Measuring Pavement Deflections Near a Super-Heavy Overload

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Effects on in-service pavements from super-heavy overloads weighing over 2,000,000 pounds are investigated. A field study was performed in which a crack survey was conducted, pavement deflections were measured using a Dynaflect before and after overload transport, and several instruments were deployed to measure surface deflection when the overload traversed the pavement. The field study also characterized materials, determined dimensions of structural layers, and measured wheel loads applied to the pavement. Measured deflections are compared to predictions that are based on models used for flexible pavement design. Results of crack surveys show no change in the visible condition of the pavement after transporting the overloads. Dynaflect measurements after transport were approximately equal to pavement deflections measured before hauling the overloads. In-transit deflection measurements show that a "big basin" results from widely distributed trailer axle/tire loads. Deflections from tractor tires were not substantially different from those caused by trailer tires. Measured in-transit deflections agree reasonably well with maximum displacement predicted using elastic layer models.

Historical data from California's Department of Transportation (CALTRANS), which is responsible for evaluating permit and variance requests, indicate that variances are being requested for heavier loads each year. Since 1982, permits and variances for overweight loads jumped 57%, from approximately thirty-seven thousand to sixty-one thousand. A conspicuous increase is the number of permits approved for super-heavy overloads, which typically exceed 300,000 pounds gross vehicle weight (GVW). Only one permit was approved in 1983; nearly twenty were granted in 1987.

California's continuing industrial and population growth promises an increasing number of heavier loads. One reason for this trend is a lower cost associated with foreign manufacture of large components, such as chemical reactor vessels, power generators and electrical transformers. However, when large components are not fabricated on site, costs and logistics of transporting these parts become very important. When public roads are used, a crucial constraint in transporting these loads is the physical limitation of highway structures, such as inadequate bridge strength (*1*).

Effects of super-heavy overloads on pavement deserve investigation. In California, as in other states, typical overloads are limited to no more than structural load limits established for bridges and overcrossings on a route. These limits, which generally use GVW, number of axles, and axle spacing as criteria, are based on structural analysis and load equivalencies. When loads slightly exceed the criteria, engineering judgment is generally invoked to set a safe load limit. However, when no structures are traversed and GVW greatly exceeds previously permitted loads, an accurate procedure for routine evaluation is not available, and engineering experience is limited.

A field study and computer modeling analysis were conducted to investigate effects of super-heavy overloads on pavements. The goals of the investigation were to determine if any observable damage was caused by overloads; to check for invisible pavement damage; to measure pavement deflections near the loads in transit; and to compare in-transit deflections to predictions from mechanistic models.

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BACKGROUND

In the spring of 1987, variances were requested to haul the two heaviest loads ever moved on a California state highway. Transporting these overloads on a state highway provided an opportunity to study in-place pavement response and short-term damage. They were to be transported on State Route 213, from the Port of Los Angeles to a refinery in Torrance, California (see figure 1). Route 213 is a four-lane, urban, principal arterial with peak hour traffic volume from 1,150 to 1,850 vehicles, and an annual average daily traffic (ADT) ranging from 19,400 to 31,000 vehicles (*2*).

The GVW of each load was estimated at 2,100,000 pounds, composed of 1,600,000 pounds from a chemical reactor vessel and approximately 500,000 pounds trailer tare. The reactors could not be transported by rail because they exceeded weight and width limits. Figure 2 shows dimensions and typical configuration of each reactor, trailers, and tractors. Table 1 shows trailer and tractor tire specifications. A total of 384 tires supported each reactor, using 24 axle lines and 16 tires per axle line. Each trailer shown in figure 2 was composed of four German-made Goldhofer trailers interconnected. These trailers have steerable axles and hydraulic suspensions that can be adjusted to maintain a balanced load during transport. Tractor GVW was approximately 110,000 pounds, composed of 62,000 pounds unladen weight and approximately 49,000 pounds from added counterweights.

Before granting variances, a reliable procedure was sought to predict pavement damage from these overloads. A literature search revealed that a Highway Research Board task force developed guidelines and recommended evaluation procedures in the early 1970s (*3*). It was recognized at that time that methods were not available for engineers to predict accurately the destructive effects of overloads on pavement. Con-

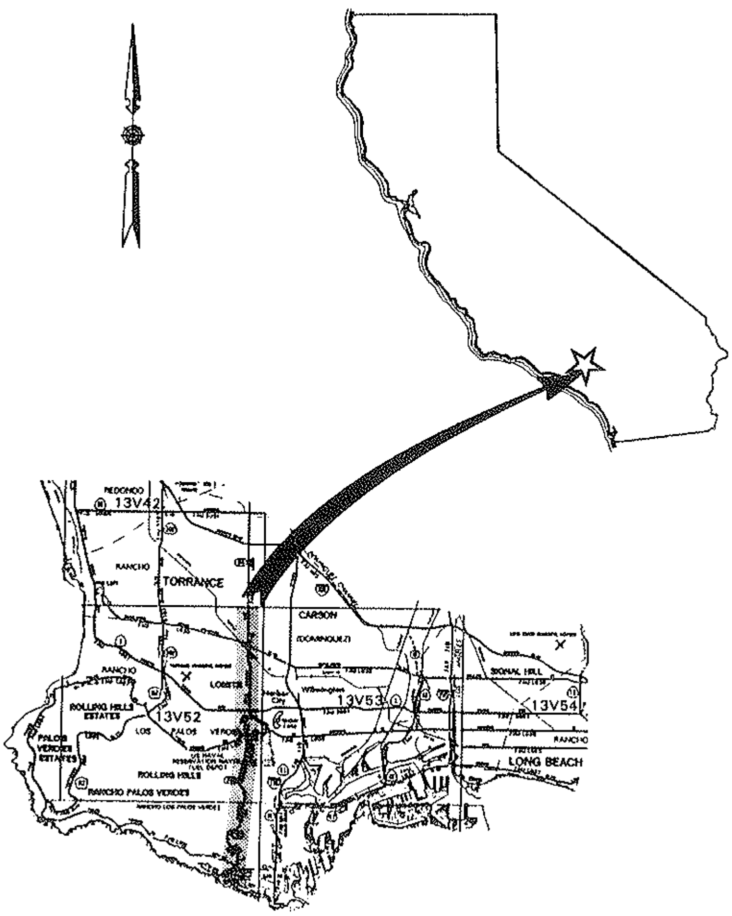

FIGURE 1 Location map for transport of overloads.

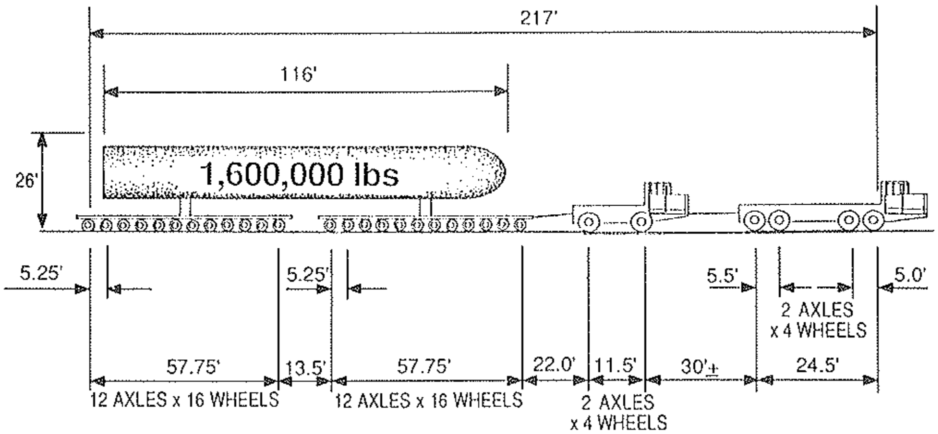

FIGURE 2 Overload configuration and dimensions.

cerns about the accuracy of predictive techniques remain to the present day.

The task force recommended a mechanistic procedure that was used subsequently in several studies (*4–6*). The mechanistic approach uses computer models and elastic layer theory to predict the allowable number of 18 kip equivalent axle load (EAL) applications on a structural section. The task force presented stress/strain limits to estimate the number of EALs that would cause failure by cracking and rutting. However, the task force warned that "it is . . . difficult to specify allowable values for stress or strain since these data are not as yet readily available from experience" (*3*). The task force's uncertainty remains justified because stress/strain response and failure of pavements under super-heavy overloads are still not known completely.

FIELD STUDY

Methodology

Concern about the uncertainties of the mechanistic approach led to a field study in which pavement response was investi-

TABLE 1 TRAILER AND TRACTOR TIRE SPECIFICATIONS

	Average Load[1] Per Tire, lbs.	Tire Size	Contact[2] Area, sq.in.	Contact Pressure, psi	Tire Pressure, psi
Trailer	5,500	8.25 x 15	60	92	70
Tractor	15,000	18.00 x 25	306	49	70

1 Average trailer tire loads from second reactor were approximately 12% higher.

2 Area shown has tread area of 15% (assumed) already deducted. Total area is estimated using field measurements of static contact perimeter.

gated. Observable damage was recorded by conducting a visual crack survey before and after passage of the reactors on Route 213. Comparing crack records would show visible distress caused by each reactor. Invisible damage was investigated by measuring pavement deflections using a Dynaflect before and after each reactor was transported along the route. Reduced structural strength of the highway would be inferred if Dynaflect deflections increased significantly after transporting the reactors.

To define existing structural sections along the route, district staff extracted cores a few days before the reactors were moved. Cores and a visual survey of the route were used to select roadway sections for before-and-after evaluation of pavement condition, as well to choose level test sites for in-transit measurements.

The most innovative aspect of the field study was measurement of pavement deflection near the outer trailer tires as each reactor passed sensors located on the surface. To measure in-transit deflections, a seismometer, accelerometer, and displacement tracker were deployed at test sites on Route 213. Deflections from trailers and tractors were also measured at the Port of Los Angeles. A seismometer was used in all field tests. The accelerometer and optron recorded deflections from reactor 2 only. No routine, mobile, and nondestructive procedures are available for measuring pavement displacement under these circumstances. Instrumenting a pavement section with linear variable differential transducers was considered, but time and funding constraints precluded their use. In fact, deflection was chosen as the measure of pavement response because instrumenting pavement sections with strain gauges was not feasible. Pavement deflections from an overload were measured by Mahoney (*5*) using Benkelman beams in a tandem configuration. The outside beam measured deflections at the fulcrum of the inside beam, which measured deflections near the trailer tires. This was done to compensate for the extraordinarily large deflection basin expected under all the closely spaced, heavily loaded trailer tires. Alternative methods were sought that could detect the trailer's "big basin" and that would provide a permanent record of deflections as the pavement was loaded and unloaded.

Only one instrument was used successfully when the first reactor was moved. A seismometer, that is, a velocity transducer, was evaluated at TransLab, and it showed that it could sense pavement displacement at frequencies expected from each trailer axle. A seismometer offered the distinct advantage of using the center of the earth as a reference point instead of measuring differential displacement from some fixed point nearby. Considering all constraints, it was the only readily available instrument to measure deflections from the first reactor. Several other methods were suggested, such as displacement transducers, optical precision levels, and laser transits, but none satisfied all constraints.

The seismometer used in the field study is a Kinemetrics model SS-1. Its practical minimum frequency response is 0.25 Hz. Its resonant frequency is 0.5 Hz, overshoot ratio is 0.05, and the damping factor is 0.70. Its use requires calibration factors that were determined at TransLab. Correction factors for near-resonant vibrations were provided by the manufacturer. The seismometer was linked to a Kinemetrics SC-1 signal conditioner, then to a Clevite brush 16-2300-00 oscillograph. Damping calibrations were performed prior to field measurements and seismometer calibration factors were verified at TransLab after the first reactor was moved. This system has a long history of stability and sensitivity in vibration studies conducted previously by CALTRANS personnel.

Figure 3 shows a plan view of the seismometer, event marker, and tire, as well as other instruments that were used when the second reactor was transported. A tire-triggered event marker was placed next to the seismometer to correlate loading with displacement and to check speed (i.e., frequency) of load.

The seismometer's trace of velocity with respect to time provides a record of zero-to-peak vertical particle velocity as the surface of the pavement near the tires is displaced. Displacement and velocity are related as shown below based on sinusoidal loading:

$$D = \frac{V}{\pi f} \qquad (1)$$

where

D = peak-to-peak particle displacement,
V = zero-to-peak particle velocity, and
f = the frequency of sensor excitation.

Some limitations are inherent in this approach. Axles may excite the seismometer below threshold so that the sensor does not detect some displacement. This appeared to be pos-

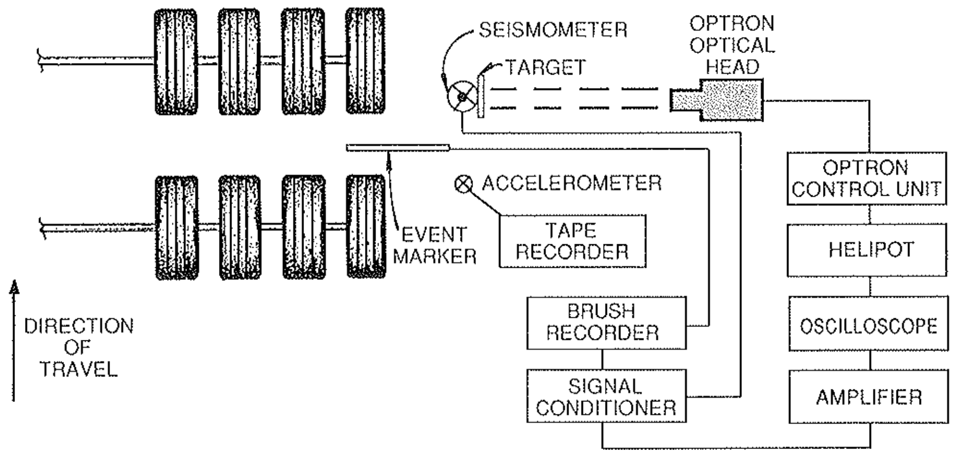

FIGURE 3 Plan schematic of instrumentation used in field studies.

sible but could not be determined without knowing the frequency of loading and the extent of deflections near the trailer tires. For example, the idealized pavement response shown in figure 4 compares one long duration, low frequency load/unload cycle under an overload to typically higher frequency axle loads from a legal-sized truck (*5*). A deflection trace for an overload is composed of repetitious displacements, which are caused by individual axle loads. These displacements are superimposed on a lower frequency cycle, which induces larger deflections than those from individual axles. These larger deflections form a "big basin" under the trailer. A seismometer was expected to detect deflections from individual axles; however, its ability to measure a "big basin" was uncertain. Another limitation is that deflections determined from the seismometer are relative displacements that are not necessarily additive. In addition, only one sensor detected data in the deflection basin. More seismometers would have been deployed had they been available.

After the first reactor was moved, there was considerable concern that substantial deflections due to the "big basin" were not detected by the seismometer. This concern was reinforced by the substantially higher model predictions (described below). These factors made it important to find instruments that were more sensitive or that could measure deflections directly.

When the second reactor was moved, two more instrument were used: a piezoelectric accelerometer and an electro-optical displacement tracker. Figure 3 shows how these instruments were deployed at the test site.

The accelerometer is a model 8318 piezoelectric sensor manufactured by Brüel and Kjaer (B&K) Instruments, Inc. Frequency response for the accelerometer is 0.1 Hz to 1 kHz. Deflections from the accelerometer were recorded on a B&K 7005 tape recorder. Frequency response on the tape recorder is 0 to 12.5 kHz. Recorded data were subsequently evaluated on a B&K dual channel signal analyzer, type 2034. Frequency range of the analyzer is 0 to 25.6 kHz.

A trace of pavement surface acceleration with respect to time provides a record of zero-to-peak vertical particle acceleration as the surface is displaced. Displacement and accel-

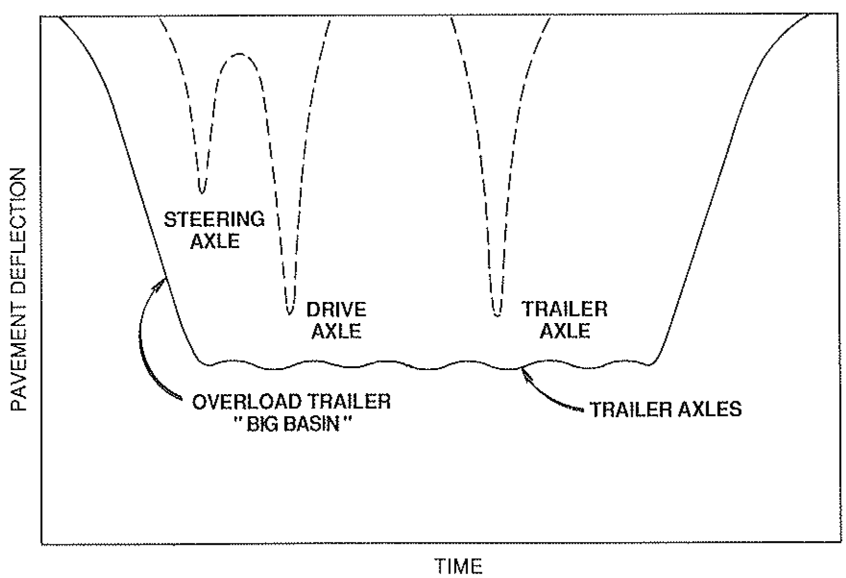

FIGURE 4 Idealized pavement response for super-heavy trailer and a typical truck.

eration are related as shown below based on sinusoidal loading:

$$D = \frac{A}{2\pi^2 f^2} \tag{2}$$

where

D = peak-to-peak particle displacement,
A = zero-to-peak particle acceleration, and
f = the frequency of sensor excitation.

The electro-optical displacement tracker, or optron, consists of a model 805M optical head and model 501 control unit, manufactured by Optron Corporation, Woodbridge, Connnecticut. The optron is used for production and testing by companies such as IBM, Xerox, Ford, and General Motors. It has been used for research at the National Aeronautic and Space Administration, Rutgers University, the University of Southern California, and by the U.S. armed forces.

Frequency response of the optron is from DC to 25 kHz. Changeable lenses allow measuring displacements with the optical head as close as 2.6 inches or as remote as 704 feet from the target. Resolution of displacement is 0.0008 inch (0.8 mils) at 11 feet, which was the distance used during this field study. The optron was linked, via other instruments shown in figure 3, to a Kinemetrics SC-1 signal conditioner, then to a Clevite brush 16-2300-00 oscillograph.

Optron displacement trackers follow the motion of a discontinuity in the image of a moving object, which in this study was a black-over-white rectangular target attached to the seismometer. The image of the target is focused on the photocathode of an image dissector tube in the optical head (see figure 5). Electrons are emitted from each point of the photocathode in proportion to the image's light intensity. The resulting electron image is refocused on a plate with a small aperture. Electrons traversing the aperture form a signal current proportional to the intensity at the corresponding point of the target. The signal is amplified and is used by a patented servo loop to keep the electron image of the target centered on the dissector aperture. As the optical target image moves, the servo control changes the current in deflecting coils so that the electron image returns to its initial position. The deflection current required to recenter the electron image corresponds to displacement of the target.

The optron offers several advantages, including direct measurement of displacement and capability of measuring DC, eliminating concerns about frequency response. It therefore has the best chance of recording displacements due to a "big basin." The optron can document pavement response during loading and unloading, providing evidence of plastic deformation if it did not rebound to its preloaded level. The target, which is expendable, can be placed closer to a tire than an expensive accelerometer or seismometer. Using the optron does have disadvantages: it is sensitive to light intensity, and the displacement record ceases if the light beam from the target is broken. Calibration of the sensitive optron can be difficult and should be performed at the test site.

In addition to measuring deflections on the highway as the reactors passed, pavement deflections were measured using the seismometer at the Port of Los Angeles before the second reactor was moved. Measurements were recorded near the trailer as it was hauled past the seismometer. Later, the trailer was detached and only the tractor passed close to the seismometer.

The purpose of measurements at the port was to compare deflections near the trailer with those near the tractor. Terrel and Mahoney (*4*) used mechanistic procedures to conclude that high tractor tire loads could be more damaging than tire loads from a trailer. It was hoped that measurements at the port would provide a rough comparison of pavement deflections under tractor and trailer tires.

Data Analysis

For reactor 1, a site to measure pavement response during the move was chosen at post mile (PM) 2.28. The structural section at this site is 0.4 foot asphalt concrete (AC) pavement, 1.3 feet untreated aggregate base, over damp silty clay. Peak hour traffic volume is 1,150 and annual ADT is 19,400 vehicles (*2*). California's Pavement Management System (PMS) contains condition survey data that were collected in 1985 along this section of Route 213. The PMS indicates that a maximum of 15% of one wheel path and 8% of both wheel paths exhibited alligator cracks. The 1985 survey also showed minor bleeding and no ruts greater than ¾ inch.

The condition survey showed no discernible difference in the pavement surface after the first reactor passed. The survey was done the afternoon before and the morning after the reactor was moved. Dynaflect measurements show substantially the same deflections before and after the reactor was

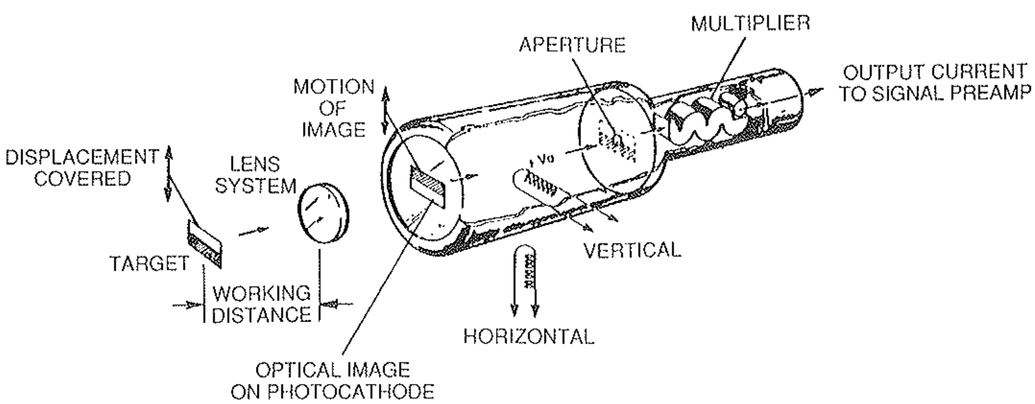

FIGURE 5 Components of optron optical head.

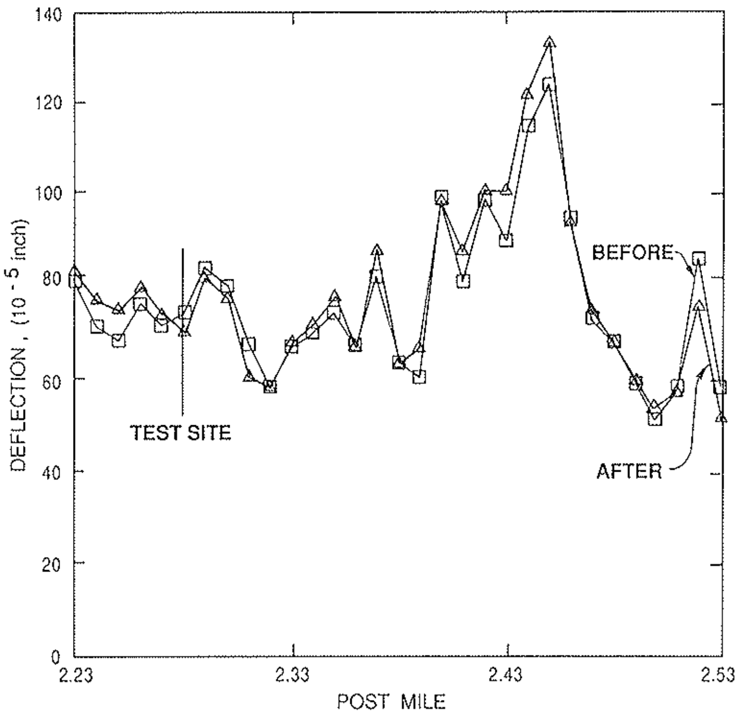

FIGURE 6 Sensor 1 Dynaflect deflections before and after moving reactor 1.

moved. Figure 6 shows sensor 1 deflections measured at PM 2.23–2.53. Before moving the reactor, deflections were measured when air temperature was 65°F and pavement temperature was estimated at 65°F under clear skies. These conditions are typical at the site during the spring (*7*). Deflections were later measured when air temperature was 70°F and pavement temperature was estimated at 90°F under sunny skies. Deflections were corrected for differences in temperature using the American Association of State Highway and Transportation Officials design guide for 1986 (*8*). Mean daily temperatures for the preceding five days were obtained from the Long Beach airport.

Deflections were measured at PM 2.23–2.53, 2.80–3.10, and 5.88–6.18 in the early morning before the reactor was transported. Deflections were measured again at the same sites in the late morning after the reactor was moved. Dynaflect measurements were recorded by a driver as another technician walked alongside to paint spots on the pavement where sensor 1 deflection was measured. After the reactor was moved, the walking technician spotted the Dynaflect to assure sensor 1 measurements were recorded on the same spots.

Results of the condition survey and Dynaflect measurements indicate that either no short-term damage occurred or else damage was not detectable using these methods. In addition, pavement response during loading is unknown. The third component of the field study, measuring in-transit deflections, provides this useful information.

The seismometer successfully measured deflections as the first reactor passed the test site. Table 2 summarizes pertinent data from in-transit measurements. The first trailer passed at a constant distance from the seismometer. The second trailer veered substantially more than the first, which seemed unfortunate initially. However, deflections closer to the tires were measured as a result. The frequency at which the individual trailer axles/tires passed was well above the minimum detectable by the seismometer. Air temperature was approximately 65°F and pavement temperature was estimated to be 75°F. The event was recorded on videotape for later verification of distances and speeds during the trailer's passage.

Pavement deflection data were studied to examine how displacement varied with distance and to estimate displacement under the outer trailer tires. Deflection data and a least-squares regression line are shown in figure 7. Pavement deflection under the outer trailer wheel is estimated to be 29 mils, although adjustments of the regression line within the confidence limits would alter this value. Figure 7 shows 95% confidence limits as dotted lines above and below the regression line. The correlation coefficient is significant at a 99% confidence interval using a two-tail test (*9*).

The seismometer velocity trace is depicted in figure 8. The abscissa shows the number of seconds since the recorder was turned on. Figure 8 shows a scale for peak vertical velocity also. Axle 9 on the second trailer caused a deflection that was unreadable. Axle 11 grazed the seismometer, which is why the trace jumped off scale. A subsequent check of the seismometer's calibration indicated no significant change.

The seismometer trace generally agrees with the pattern of deflections expected from individual axles shown for an overload trailer in figure 4. The repetitious velocity shifts in figure 8 correspond to deflections induced by individual axles. The seismometer data do not indicate additional deflection expected from a "big basin," however. Assuming that such a basin did in fact exist, the rate of pavement displacement probably occurred below the detection level of the seismometer.

For reactor 2, a site was chosen at PM 5.90 to measure

TABLE 2 SUMMARY OF IN-TRANSIT SEISMOMETER MEASUREMENTS

	Distance, feet		Deflection, mils		Average Vehicle	Frequency of Loading, Hz	
	Range	Mean	Range	Mean	Speed, mph	Range	Mean
REACTOR #1							
(PM 2.28)							
1st Trailer	2.0	2.0	1.6 - 2.3	1.9	3.8	0.98 - 1.12	1.06
2nd Trailer	0.2 - 1.0	0.6	6.5 - 24.5	12.7	3.8	0.82 - 1.19	1.07
REACTOR #2							
(PM 5.90)							
1st Trailer	2.5 - 3.0	2.8	0.5 - 1.1	0.6	3.0	0.80 - 0.90	0.84
2nd Trailer	2.3 - 3.2	2.8	0.4 - 1.3	0.6	3.4	0.90 - 1.00	0.96
REACTOR #2							
(Port)							
Run 1 -							
1st Trailer *	2.0	2.0	1.3 - 2.3	1.9	1.8	0.50	0.50
2nd Trailer	2.0	2.0	1.0 - 3.7	2.7	2.1	0.50	0.50
Run 2 -							
1st Trailer	3.2 - 3.9	3.5	0.5 - 1.3	0.8	4.4	2.50	2.50
2nd Trailer	0.8 - 3.0	1.3	1.4 - 9.3	6.4	4.6	1.14 - 1.39	1.28
Tractor **							
Front Axle	2.7 - 5.2	3.6	0.20 - 2.0	1.2	3.7	0.89 - 2.50	1.50
Rear Axle	2.7 - 5.2	3.6	0.3 - 3.8	1.8	3.7	0.72 - 1.39	0.99

* Average wheel load on trailer was approximately 6,200 lbs/tire.

** Average wheel load on axle 1 was approximately 12,800 lbs/tire. For axle 2, average load was 16,000 lbs/tire.

pavement response during passage of the reactor. The structural section at this site is 0.2 feet AC, 0.65 feet portland cement concrete pavement (PCCP), over fine, brown silty sand. Traffic at the site is typical for this route, peak hour traffic volume is approximately 1,200, and annual ADT is estimated at 20,400 vehicles (*2*). The PMS contains condition survey data that were collected in 1985 along this section of Route 213 and indicates that 16% of one wheel path and 6% of both wheel paths showed alligator cracks. The 1985 survey also showed localized bleeding and no ruts greater than ¾ inch.

As before, the pavement condition survey showed no discernible difference in the pavement surface from transporting the second reactor. The survey was done the morning before and the morning after reactor 2 was moved. Dynaflect measurements again show similar deflections before and after reactor 2 passed. Figure 9 shows sensor 1 deflections measured at PM 5.92–6.22. Dynaflect deflections measured before hauling the reactor were recorded when the air temperature was 80°F and pavement temperature was 85°F under clear skies. Deflections measured after the reactor passed were taken when the air temperature was 65°F and pavement temperature was 69°F under hazy skies. Again, these are typical spring conditions at the site (*7*). Deflections again were adjusted for differences in temperature (*8*). A wider difference between before and after deflections is partially attributable to a more complex response of overlaid PCCP to temperature changes. In addition, joints and cracks that were not visible in the underlying PCCP may have affected deflections.

Deflections were measured midday before reactor 2 was

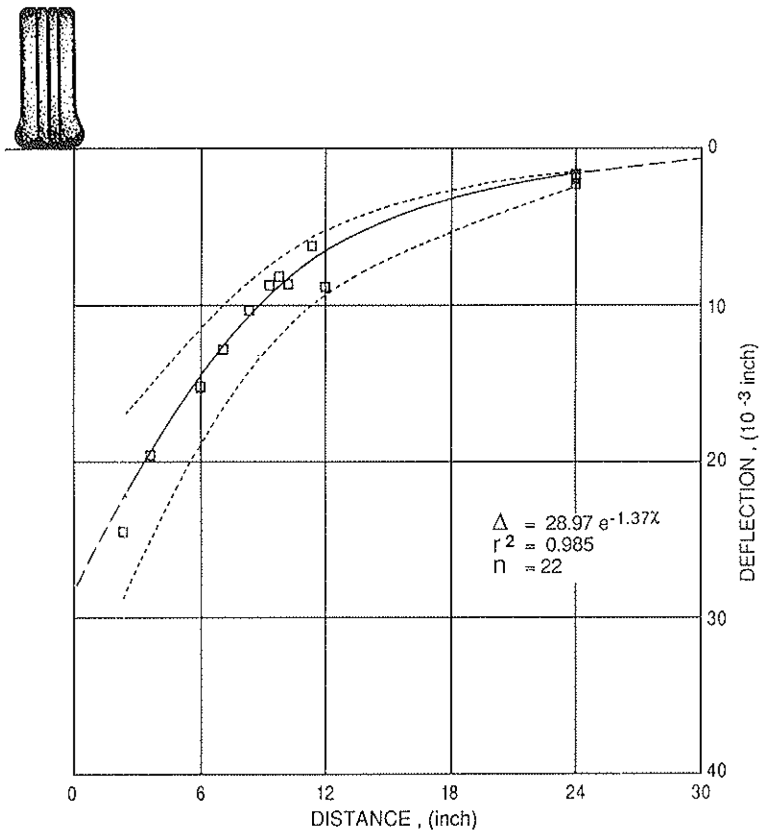

FIGURE 7 Pavement surface deflections near outer trailer tires for reactor 1.

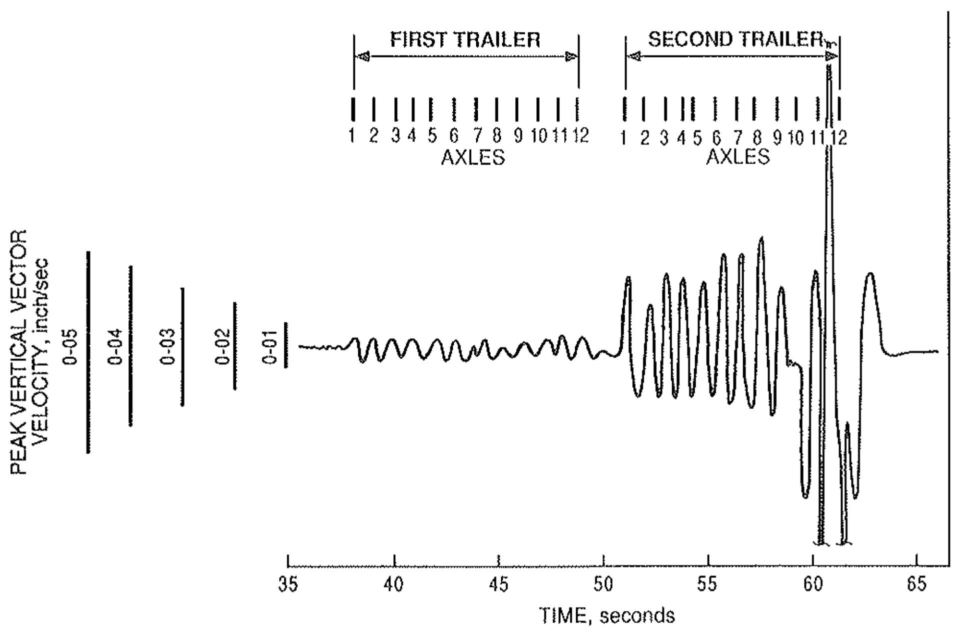

FIGURE 8 Seismometer velocity trace.

moved and the morning after. Deflections were measured at PM 5.40–5.70, 5.92–6.22, and 7.00–7.30. Unlike the first study, Dynaflect measurements were taken by only one technician. He judged from the driver's seat how close sensor 1 was to its previous locations. This probably caused some of the difference between before-and-after measurements mentioned above.

As was the case with the condition survey and Dynaflect results for the first reactor, either no short-term damage occurred or damage was not detectable by these means.

All instruments successfully measured deflections from the second reactor. Table 2 shows pertinent in-transit data for reactor 2. Frequency of tire load application varied from 0.80 to 0.90 Hz, which is above the minimum frequency detectable

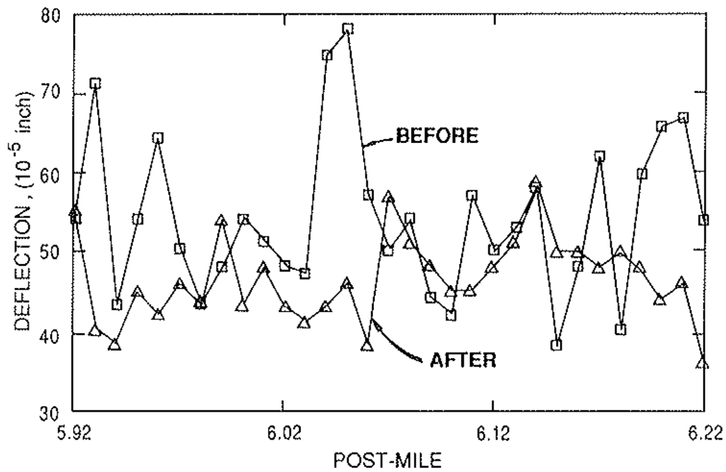

FIGURE 9 Sensor 1 Dynaflect deflection before and after moving reactor 2.

by the seismometer and accelerometer. Air temperature was approximately 65°F and pavement temperature was measured at 70°F when the reactor passed.

The optron deflection trace shown in figure 10 provides evidence of a "big basin." Displacements inferred from seismometer velocities are depicted superimposed on the optron trace, assuming that it represents mean deflection. Optron deflections were typically three to four times the displacement detected by the seismometer. The ratio of optron/seismometer measurements is important to discussions presented later in this paper. The optron trace clearly shows a slow displacement occurring during three to four seconds as the first trailer axle approached the target; no deflection is evident based on the seismometer trace during this time. After the last axle passed, the seismometer almost immediately returned to zero, although the optron shows that rebounding continued for nearly eight seconds. The optron trace shows that the target returned to its initial position.

Preliminary analysis of accelerometer data showed general agreement with the optron in detecting the "big basin." These data are being studied further. The accelerometer data also show some higher frequency vibrations. It was concluded that the accelerometer bounced slightly on the pavement as the tractor and trailers passed, probably because of its light weight (470 grams). Displacements due to these vibrations were filtered in computing deflections.

Pavement deflections again were studied as a function of distance from tires. Least-squares regression did not show the good correlation that was seen for the first reactor. Poor correlation is likely caused by the consistent remoteness of the trailer wheels from the sensors and by dissimilar response of the AC overlay and PCCP layers. Unobserved joints and cracks probably also contributed to this response. Peak deflection was not estimated for this test site.

To compare effects from tractor tires to those from trailer tires, deflections were recorded near berth 131 at the Port of Los Angeles. The structural section where deflections were measured is 9 inches AC over 8 inches untreated aggregate base on compacted silty sandy clay (*10*). No surface cracking or rutting was evident in the test area. Air temperature during the test was approximately 75°F, and pavement temperature was estimated to be 100°F.

The seismometer successfully measured deflections from trailer and tractors at the port. Deflection data from the trailers and tractors are shown in table 2. Deflections and distances were well-distributed during run 2 and are the basis of the

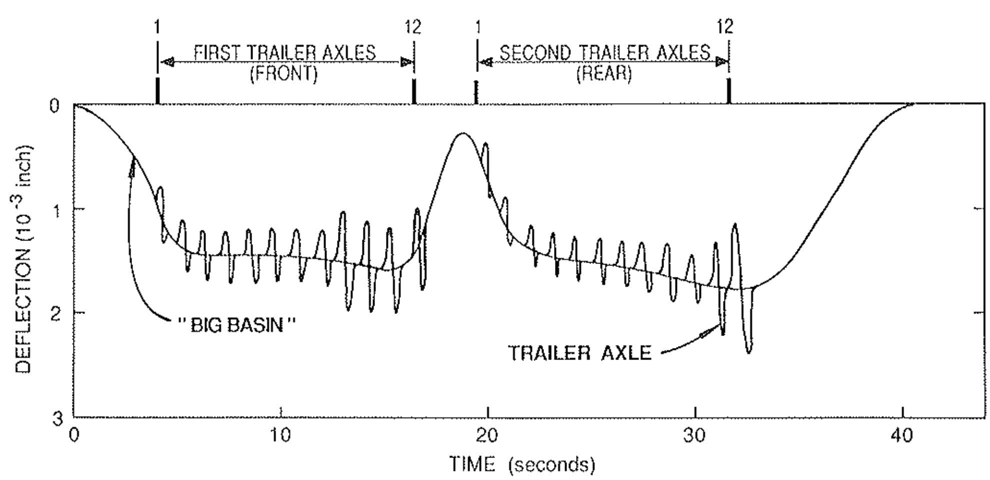

FIGURE 10 Optron displacement showing superimposed deflections from seismometer trace.

regression line shown in figure 11. For run 1, consistent deflection levels resulted from the minor change in distance from the tires to the sensor. In addition, frequency of axle loadings was near the seismometer's resonant frequency. Therefore, these data were not included in the least-squares regression analysis and are not shown in figure 11. The tractor made several passes at roughly equal speeds. Figure 11 shows deflections and distances from the tractor tires. Unfortunately, tractor tires came no closer than 2.7 feet to the sensor because of concerns about hitting the seismometer.

Figure 11 provides a rough comparison of deflections that resulted from trailer and tractor tires. It also shows a regression line and 95% confidence limits for deflections from trailer tires. Most of the tractor-induced deflections fall close to the regression line for displacements from the trailers. A least-squares regression line is not shown for the tractor data because of the few number of deflections measured at a limited range of distances.

The trend in deflection shown in figure 11 is similar to that in figure 7. Deflections are close to those from reactor 1. Pavement deflection under the outer trailer wheel is estimated to be 18 mils. Once again, adjustments of the regression line within the confidence limits would alter this value substantially. The correlation coefficient is significant at a 99% confidence interval using a two-tail test (*9*).

Deflections from tractor tires are not substantially higher than displacements from trailer tires at the distances measured. Figure 11 shows that deflections from the tractor's rear axle were higher than for the front. The rear axle was about 25% heavier because the counterweight was carried toward the back of the tractor. Figure 11 also shows that most of the deflections from the tractor's rear axle are significantly higher than displacements from trailer wheels. Based on seismometer data, deflections close to the tractor tires could be inferred to be several times higher than those measured close to trailer wheels. However, it is believed that deflections from tractor wheels were not significantly higher. In fact, peak deflections may be very close, if seismometer deflections from the trailer are increased by a factor of three to four. This increase is based on the ratio of optron/seismometer measurements discussed previously and assumes that seismometer measurements of tractor-induced deflections do not need adjustment. Similar deflections for tractors and trailers are likely due to the fact that, even though tractor wheel loads were two to three times as heavy as trailer tires, lower contact pressures (from larger contact area—see table 1) occur under the tractor tires. Levels of stress, strain, and shear induced by trailer and tractor tires remain unknown but should be investigated.

MECHANISTIC MODELING

Model predictions that were used initially to evaluate the variance request were subsequently compared to measured deflections. In this way, measurements served as a verification database. Field verification of model predictions could eventually yield a sufficiently accurate mechanistically-based procedure for routine evaluation of variance requests.

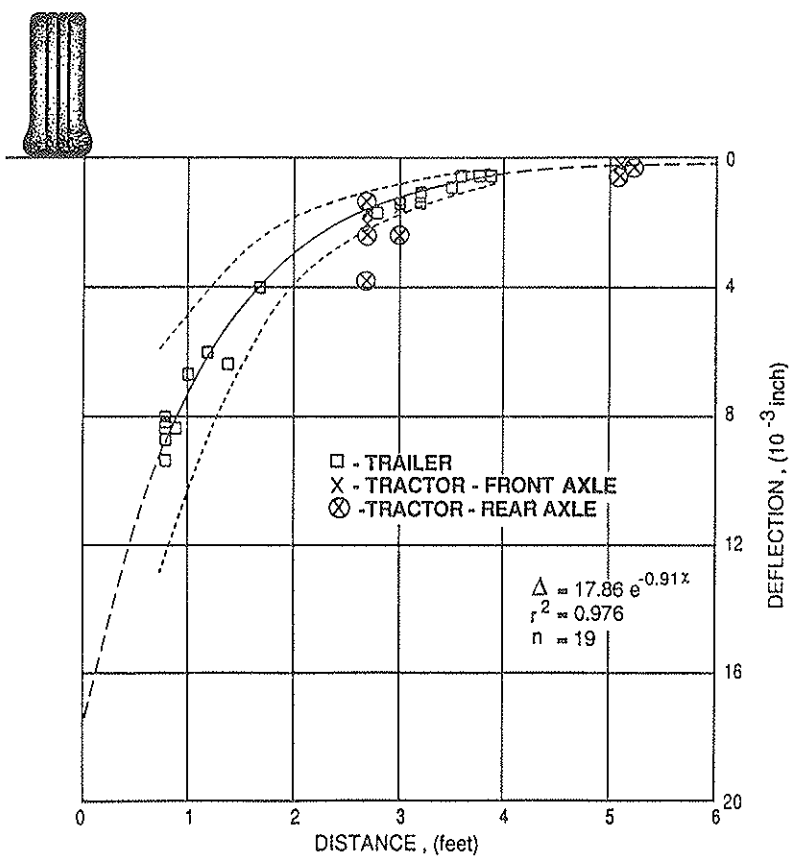

FIGURE 11 Pavement surface deflections near outer tires of trailer and tractor.

TABLE 3 INPUTS USED FOR COMPUTER MODELS

Layer	Thickness	Poissons Ratio	Resilient Modulus, ksi Best Case	Worst Case
1-ACP	5"	0.40	1,000	500
2-Base	5"	0.35	35	25
3-Base	5"	0.35	30	20
4-Base	5"	0.35	25	15
5-Subgrade	∞	0.35	10	4

Wheel Load

Load:	5,500 lbs/tire
Contact Area:	55 in^2
Contact Pressure:	100 psi

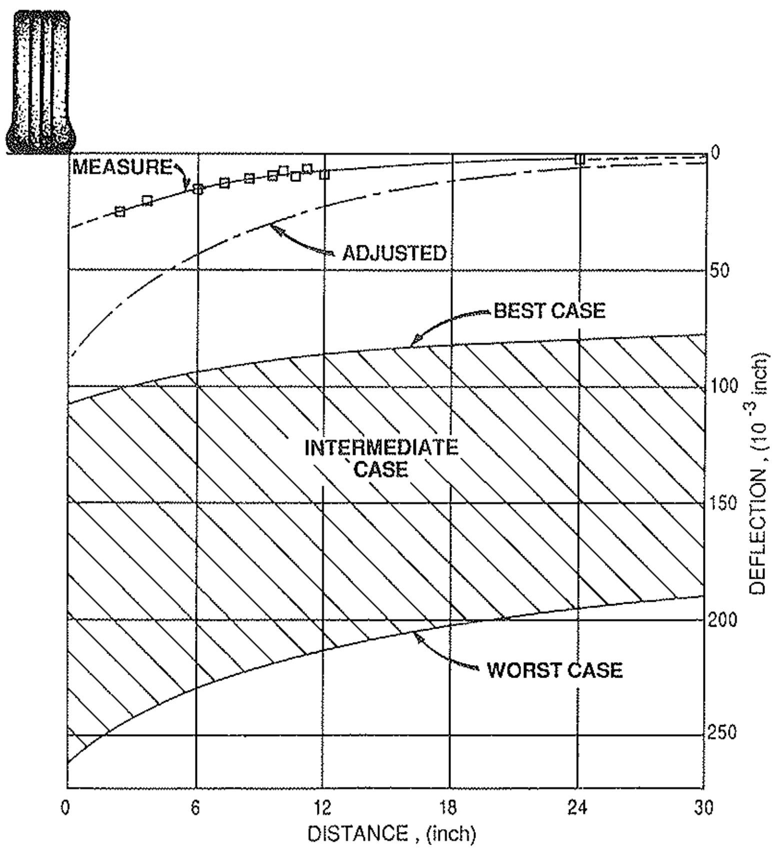

FIGURE 12 Predicted, measured, and adjusted pavement surface deflections near outer trailer tires for reactor 1.

Measurements recorded when the first reactor was moved were compared to predictions from elastic layer computer models. Computer modeling was not done for the second reactor, because a computer model for rigid pavement was not available. Deflections measured at the Port of Los Angeles were not modeled due to substantial uncertainty about material properties used in the test area (*10*). Model predictions were used to set seismometer signal attenuation prior to the field study and are presented here for a comparison to subsequent seismometer and optron measurements.

Predictions were obtained using ELSYM5 and BISAR computer models, which rely on elastic layer theory and simplifying assumptions to calculate primary response (*11, 12*). Structural section geometry was characterized using data from cores. Load inputs were based on information from the transporter. Best- and worst-case scenarios were developed using estimated materials properties (*6, 13*). Table 3 shows inputs used for model predictions. Figure 12 shows measured data and predicted deflections under best- and worst-case scenarios.

Generally poor correlation in magnitude of predicted-to-measured deflections is shown in figure 12, although the gradient of deflections is similar for measurements and predictions. A likely reason for systematic overprediction is incorrect characterization of materials properties and conditions (such as resilient modulus, moisture content, and density, among others).

Another reason for poor correlation is that the seismometer detected only localized deflections caused by each passing axle and missed the "big basin" deflection. For example, when the second reactor was moved, the optron recorded deflections that typically were three to four times higher than those detected by the seismometer. The optron's sensitivity to direct displacement allowed it to record slow loading and rebounding that the seismometer could not detect. The "adjusted" deflection line shown in figure 12 results if a factor of three is multiplied times the seismometer regression line. This "adjusted" line represents an estimate of deflections that the optron likely would have measured. It nearly intersects the best case line at the ordinate axis, where the maximum deflection occurs.

A more accurate determination of the ratio of optron displacement to seismometer deflection is not possible with these data, but three appears to be a reasonable minimum. Detection of displacement by the seismometer should have been very similar for both reactors since load frequency for both reactors was approximately 1 Hz, which is well above the minimum frequency detectable by the seismometer. In addition, air and pavement surface temperatures were nearly identical when each reactor passed by. It is unclear, however, how the PCCP at the second site influences this ratio.

CONCLUSIONS

1. Results from the condition surveys do not show any discernible short-term damage to the pavement after the reactors were moved. Damage may have occurred that is simply not detectable by these means.
2. Measurements from the Dynaflect reveal that pavement deflections are not perceptibly different from those recorded before the reactors traversed Route 213.
3. Deflections measured near the tires must be evaluated in light of the instruments used to detect them. Seismometer deflections provide a good estimate of localized deflections due to individual axles. However, optron data show a "big basin" under the trailers that the seismometer did not detect. The accelerometer appears to have detected this basin also. Optron deflections were a minimum of three times the displacements detected by the seismometer.
4. Deflections from the tractor tires were not substantially different from those caused by trailer tires. However, the optron was not available to verify or augment these measurements.
5. Mechanistic models yielded conservative estimates of seismometer deflections. Predicted maximum deflection is close to measured deflection when seismometer data are adjusted by a factor of three, which is the ratio of optron/seismometer measurements.

RECOMMENDATIONS

1. Condition surveys should be used to evaluate visible effects from overloads but should not be the sole basis of investigating damage.
2. A Dynaflect or other nondestructive instrument should be used to detect invisible damage. Backcalculation of layer moduli should be further studied for evaluating changes in material conditions after passage of super-heavy overloads. Laboratory and field analyses (such as resilient modulus, moisture content, and density, among others) should be a part of future investigations.
3. Further research will be conducted to compare instruments used for in-transit measurements. A seismometer should not be used for loads that move as slowly as those described herein. Use of an accelerometer and optron should be further investigated for measuring deflections induced by slow moving loads. The optron will be correlated to seismometer response and used for further pavement research.
4. Accelerated pavement failure due to excessive stresses and strains from super-heavy overloads should be investigated. Better understanding of failure mechanisms from such overloads ultimately will improve the accuracy of mechanistic-based predictions.

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