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Continuous Deflection Basin Measurement and Backcalculation Under a Rolling Wheel Load Using Scanning Laser Technology

William J. Herr[1], Jim W. Hall, Jr.[2], Thomas D. White[3], Wayne Johnson[4]

Abstract

A review is presented of past and current technology used to measure pavement deflection. Requirements are given for an improved system for deflection measurement and backcalculation of layer moduli from a rolling wheel load. Pavement deflections are predicted using a 3D Dynamic Finite Element Model (3D-DFEM) for a rolling wheel load at a range of speeds for representative pavement types. The design of a Rolling Wheel Deflectometer (RWD) based on scanning laser profiling is described. Finally rationale for RWD use and data analysis is presented.

Introduction

Beginning with the Benkleman Beam in the 1950s (Benkleman 1953), a variety of methods for measuring the deflection of pavement under load have been developed. These methods involve a mechanism with a reference base located at a datum outside the test load zone of influence. Such methods are limited for cost-effective use on inservice pavements because of the time required and the necessity to stop and/or divert traffic. A variety of loading techniques have been employed. The Benkleman beam measures the rebound of the pavement when an 18,000 pound truck is driven from the measurement point. Other approaches included low amplitude vibratory loading, as in the Dynaflect and Shell systems, and impulse loading due to the Falling Weight Deflectometer systems (FWD) (Scrivner et al. 1969). Generally, for analysis, these dynamic loads have been assumed to be static and the pavement materials have been assumed to be elastic. However despite these assumptions, non-destructive testing (FWD) and backcalculation of elastic layer moduli have become standard procedures for pavement evaluation. Using estimates or measurements of the layer

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1. Member IEEE, SPIE, ASTM. President, Phoenix Scientific Inc., 1790-104 La Costa Meadows Drive, San Marcos, CA 92069
2. Member ASCE (News Correspondent, Air Transportation Division; Member and past chairman, Airfield Pavement Committee). Senior Pavement Engineer, Applied Research Associates, 3202 Wisconsin Avenue, Vicksburg, MS 39180
3. Member ASCE. Professor of Civil Engineering, Purdue University, 1284 School of Civil Engineering, West Lafayette, IN 47907-1284
4. Member ASCE, NSPE, Mississippi Engineering Society (MES), Society of American Military Engineers (SAME). Civil Engineer, USAE Waterways Experiment Station, Geotechnical Laboratory, Airfields and Pavements Division GP-Q, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

thicknesses, backcalculation methods have been developed to determine the strength of each layer. Models are then employed to predict the bearing capacity and remaining life for the design load.

Recent research confirms that there is difference in loading rate and manner of load application between the FWD and moving wheel loads and that the difference is significant in determination of the effective moduli of the pavement layers. Vehicles traveling 20 to 40 mph equate to loading frequencies of 2-4 Hz while the FWD loading is at 20 Hz. Also, the manner of load application is quite different with the FWD applying a vertical load pulse while the moving wheel has both vertical and horizontal force components. Moduli backcalulated from FWD tests could not predict measured deflections under moving wheel loads on flexible pavements. One recommendation from this research is to investigate a rolling wheel load for deflection measurement (Hall 1994).

The Deflectograph, originally developed in France and used extensively in the UK (Kennedy et al. 1987), uses two mechanisms, each similar to a Benkleman Beam configured on a T-bar with an apparatus to pick it up and move it forward 3 m after each measurement, permitting slow but continuous operation at a few Km/hr. The T-bar dimensions are not adequate to span the full deflection basin. Consequently only relative deflection magnitudes are determined. However the Transportation Research Road Laboratory (TRRL) has found this adequate for correlation to structural performance and maintenance decision making. In France, CEBTP has released an updated Curvimeter which employs a mechanism to translate three geophones at up to 15 Km/hr. The benefit of this system is that the end geophones are separated enough to ensure that absolute deflection magnitudes are measured. However it is difficult to conceive of these mechanistic translation devices operating at full highway speeds.

Ground truth data for non-destructive testing has been obtained from Multi-depth Deflectometers (MMDs) (White 1981). MMDs consist of a vertical rod installed in a hole in the pavement to the level where no deflection is likely to occur with displacement sensors, typically LVDTs, mounted at the desired levels along the rod. Other efforts have used instrumented non-contact overhanging beams to map the deflection impression caused by the passage of a rolling wheel (Harr and Ng-A-Oui 1977). While these techniques provide the desired measurements even from rolling wheels, they involve a fixed installation and thus are not suitable for production testing of in-service structures.

Requirements for a new generation of pavement deflection measurement technology are that it should have the improved capabilities and resulting operational benefits outlined in Table 1.

Prediction of Pavement Deflection Response to Rolling Wheel Loads

To establish performance requirements to guide development of the rolling wheel deflectometer (RWD), predictions were made of pavement systems' deflection from a rolling wheel load. These predictions were used to quantify the deflection profiles to be measured. Since the RWD has application to both highway and airfield pavements both types were analyzed. There are in general significant differences in thicknesses of highway and airfield pavements. Highway pavements can be characterized as having relatively light loads and high traffic volumes. On the other hand, airfield pavements are described as having heavy loads and relatively low traffic volumes. The loads considered were a truck super single wheel load of 9,000 lb. with 100 psi tire pressure and an aircraft single wheel load of 40,000 lb. and with 170 psi tire pressure.

In addition to the load, deflection profiles are affected by wheel speed, pavement material types and temperature, and layered structure of materials. Deflection magnitude is inversely proportional to load speed. Larger deflections would be easier to detect with the proposed RWD. However, at lower speeds RWD efficiency would be low because the rate of coverage would be low. To support a trade-off between speed and deflection, pavement response was predicted for four wheel speeds: 4,15,25 and 50 mph.

Table 1: Requirements for new deflection measurement technology

- Use of design load wheel type and speed.
- Continuous measurement of deflection to give detailed project level information and improved statistical validity to deflection-based decision making.
- Increased operator safety by measurement of deflection from a moving vehicle, eliminating the need to stop traffic to perform deflection testing.
- Reduced operational cost of testing by:
    - \+ Measurement of deflection and longitudinal profile simultaneously (reduces operational time, manpower and equipment requirements).
    - \+ Deflection measurement from moving vehicle speeds the data collection permitting use for Network level applications and more frequent measurements in areas with seasonal variations (water content and freezing).

Pavements are categorized as being flexible or rigid and the pavement structure usually consists of layers of various material. Flexible pavements may have an asphalt concrete (AC) surface, granular base and granular subbase constructed on the subgrade or may be full depth AC constructed directly on the subgrade. Rigid pavement structures consist of a Portland cement concrete (PCC) surface placed directly on the subgrade or on a granular or stabilized subbase. The eight pavement sections analyzed were selected to represent light-duty and heavy-duty sections of flexible and rigid highway and airfield pavements:

Flexible (AC) Highways
    Light-duty: 2" surface, 6" granular base, 0" granular subbase, CH subgrade
    Heavy-duty: 14" full depth asphalt, CH subgrade
Rigid (PCC) Highways
    Light-duty: 8" jointed plain concrete, 0" subbase, CH subgrade
    Heavy-duty: 10" jointed plain concrete, 5" stabilized subbase, CH subgrade
Flexible (AC) Airfields
    Light-duty: 4" surface, 6" granular base, 20" granular subbase, CH subgrade
    Heavy-duty: 17" full depth asphalt, CH subgrade
Rigid (AC) Airfields
    Light-duty: 10" jointed plain concrete, 6" granular subbase, CH subgrade
    Heavy-duty: 18" jointed plain concrete, 6" stabilized subbase, CH subgrade

In the selection of pavement sections for analysis only a CH subgrade soil was considered. Pavement sections were selected on the basis of minimum thicknesses, current experience, and design estimates. Flexible airfield pavement thicknesses were selected using design requirements for the B727. After estimating the flexible pavement layer thicknesses the section was converted to a full depth asphalt section using layer equivalencies (Yoder and Witezak 1975).

Primary analysis was conducted using a three-dimensional, dynamic finite element method (3D-DFEM) and a commercial program (ABAQUS 1989). This program has the capability of analyzing the moving wheel load problem as well as modeling elastic and plastic layer material characteristics. Studies have verified the 3D-DFEM static and dynamic analysis of both flexible and rigid pavements (Zaghloul and White 1993a), and (Zaghloul and White 1993b). In these studies no significant difference was found between the predicted pavement response and the measured pavement response from moving truck loads as well as rutting accumulations on a test section trafficked with an aircraft single wheel load with this technique (White and Zaghloul 1994).

Table 2: Material properties used in the 3D-DFEM calculations

Material	Parameter	Value
Subgrade (CH)	Modulus of Elasticity (psi)	4500
	Poisson's Ratio	0.4
	Angle of Internal Friction (degree)	10.53
	Cohesion (psi)	11.11
	Yield Stress (psi)	18.143
	Damping Coefficient (%)	5
	Density (pcf)	120
Granular Subbase	Modulus of Elasticity (psi)	25,000
	Poisson's Ratio	0.35
	Angle of Internal Friction (degree)	46
	Cohesion (psi)	0
	Yield Stress (psi)	80
	Damping Coefficient (%)	5
	Density (pcf)	120
Granular Base Coarse	Modulus of Elasticity (psi)	75,000
	Poisson's Ratio	0.4
	Angle of Internal Friction (degree)	46
	Cohesion (psi)	0.0
	Yield Stress (psi)	105
	Damping Coefficient (%)	5
	Density (pcf)	120
Stabilized Base	Modulus of Elasticity (psi)	$1x10^6$
	Poisson's Ratio	0.15
	Initial Compressive Strength (psi)	750
	Damping Coefficient (%)	5
	Density (pcf)	138
Concrete	Modulus of Elasticity (psi)	$4x10^6$
	Poisson's Ratio	0.15
	Initial Compressive Strength (psi)	3,000
	Damping Coefficient (%)	5
	Density (pcf)	142
Asphalt	Modulus of Elasticity (psi)	
Airfield, Lt. Duty		300,000
Airfield, H. Duty		--
0-4 inch		300,000
4-10 inch		350,000
10-17 inch		500,000
Highway,Lt.Duty		300,000
Highway,H.Duty		--
0-2 inch		350,000
2-8 inch		350,000
8-14 inch		350,000
	Poisson's Ratio	0.35
	G-Ratio	0.75
	Damping Coefficient (%)	5
	Density (pcf)	140

The material properties used in the analysis are given in Table 2. An elastic foundation was assumed at the sides, ends and bottom of the pavement sections. Plan dimensions of the highway pavement sections were 12 ft wide x 20 ft long for the concrete sections and 12 ft x 18 ft for the asphalt sections. Airfield sections were 20 ft x 20 ft and asphalt sections were 9.3 ft x 24 ft.).

For ease of modeling, the tire contact was assumed to be rectangular with an area equal to the load divided by the tire pressure. Tire width was 12.5 in for the highway load and 12.2 in for the airfield load. The contact area was calculated from the load and pressure given above and the contact length was obtained by dividing the area by the width. The highway load contact length was 7.2 in and the area was 90 in^2. The airfield load contact length was 19.3 in and the area was 235 in^2.

Finite element mesh size with depth was controlled by layer thicknesses and the need to maintain a reasonable aspect ratio. Mesh size in plan view was controlled by tire contact area dimensions. Transverse mesh dimensions were selected to coincide with load contact widths. Mesh element length was set equal to the length of the load for the highway sections and to one-half the load length for the airfield sections. The moving wheel load was simulated by loading elements for the time it would take the wheel to travel a distance equal to the length of the element at the specified test speed. A multi-step load function was used to apply and remove the load to each element as an approximation of the actual rolling wheel behavior. The simulation involved application of the load along eight sequential longitudinal elements centered in the mesh lengthwise to eliminate interactions with the beginning and ending mesh boundaries.

Figure 1a-d shows the predicted longitudinal surface deflection profiles along the transverse center line for the AC structures. The same results for the jointed PCC pavements are plotted in Figure 2a-d All the graphs are shown with the same Y axis scale to facilitate visual comparison of the deflection magnitude from the different structures. This results in low resolution for the PCC plots, particularly for the heavy-duty pavement. Consequently the heavy-duty PCC structure tested at high speeds is the driver in setting the resolution requirement for the RWD. The thinner AC and PCC highway structures exhibit smaller deflection than the thicker airfield structures. The visco-elastic characteristic of AC pavements is reflected in the wider deflection basin on the trailing side of the load. This result is more pronounced at higher speeds as expected

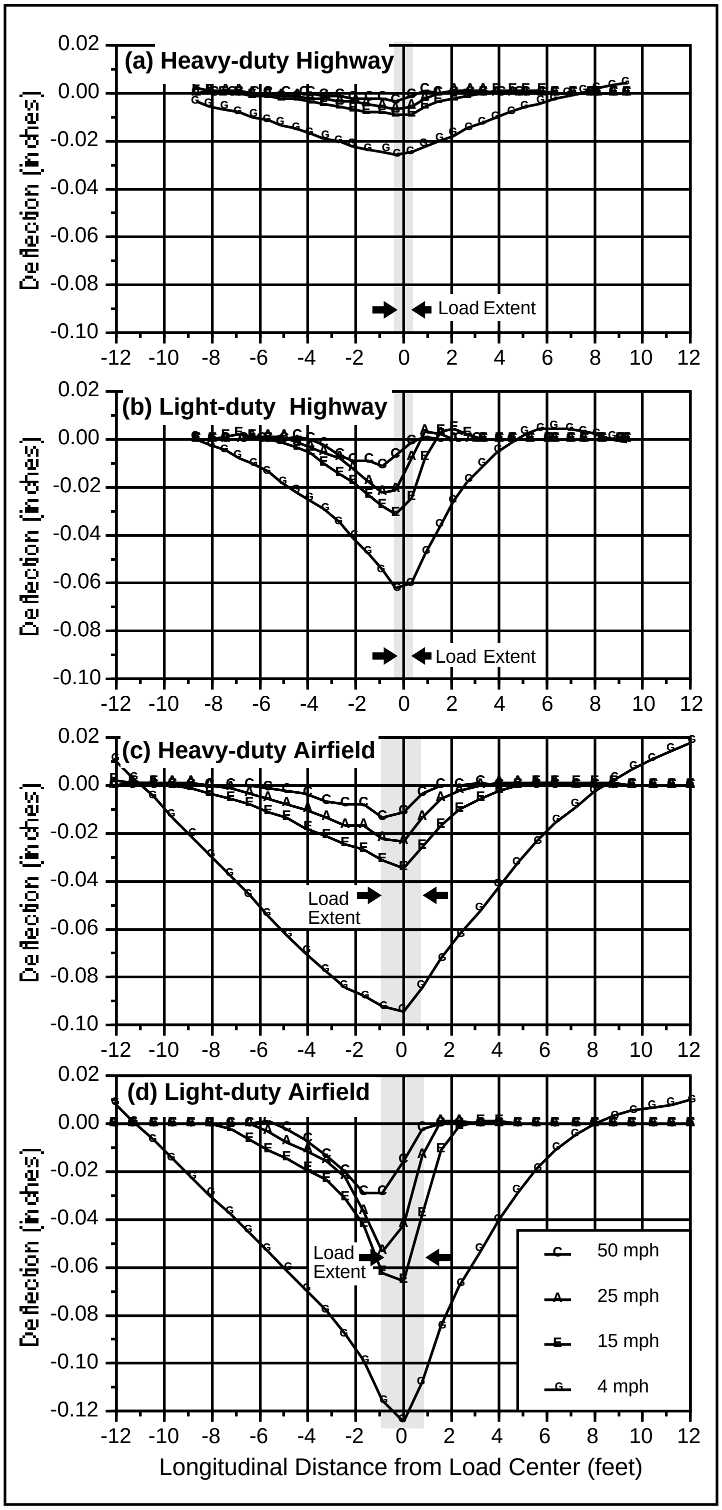

Figure 1: AC Pavement Deflection Profiles

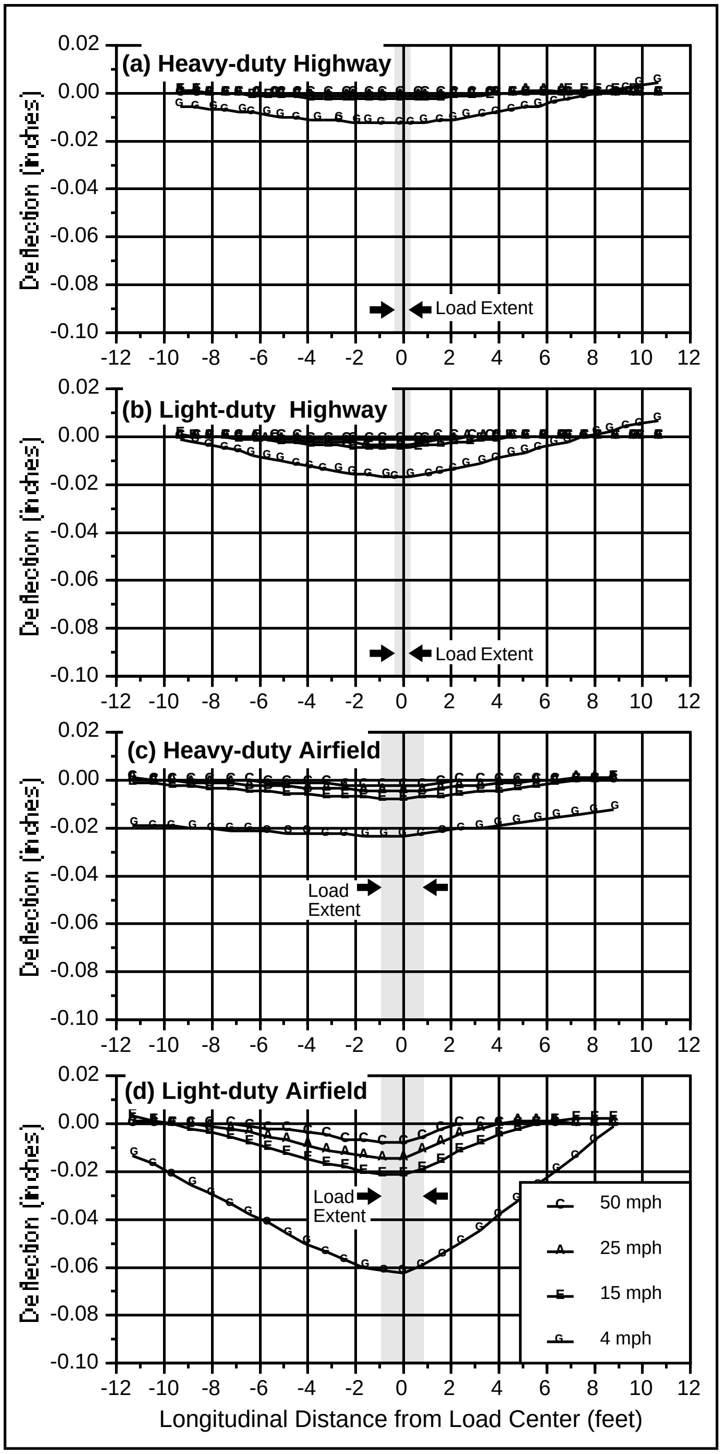

Figure 2: PCC Pavement Deflection Profiles

These predicted pavement surface deflections have been used in establishing the magnitude and extent of deflections the RWD will have to measure. The wheel load magnitude and speed determine the deflection response for a particular pavement structure. The optimum RWD operational speed and load for the specific pavement structures to be tested can be established using this approach. The objective is to generate a measurable deflection response with the maximum speed to minimize test time and impact on traffic and to assure that the pavement is not unduly over stressed.

ASTM D-4694-87, Standard Test Method for Deflections with a Falling Weight Type Impulse Load Device, specifies the accuracy of measuring vertical movement of the pavement as ±2% or ±2µm (0.08 mils), (paragraph 6.1.2). When ±2µm equals ±2% of the peak deflection, the peak deflection magnitude would be 100µm (4 mils). Across the spectrum of pavement types and rolling wheel load configurations only a small subset had deflections this small. The 3D-DFEM simulations of the rolling wheel load indicate that the resulting deflections are not significantly different in lateral extent but are generally greater in vertical magnitude than those produced by the falling weight type load, provided the rolling wheel load and speed are properly matched to the pavement strength. The rolling wheel deflections are expected to be somewhat larger than the FWD mainly because of higher loads and lower frequency of loading. Accuracy requirements in terms of percent should be the same as for the FWD, but in terms of magnitude, the accuracy may be a larger value. Accuracy requirements may vary depending on the application of the results and the model used for analysis.

From a purely practical consideration, the FWD absolute minimum accuracy specification is impractical to attain with modulated light systems since it is on the order of a few wavelengths of the visible and near infrared radiation. For example at the laser diode wavelength of 800 nm, the wavelength is 40% of the minimum ASTM specification. Interferometric techniques are required to resolve distances on the order the optical radiation wavelength. In a previous effort, PSI has established that interferometric based techniques are not suitable for use on pavement surfaces since the roughness of the surface makes fringe tracking and related imaging approaches impractical.

Based on the 3D-DFEM simulations and the assumption that the rolling wheel load and speed can be adjusted to elicit the appropriate deflection response, the RWD is designed for a measurement accuracy of ±25µm (1.0 mils). This would give a resolution of from 1:10 for the smallest deflections to 1:50 for the greater deflections. However in the event that better resolution is produced by the demonstration system, excess resolution has been provided for in the acquisition, storage, and processing paths of the data to capitalize on the better performance.

RWD Feasibility Demonstration System Description

The RWD system operates by computing the deflection basin under the rolling wheel by processing the pavement surface profiles before and during pavement deflection. The profiles are each measured with custom Laser ranging scanners specially designed from the ground up for the high precision and data rates required for measurement of pavement deflection from moving loads.

Design of the first RWD is based on demonstrating the feasibility of the RWD concept and acquiring sufficient data and experience to guide development of backcalculation techniques and future versions of hardware and software. RWD concept implementation is illustrated in Figure 3. The RWD is shown installed on a 48 foot trailer with air-suspension system, single axle, and super-single tires with 10,000 pound capacity per wheel. This configuration is suitable for testing all types of highway and light-duty airfield pavements. Over rough pavements at higher speeds, the deflection

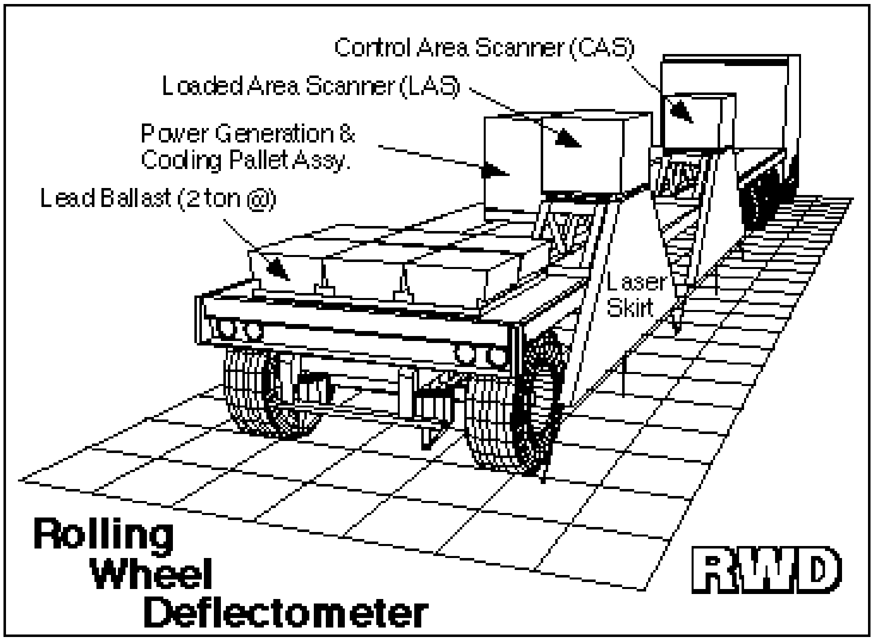

Figure 3: RWD Demonstration and evaluation system.

inducing load will vary from zero to 180% of the static load at the bounce rate of the trailer. This will complicate backcalculation. One concept is to provide a active control on the trailer suspension to maintain a constant load, see Appendix B of (Spangler 1992). This is costly and raises other questions about the meaning of the pavement response to a load regime different than experienced in normal use. For the demonstration system, the load will be measured and recorded, however the primary focus will be testing on reasonably smooth pavements and at suitable speeds such that the dynamic load is with ±10% of the static load. Implementation of a vehicle configuration with the load capacity for heavy airfields and the capability of over-the-road transport is planned for a follow-on version.

Primary elements of the RWD System are the Control Area Scanner (CAS) and the Loaded Area Scanner (LAS) which are environmental enclosures containing a Lidar scanner, associated sensors, and computer. They are shock mounted to a frame which is attached to the trailer. The top level system diagram, Figure 4, illustrates that the operator monitors and controls the state of the system from the tractor cab with a Graphical User Interface on the Laptop computer and a serial link to the LAS and CAS. The RWD system is structured to permit storage of all data collected from 5 miles of testing at 50 MPH for extensive analysis off-line. This architecture will permit the evaluation of the system function and deflection data and investigation of the optimum architecture for a follow-on design suitable for production testing. The configuration of the RWD preliminary design will accommodate an evolutionary upgrade of the prototype with relatively minor changes to the computers and data storage equipment. The CAS and LAS are nearly identical, including unit computers which are functionally identical, except that the LAS has external sensor inputs for distance traveled and wheel load. The layout of the LAS and CAS is shown in Figure 5.

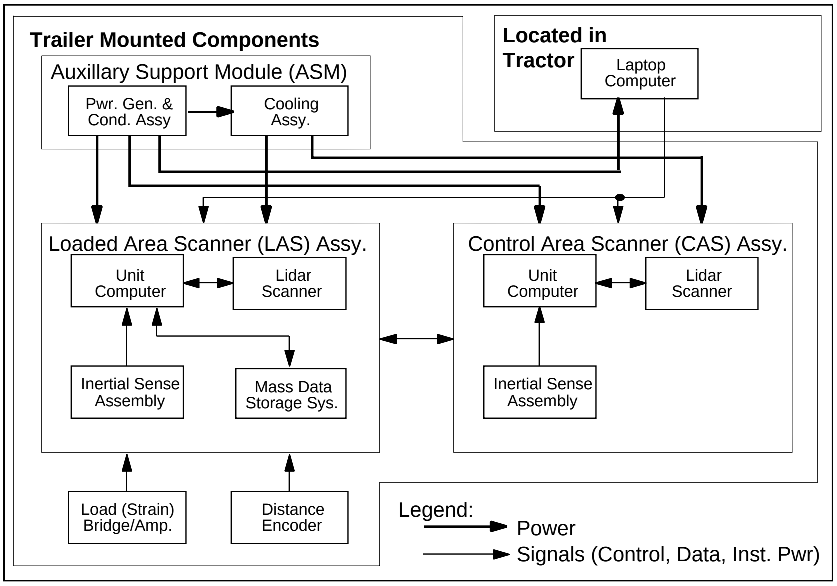

Figure 4: RWD demonstration system top-level diagram.

A precise profile of the pavement surface along a line is determined from a sequential set of distance measurements made by the scanners from a point centered above the line on the road surface to points on the pavement along the line. Only the optical bench and polygon are illustrated from an end view in Figure 5. The scanner optics layout plan view is shown in Figure 6 as viewed from the right side of the trailer. The polygon is shown in the two positions representing the beginning and end of scan. Vertical rays are also shown for clarity although the polygon is not shown in that position.

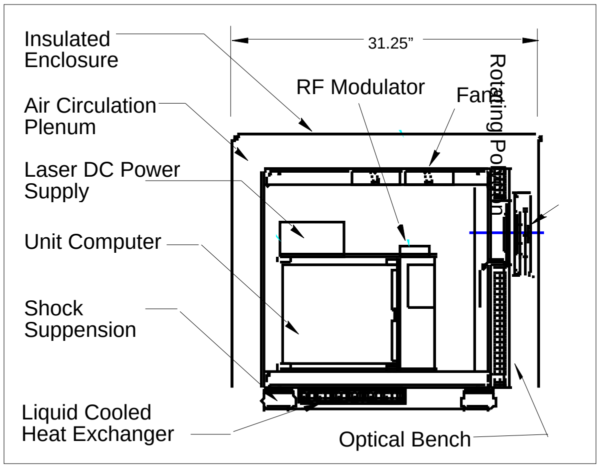

Figure 5: LAS/CAS Layout viewed from the rear of the trailer

The scanners are positioned above the pavement with the polygon rotational axis parallel to the plane of the pavement. The laser and detector are positioned in relation to the polygon so that one face of the polygon deflects the laser to the pavement. The adjacent face reflects light returning from the pavement area illuminated by the laser through field stops and collection optics onto the detector. Each time the polygon rotates $360/n_s$ degrees, one scan is completed. If the rotating scanner is stationary at one position above the pavement, a line on the surface of the pavement is illuminated perpendicular to the polygon's rotational axis. Thus, this type of scanner configuration is sometimes referred to as a line scanner, and the scanned area is referred to as the scan line

Amplitude modulation with phase shift measurement is used to attain the required data rates and resolution. This technique measures the time required for light, at a reference phase angle, to travel from the sensor to the pavement and back to the scanner. To a distance of one-half the modulation wavelength (to account for the round-trip distance), an unambiguous phase shift results. However beyond a distance of one half wavelength, the phase cycles through 2π radians every half wavelength, and thus becomes ambiguous. Consequently the distance of one half wavelength at the modulation frequency is defined as the ambiguity interval. By operating at 1.4648 GHz, it is easy to track the phase wrapping since the ambiguity interval of 10.24 cm (4 inches) is much greater than the range changes between samples separated by tenths of an inch. With 12 bit phase resolution the system will be able to measure deflection to 0.25μm (1 mil). A key feature of this design is the proposed approach to extend the range precision and data rate performance

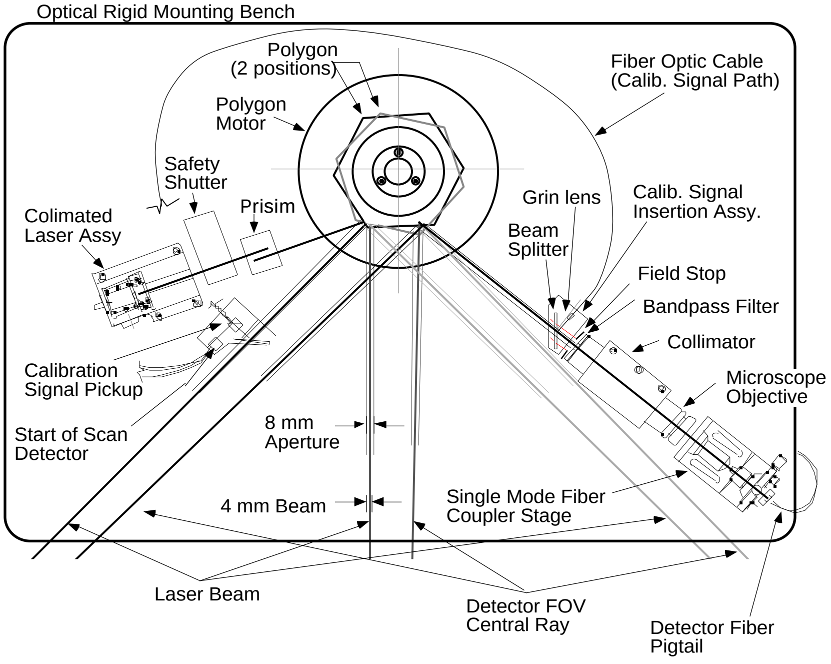

Figure 6: Lidar optics assembly detail.

by a state-of-the-art solution for phase measurement and the use of direct modulation of high power laser diodes.

By mounting the scanners so that the scan beam just clears the wheels, the scan lines are as close to bisecting the deflection basin as physically possible. The control area scanner (CAS) measures the undeflected pavement profile along a line sufficiently behind the lead wheels to allow the pavement to recover from those loads. The loaded area scanner (LAS) measures the deflected pavement profile and a portion of undeflected pavement profile as well. The scan lines are nominally 12-14 feet long. The LAS scan is positioned to cover 1 foot aft of the tire print (so as to measure the peak deflection on pavements with high visco-elasticity), forward over the nominal 6-8 foot of deflection to encompass 4-5 feet of undeflected pavement.

The deflection basin is determined by processing LAS and CAS scans that are spatially coincident. After preprocessing and polar-to-rectangular conversion of each scan, the LAS scan is transformed so that the leading undeflected 4 feet is aligned statistically with the same part of the CAS scan. Then the deflection basin is determined by subtracting the CAS scan from the LAS scan. This algorithm accomplishes two important processes: 1) it eliminates the need to try to position a second sensor precisely in time and space to measure the precise same point as was measured by the first sensor, and 2) it removes inherent topography such as cracks from the deflection profile. This system will provide a very accurate measurement of joint load transfer efficiency.

A line scan rate of 1 KHz was selected to minimize distortion of individual profile scans due to pavement roughness induced motion, which will be below 15 Hz. Inertial sensors in the LAS and CAS monitor motion on the body axes which can impact profile accuracy (i.e. heave, pitch and roll). When the parameters exceed threshold levels the data can be excluded or corrected in post processing during the spherical to rectangular transformation of the scan using the motion data.

A variable sample rate is required to generate samples that are evenly spaced along the pavement due to the constant angular scan rate. The average rate required to produce 1000 points per scan line is 1.3 MHz, assuming a hexagonal scanner with 75% duty cycle. With a 12 foot scan line the samples will be separated by 0.37 cm (0.14 inches). Statistical processing will be used to determine a "mean" elevation over nominally 30.4 cm (1 foot) segments of the profile. The most demanding instrumentation requirement in the system derives from the scanning process. To limit distortion in each sample of range to less than the resolution requirement of 25μm (1 mil), the data must be sampled in 5.7 nsec because the rate of change in distance to the pavement at the maximum scan angle is so large.

RWD Applications and Data Analysis

The Falling Weight Deflectometer (FWD) is used to test discrete points on a pavement from a static position. A Rolling Wheel Deflectometer (RWD) will provide essentially continuous deflection testing from a moving vehicle. The RWD will provide higher resolution for project level applications and make extensive and more-frequent network level applications viable.

Current backcalculation procedures utilize linear elastic multi-layer or finite element analysis models to predict surface deflections. The analysis is iterated, varying the elastic moduli of the layers, until reasonable agreement is achieved between the predicted and measured surface deflection basins. Input to the FWD backcalculation process includes the dynamic load of the falling mass, peak deflections at the point of loading and at offsets along a radial line from the load, and the various layer thicknesses. In the analysis, the dynamic load is assumed to be a static load. Materials are indirectly identified by assigning Poisson's ratios and initial linear elastic moduli to the pavement layers. The type of material in each layer may be identified directly with cut-off limits of each respective modulus. In any case, analysis based only on elastic material characterization does not capture the nonlinear and time dependent behavior of pavement structures.

It has been expedient for FWD backcalculation to assume that the dynamic load caused by the falling weight is static and that the pavement layer materials are linear and elastic. However, 3D-DFEM analysis provides a much better representation of the pavement response and more accurate backcalculation of pavement layer material properties (White et al. 1993). Using the 3D-DFEM type model, the materials can be represented by expressions that account for the linear, nonlinear, and time and temperature dependent characteristics. For these reasons, 3D-DFEM will be used in subsequent efforts to analyze RWD results and develop the foundation for practical backcalculation of RWD data.

The current 3D-DFEM requires a workstation class computer, high-end software and considerable CPU time. Advances in software efficiency (explicit finite element engine and reduction to 2D mesh in the vertical longitudinal plane) and hardware throughput are possible, however 3D-DFEM computation for production test results analysis will probably always be less cost-effective than derivative data driven approaches. It is anticipated that 3D-DFEM will be employed to generate a database of pavement structure response. Then lookup tables or regression expressions will be developed for production backcalculation. Of the two methods, regression equations offer more flexibility. The amount of work can be reduced by the use of partial factorial experiment design to guide the analysis of the major factors. Prior work shows regression expressions effectively capture the various types of material properties and pavement responses (White et al. 1993). Neural network methods could be applied as well. Regression expressions similar to those used for FWD analysis would be developed for the RWD. Expected input to the analysis would be temperature, layer material type and thickness, rolling wheel load area, magnitude and speed and surface deflection profile. The corresponding regressions can be executed quickly on a personal computer (White et al. 1993). The ultimate goal is to develop on-board analysis capability for the RWD.

Conclusions

The RWD system currently under development will provide the ability to measure the deflection of pavement under the actual load conditions experienced by the pavement structures. This representative test loading may overcome the technical limitations of the fast transient load of the FWD. The 3D-DFEM techniques presented provide the basis for analysis of the RWD results using the actual material properties involved, thereby overcoming the limitations of the linear elastic assumptions inherent in the standard FWD backcalculation procedures. Finally, testing from a moving vehicle with a high-bandwidth improves safety by removing the technicians from the pavement service, minimizes impact on traffic, and produces a highly cost-effective system. Other benefits of the RWD may include its inherent ability to measure longitudinal profile and joint load transfer dynamics.

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