

Heavy vehicle pavement loading: a comprehensive testing programme

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This paper discusses the overall goals and initial applications of research conducted under the Federal Highway Administration's (FHWA) "Truck-Pavement Interaction" High Priority National Program Area (HPNPA). In this research, results from a comprehensive testing program involving full-scale field tests on pavements and laboratory tests on heavy vehicles are combined with computer simulations to supplement each other.

TRUCK PAVEMENT INTERACTION HPNPA

The FHWA's Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia, has developed a variety of uniquely different full-scale truck-pavement-related test facilities designed to support the TPI HPNPA. They presently include the Pavement Test Facility (PTF) (ref. 1), the Pavement Isothermal Test System (PITS) (ref. 2), the FHWA Test Road Facility (ref. 3), and a prototype dynamic truck actuation system called DYNTRAC. Each provides FHWA with uniquely different but interrelated pavement/vehicle analysis capabilities. Results from experiments conducted at each of these facilities will be used in the conduct of the TPI HPNPA. Presentations in this paper are limited solely to aspects involving the FHWA Test Road Facility and DYNTRAC as they relate to the three research phases of the TPI HPNPA: Phase I: Load Equivalency Study, Phase II: Primary Response Analysis, Phase III: Vehicle/Pavement Interaction.

FHWA TEST ROAD

Design and Construction

The Test Road contains a thick and a thin test section, each 30 m long, separated by a 7.6-m transition zone. It resulted from the reconstruction of the inbound lane of the access road connecting Virginia Route 193 with the TFHRC. The subgrade is a silty sand, classified as an A-4 with a California Bearing Ratio value of 5. A crushed stone base was placed to a depth of 305 mm. A 178-mm and an 89-mm thickness of recycled asphalt concrete pavement were then placed to form the thick and thin pavement test sections, respectively (ref. 3).

Instrumentation

The test sections were designed to accommodate strain and deflection instruments placed along the center of the left wheel path of each section (refs. 3,4). Thirty-six H-type tensile strain gages spaced .305 m apart were placed on top of the base course in the thick section to

measure longitudinal strain on the underside of the asphalt concrete pavement layer. Four Alberta Research Council (ARC) tensile strain gages were also placed (two rows of two) in each section. Four ARC single-point deflectometers (SLD) were placed (two rows of two) in each section to measure displacement of the pavement's surface. One multidepth deflectometer (MDD) was placed in each section to measure displacement with depth.

Test Series I

Controlled moving load vehicle tests were conducted over a 3-day period during August 1990. (Test Series II will measure the primary response when the vehicle is subjected to additional excitations from bumps placed on the pavement.) The dependent variable levels and level values used are given in Table 1.

Table 1. Dependent variable levels and level values for Test Series I

Variable	Levels
Tire pressure	515 kPa, 760kPa
Speed	8 km/h, 72 km/h
Pavement thickness	177 m, 88 m
Test vehicles	3 vehicle types, 3 axle load levels

The three classifications of vehicles used were: Single Unit Truck (truck 1), Tractor-Tandem-Axle Semi-Trailer (truck 2), Tractor-Tridem-Axle Semi-Trailer (truck 3). The load levels used for the individual tandem and tridem axles are given in Table 2 to the nearest 0.1 KN.:

Table 2. Load levels for tandem and tridem axles.

Level	Tandem		Tridem		
HIGH	48	48	49	45	45
MEDIUM	36	36	33	31	31
LOW	22	22	20	19	18

PHASE I: LOAD EQUIVALENCY STUDY

The primary response data collected in Test Series I were used along with two selected strain-based and two deflection-based Primary Response LEF methods (ref.4). The study concluded that the surface deflection methods (Christison (ref. 5) and Hutchinson (ref. 6) were far more reasonable in estimating the AASHO LEF's than were the tensile strain methods (refs 5,7) . The Hutchinson method was judged the best overall. The equation used for both deflection methods is:

$$LEF = \left(\frac{D_1}{D_s}\right)^c + \sum_{i=1}^{n-1} \left(\frac{\Delta_i}{D_s}\right)^c \quad (1)$$

where D_1 is the primary displacement peak of an axle group due to any load, D_s is the displacement peak due to a standard single-axle load, Δ_i is the displacement between valley and peak, and c is a constant. The largest global peak is taken as the primary peak in the Hutchinson method whereas Christison uses the first peak. Christison's curve is copied from another study (ref.8) for a tandem-axle group with variable wheel spacing (a viscoelastic pavement having complete unload deflection is assumed) in Fig. 1. Hutchinson's curve is also shown herein for comparison. Note the discontinuity that exists at 1.22 m for the Christison curve. This discrepancy is overcome using the Hutchinson definition of peaks but it is interesting to note that a minimum exists for the Hutchinson definition.

Analysis of variance (F-test) was conducted for the LEF's calculated using the Hutchinson method. The factors found to be significant (at a significance value $\alpha=.01$) in order of F-value are: Load-102, Load x Axle-30, Axle Type x Speed-11, Load x Tire Pressure-7, Load x Axle x Speed-4.

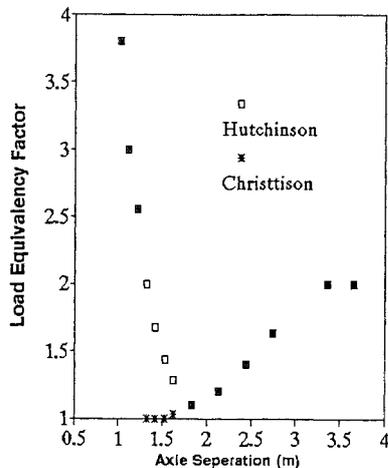


Figure 1 Load Equivalency Factor For Various Axle Spacing

PHASE II: PRIMARY RESPONSE ANALYSIS

Detailed descriptions of measured data obtained from the LVDT's Have been presented elsewhere (ref. 9), and detailed descriptions of measured data obtained from the longitudinal layer interface ARC strain gages (ref. 10). In addition, supplementary investigations were conducted: Linear and nonlinear elastic layer theory models were used with FWD deflections to backcalculate layer moduli. Linear layer theory was used to calculate the movement of the MDD LVDT's and anchor. The MDD anchor movement was also measured directly and the movement was compared with that calculated with layer theory. The effect of temperature change on measured pavement deflection and strain was calculated using the regression equations developed at the ALF site. Results reflect (a) responses from the MDD's and the ARC gage set 1 for each section, (b) the trailer tridem axle from truck 3, and (c) the tractor tandem axle from truck 2.

Vertical Deflection Response

Peak surface deflection (figs 2 and 3) decreases as speed is increased but increases with the number of axles in the axle group. The greatest peak compressive strain occurs in the top of the subgrade (fig. 4). Peak vertical compressive strains increase more rapidly for heavier loads (fig. 5). For the base course, the rate of change of vertical strain with respect to load increases 10 to 40 times as speed is increased from 8 to 72 km/h (fig. 6).

Horizontal Strain Response

A typical longitudinal strain response at the bottom of the asphalt layer is shown for truck 3 in fig. 7. In general, compression peaks range between 18% and 29% of total peak to peak strain. On the average, tension peaks at 8.04 km/h are up to 41% greater than those at 72.4 Km/h. The compression peaks are similarly 26% greater. It is important to note that at low load levels in the thin pavement, speed had little (or negative) effect (eg strains are higher at higher speeds). Fig. 8 confirms the well-known inverse relationship between time duration of response and speed.

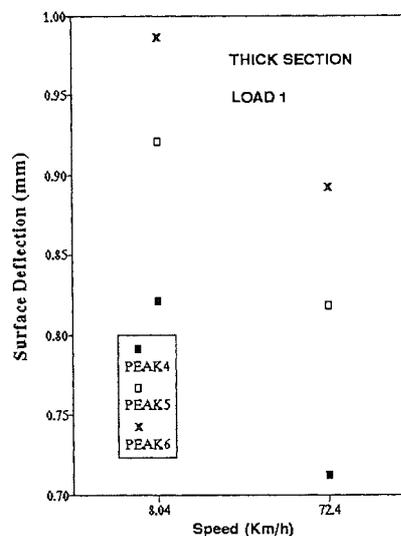


Figure 2 Surface Deflection Vs Speed

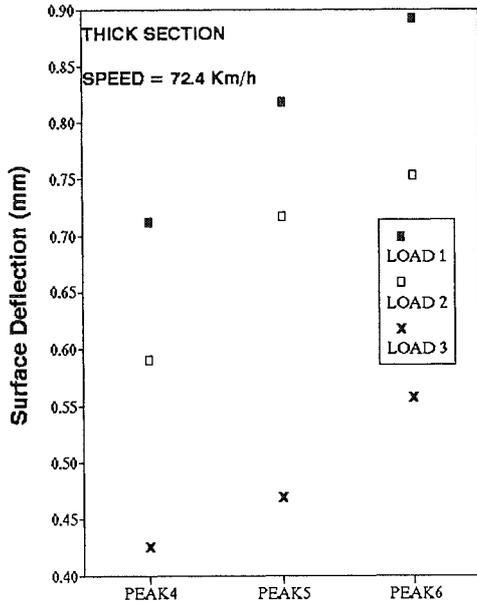


Figure 3 Surface Deflection (mm)

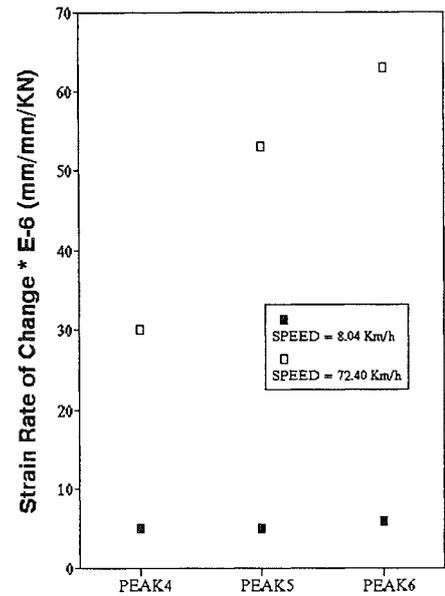


Figure 6 Rate of Change of Vertical Strain of Agg. Base w.r.t. Load

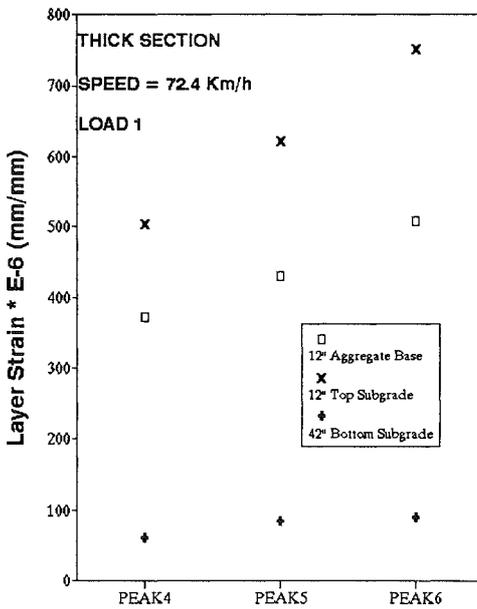


Figure 4 Compressive Vertical Strain

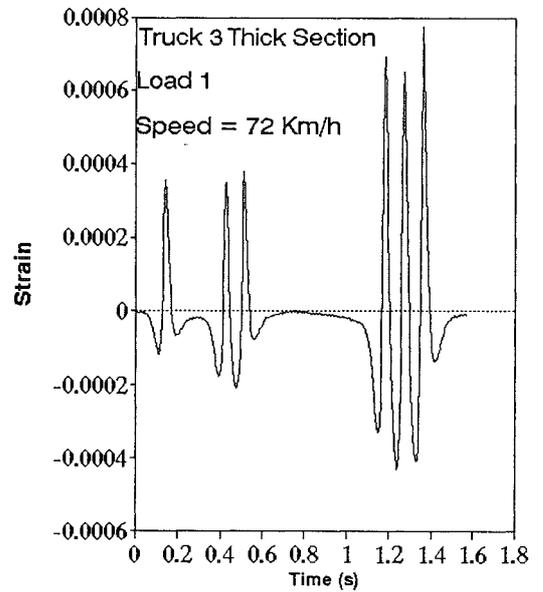


Figure 7 Strain Response

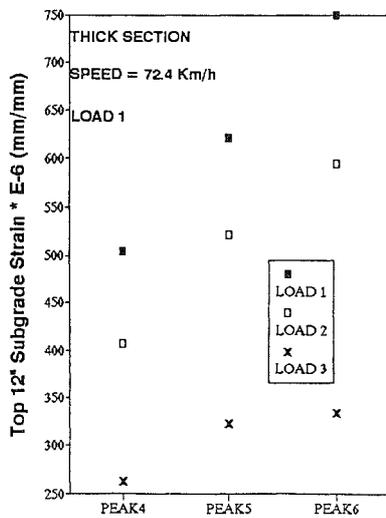


Figure 5 Vertical Compressive Strain

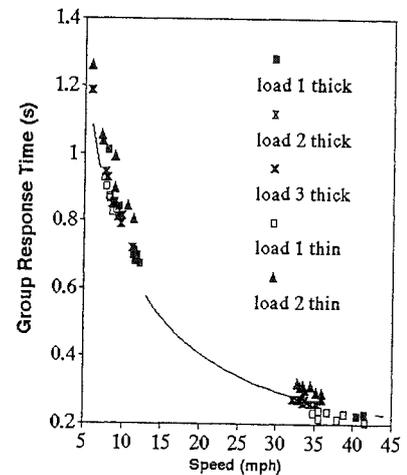


Figure 8 Response Duration Tractor Tandem Truck 2

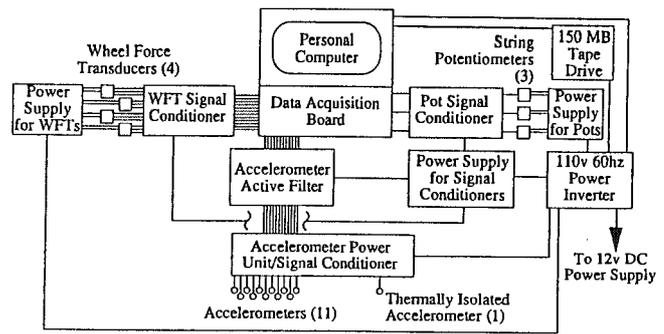
PHASE III: VEHICLE/PAVEMENT INTERACTION

The main objective of the tests conducted in this phase is to investigate dynamic forces applied by truck tires to pavements under well-controlled laboratory conditions for a range of parameters representing truck dynamics. The laboratory experiments are performed using a computer-controlled hydraulic actuator system called DYNTRAC. The system has four actuators, one for each tire or dual-tire unit of a two-axle truck. The four actuators can also be used to support each dual-tire unit of a tandem suspension trailer with the front of the trailer supported by a custom-designed fifth wheel structure or a stationary tractor. DYNTRAC is equipped with two computer systems, one for control of hydraulic actuators and the other for data acquisition. A measured or a synthesized road profile, stored in a computer disk file, is transformed via the DYNTRAC control system into vertical displacements of the actuators. The input profile contains two columns, one each for the left and right wheel tracks. The rear actuator motion is the same as the motion of the front actuator in the same track, delayed by the time depending on the simulated speed and the test vehicle wheelbase. The actuators have a 25.4-cm stroke; however, the input profile amplitude variations are limited to +7.6 cm with respect to the initial zero position to provide a margin of safety. The data acquisition system collects, stores, and displays results of measurements of actuator positions, accelerations, and differential pressures across the actuator pistons. Wheel scales are currently being designed to measure dynamic tire loading. The wheel scales will be installed on the actuators and their outputs will be added to the DYNTRAC data acquisition system.

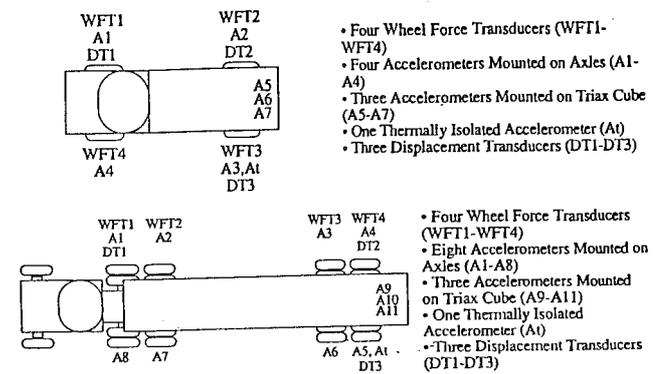
A two truck-axle is being used as a primary test vehicle. The truck has been fully instrumented and equipped with an on-board data acquisition system. A schematic of the vehicle data acquisition system and the locations of sensors on two- and five-axle trucks are shown in figs 9 and 10, respectively. The wheel force transducers have not yet been fully developed and are currently replaced by strain gauges installed on the truck axles. The signals from the strain gauges together with the signals from the accelerometers mounted on the axles are used to calculate tire forces.

The main independent variables in the DYNTRAC test program are: type of tire, tire inflation pressure, type of truck and truck suspension, truck speed, and road roughness. Three types of tires were selected for the testing program: conventional radial tire, low-profile radial tire, and wide-base (or super single) radial tire. The first two tires are the most common types of tires used on trucks in the United States. The third selection was based not on the popularity of this type of tire but, rather, on its distinctly different dynamic characteristics, which are considered to be particularly damaging to pavements. Four trucks were selected for the study, with each truck

representing a different combination of suspension type and axle configuration:



9. Schematic of vehicle data acquisition system.



10. Instrumentation arrangement for two and five axle trucks.

- Two-axle truck with leaf spring suspension.
- Two-axle truck with air spring suspension.
- Five-axle tractor semi-trailer with leaf spring suspension.
- Five-axle tractor semi-trailer with walking beam suspension.

The results of the tests with the selected vehicles should facilitate comparisons between different suspensions used on similar types of trucks and between trucks with different axle configurations but the same suspension type. Vertical tire load is tested at four levels, while tire inflation pressure and truck speed are varied at three levels. Finally, longitudinal elevation profiles of three road sections of relatively low, medium, and high roughness, measured with a road profilometer, are used as input signals to DYNTRAC. Field tests will also be conducted with the instrumented truck on the medium roughness road and on the FHWA Test Road. The measurements of tire forces and truck dynamic response obtained in the field tests will then be compared with the same measurements obtained on DYNTRAC. It is recognized that tire forces as well as truck accelerations and displacements measured on DYNTRAC will not be identical with the analogous measurements recorded in the field tests.

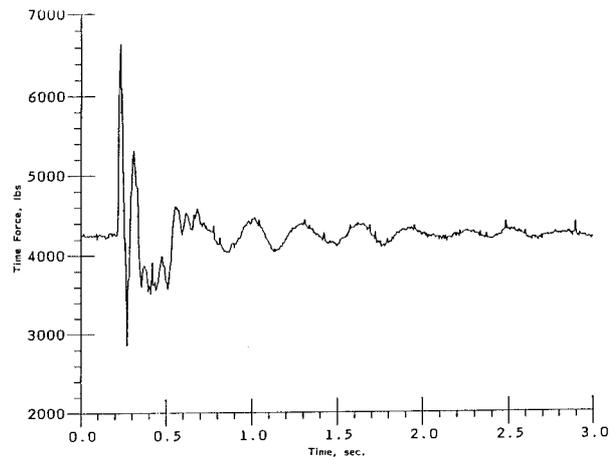
However, an analysis of the discrepancies between field and laboratory data that occur under various test conditions will provide important information for determining the validity of the DYNTRAC system as a laboratory tool for simulating truck dynamic response to road roughness.

The third approach to the problem of truck-pavement interaction, besides laboratory and field tests, is via computer simulation. The available computer programs vary in their size and complexity from relatively simple ones that can be executed on personal computers to sophisticated codes, requiring high-speed mainframe machines (refs 11,12). However, even the most sophisticated programs are only as accurate as the estimates of model parameters employed in the simulation. Therefore, considerable effort has been directed in this study toward identification of truck parameters. Most of the two-axle truck parameters were measured using facilities of the Altoona Bus Research and Testing Center (ABRTC) operated by the Pennsylvania Transportation Institute of The Penn State University. These parameters include wheelbase, weight distribution between axles, truck center of gravity position, roll, pitch and yaw moments of inertia, suspension spring rate and Coulomb friction, and so on. Tire characteristics were measured by The Goodyear Tire & Rubber Company using the force pin method. The measured tire characteristics included net and gross contact area, load-deflection curves, and contact pressure distribution. It must be recognized that all results of the parameter measurements involve measuring errors of various magnitudes. Some measurements, such as measurements of truck geometrics, are relatively accurate, while others, such as measurements of tire and suspension viscous damping, may involve a significant error. Fig. 11 shows a tire force measured on the instrumented two-axle truck in response to a 1.27-cm step change in position of DYNTRAC actuators. Fig. 12 shows the same variable obtained from computer simulation using program Phase 4 and the measured values of the truck parameters. The two responses look similar, although there are, clearly, noticeable discrepancies. For instance, the 2.5-Hz (approximately) oscillations in the actual truck response are sustained for almost 3 seconds, whereas in computer simulation these oscillations die out after 1 second. It is assumed that the structure of the computer model is correct and that the discrepancies between measured and computed responses are caused primarily by errors in measurements of parameters of truck dynamics. The estimates of the truck parameters will therefore be further fine-tuned until the computed responses match the measured responses with minimum error. This process of model parameter identification is currently under way.

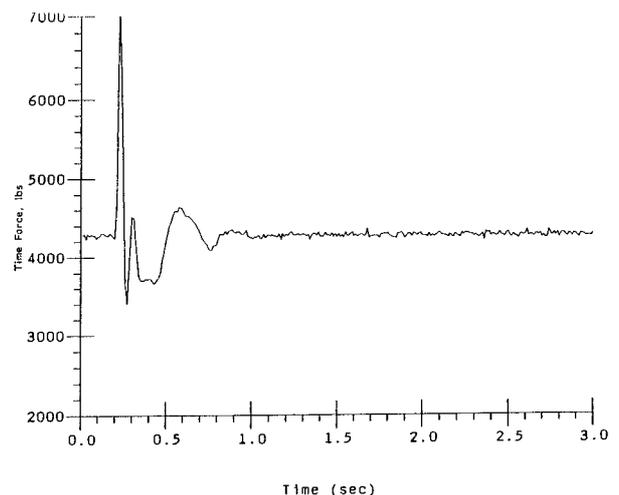
CONCLUSIONS AND RECOMMENDATIONS

The prediction of pavement responses under surface loads constitutes an important component of the mechanistic analysis of flexible

pavements. These responses are a function of both the pavement structure and the load characteristics. Factors such as tire pressure, axle load, axle configuration, vehicle speed, layer thickness, and time-dependent material properties influence the response. The FHWA Test Road was constructed to evaluate these functions as they relate to the verification of elastic and viscoelastic layer theory. An in-depth study of the effects of truck dynamics on the tire forces applied to pavements is being conducted on the hydraulic actuator system DYNTRAC. The experiments conducted at this facility promise to provide important insight into improving knowledge of the interactive relationship between vehicle performance and pavement behavior.



11. Measured tire force step response for a two-axle truck.



12. Computed tire force step response for a two-axle truck model.

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