of degrees of freedom.

While the tractor-semitrailer combination has been reasonably well defined, simulation models are required for truck-trailer combinations such as those shown in Fig. 3. It is interesting to note that a study is currently underway by the Transportation Research Board to examine the alternate truck combinations which might cause less damage to the highway, yet with the ability to carry equal or greater total loads per truck unit (5). In order for such studies to be conclusive, a measure of the dynamic as well as static response of the axles are required as a function of pavement roughness.

INSTRUMENTED TRAILER - To obtain a measure of pavement roughness, many agencies today use Car Ride Meters. There is a major concern, however, with this type of equipment, i.e., does the roughness which it measures reflect the way truck suspensions will react dynamically.

An alternative approach would be to develop an instrumented truck-trailer combination like that shown in Fig. 4. Because this trailer will be used to determine the road profile while computing the dynamic loads actually applied to the pavement, it is important that its frequency response be flat ("to an engineering degree") in the range 1 to 20 Hz. This is desirable so that the


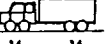
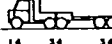
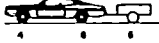
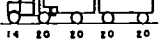
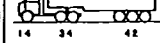
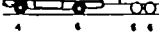
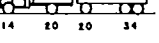
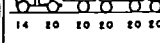
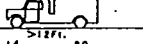
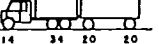
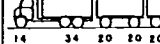
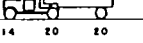
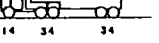
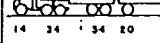
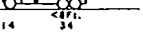
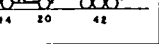
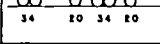
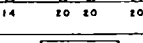
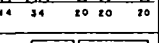
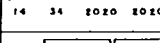
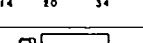
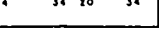
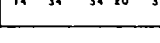

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3	 4 6 6 6	22	12	-	12	 14 20 20 34	88	51	-	20	 14 20 20 20 20 20	134	70	-
4	 14 >12PI. 20	34	21	-	13	 14 34 20 20	88	52	-	21	 14 34 20 20 20 20	128	72	-
5	 14 20 20	54	30	-	14	 14 34 34	82	53	-	22	 14 34 34 20 20	122	74	-
6	 14 <12PI. 34	48	31	-	15	 14 20 42	76	54	-	23	 34 20 34 20 20	128	76	-
7	 14 20 20 20	74	40	-	16	 14 34 20 20 20	108	62	-	24	 14 34 20 20 20 20	148	82	-
8	 14 20 34	68	41	-	17	 14 34 20 34	102	63	-	25	 14 34 34 20 34	136	85	-
9	 14 34 20	68	42	-	PAT TRUCK VEHICLE CLASSIFICATION WEIGHT IN KIPS (1,000 lbs.)									

Fig. 3 - Pat Truck Vehicle Classifications.

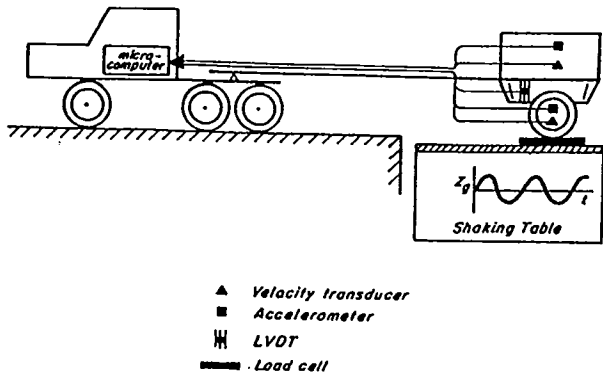


Fig. 4 - "Calibration" of an Instrumented Truck Trailer Using a Shaking Table.

calibrated vehicle may be equally sensitive to a diversity of road inputs.

To "create" a vehicle with such dynamic parameters, a shaking table or equipment like that available at PACCAR could first be used to determine the masses, spring constants, and dashpot coefficients for the given unloaded trailer (for simplicity, it is desirable to use a long trailer with only one axle and an air bag suspension). Based on these values, the magnitude of the loads to be added to the body and axle suspensions, the tire pressure, and suspension pressure could then be computed.

Final verification of the dynamic properties could be made by placing the trailer (with the added loads and corrected pressures) on a shaking table and measuring its response for the range of frequencies of interest (1 to 20 Hz). Monitoring of the dynamic response of the trailer is done with an onboard micro-computer into which the output of the accelerometers, LVDT's and velocity transducers mounted on the trailer's body and axle are fed.

Verification of the accuracy of this instrumented vehicle could be achieved by comparing the computed loads applied by the wheels with the values measured by load cells placed under the wheels, while excited by a known input.

When adequate accuracy is achieved, this instrumented vehicle could then be used to:

- a) apply, and continuously measure, dynamic loads to the pavement at special pavement test sites;
- b) determine the road profiles at the test sites to be used in the validation procedure;
- c) determine a measure of pavement roughness of selected highways;
- d) determine a measure of loads actually being applied to the pavement.

There are several advantages to using this instrumented truck to determine road roughness over the Car Ride Meter:

- a) the vehicle could be designed to be equally sensitive to several types of road profiles;

- b) The size of the instrumented trailer wheels are roughly the same as those of other trucks and, therefore, all inputs are filtered by the same magnitude;
- c) the weight of the instrumented truck would be about the same as that of a loaded truck; therefore, profile variations (and consequently load variations) due to pavement deflections would also be incorporated in the measurements;
- d) the use of the instrumented truck would allow direct determination of the time history of the loads applied by the wheels.

FIELD MEASUREMENTS

DYNAMIC LOAD MEASURING SYSTEM - It is difficult, if not impossible, to measure dynamic loads at the pavement surface with available equipment. Plots of time histories of loads, e.g., Fig 5 (11), applied by the loaded trucks to the roads, indicate that any instantaneous reading of the load obtained by existing weight in motion (WIM) devices will not:

- 1) Measure static components of the loads (except if the devices are placed on pavements with sufficiently low roughness and if they do not introduce, by themselves, any dynamic components to the loads they are measuring);
- 2) Provide any information concerning the dynamic characteristics of the trucks and suspension.

These limitations could be overcome with a device capable of continuously measuring load variations of a truck wheel over a period of 0.5 seconds, which at 55 mph, corresponds to a device 40 feet long. The frequency of vibration of the trucks and suspensions can vary between 2 and 15 Hz (6). In order to measure excitations with frequencies at the low end of this range, it is necessary to have a device at least 40 feet long.

One approach would be to develop a "blanket" composed of 256 (two inches wide by four feet long) strips of piezoelectric film which could be placed on a pavement covering half of one lane. If full lane coverage is judged necessary, then two "blankets" would be required, enabling it to record left and right wheel loads, Fig. 6

In order to simplify data analysis, the pavement underneath the "blankets" should be smooth. However, the pavement immediately preceding should, in fact, be as rough as possible so that all possible modes of vibration of truck and suspension will be excited.

Each of the strips would be independently connected to a microcomputer through a data acquisition unit. The excitation of the first strip and the time delay between the excitation of strips would provide information on truck speed and axle configuration. However, the

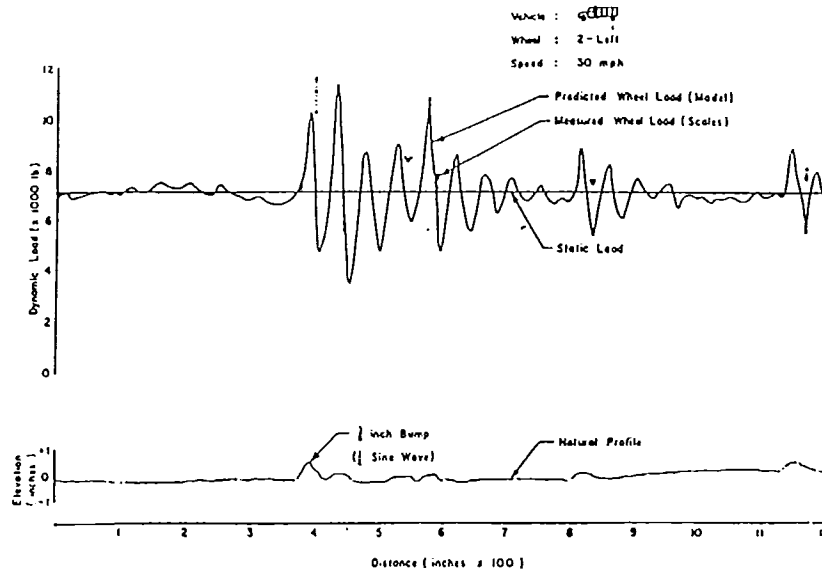


Fig. 5 - Comparison of measured and computed dynamic loads - truck fully loaded (after Reference (1)).

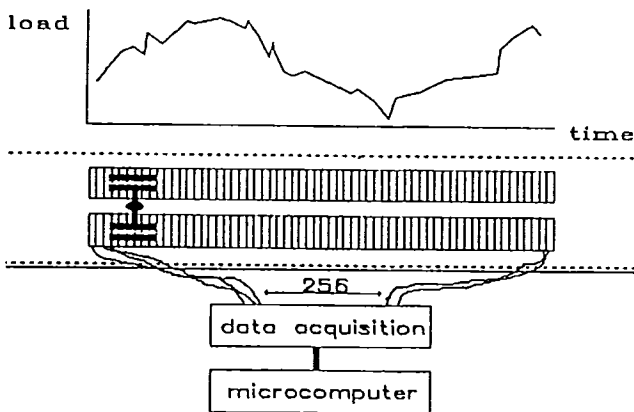


Fig. 6 - Piezoelectric Strips Installation to measure dynamic wheel loads.

major advantage of this system is its capability to measure and record wheel load variation. With this information, the software is capable of determining the static component of the load, as well as the energies associated with the predominant frequencies characterizing the body and suspension assembly. In light of the new methodologies, this information is indispensable in order to classify vehicles in terms of relative damage potential; the static component of the loads applied by the vehicle is not sufficient.

Such a device would be most useful in field tests to record the time histories of the loads applied by selected trucks.

PAVEMENT MODEL VALIDATION - In order for the approach suggested herein to be accepted, it must be validated through controlled field tests. Thus, it is essential that tests be conducted on both an instrumented asphalt concrete and an instrumented portland cement

concrete pavement.

Asphalt Concrete Pavement Structure -

Dynamic truck loads produce displacements and accelerations at the surface of the pavements. Thus, a validation could be made by verifying if measured displacements and accelerations can be predicted by a pavement model such as that described herein and given the proper time histories of loads and material properties for a range of input conditions, e.g., different loads, different speeds, and different temperatures.

At a specific site the dynamic loads applied by the selected truck could be monitored by the piezoelectric strips, the displacements of the pavement surface determined by LVDT's placed in 20 ft deep, 2 in. diameter holes lined with TEFLON and the accelerations by accelerometers placed in small recesses on the pavement surface. A microcomputer equipped with analog to digital converters provides a relatively straightforward methodology for data acquisition. It is suggested that at least two pavement models be used in predicting displacement and acceleration values, SAPSI and ELSYM. The material properties of the layers should be defined by laboratory tests and used as inputs for the programs.

SAPSI can be used to calculate the response of a viscoelastic layered system subjected to surface circular loads. It can be assumed that the layered system is resting on a half space. This is simulated by vertically extended layers and by a series of dashpots attached to the bottom of the extended layers. The layer properties, which include: the shear modulus, the damping ratio, and Poisson's ratio may be varied with the excitation frequencies of the loads. Multiple loads (up to 40 loads) are acceptable for both harmonic

and transient motions. The loads may have different radii and time histories. Static loads can be simulated by specifying a harmonic motion with zero excitation and frequency. Time histories of displacements can be obtained at the surface as well as time histories of strain at in the middle of the layers.

Comparisons of the measured and predicted values should provide the necessary validation of this approach. It should be emphasized that some modifications may be required in the modelling process to insure that the measured and computed results reasonably agree.

Portland Cement Concrete Pavement Structure - Dynamic truck loads produce relative displacements and accelerations within and between slabs of portland cement concrete pavements. An approach similar to that followed for asphalt concrete pavement model validation should be pursued for the validation of a model to determine the dynamic response of portland cement concrete pavements. Material properties can be determined in the laboratory, loads measured by the piezoelectric strips, and displacements and accelerations of two continuous slabs and subgrade synchronously monitored, analyzed and stored directly in the microcomputer. A pavement model would then be validated by comparing measured and predicted time histories of displacements and accelerations.

APPLICATIONS OF PROPOSED RESEARCH

There are a number of areas where the results of the proposed research program can be utilized. Two examples will be presented. One would be a parametric study of the effects of significant variables on pavement performance, while the other would be concerned with vehicle suspension and design.

PARAMETRIC STUDY OF TRUCK AND PAVEMENT VARIABLES - In Table 1 are listed a number of variables which might be assessed within the framework discussed herein. Fig. 7 illustrates how this might be accomplished and provides an indication of the magnitude of the analyser problem. If all of the variables of Table 1 were considered, approximately 750,000 analyses would have to be made. For the considerations shown in Fig. 7, this has been reduced to about 5,200.

Results of the parametric analysis should permit a classification to be developed of the probable influences of the various factors on pavement performance. Moreover, such a study should permit definition of those areas requiring additional development or refinement.

VEHICLE SUSPENSION DESIGN - Earlier it had been indicated that the framework of Fig. 1 could be used to develop improved vehicle suspensions which would be effective relative to the goods transported as well as to the pavement on which the vehicle/suspension travels.

TABLE 1 - EXAMPLES OF PARAMETERS TO BE CONSIDERED IN TRUCK AND PAVEMENT INTER-ACTION STUDIES

Truck configurations	Flexible (truck) Rigid (bus)
Suspension types	Air bag Walking beam Four-leaf
Tire configuration	Single Dual
Tire types	Bias ply Radial Low profile Super-single
Tire pressure	1.0* recommended 1.2* recommended 1.4* recommended
Axle configurations	Single axle Tandem axle Tridem axle
Axle spacings	1.0* standard 1.2* standard 1.4* standard
Axle types	Steering Nonsteering
Axle locations	Standard Nonstandard
Load levels	1.0* regulations 1.2* regulations 1.4* regulations
Speeds	25 mph 55 mph
Conditions	Constant speed Acceleration/ Deceleration
Connections vehicles	Dolly 5th wheel
Operating conditions	Smooth Rough Jointed
Pavement types - conditions	PCC with weak support PCC with stiff support AC hot day AC normal day

Analyses (7, 8) and field measurements (9, 10) have demonstrated that the influence of alternative tandem axles on pavement performance can be substantially different. For example, it would appear that walking beam suspensions may be more damaging than four spring/short rocker suspensions due to a lack of damping in the load equalization method. This conflict between load equalization and peak force damping implies that optimization to minimize road damage could yield significant

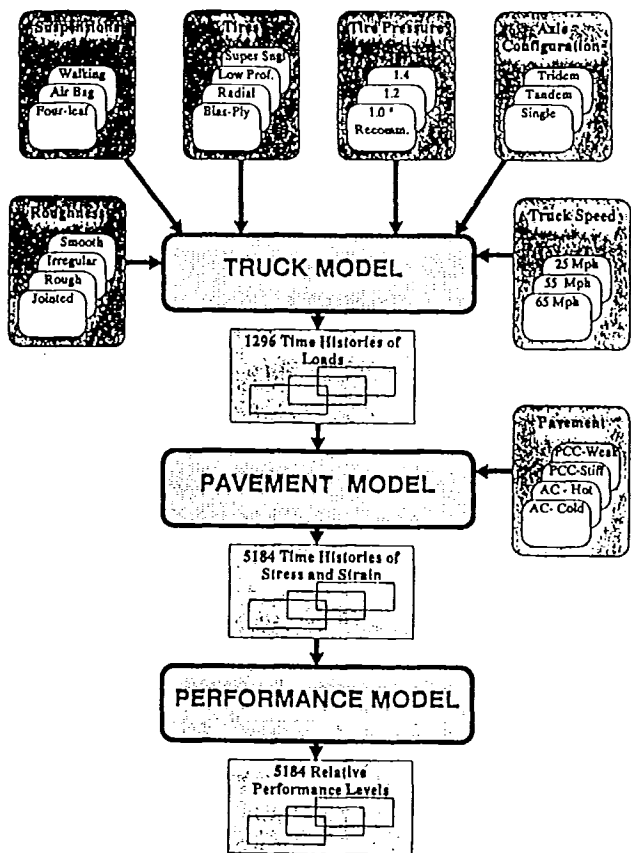


Fig. 7 - Example of a parametric study to define the relative influence of truck and pavement variables.

improvements. There are currently a wide variety of tandem axle suspensions on the market; a study to determine the relative road damaging capability of these suspensions as well as how they could be redesigned to produce less road damage is necessary.

An area that has not received much attention is the study of tridem axle suspensions. As the number of these multiple axle combinations increase, their contribution to pavement deterioration clearly increases and the analysis of their road damage potential becomes essential. It is certainly possible that minor suspension modifications in these multiple axle combinations could yield significant reductions in pavement damage. The framework proposed herein permits this to be accomplished so long as the necessary parameters are defined.

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