DYNAMIC AXLE LOADS
AND
PAVEMENT RESPONSE

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ABSTRACT

As part of the Pavement Impact Research Program carried out under the Vehicle Weights and Dimensions Study, an experimental investigation was conducted to explore the effects of heavy truck axle load dynamics on the magnitude of pavement surface deflections.

The dynamic axle loads were induced by bumps on the road surface and the magnitude of these axle loads was measured onboard the vehicle. Pavement deflection was measured using instruments contained within the road structure.

This paper describes the experiment, the loading conditions investigated and summarizes the surface deflection and axle force measurements. Dynamic imposed surface deflections have been compared to those recorded with no perturbations in place.

INTRODUCTION

In the fall of 1985 a field study to determine the effects of heavy truck axle load dynamics on the magnitude of pavement surface deflections was conducted at an instrumented pavement test site in the province of Quebec. This experimental investigation, conducted jointly by the Alberta Research Council and the National Research Council of Canada, formed part of the Pavement Impact Research Program carried out under the Vehicle Weights and Dimensions Study. The test program involved placing perturbations on the road surface to vertically excite axles of an instrumented vehicle and recording axle forces and pavement surface deflections as the vehicle passed over surface - set deflection transducers. A single perturbation was used to generate relatively high frequency axle dynamics and a series of perturbations were employed to obtain a lower frequency whole body dynamic loading condition.

This paper contains a brief description of the instrumented pavement test site and test vehicle. Loading conditions investigated and testing procedures followed are presented and surface deflection and axle force measurements are summarized. Dynamic imposed surface deflections have been compared to those recorded with no perturbation(s) in place. From these comparisons, trends in the magnitude of pavement deflections with changes in axle suspension inputs and test conditions are presented.

PAVEMENT TEST SITE

The test site selected for the study is located on Route 363 approximately 70 kilometers west of Quebec City, Quebec. Details of the pavement structure at the site, and a description of the instrumentation and data acquisition system used to measure and record pavement response variables under moving wheel loads, are presented in Ref. 1. Briefly, the structure of this two lane, low traffic volume, roadway consists of a 56 mm asphalt concrete surface with a 750 mm granular base overlying a clay subgrade. Instrumentation installed at the site includes three subsurface referencing assemblies for housing surface-set differential transformers, DC-DTs, to measure total pavement deflections and three strain transducers positioned at the asphalt concrete-base layer interface to measure longitudinal interfacial strains. The instrumentation is positioned across the outer wheel path of the north bound lane. The data acquisition system used to record pavement responses is developed around a mini-computer and, for field operations, is housed in a van with a self-contained power source. Using real time clocks, the system provides continuous records of pavement responses as a vehicle traverses the transducers. As previously noted, the investigation carried out at the site and reported herein focused on determining the effects of bump induced axle loads on the magnitude of pavement deflections.

TEST VEHICLE

A schematic of the test vehicle is shown in figure 1.

| 1 | | 2 | 3 | | 4 | | 5 | 6 |
| 3.25m | | 1.55m | | 6.0m | | 2.70m | | 1.27m |
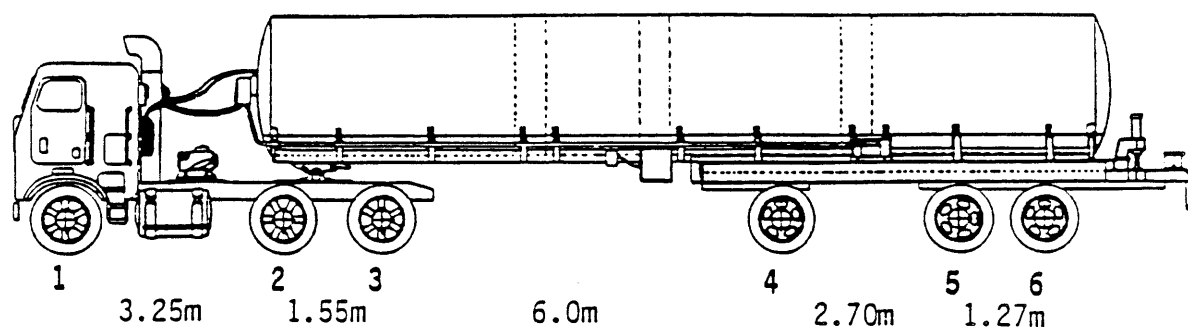
Tractor: -Tandem drive axles, Hendrickson RTE440 suspension, 12x22.5 tires.

Trailer: -Single lift axle, Neway AR95-A suspension, 11x22.5 tires.
         -Tandem axle, Reyco 21B four leaf suspension, 11x22.5 tires.

Figure 1. Test Vehicle

     Water in the four compartment tanker provided the following static gross axle weights to the study.

Loading			Gross Weights (kg)			
Condition	Axle 2	Axle 3	Axle 4	Axle 5	Axle 6
Lift Axle Up	8600	8600	-	8800	8800
Lift Axle Down	7500	7500	7000	6700	6700

     Inflation pressure of all tires was held constant and equal to 690 kPa during testing.   A cab mounted throttle device enabled very close control and replication of vehicle velocity. Details of the instrumentation and onboard data acquisition system used to measure and record the dynamic axle loads are presented in Ref. 2.   Briefly, the instrumentation included accelerometers, extensometers and a series of strain gauges stratigically positioned on each drive and carrying axle for axial brake, vertical force and relative displacement measurements. Basic components of the acquisition system consisted of necessary signal condition units, a multi-channel magnetic tape recorder, and multi-channel analog oscillographic recorders.

TEST PROGRAM

     A series of preliminary vehicle test runs were carried out to ensure synchronization of timing devices developed for the pavement response and axle force data acquisition systems and to establish a test sequence that would provide necessary data for assessing the effects of high frequency axle dynamics on the magnitude of pavement surface deflections.   The pavement response

acquisition system was activated when the steering axle of the test vehicle contacted a tape switch positioned 2.4 m upstream of the deflection transducers. To activate the onboard axle force data acqusition system, a second tape switch was positioned immediately adjacent to that used for the pavement response system. Upon tire contact, a strobe light transmitter located on the shoulder of the roadway was triggered and a light sensing receiving device mounted on the tractor of the vehicle actuated the axle force recorders.

High Frequency Axle Dynamics

High frequency axle impulses were generated using a single 40 mm high by 240 mm wide wooden plank fixed transversely across the lane upstream of the deflection transducers. Plank locations, loading conditions and vehicle velocities included in the study are presented in table 1. A minimum of two test runs were carried out at each velocity within a test series. Following each test series the perturbation was removed and testing was repeated. Employing this procedure, comparisons between the magnitude of maximum pavement surface deflections recorded under each axle with the plank in place to those recorded with no perturbation were made at comparable vehicle velocities and pavement temperatures. These comparisons, which are in the form of deflection ratios (deflection with perturbation/deflection with no perturbation) allowed the influence of perturbation location and vehicle velocity on the magnitude of pavement deflections to be identified.

Table 1
Test Conditions - High Frequency Axle Dynamics

Test Series	Distance of Perturbation from DC-DTs (m)	Loading Condition	Vehicle Velocity (km/h)
1	2.85	Lift Axle (4) Up	18
2	2.16	Lift Axle (4) Up	18
3	1.27	Lift Axle (4) Up	18
4	0.70	Lift Axle (4) Up	18
5	0.0	Lift Axle (4) Up	18,37,60
6	0.0	Lift Axle (4) Down	18,37,60

Maximum deflections were recorded when the wheels of an axle were directly over the transducers. Dynamic axle forces coinciding with the time of monitoring maximum deflections were available for a number of test runs within test series 1, 2, 5 and 6. Ratios of the recorded dynamic to static axle loads, termed the dynamic impact factor (DIF), were determined and used in analyses carried out to assess the effect of dynamic axle loadings on pavement deflections.

Whole Body Dynamics

To examine the effects of whole body dynamics on the magnitude of pavement deflections, the Reyco trailer suspension was vertically excited at the natural frequency of the sprung mass. Six 40 mm high by 90 mm wide wooden planks fixed to the pavement surface at centre to centre spacings equal to the axle spread of the trailer suspension (1.27 m) were used to vertically excite the trailer. With this perturbation layout, the estimated vehicle speed corresponding to the fundamental vertical frequency of the suspension was 9 to 11 km/h. All tests were carried out at vehicle velocities within this range and the average velocity was 9.5 km/h. Deflections caused by the oscillating tandem carrying axles were recorded when the last traversed plank of the six plank configuration was positioned 0.45, 0.58 and 1.27 m upstream of the transducers. In addition, one test series was conducted with no perturbations. A minimum of four vehicle runs were conducted per series and, during all tests, axle four (4) was in the lift position.

TEST RESULTS

High Frequency Axle Dynamics

Using average maximum deflections recorded at 18 km/h and axle four (4) in the lift position, the influence of perturbation location on the magnitude of deflections is shown in figure 2.
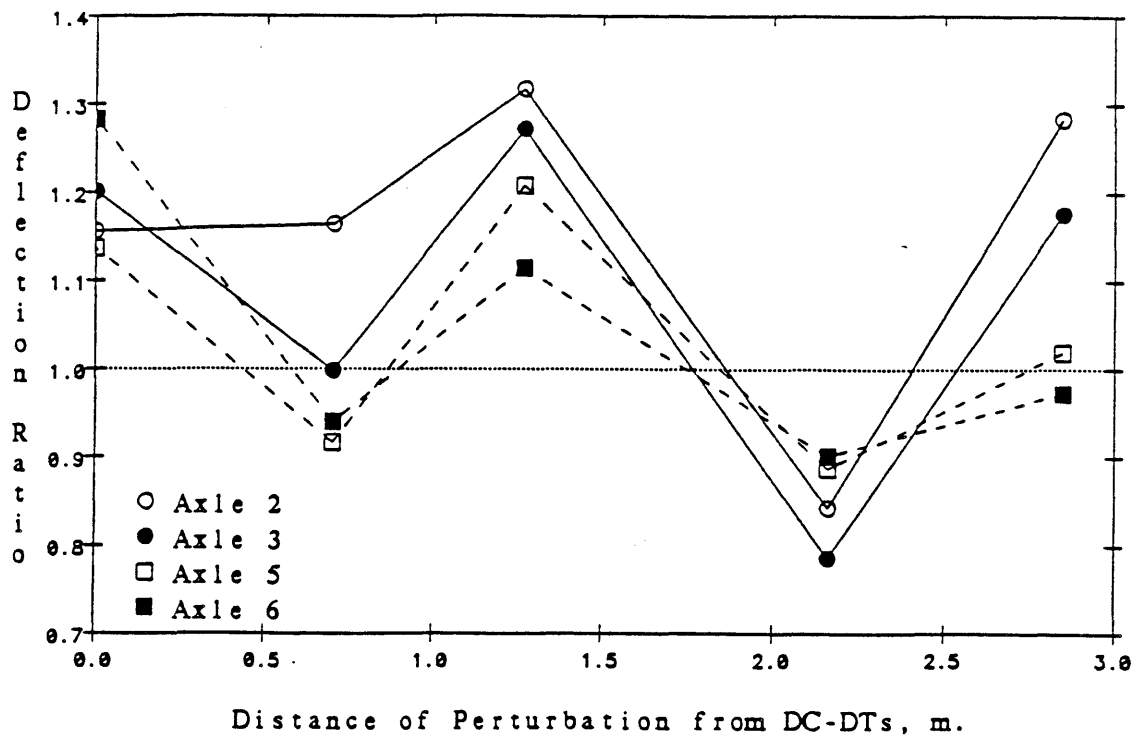

Figure 2 Influence of Perturbation Location on Deflections

Recorded deflections were dependent on and exhibited cyclic trends with perturbation location. At 18 km/h, maximum deflections under each vertically excited axle were approximately 1.1 to 1.3 times the magnitude of those monitored during normal tests. The cyclic deflection pattern reflects the response of the pavement to the 3.1 hertz whole body frequency of the vehicle. A test program incorporating a larger number of single perturbation locations, or a field installation having a series of deflection transducers positioned longitudinally in the wheel path, would be required to better define the apparent cyclic trends in deflection response with distance.

Examination of the deflection data revealed that, with the plank positioned directly over the transducers, deflections under the lead axle of each tandem group and under the lift axle increased with increasing vehicle velocity, and deflections caused by the second or last axle of each tandem configuration were maximum at 37 km/h. For normal test conditions, deflections remained relatively constant or decreased with increasing velocity. Measures of the overall effect of vehicle velocity on the magnitude of deflections recorded under each vertically excited axle, relative to those recorded under normal test conditions, are shown in figure 3. At 60 km/h, deflections caused by the lead axles (2 and 5) and the lift axle (4) were approximately 1.7 to 1.85 times the magnitude of those recorded at the same velocity during normal test runs. The marked decrease in the relative deflection value for axle three (3) at 60 km/h may be attributed to the fact that axles two (2) and three (3) of the walked beam suspension are mechanically coupled. At 60 km/h, axle two (2) was in a rebounding state resulting in an underloading of axle three (3) the instant it passed over the transducers. Results of tests carried out with axle four (4) in the lift position yielded similar relative deflection/velocity trends to those shown in figure 3.
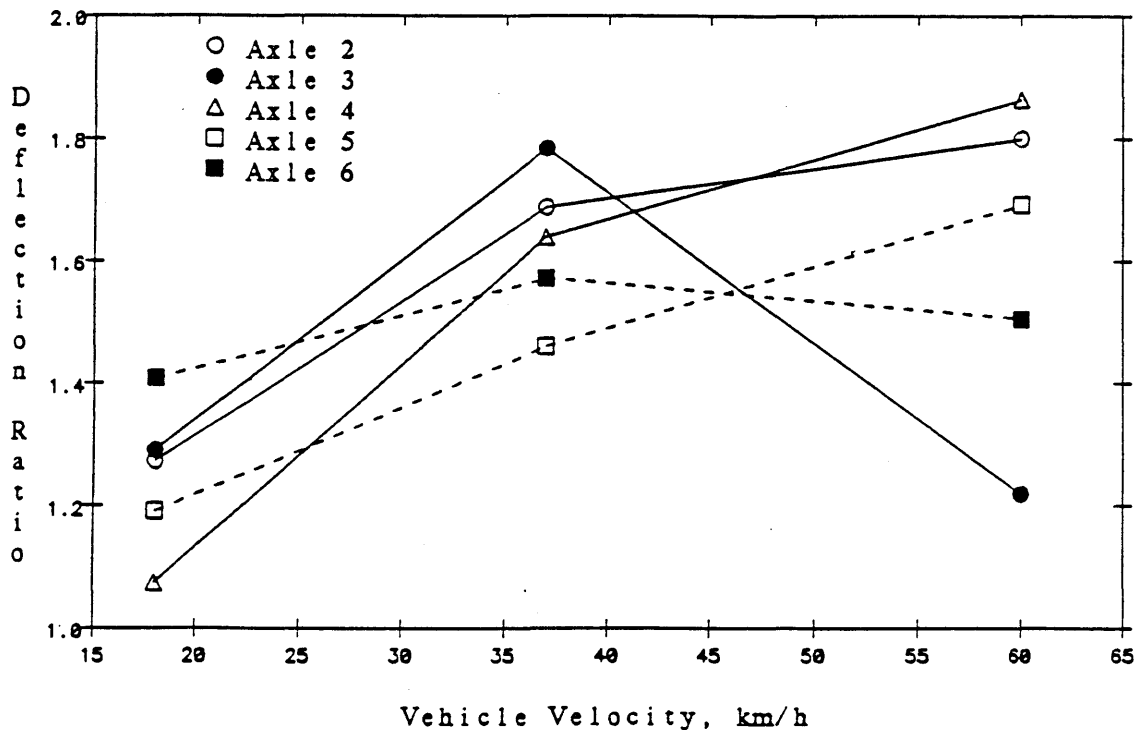

Figure 3 Influence of Vehicle Velocity on Deflections

Recorded dynamic axle loads and calculated impact factors (average dynamic
axle load/static axle weight) are summarized in table 2. Maximum dynamic

Table 2
Summary of Dynamic Axle Loads

Test Series	Distance of Perturbation from DC-DTs (m)	Veh. Vel. (km/h)	Axle No.	No. of Tests	Dynamic Axle Load (Metric Tonnes)			Dynamic Impact Factor
					Min.	Avg.	Max.	
1	2.85	18	2	3	12.0	12.3	12.5	1.43
			3	4	9.1	9.3	9.5	1.08
			5	5	10.9	11.2	11.6	1.27
			6		8.8	9.3	9.6	1.05
2	2.16	18	2	5	0.8	1.6	2.7	0.18
			3		4.0	4.3	4.4	0.50
			5	5	8.5	8.8	9.3	1.00
			6		8.5	9.0	9.4	1.02
5	0	18	2	1	-	12.4	-	1.44
			3		-	12.1	-	1.41
			5	1	-	13.5	-	1.53
			6		-	14.7	-	1.67
	0	37	2	1	-	10.9	-	1.27
			3		-	10.7	-	1.24
			5	2	13.2	13.4	13.5	1.52
			6		12.0	12.2	12.4	1.39
	0	60	2	1	-	11.4	-	1.33
			3		-	11.2	-	1.30
			5	1	-	14.9	-	1.69
			6		-	14.3	-	1.63
6	0	18	2	2	11.4	11.9	12.4	1.59
			3		11.2	11.7	12.1	1.56
			4	2	10.2	10.2	10.2	1.46
			5	2	12.1	12.3	12.5	1.84
			6		12.2	12.9	13.6	1.93
	0	37	2	3	11.9	12.2	12.9	1.63
			3		11.6	11.9	12.6	1.59
			4	3	10.4	12.3	13.9	1.76
			5	3	11.8	12.7	13.5	1.90
			6		12.4	12.7	13.2	1.90
	0	60	2	1	-	11.4	-	1.52
			3		-	11.2	-	1.49
			4	1	-	13.4	-	1.91
			5	1	-	14.2	-	2.12
			6		-	-	-	-

loadings were generally associated with the Reyco four leaf suspension (axles 5 and 6). For test series 6, dynamic axle loadings on this suspension were approximately 13 000 kg or nearly twice the magnitude of the static axle weights. Dynamic impact factor versus absolute deflection relationships for axles 4 and 5 and selective test runs are presented in Ref. (2). A plot of dynamic impact factor versus deflection ratio for axles 4, 5 and 6 and test conditions of series 1,2,5, and 6 is shown in figure 4. As previously noted, the deflection ratio has been defined as the magnitude of the deflection recorded under dynamic axle loads induced by perturbations on the road surface divided by the deflection measured under the same wheel, vehicle velocity and pavement temperature with no road surface perturbations in place. A regression analysis correlating the impact factors with the deflection ratios yielded the expression:

$$\text{Deflection Ratio} = 0.27 + 0.659 \ (\text{DIF}) \tag{1}$$

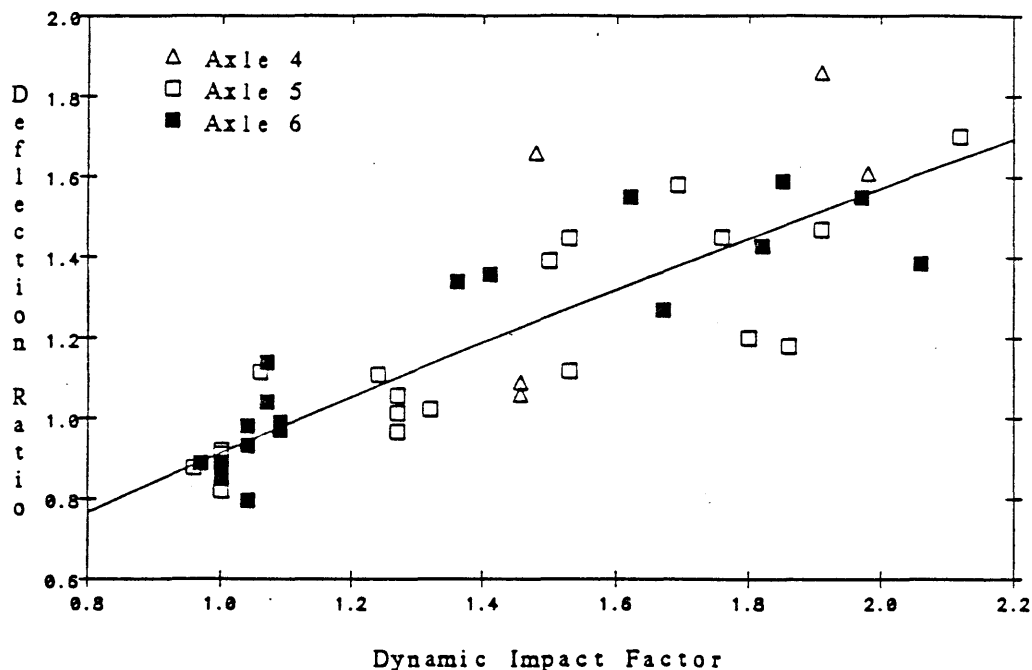$$N = 41 \quad r^2 = 0.73 \quad Sey = 0.148$$

Figure 4 Dynamic Impact Factor Versus Deflection Ratio

Dynamic load/deflection trends for the tandem drive axles (2 and 3) exhibited greater scatter than shown in figure 4 for the carrying axles. The majority of data scatter was associated with tests conducted at 37 km/h. At comparable impact factors, deflection ratios for the drive axles at this velocity were approximately 30 percent larger in magnitude than deflection ratios determined at other velocities and loading conditions. This may be attributed to the fact that the drive axles are coupled via the walking beam forming a separate mechanical system having a natural frequency of 15 hertz. At the 37 km/h the 1.52 m axle spacing coincides with the 15 hertz natural frequency peak, causing an amplification of dynamic force and corresponding increases in pavement deflections. Deleting the 37 km/h data, the best-fit correlation relating the deflection ratios to dynamic impact factors for the tandem drive axles was:

$$\text{Deflection Ratio} = 0.66 + 0.437 \ (DIF) \tag{2}$$

$$N = 22 \quad r^2 = 0.68 \quad Sey = 0.174$$

From equations 1 and 2, a single road surface perturbation causing dynamic axle loadings equal to 1.5 times the static weight yield pavement surface deflections which are, on average, 1.3 times the magnitude of the deflection under the same axle on a relatively smooth pavement surface.

Results of analyses carried out on deflections recorded under a wide range of tandem axle dual tire loads included in the Pavement Impacts Investigation and tested at the site are presented in Reference 3. The results indicate that under normal test conditions pavement surface deflections are proportional to static axle weight raised to the power of 0.747. Employing this relationship, 50 and 100 percent increases in static axle loads cause 35 and 68 percent increases, respectively, in pavement deflections. In comparison, using equation (1), percent changes in the magnitude of surface deflections caused by 50 and 100 percent variations in dynamic axle loadings are 35 and 70 , respectively. These comparisons suggest that the effect of changes in dynamic and static wheel loads on the magnitude of pavement surface deflections are similar.

Whole Body Dynamics

Pavement surface deflections recorded under the tandem carrying axles when excited by a series of equally spaced planks are presented in table 3.

Table 3   Summary of Pavement Surface Deflections
           Whole Body Dynamics Loading Condition

Distance of Closest Plank from DC-DTs (m)	Axle No.	No. of Tests	Surface Deflection (mm)		
			Dmin.	Davg.	Dmax.
1.27	5	5	0.673	0.831	0.927
	6		1.031	1.100	1.179
0.58	5	4	1.857	1.956	2.070
	6		1.756	1.856	1.953
0.45	5	6	1.625	1.694	1.793
	6		1.504	1.575	1.664
No Perturbations	5	5	0.886	0.998	1.046
	6		0.907	1.044	1.097

Maximum deflections were recorded when the last tranversed plank was positioned 0.58 metres upstream of the transducers. Deflections under each axle during this test series were, on average, 1.9 times the magnitude of those recorded under normal test conditions. Typical recorded time - deflection plots for these two test conditions are shown in figure 5. With the perturbations, deflections caused by the lead axle were largely dissipated prior to passage of the second axle. That is, the deflection response under the bouncing tandem axles approximated the response of two single axles.
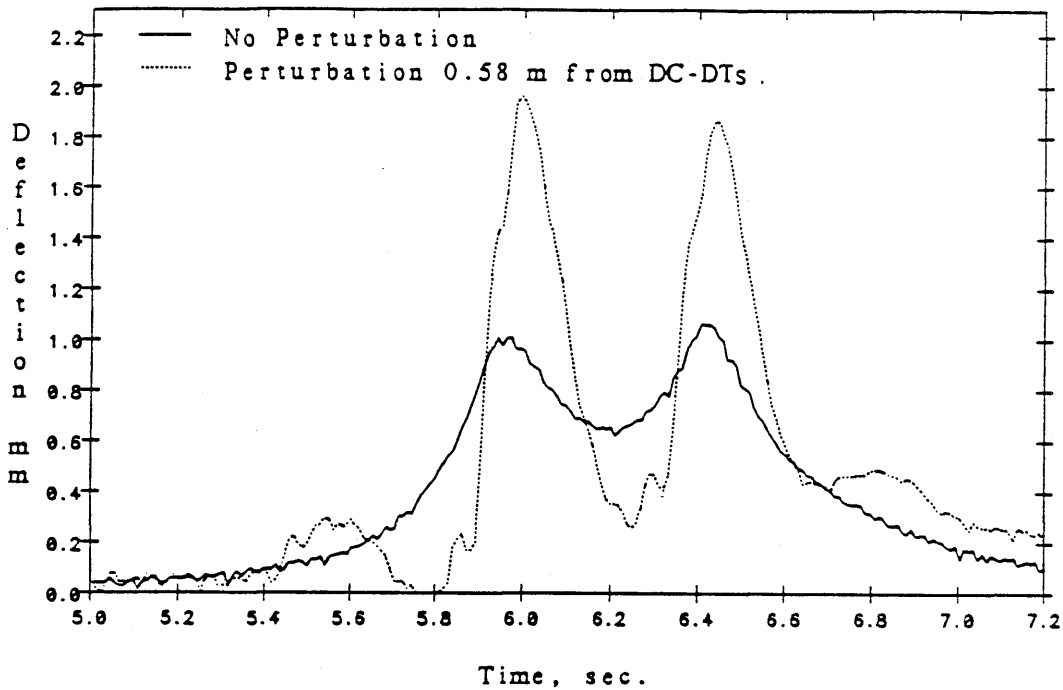

Figure 5 Typical Deflection Response Under Tandem Axles

Following the test series for whole body dynamic loadings the perturbations were removed and deflections were recorded under an 8160 kg single axle-dual tire load of a Benkelman Beam test vehicle at a velocity of 18 km/h. The average maximum deflection caused by this standard load was 0.79 mm. Using this average value and following procedures described in Reference 3, the predicted load equivalency factor for the 17 600 kg tandem axle under normal test conditions was 2.5. (This load factor was calculated assuming that differences in the magnitude of deflections at 18 km/h and at the test velocity of the instrumented vehicle, 9.5 km/h, are small.) Since tests with the Benkelman Beam test vehicle traversing the planks were not performed, only a rough estimate could be made of the load equivalency factor for the tandem axles when subjected to the whole body dynamics loading condition. As previously noted, maximum deflections under vertically excited axles at 18 km/h were approximately 1.1 to 1.3 times the magnitude of those recorded during normal test runs. Applying these relative pavement deflection increases, to the 0.79 mm deflection recorded under the standard load during normal test runs, estimated deflections caused by an 8160 kg single axle subjected to perturbations range from 0.87 to 1.03 mm. Using these estimated deflections, predicted load equivalency factors for the bouncing tandem carrying axle range from 16.2 to 30.8. Comparisons between these load factors and the factor of 2.5 determined for normal test conditions

suggest that, at a static weight equal to 17 600 kg, one application of an oscillating tandem configuration is approximately equivalent in potential damaging effect to 6.5 to 12.5 applications of the same configuration on a smooth pavement surface.

SUMMARY

Using an instrumented six (6) axle tractor-semitrailer unit, a field study to determine the effects of dynamic axle loads on the magnitude of pavement surface deflections was carried out at an instrumented pavement test site. Artificial road surface perturbations were employed to obtain both high frequency and whole body dynamic loading conditions. Observations from this experimental investigation are:

High Frequency (Single Perturbation) Loading Condition

1. The magnitude of pavement surface deflections increased with increasing vehicle velocity. At 18 km/h, maximum deflections recorded under the bouncing axles were approximately 10 to 30 percent, and at 60 km/h, 70 to 85 percent larger in magnitude than deflections recorded at the same velocity and no perturbations.

2. Maximum dynamic axle loads ranged from approximately 130 to 200 percent of the static axle loads. For the range of loading conditions investigated, overall average maximum dynamic axle loads were 145 percent of static axle loads.

3. Pavement deflection response was dependent on both the low frequency (3 hertz) whole body and high frequency (15 hertz) axle response.

4. Relative to normal test conditions, pavement deflections tended to increase linearly with increasing dynamic axle load. Changes in pavement deflection with variations in dynamic axle load were in close agreement with those obtained from analyses of deflections recorded under a range of axle loads and no perturbations.

Whole Body (Multiple Perturbations) Loading Condition

1. Maximum deflections caused by the oscillating tandem carrying axles were approximately twice the magnitude of deflections recorded under the same 17 600 kg tandem group during normal test conditions. The deflection response caused by the oscillating tandem group approximated the response of two single axles.

2. Using the recorded deflections, estimated load equivalency factors for the bouncing tandem carrying axles were 6.5 to 12.5 times the magnitude of the predicted equivalency factor for the same tandem axles on a relatively smooth pavement surface.

REFERENCES

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