DYNAMIC VEHICULAR LOADING OF THE HUBBARD CREEK RESERVOIR BRIDGE, 1975

By

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CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN
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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

This investigation was initiated on December 4, 1974, for the Texas Highway Department, by Phillip L. Wilson, Director, Planning and Research Division; T. R. Kennedy, D-10, Planning and Research Division; Lawrence E. Schultz, District Engineer, District 23 (Brownwood); and R. S. Martin, District 23. Field studies were conducted on December 6 and 7.

Center for Highway Research personnel who performed the field studies and analyses of data are H. H. Dalrymple, Research Engineer Associate, Noel C. Wolf, Technical Staff Assistant, and Randy B. Machemehl, Research Engineer Assistant. The analytical concepts, data reduction processes, computer simulation techniques, and equipment used in the investigation have been developed during the past several years through the Center's Cooperative Highway Research Program with the Texas Highway Department and the Federal Highway Administration in the following studies:

3-10-63-54	-	A Portable Scale for Weighing Vehicles in Motion,
3-8-67-108	-	Dynamics of Highway Loading,
3-8-71-160	-	Dynamic Traffic Loading of Pavements,
3-8-63-73	-	Development of a System for High-Speed Measurement of Pavement Roughness,
3-8-71-156	-	Surface Dynamics Road Profilometer Application,
IAC(72-73)-107	-	Development of In-Motion Weighing Systems, and
IAC(72-73)-686	-	Operational Procedures, Final Evaluation of Equipment, Its Use and Maintenance.

ABSTRACT

Since its construction in the early 1960's, the three-quarter-mile-long predominantly reinforced concrete bridge structure on U.S. Highway 180 over the Hubbard Creek Reservoir in north central Texas has developed significant permanent deformation or sag near the center of most of the 40-foot-long simply supported pan girder type spans. This undulating profile tends to cause trucks operating at certain speeds to bounce and pitch rather severely, and thereby produces dynamic loads that are more than 1.5 times the static weight of the vehicle.

A computer simulation technique which was used to investigate the complex interaction between the existing road surface profile and representative heavy vehicles operating at various speeds indicated that the potentially damaging dynamic loads can be reduced to near static load levels by either keeping truck speeds below about 20 mph or by smoothing the bridge deck with an overlay.

SUMMARY

A computer modeling technique was used to evaluate the magnitude and frequency of dynamic wheel loads and total vehicle loads that will result from three representative types of heavy commercial vehicles operating at various speeds over the undulating road surface profile of the Hubbard Creek Bridge on U.S. Highway 180 west of Breckenridge in Stephens County, Texas. At 20-mph vehicle speeds, the dynamic wheel forces are expected to vary up to about 25 percent in magnitude from the static wheel weights and at frequencies generally in the 10 Hz range.

As vehicle speed increases up to 60 mph, the dynamic wheel forces in the critical frequency range of 2 to 3 Hz (which is near the natural frequency of the structure) will increase significantly. At 60 mph, dynamic wheel forces range from zero to more than 1.5 times the static wheel weight.

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The Hubbard Creek Reservoir Bridge is located in Stephens County in north central Texas approximately 3 miles west of Breckenridge on U.S. Highway 180. The structure, which was completed in December 1962, is 3,751 feet long and consists of 88 simply supported reinforced concrete pan girder spans, each 40 feet long, plus one 230-foot-span continuous steel I-beam unit. Virtually all the reinforced concrete sections now have some permanent deformation or sag at mid-span. Profile measurements obtained during this study indicate elevation differences of as much as 0.75 inch relative to the road surface over the supporting bents. This undulating surface profile forces vertical translation of the wheels of vehicles crossing the bridge, and at certain speeds the sprung mass (body) of some vehicles is caused to bounce, roll, and pitch rather violently. Under critical conditions, when the vertical movements of the vehicle are reinforced by each wave in the road profile, large dynamic forces are produced. Previous research (Refs 1, 2, and 3) has shown that the resulting wheel impact forces can be more than twice the static wheel weight. These severe dynamic loads need to be minimized in order to prolong the service life of the structure and to provide acceptable riding quality to the road users.

There are several possible approaches to reducing or minimizing the magnitude of the dynamic loads caused by the rough profile. The bridge could be load-zoned so as to limit the gross loads of vehicles using the structure. A second alternative would be to smooth the road surface by constructing an overlay. Or, a third approach might be to control the speed of vehicles by speed-zoning so that the dynamic interaction between the moving vehicles and the undulating road profile does not result in excessive impact forces.

The Center for Highway Research at The University of Texas at Austin has been asked to apply the experience in dynamic traffic loading that has been gained through previous research with the Texas Highway Department and the Federal Highway Administration for analyzing the nature and magnitude of dynamic loading that results from mixed traffic using the Hubbard Creek Reservoir Bridge and to suggest remedial measures for controlling the loads. Computer simulation techniques have been used to describe the complex dynamic behavior of representative vehicles traveling at various speeds over the undulating bridge surface profile and typical dynamic loading patterns have been developed.

Field Measurements

Longitudinal profile measurements in each wheel path of the structure were needed for input to the computer simulation program. The General Motors Road Surface Dynamics Profilometer operating under Research Study No. 3-8-71-156 was used to obtain field data in a manner analogous to that used in the speed-zoning study of the Port Isabel Causeway (see Ref 3).

The profile of the full length of the structure was plotted and examined visually to determine zones with profile characteristics that were likely to cause large impact loads. The surface was generally free of small irregularities, but a definite pattern of sags between supports was evident throughout the length of the structure. A section of the continuous steel spans seemed to be slightly rougher than those sections over the concrete spans; therefore, two 300-foot sections were chosen for analysis. One of these profiles in the westbound lane near the east end of the bridge was typical of the concrete spans while the other, also in the westbound lane but near the west end of the bridge, was representative of the continuous steel spans. The profiles in the right wheel path of the two sections are shown in Figs 1 and 2, respectively.

Observations of traffic made during the day in which field data were gathered (5 December 1974) indicated that most vehicles were running between 55 and 65 miles per hour. Overall average speed was determined to be 61.3 miles per hour. Other traffic data provided by the Planning and Research Division, D-10, of the Texas Highway Department are shown in Table 1.

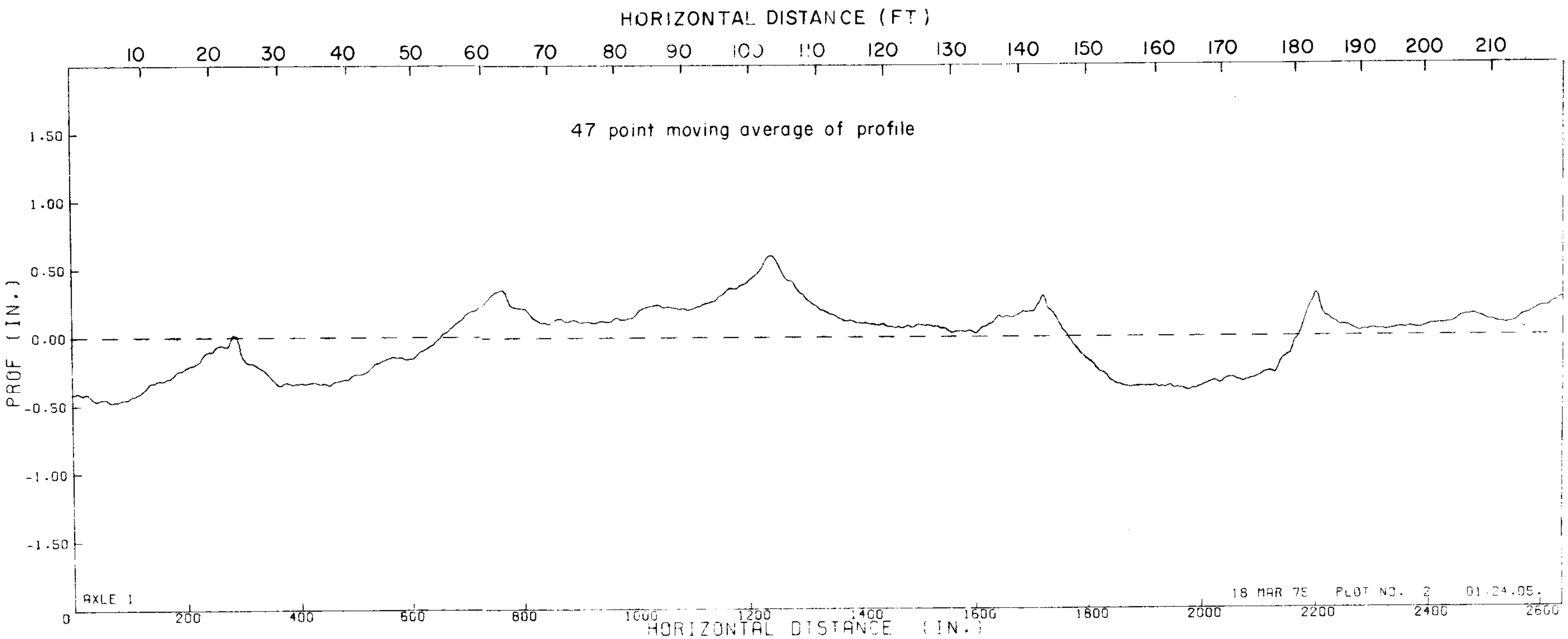

Fig 1. Profile for left wheel path of westbound lane beginning approximately 400 feet from west end of bridge.

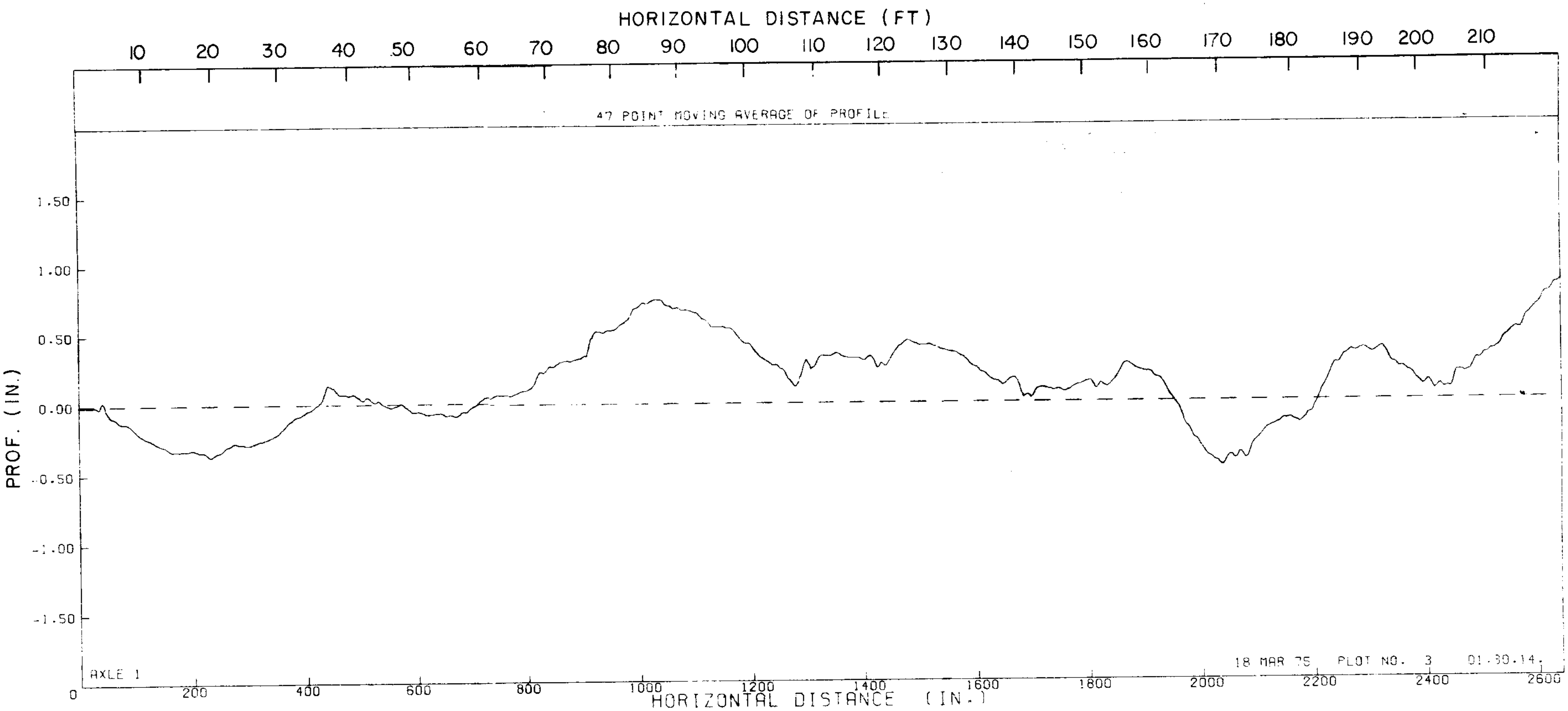

Fig 2. Profile for left wheel path of westbound lane beginning approximately 3200 feet from east end of bridge.

TABLE 1. TRAFFIC DATA BASED ON YEAR 1973

Average Daily Traffic	2740 VPD
20-Year 1993 Projection	4000 VPD
Directional Distribution	56% - 44%
Trucks	17.6% of ADT
Trucks	10.3% of DHV
18-Kip Equivalencies	1,408,000 rigid 1,103,000 flexible

Vehicle Simulation

Although a wide variety of vehicles use the bridge, critical dynamic loading is likely to result from a few commercial vehicle configurations. The representative vehicles which were used in the analysis were (1) a single-unit two-axle dual-tire vehicle (Type 2D); (2) a three-axle single-unit vehicle (Type 3A); and (3) a five-axle tractor-semi-trailer articulated vehicle (Type 3S-2). All vehicle parameters needed to characterize these vehicles were available from previous simulation experience and are summarized in Table 2.

Model Analysis

Mathematical models of the three vehicles described above were, by simulation, "driven" over the two bridge profile sections at speeds of 20, 40, and 60 miles per hour. Tire forces resulting from the interaction of the various vehicles with the road surface of the typical concrete span profile section are plotted in Figs 3 through 8. Spring stiffness, damping coefficients, static wheel weights, and speed are tabulated in Table 2.

These figures show the magnitude and placement of the dynamic tire forces which result from the vehicles moving across the bridge at various speeds. The smaller wheel masses (unsprung masses) oscillate generally at frequencies in the range of 8 to 12 Hz (cycles per second) while the large body mass, representing everything supported by the suspension system of the vehicle,

TABLE 2. VEHICLE CHARACTERISTICS

I. Two axle single unit (2D)

Body Mass	47.91	$(lb\text{-}sec^2)$ / in.
Tread Width		
Axle 1	74.0	in.
Axle 2	70.0	in.
Axle Spacing	153.0	in.
Wheel Weights		
1 Right	3139	lb.
1 Left	3012	lb.
2 Right	7780	lb.
2 Left	7103	lb.
Suspension System		
<u>Spring Stiffness</u>		
Axle 1 Right and Left	535	lb/in.
Axle 2 Right and Left	3750	lb/in.
<u>Damping</u>		
Axle 1 Right and Left	5	percent of critical
Axle 2 Right and Left	3	percent of critical
Tires		
<u>Stiffness</u>		
Axle 1 Right and Left	4000	lb/in.
Axle 2 Right and Left (Duals)	8000	lb/in.
<u>Damping</u>		
Axle 1 Right and Left	2	percent of critical
Axle 2 Right and Left	2	percent of critical

(continued)

TABLE 2. (continued).

II. Three Axle Single Unit (3A)		
Body Mass	80.27	(lb-sec^2) / in.
Tread Width		
Axle 1	78.0	in.
Axle 2	72.0	in.
Axle 3	92.6	in.
Axle Spacings		
Axle 1-2	226.0	in.
Axle 1-3	274.0	in.
Wheel Weights		
1 Right	4729	lb.
1 Left	4986	lb.
2 Right	6624	lb.
2 Left	6575	lb.
3 Right	6516	lb.
3 Left	6585	lb.
Suspension System		
<u>Spring System</u>		
Axle 1 Right and Left	1750	lb/in.
Axle 2 Right and Left	5000	lb/in.
Axle 3 Right and Left	5000	lb/in.
<u>Damping</u>		
Axle 1 Right and Left	5.0	percent of critical
Axle 2 Right and Left	6.0	percent of critical
Axle 3 Right and Left	6.0	percent of critical
Tires		
<u>Stiffness</u>		
Axle 1 Right and Left	4000	lb/in.
Axle 2 Right and Left	8000	lb/in.
Axle 3 Right and Left	8000	lb/in.
<u>Damping</u>		
Axle 1 Right and Left	0.50	percent of critical
Axle 2 Right and Left	1.00	percent of critical
Axle 3 Right and Left	1.00	percent of critical

(continued)

TABLE 2. (continued).

III. Five Axle Articulated (3S-2)		
Cab Mass	33.76	$(lb\text{-}sec^2)$ / in.
Trailer Mass	74.43	$(lb\text{-}sec^2)$ / in.
Tread Width		
Axle 1	77.0	in.
Axle 2	71.0	in.
Axle 3	71.0	in.
Axle 4	73.0	in.
Axle 5	73.0	in.
Axle Spacing		
Axle 1-2	147.0	in.
Axle 1-3	196.0	in.
Axle 1-4	409.0	in.
Axle 1-5	460.0	in.
Wheel Weights		
1 Right	3998	lb.
1 Left	4270	lb.
2 Right	5680	lb.
2 Left	5341	lb.
3 Right	4681	lb.
3 Left	4115	lb.
4 Right	5729	lb.
4 Left	5710	lb.
5 Right	5641	lb.
5 Left	5839	lb.
Suspension System		
<u>Spring Stiffness</u>		
Axle 1 Right and Left	2000	lb.
Axle 2 Right and Left	6000	lb.
Axle 3 Right and Left	4500	lb.
Axle 4 Right and Left	6000	lb.
Axle 5 Right and Left	6000	lb.
<u>Damping</u>		
Axle 1 Right and Left	4.5	percent of critical
Axle 2 Right and Left	3.0	percent of critical
Axle 3 Right and Left	3.0	percent of critical
Axle 4 Right and Left	1.5	percent of critical
Axle 5 Right and Left	1.5	percent of critical

(continued)

TABLE 2. (continued).

Tires		
Stiffness		
Axle 1 Right and Left	4500	lb/in.
Axle 2 Right and Left	8000	lb/in.
Axle 3 Right and Left	8000	lb/in.
Axle 4 Right and Left	7500	lb/in.
Axle 5 Right and Left	7500	lb/in.
Damping		
Axle 1 Right and Left	0.01	percent of critical
Axle 2 Right and Left	0.50	percent of critical
Axle 3 Right and Left	0.50	percent of critical
Axle 4 Right and Left	0.25	percent of critical
Axle 5 Right and Left	0.25	percent of critical

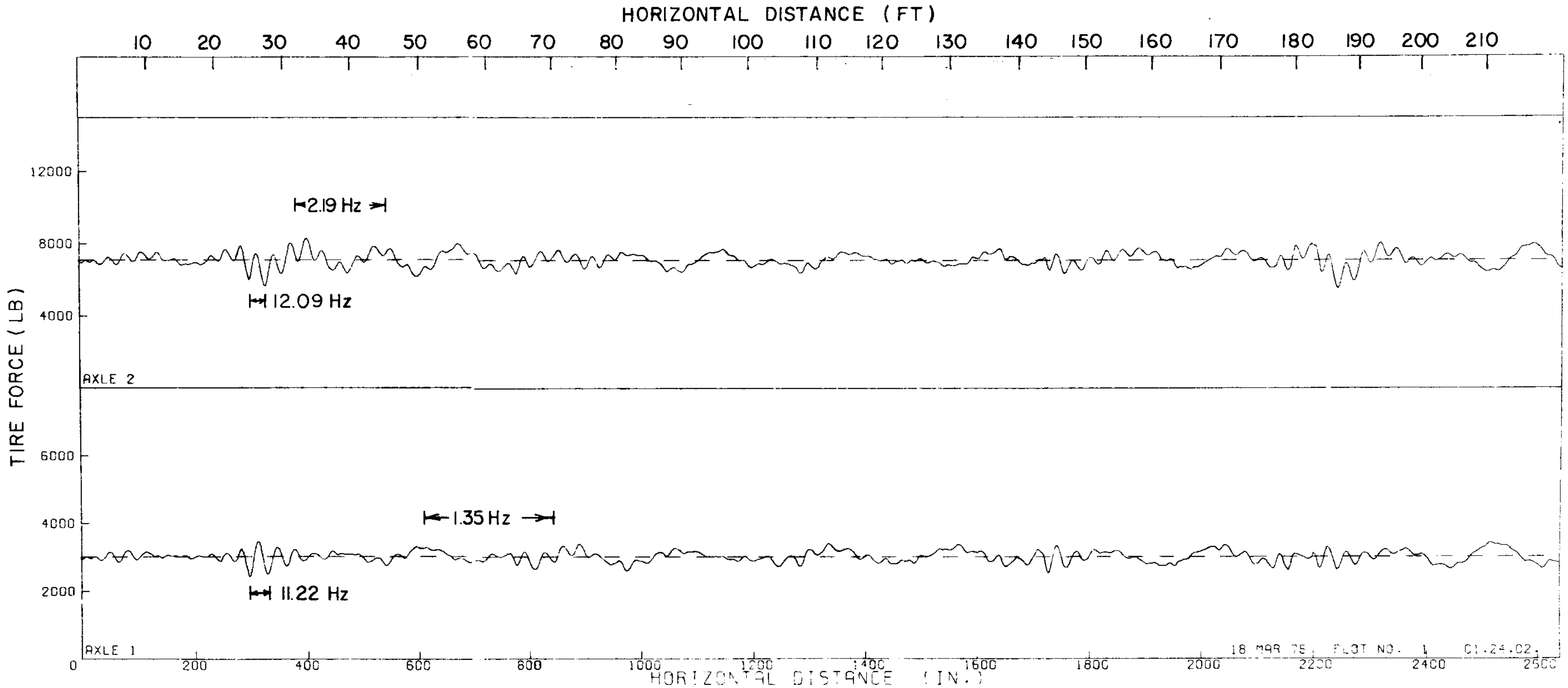

Fig 3. Predicted tire forces for 2D type vehicle at 20 mph speed on profile of Fig 1.

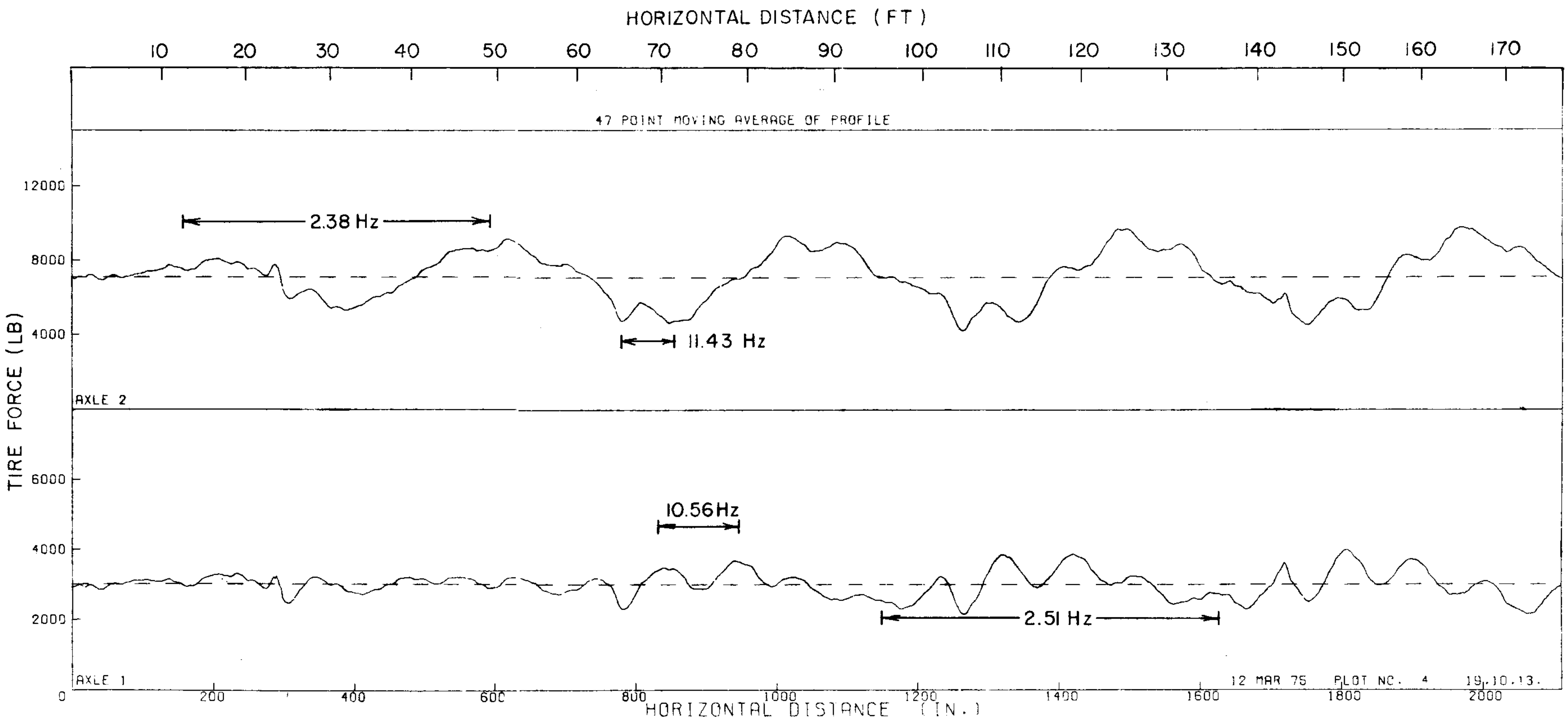

Fig 4. Predicted tire forces for 2D type vehicle at 60 mph speed on profile of Fig 1.

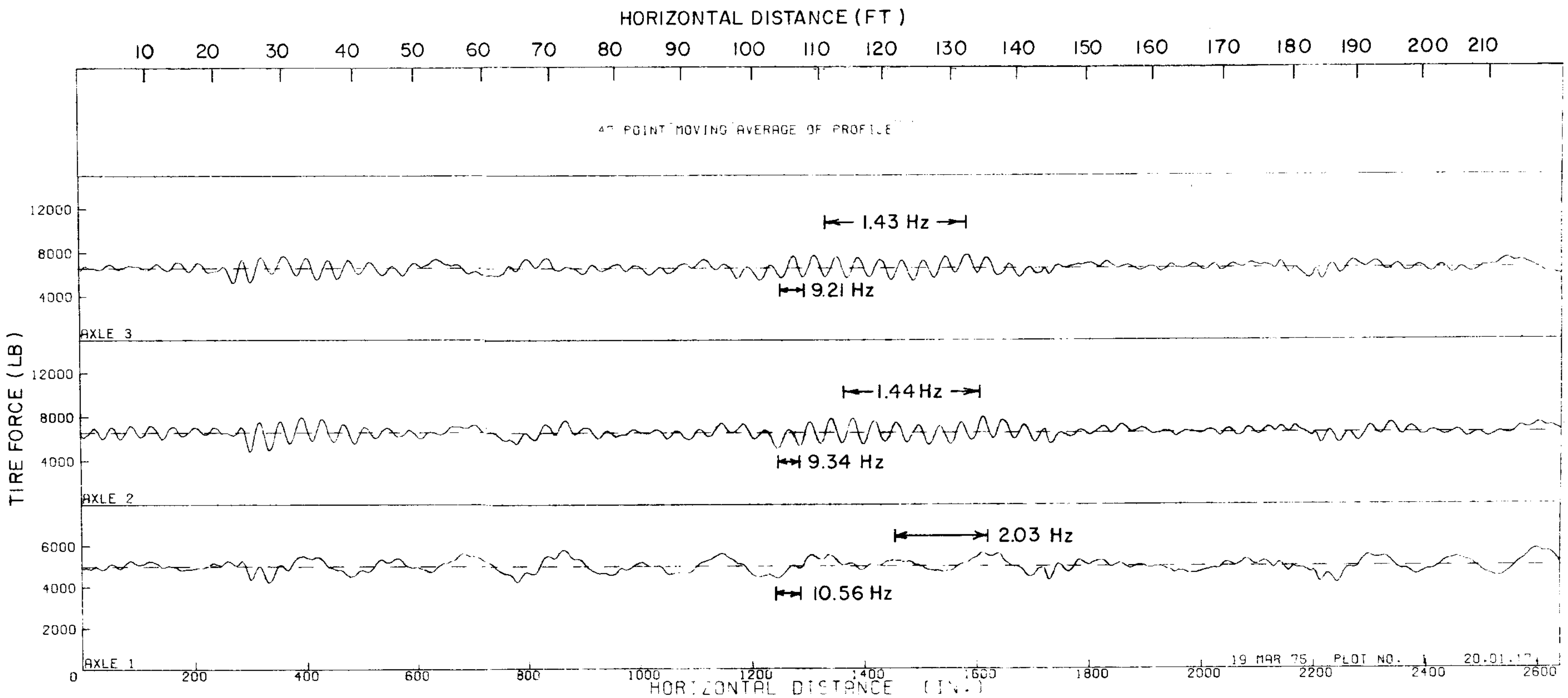

Fig 5. Predicted tire forces for 3A type vehicle at 20 mph speed on profile of Fig 1.

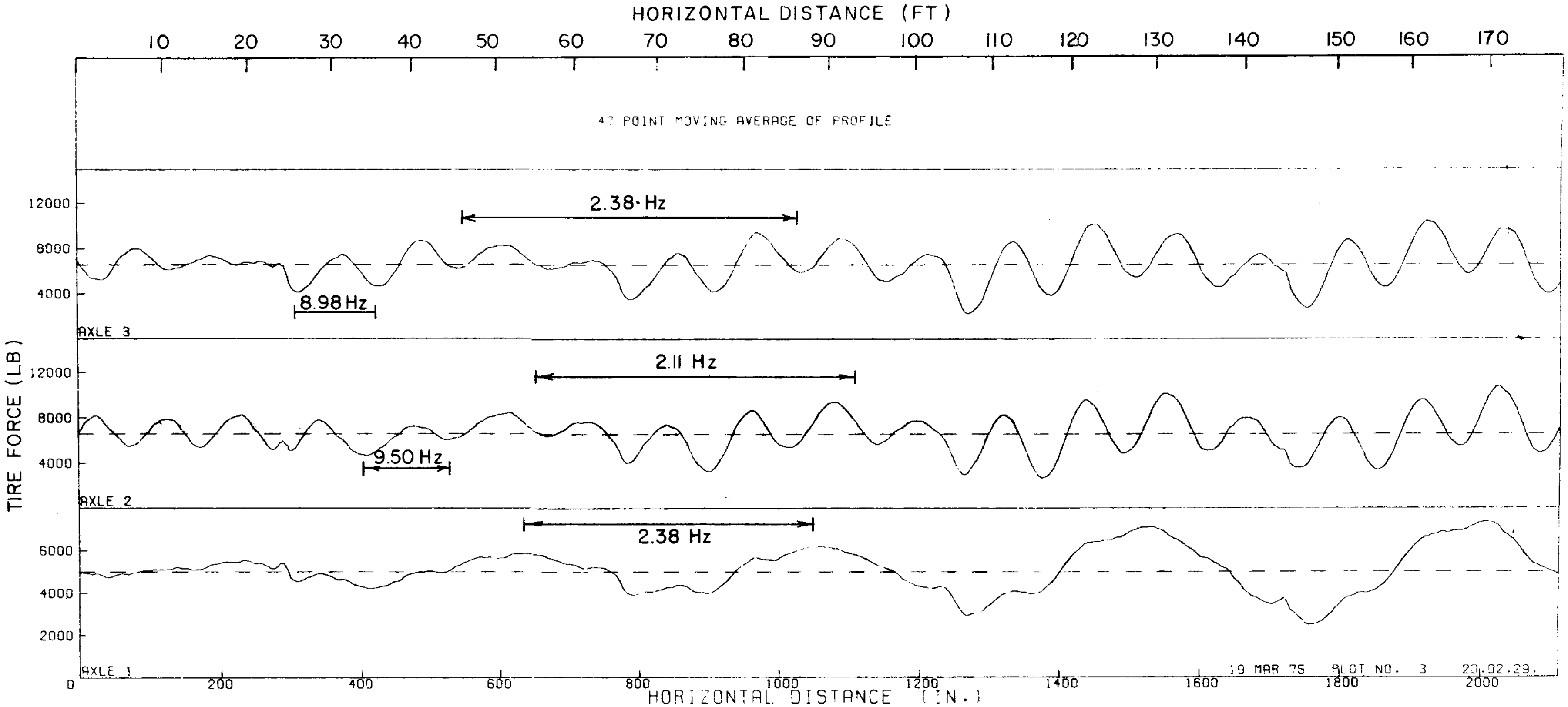

Fig 6. Predicted tire forces for 3A type vehicle at 60 mph speed on profile of Fig 1.

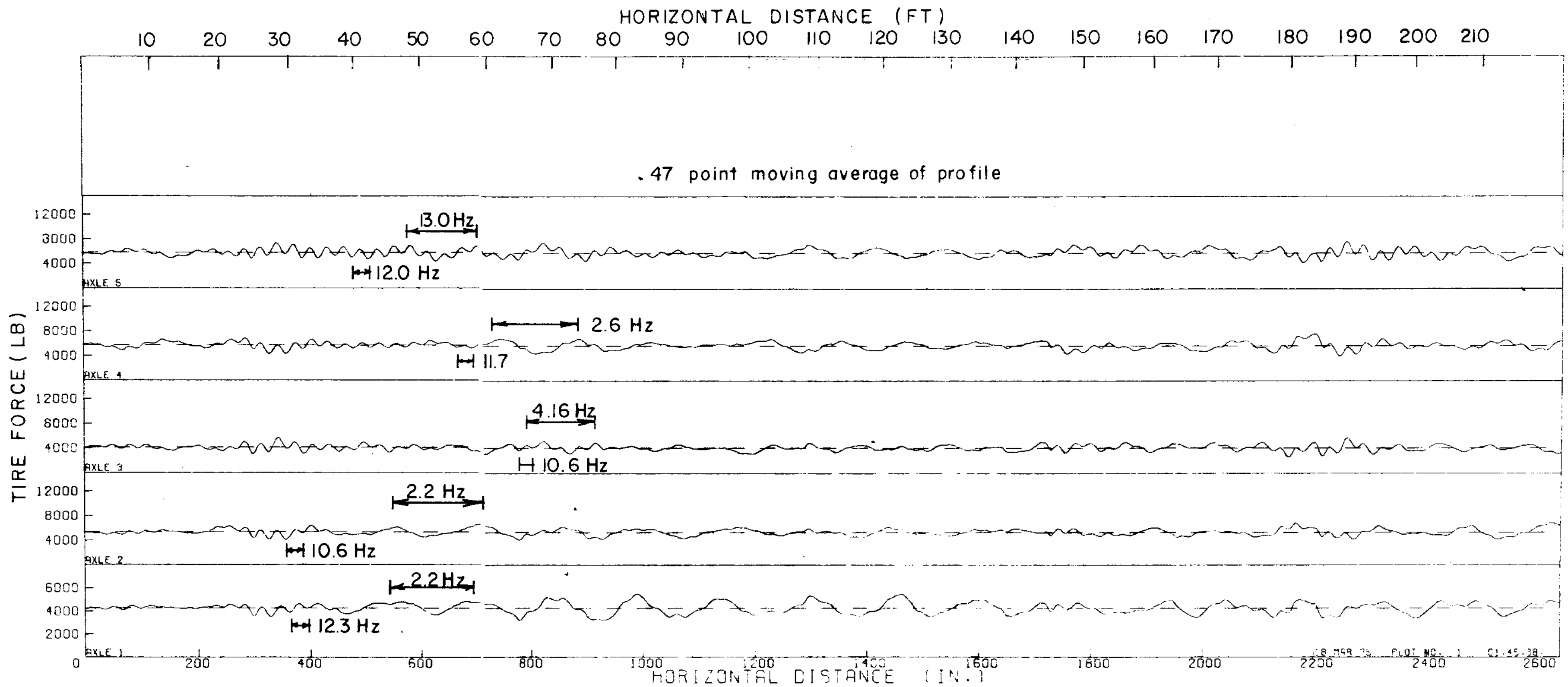

Fig 7. Predicted tire forces for 3S-2 type vehicle at 20 mph speed on profile of Fig 1.

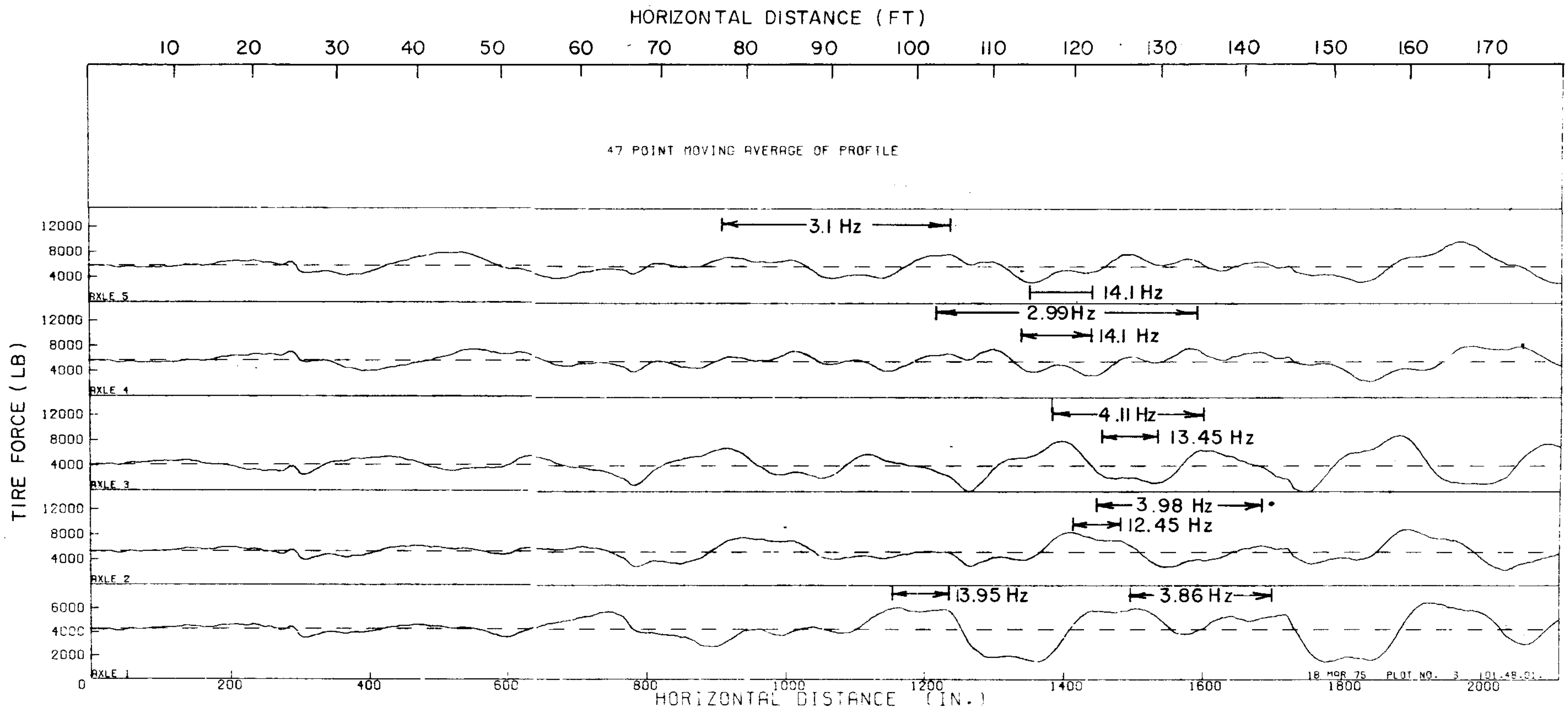

Fig 8. Predicted tire forces for 3S-2 type vehicle at 60 mph speed on profile of Fig 1.

moves cyclically at about 2 to 4 Hz. The dynamic tire forces result from these combined movements.

At 20 mph, all three vehicles produce dynamic tire forces that vary up to about 25 percent from the static wheel weights. As vehicle speed increases, up to a certain point, dynamic wheel forces increase, and the bridge profile with its 40-foot-long waves interacts increasingly with the sprung mass (body and load of the vehicle). The effects of the increased vehicle-profile interaction at 60 miles per hour may be noted in the predicted tire forces shown in Figs 4, 6, and 8. Excitation of the sprung mass is evidenced in the wheel force diagrams by the periodic nature of the dynamic wheel forces at frequencies of about 2 to 3 Hz and by the larger magnitude of force change. Dynamic tire forces vary by more than 1.5 times the static wheel weights in some areas.

The increase in vehicle-profile interaction with increased speed can be further explained by the fact that the frequency of the excitations experienced by a vehicle traveling over the 40-foot waves increases with vehicle speed. Table 3 summarizes the calculated frequency of excitation for vehicle speeds of 20 through 70 miles per hour. Since the natural frequency of the unsprung mass of the vehicle is between 2 and 3 Hz, it is apparent that as vehicle speed approaches the 60 to 70 mile per hour range the frequencies of oscillation of the vehicle and the frequency of excitation approach each other.

TABLE 3. FREQUENCY OF EXCITATION VERSUS VEHICLE SPEED FOR 40-FOOT WAVES

Vehicle Speed (mph)	Frequency of Excitation (Hz)
20	0.74
40	1.47
60	2.20
70	2.57

Predicted tire forces for the bridge section over the continuous steel span are plotted in Figs 9 through 14 and demonstrate the same general trends of higher dynamic loads with higher vehicle speeds. However, in this case the cyclic pattern of excitations is not as apparent as in the previously described profile section. The relatively large changes in elevation occurring over fairly small distances in the latter section of the profile (see Fig 2) caused violent reactions by all three vehicles even at low speeds (see Figs 9, 11 and 13). Higher speeds caused increases in the predicted tire forces (see Figs 10, 12, and 14). The sudden elevation changes are more pronounced beginning approximately 3,300 feet from the east end of the bridge.

Although Figs 3 through 14 illustrate the manner in which tire forces vary with distance, they do not represent the variation of total force exerted by a vehicle on the bridge surface. Figure 15 illustrates the variation of total force (sum of all tire forces) exerted on the first profile section by the five-axle articulated (3S-2 type) vehicle for a speed of 60 miles per hour. Figure 15 indicates that for a vehicle speed of 60 miles per hour the total force exerted on the bridge structure varies from less than the vehicle's static gross weight to approximately 1.25 times the static value. This total force information is of particular interest to bridge designers for analysis of major structural members whereas the dynamic wheel forces are concentrated on the deck and need to be considered in analyzing this element of the bridge.

Conclusions

The simulation study indicates that the magnitude of dynamic tire forces which can be produced on the Hubbard Creek Reservoir Bridge in its present condition by typical commercial vehicles is more than 50 percent greater than the static wheel weights. The magnitude of the peak tire forces is dependent on vehicle speed. Reducing vehicle speed from 60 miles per hour to 20 miles per hour effectively reduces the peak dynamic tire forces by 25 percent. At least this much reduction in dynamic loading can be realized by smoothing the surface with an overlay. The practical solution to improving riding quality and reducing dynamic loads in this case appears to be an overlay.

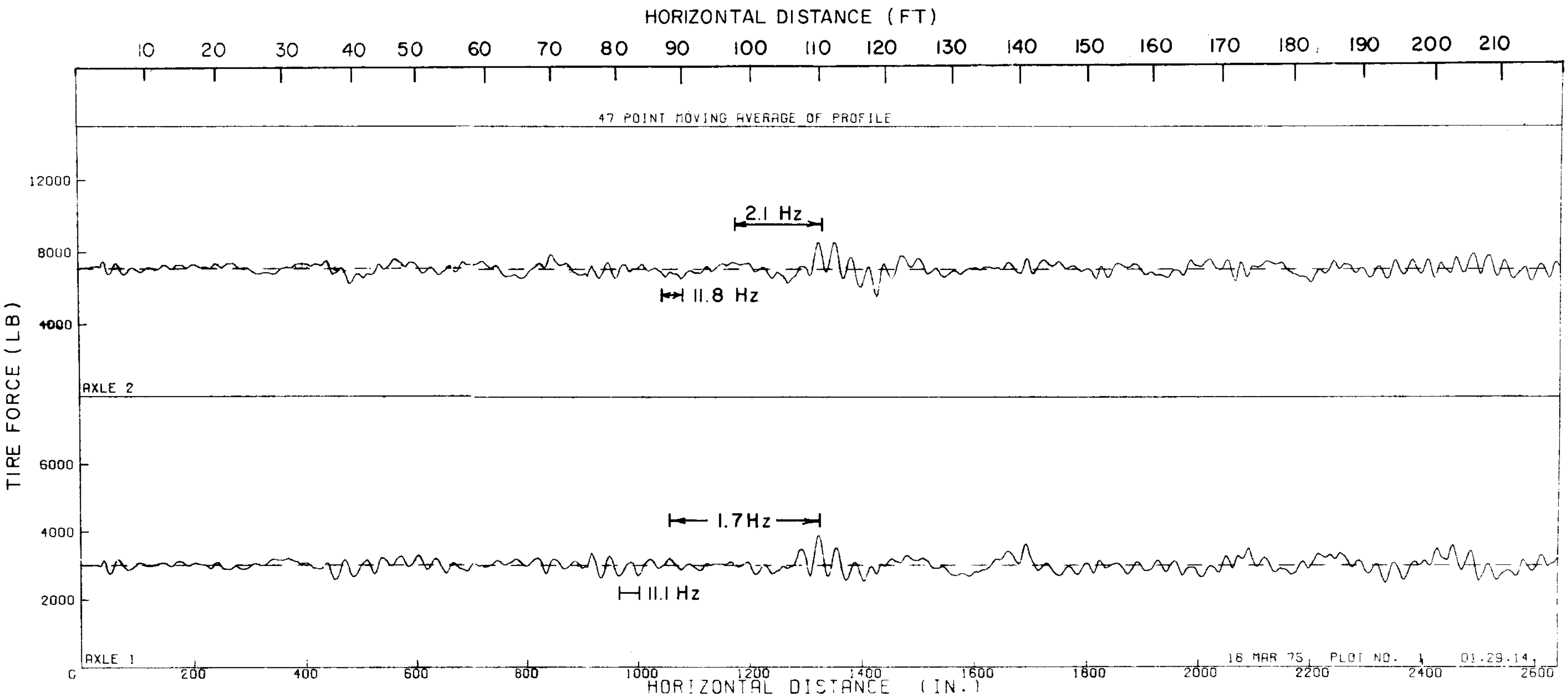

Fig 9. Predicted tire forces for 2D type vehicle at 20 mph speed on profile of Fig 2.

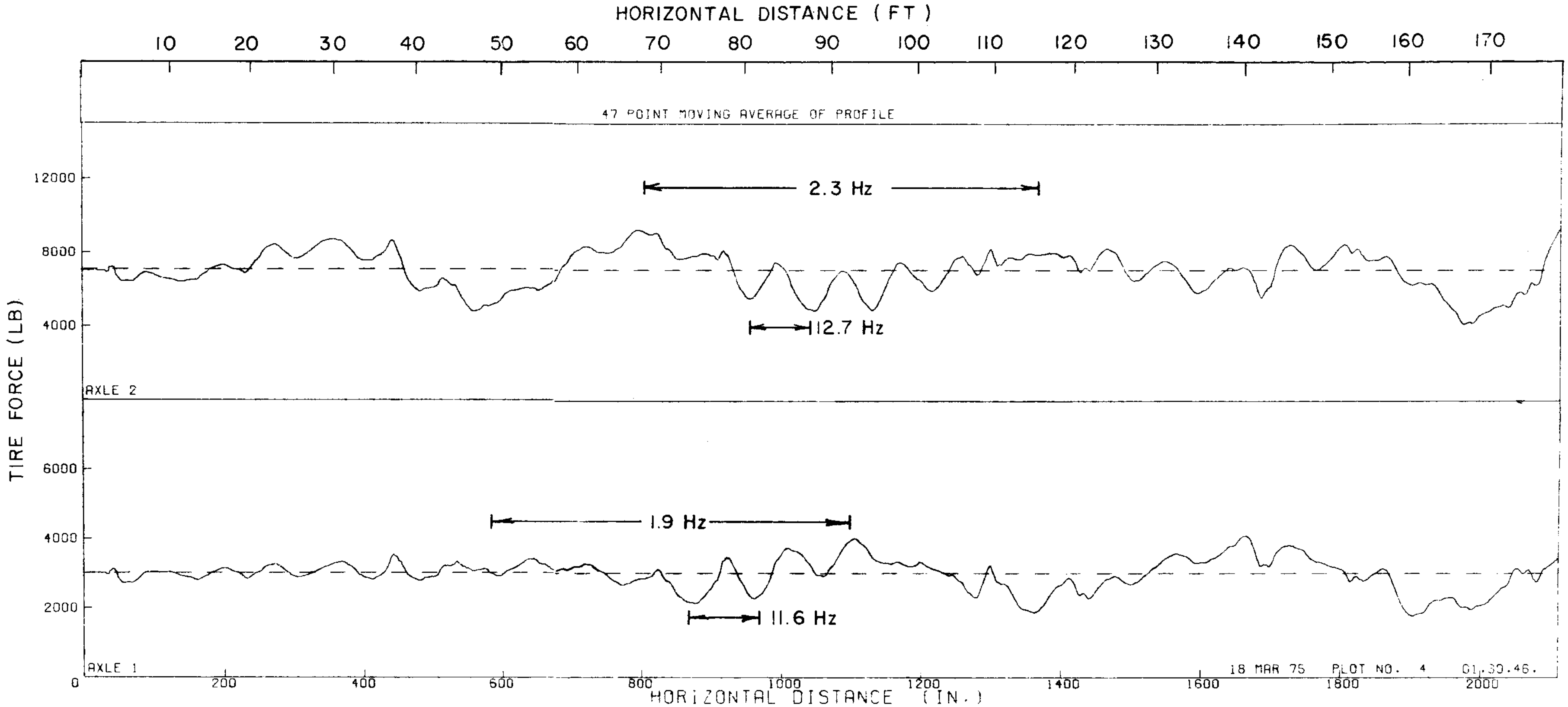

Fig 10. Predicted tire forces for 2D type vehicle at 60 mph speed on profile of Fig 2.

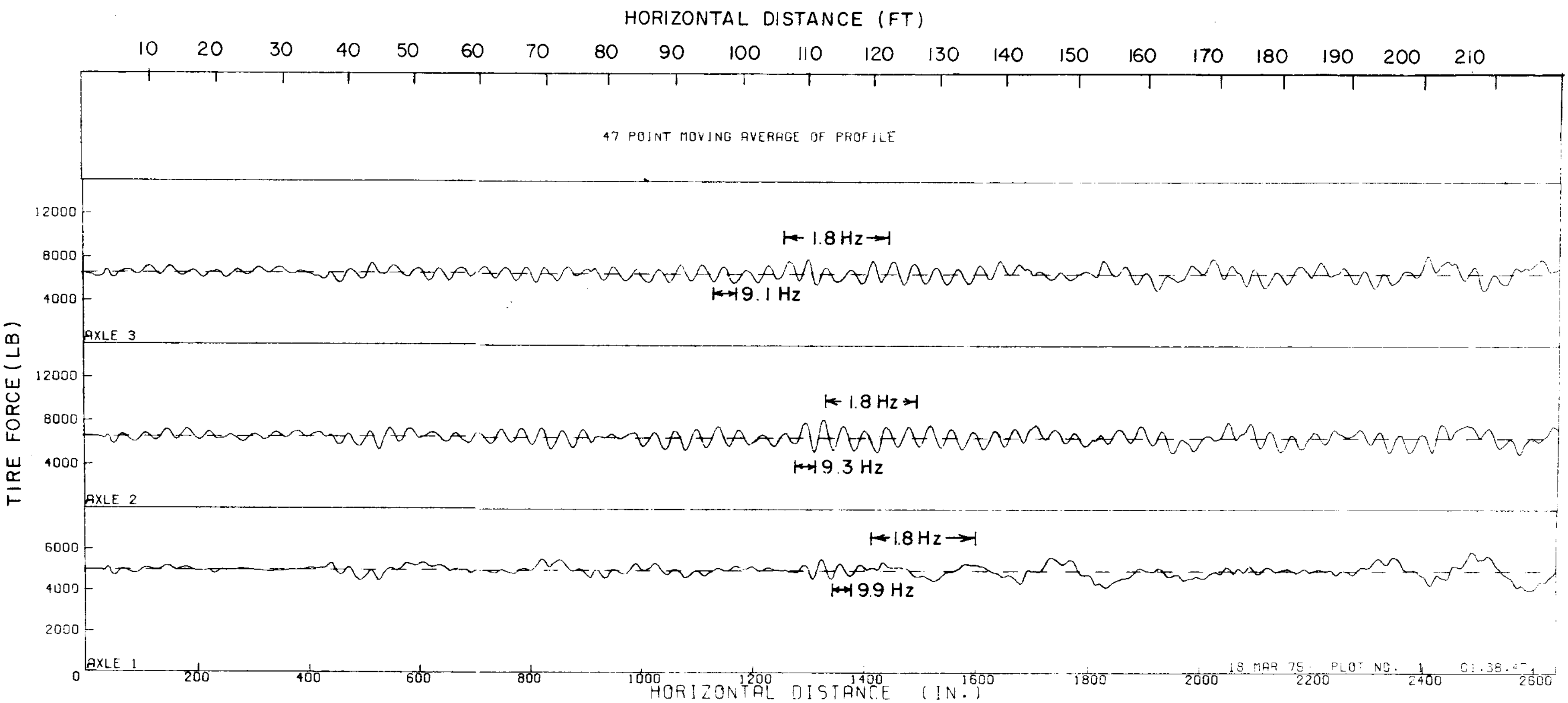

Fig 11. Predicted tires forces for 3A type vehicle at 20 mph speed on profile of Fig 2.

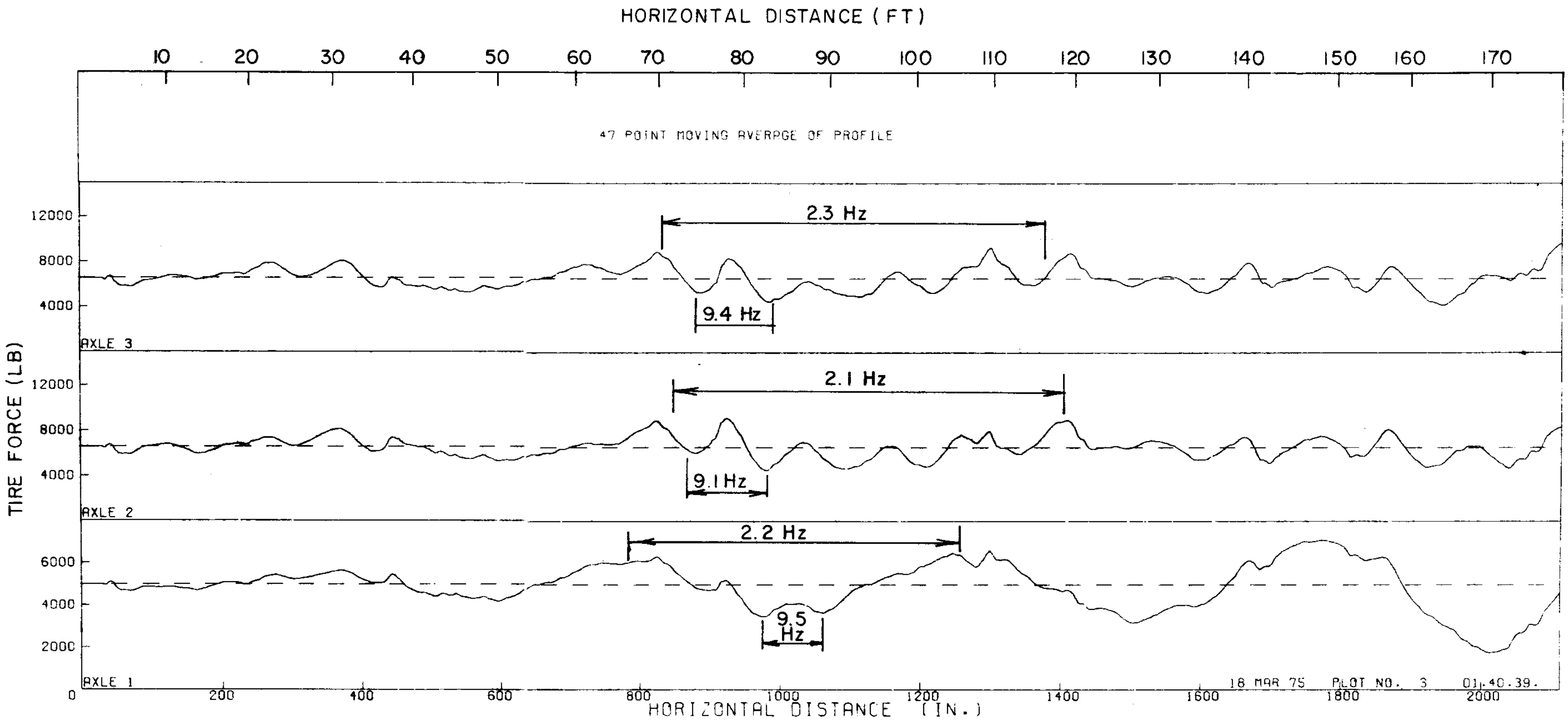

Fig 12. Predicted tire forces for 3A type vehicle at 60 mph speed on profile of Fig 2.

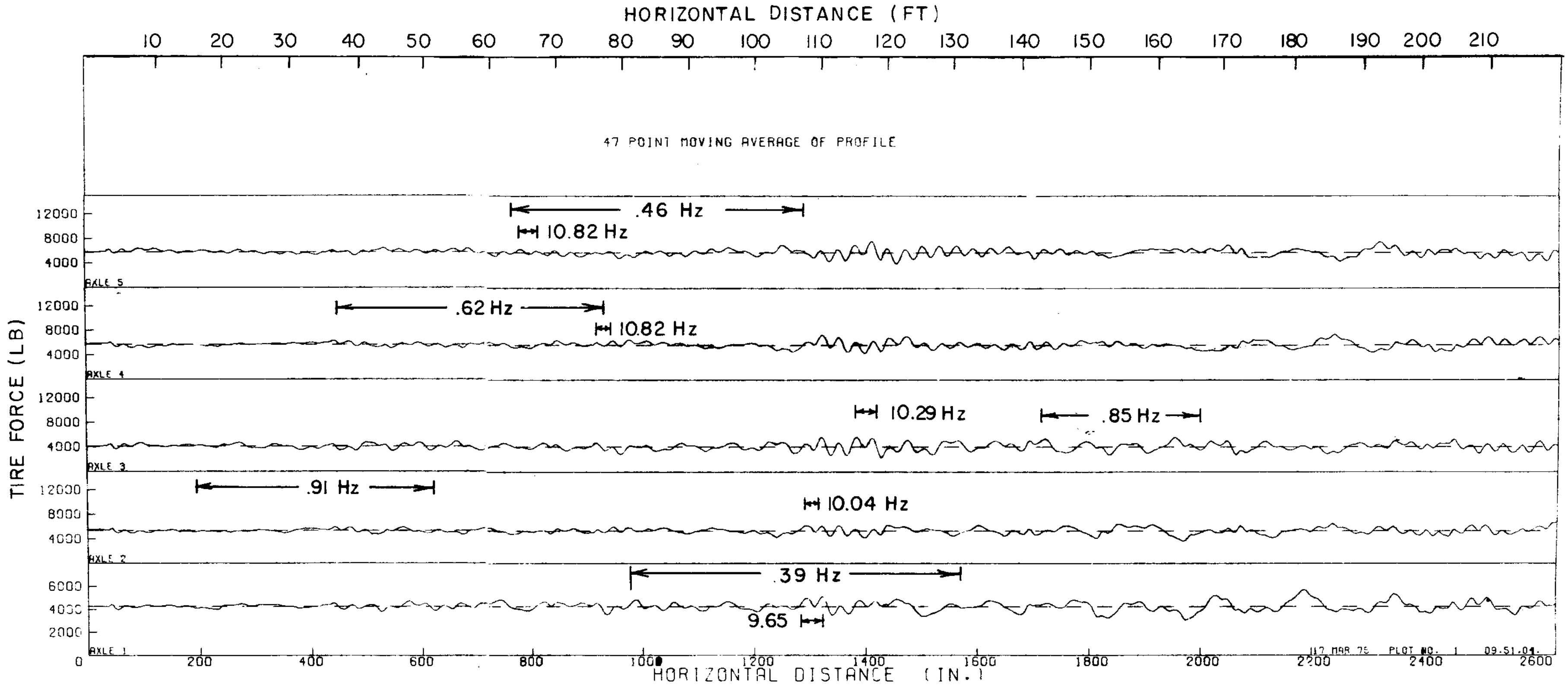

Fig 13. Predicted tire forces for 3S-2 type vehicle at 20 mph speed on profile of Fig 2.

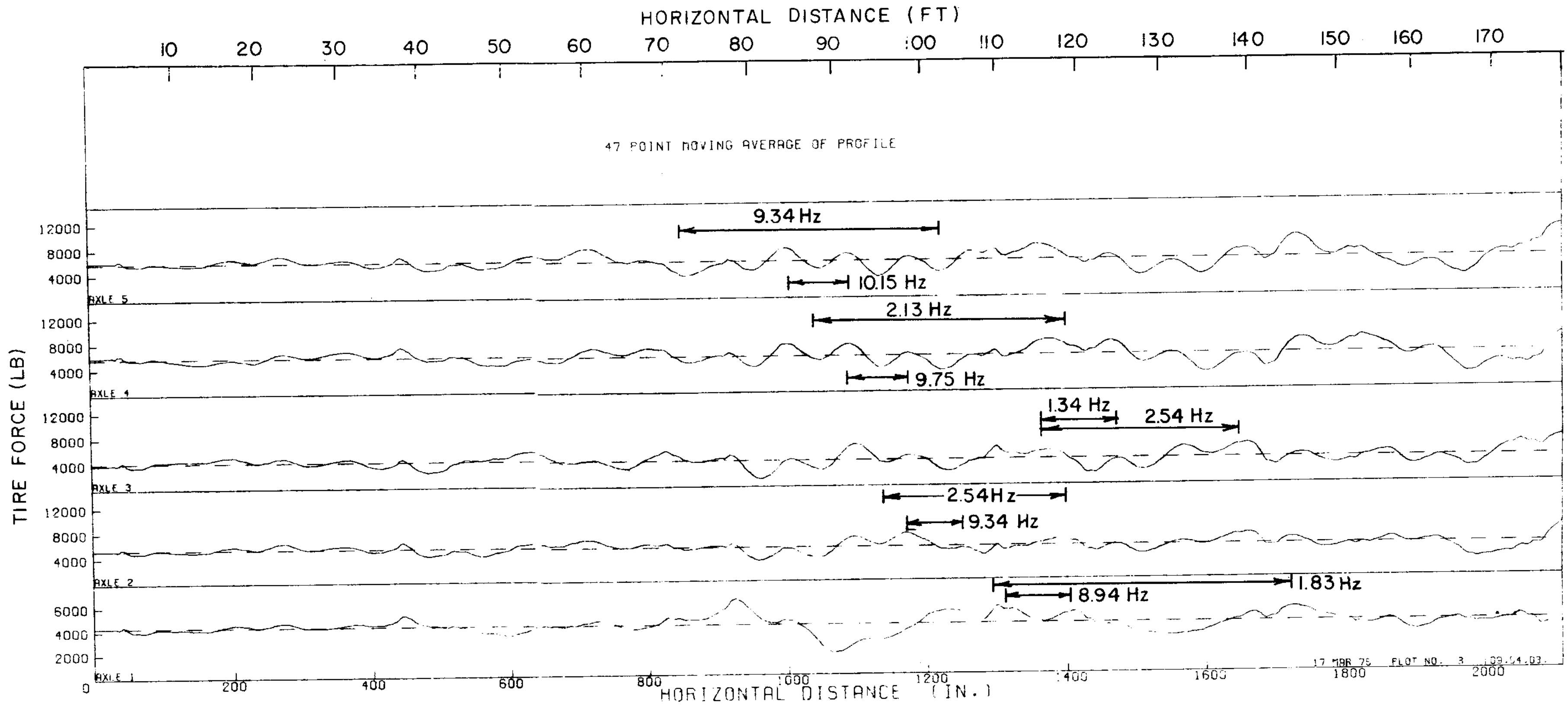

Fig 14. Predicted tire forces for 3S-2 type vehicle at 60 mph speed on profile of Fig 2.

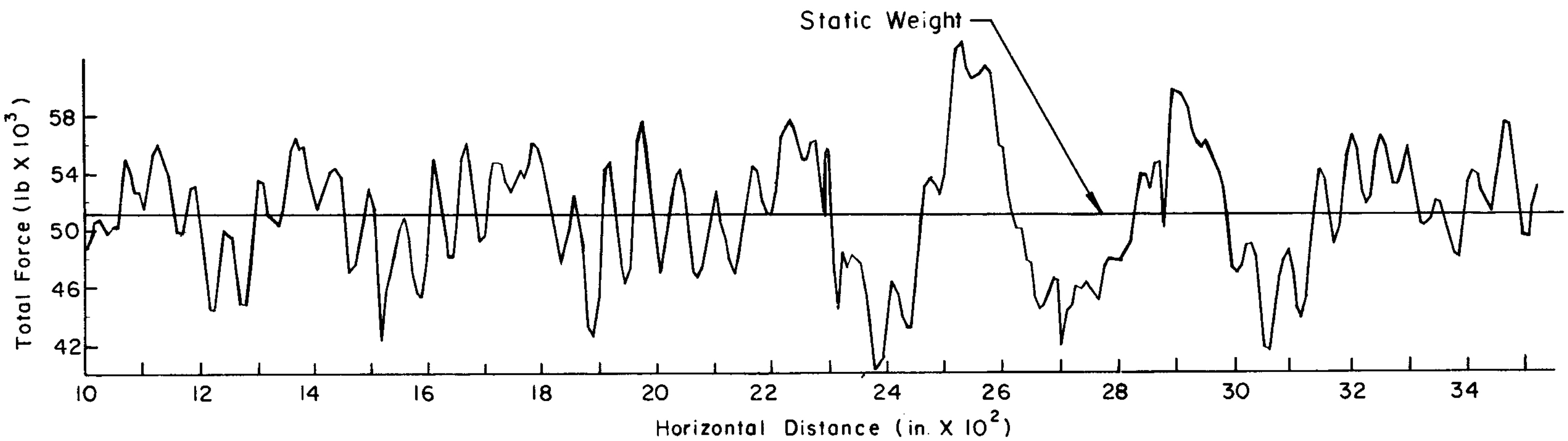

Fig 15. Total force exerted on bridge deck by 3S-2 vehicle traveling 60 mph over continuous steel spans.

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