# SPEED-ZONING TO REDUCE DYNAMIC LOADS ON THE PORT ISABEL CAUSEWAY

by

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conducted for

The Texas Highway Department

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

March 1974

# PREFACE

This investigation was initiated on February 14, 1974, at the request of the Texas Highway Department by James L. Brown, D-10, Planning and Research Division (Austin); Don W. McGowan, D-18, Maintenance Operations Division (Austin); and Sam Cox, District 21 (Pharr). Field studies were conducted February 20-22, and recommendations were reported to Mr. McGowan and H. B. Butler, D-5, Bridge Division (Austin) on March 5, 1974.

Center for Highway Research personnel who performed the field studies and the analyses were H. H. Dalrymple, Research Engineer Associate; Randy B. Machemehl, Research Engineer Assistant; Robert F. Inman, Technical Staff Assistant; and Noel C. Wolf, Technical Staff Assistant. The analytical concepts, data reduction processes, computer simulation techniques and equipment used in the investigation have been developed over the past several years under the continuing Cooperative Highway Research Program through 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,
1AC (72-73)-107 - Development of In-Motion Weighing Systems, and
1AC (72-73)-686 - Operational Procedures, Final Evaluation of Equipment, Its Use and Maintenance.

# DISCLAIMER

# ABSTRACT

Since its construction in the early 1950's, the mile-long reinforced concrete causeway structure which connects Padre Island with the Texas mainland has developed significant permanent deformation or sag in most of the 30-foot-long simply supported pan girder type spans that compose the 26-foot-wide roadway. The resulting profile tends to cause trucks operating at certain speeds to bounce and pitch rather violently and thereby produce dynamic loads that can be more than double the static weight of the vehicle. In order to preserve the structural integrity of the old causeway for the next few months until a new structure can be completed, heavy traffic loads must be controlled.

A computer simulation technique, which was used to investigate the complex interaction of the actual road profile with a critical vehicle type (transit-mix concrete truck) operating at various speeds, indicates that potentially damaging dynamic loads can be reduced to tolerable levels if truck speeds are kept below about 20 mph. Speed-zoning is recommended as a practical means of reducing dynamic loads on the old causeway.

# SUMMARY

A computer modeling technique was used to evaluate the magnitude and frequency of dynamic wheel loads that would result from a heavy (8 or 9-cubic-yard capacity) transit-mix concrete truck operating at various speeds over the undulating profile of the old Port Isabel causeway between the mainland and Padre Island. At 20 mph, dynamic wheel forces were found to vary at frequencies in the 10 Hz range up to about 50 percent in magnitude from the static wheel weights of the rear axles and at lower frequencies and smaller magnitudes for the front axle.

As vehicle speed increased up to 55 mph, dynamic wheel forces in the critical frequency range of 2 to 3 Hz (which is near the natural frequency of the structure) increased significantly. At 55 mph, dynamic wheel forces varied from zero to more than double the static wheel weight.

Speed-zoning to control truck speeds below 20 mph is recommended. The relatively small delays to traffic resulting from lower speeds are preferable to load-zoning or surface overlay construction as a practical means for reducing dynamic loading on the causeway structure.

# SPEED-ZONING TO REDUCE DYNAMIC LOADS ON THE PORT ISABEL CAUSEWAY

The only highway link between the Texas mainland and Padre Island, the southernmost of the inner coastal islands lying beyond the Laguna Madre in the Gulf of Mexico, is the Port Isabel causeway. This two-lane concrete structure, which was built in the 1950's, has served traffic to and from the island adequately through the years, but increasing traffic demand has made it necessary to provide better access. A modern structure with a clear roadway width of 65-1/2 feet is now under construction, but it will probably not be opened to traffic until early 1975.

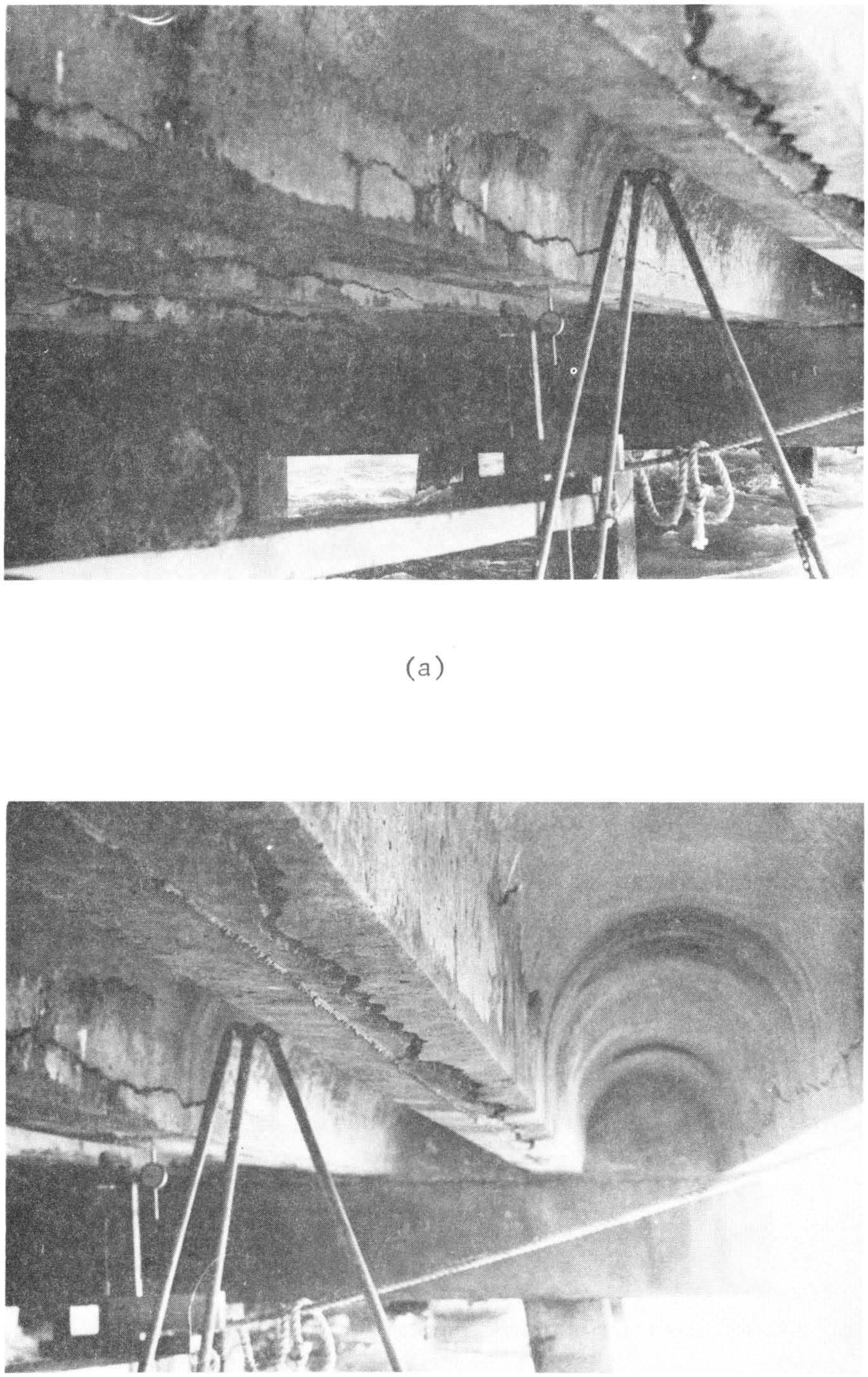
In the meantime, the old causeway is carrying significant numbers of heavy vehicles, including commercial trucks, buses, and large transit-mix concrete trucks. Texas Highway Department engineers in District 21 and in Austin are concerned about the potential destructive effects of the dynamic wheel loads that will be produced by these vehicles crossing the old structure during the coming months. Traffic service to the island must be maintained over the old causeway at least until the new structure is finished.

## THE PROBLEM

This old causeway is a reinforced concrete pan girder type structure composed of simply supported spans, each 30 feet long.

The mile-long structure is only a few feet above mean sea level and has thus been exposed to the salt air atmosphere for many years. This corrosive environment combined with a history of heavy traffic loading has caused considerable cracking in the concrete cover over the reinforcing steel in the girders (see Fig 1). Even though repairs have been effected through the years, there is evidence of rusting of the reinforcement, and most of the spans have obvious permanent deformation or sag near the middle. A recent rod and level survey showed that mid-span elevations of the roadway surface were as much as 0.075 foot below the mean elevation of adjacent supports.

Such an undulating road surface profile causes vehicles running at certain speeds to bounce, roll, and pitch because of the forced vertical translation



(a)

(b)

Fig 1. Deterioration of pan girder structural members.

of the wheels acting on the sprung mass (body) of the vehicle through the suspension system. Under critical conditions, when the vertical movements of the vehicle are reinforced by each wave in the road profile, very large dynamic wheel forces are produced. Previous research (Refs 1 and 2) has shown that these impact forces can be more than twice the static wheel weight of the subject vehicle. These severe dynamic loads need to be minimized in order to preserve the structural integrity of the old causeway.

Solution of the problem lies in controlling the traffic loads. Load-zoning is one possible approach, but since it is impractical to reduce the gross weight of the transit-mix concrete trucks, which are prominent users of the causeway, below a certain point, this is not a desirable solution. An alternative approach is 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. Or, a third approach to solving the problem is to remove the waves from the roadway surface by constructing an overlay. This rather expensive operation seems unjustified in view of the forthcoming opening of the nearby new structure in a few months.

Since speed-zoning appears to be the preferable solution to the traffic loading problem, personnel at the Center for Highway Research, The University of Texas at Austin, who have developed expertise in dynamic traffic loading through previous cooperative research with the Texas Highway Department and the Federal Highway Administration were asked to conduct an investigation and recommend an appropriate speed limit for posting on the causeway. Computer simulation techniques were proposed for evaluating the complex dynamic behavior of the vehicles traveling at various speeds over the undulating causeway surface profile.

## FIELD MEASUREMENTS

Accurate 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 these data. This sophisticated device which incorporates a pair of stable accelerometers, a computer for integrating the acceleration signals twice, and a pair of linear displacement transducers attached to low inertia road following wheels produces a continuous record on magnetic tape of the road surface elevations in each wheel path relative to an imaginary horizontal plane in space. Waves in the profile up to 200 feet long can be detected with this instrument, depending upon the speed at which the profilometer vehicle is driven. For the causeway study, the profilometer was operated at speeds of 10, 20, and 34 mph in order to resolve small surface irregularities as well as waves in the profile up to 40 feet or more in length.

Of course, the road surface profile of a bridge changes with the live load applied by traffic. The profilometer vehicle, which weighs only about 5,000 pounds, caused negligible live load deflections; therefore, it was still necessary to examine the magnitude of bridge deck movements under the heavier vehicles using the causeway. If these deflections were significant, they could be included in the computer simulation process; if not, the measured profile could be used unmodified.

An improvised reference platform resting on solid ground beneath the shallow water was constructed under the westernmost span of the causeway to support a linear displacement transducer in contact with selected girders at midspan. Electrical signals from the transducer which were proportional to the vertical displacement of the bridge deck were recorded with respect to time as trucks passed over the span. The maximum deflections observed were on the order of 0.050 inch; therefore, no modification to the road surface profile was required.

The profile of the full length of the causeway structure was plotted and examined visually to determine the zones with profile characteristics likely to cause large impact loads. The riding surface was generally free of small irregularities, but a definite pattern of sags between span supports was evident over the full length of the structure. A 300-foot section of the profile near the west end was selected as being representative of the overall profile pattern and was used as input to the computer simulation model. The profile of the left wheel path in the eastbound lane is shown in Fig 3. Very small surface irregularities do not show in this plot since a running average of the elevations in an 8-inch length was used to simulate the contact length of a truck tire.

Observations of heavy vehicles made during a day spent at the site (February 21, 1974) indicated that most of the trucks were running between 25 and 30 mph. A recent speed study by Texas Highway Department personnel showed that the 85 percentile speed of all traffic on the causeway was 44 mph.

## VEHICLE SIMULATION

Even though a wide variety of heavy vehicles use the causeway, critical loading of the 30-foot spans is likely to be produced by the large single unit transit-mix concrete trucks that have 8 or 9-cubic-yard payloads. These are unique vehicles that are permitted to operate under special bonds and to carry axle loads in excess of the normal legal weight limits. This type of vehicle was chosen to represent the critical traffic load for the simulation study.

Cooperation of a ready-mix concrete supplier in Austin made it possible for Center personnel to examine a typical 8-yard transit-mix truck and measure suspension displacements when the vehicle was empty and again when loaded. Other measurements including width, length, axle spacing, tread width, and gross vehicle weight were also made in order that a mathematical model of the vehicle could be configured (see Fig 2). All vehicle parameters needed for the simulation model of a representative transit-mix truck were measured, calculated, or deduced from previous experience. Gross weight of the vehicle was taken as 55,000 pounds.

## MODEL ANALYSIS

The mathematical model of the critical vehicle was then "driven" over the causeway profile (see Fig 3) at speeds ranging from 10 to 70 mph. Tire forces resulting from the interaction of the vehicle and the road surface were calculated and plotted as shown in Figs 4 through 8. Spring stiffnesses, damping coefficients, static wheel weights, and speed are tabulated in each figure.

These figures show the variations in the dynamic tire forces which result from movements of the wheels and from movements of the body of the vehicle. The smaller wheel masses (called the unsprung masses) oscillate typically at frequencies in the range of 8 to 12 Hz (cycles per second) while the large mass which represents everything above the suspension system of the vehicle (the sprung mass) moves at about 2 to 4 Hz. The dynamic tire forces reflect the effects of these combined movements.

At 20 mph, the relatively stiffly sprung and heavily damped transit-mix vehicle interacted with the causeway profile (see Fig 3) to produce tire forces up to about 50 percent greater than static wheel weight (see Fig 4). Dynamic loading by the front wheels was not severe at this speed, and nearly all impact

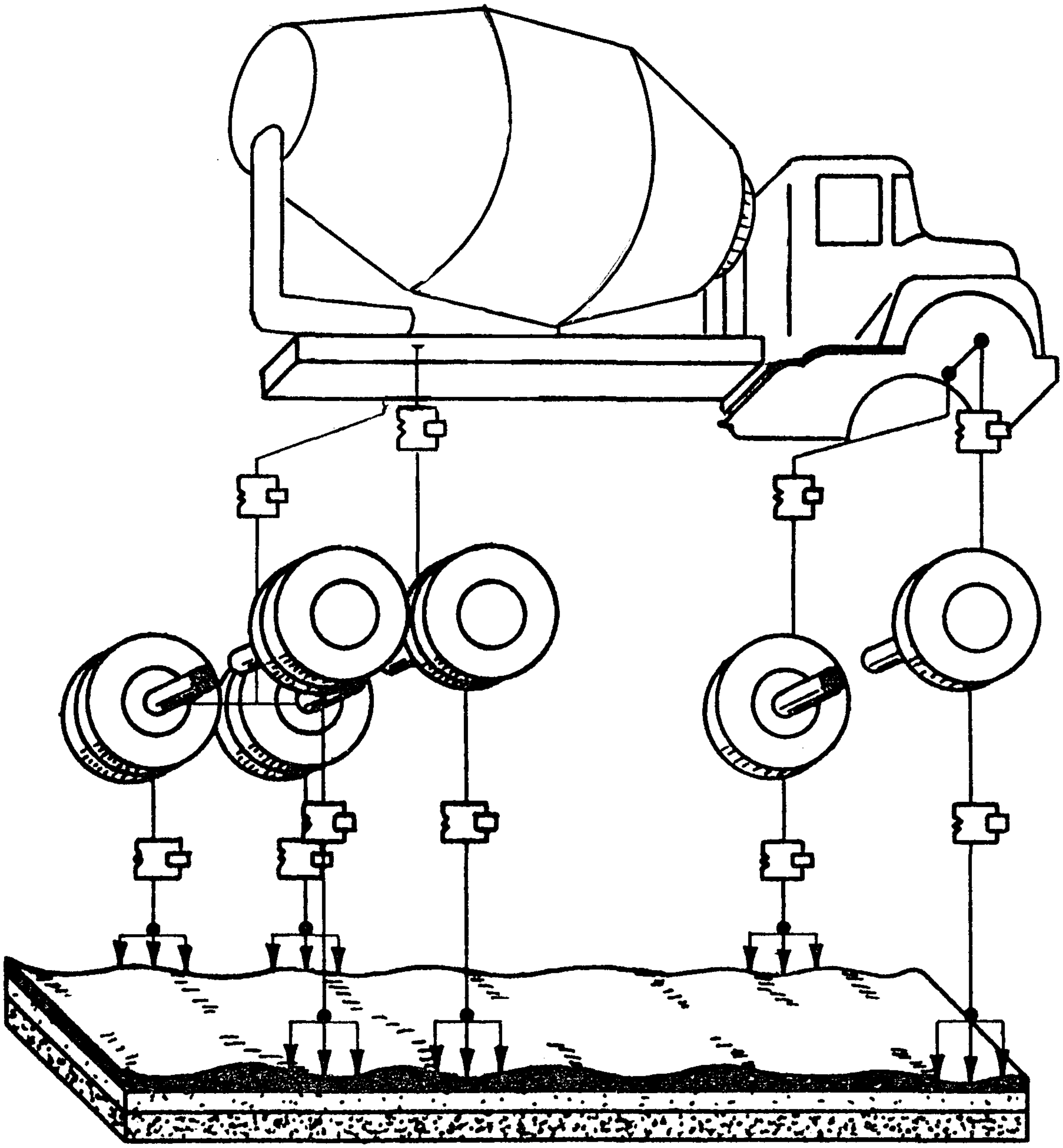


Fig 2. Class III vehicle model.

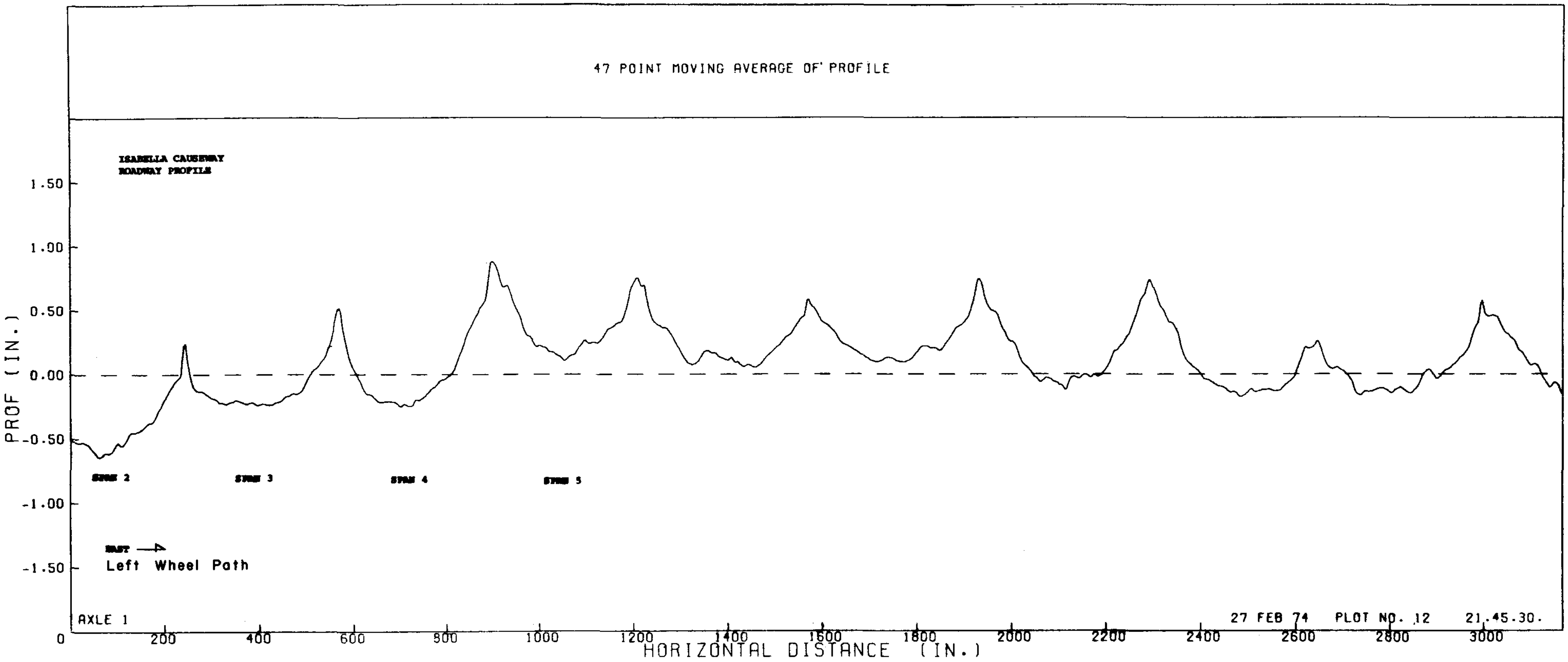

47 POINT MOVING AVERAGE OF PROFILE
ISABELLA CAUSEWAY
ROADWAY PROFILE
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
PROF (IN.)
SPAN 2
SPAN 3
SPAN 4
SPAN 5
EAST →
Left Wheel Path
AXLE 1
27 FEB 74
PLOT NO. 12
21.45.30.
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
HORIZONTAL DISTANCE (IN.)

Fig 3.

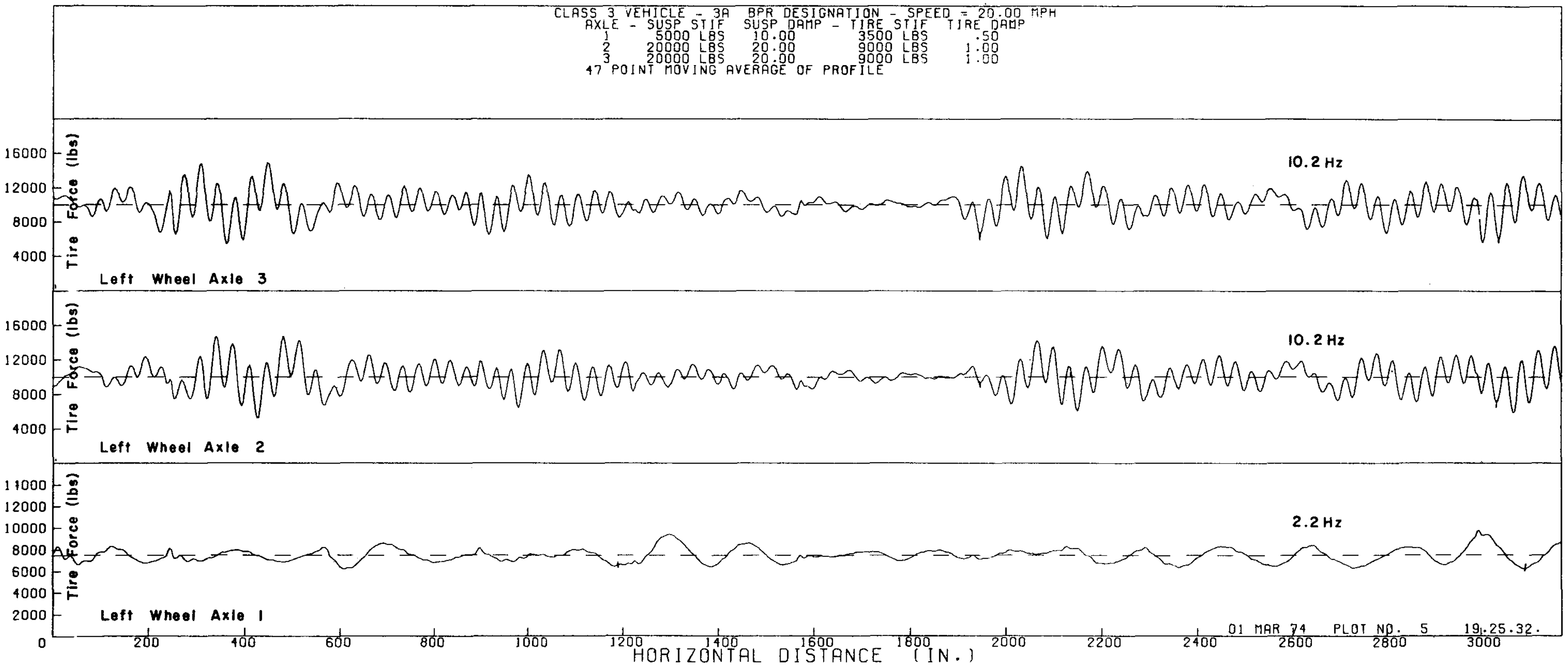

CLASS 3 VEHICLE - 3A BPR DESIGNATION - SPEED = 20.00 MPH
AXLE - SUSP STIF SUSP DAMP - TIRE STIF TIRE DAMP
1 5000 LBS 10.00 3500 LBS .50
2 20000 LBS 20.00 9000 LBS 1.00
3 20000 LBS 20.00 9000 LBS 1.00
47 POINT MOVING AVERAGE OF PROFILE
10.2 Hz
Tire Force (lbs)
16000
12000
8000
4000
Left Wheel Axle 3
10.2 Hz
Tire Force (lbs)
16000
12000
8000
4000
Left Wheel Axle 2
2.2 Hz
Tire Force (lbs)
14000
12000
10000
8000
6000
4000
2000
0
Left Wheel Axle 1
01 MAR 74 PLOT NO. 5 19.25.32.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
HORIZONTAL DISTANCE (IN.)

Fig 4.

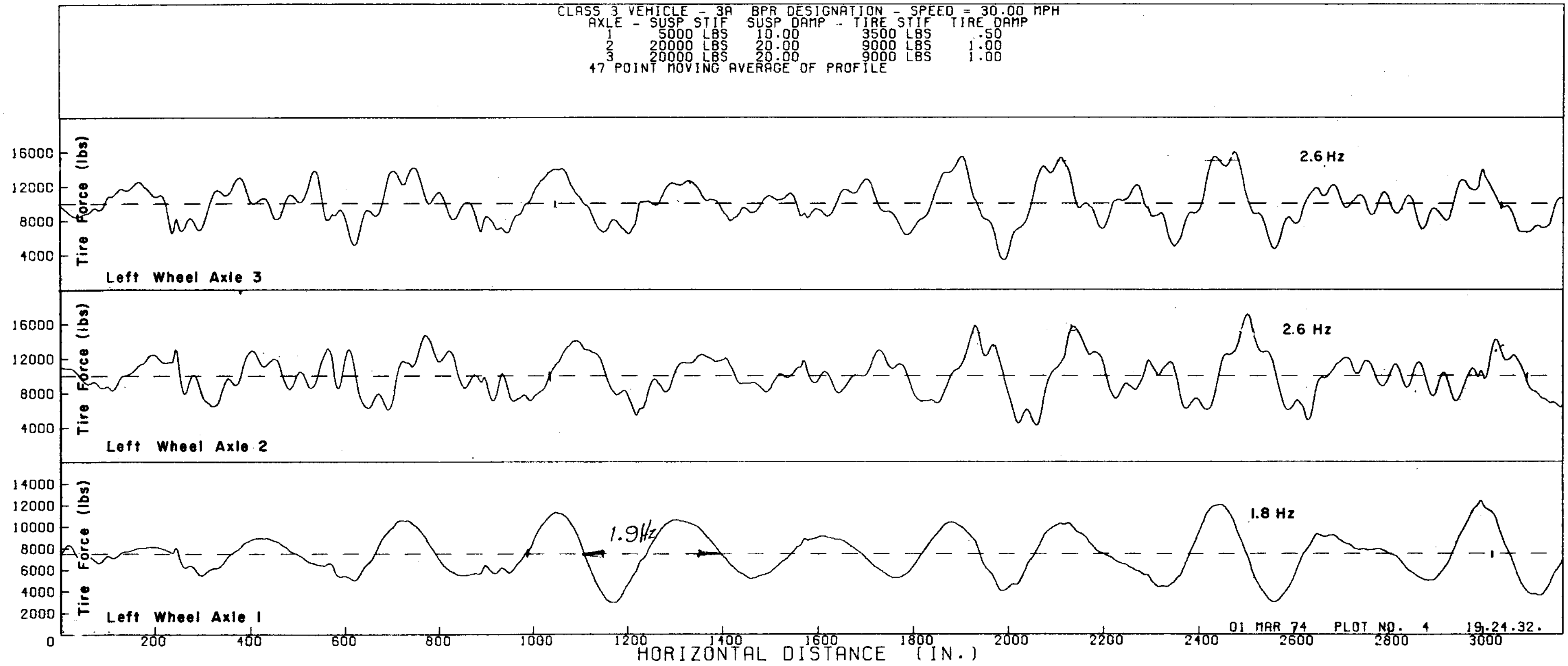

CLASS 3 VEHICLE - 3A BPR DESIGNATION - SPEED = 30.00 MPH
AXLE - SUSP STIF SUSP DAMP - TIRE STIF TIRE DAMP
1 5000 LBS 10.00 3500 LBS .50
2 20000 LBS 20.00 9000 LBS 1.00
3 20000 LBS 20.00 9000 LBS 1.00
47 POINT MOVING AVERAGE OF PROFILE
16000
12000
8000
4000
Tire Force (lbs)
Left Wheel Axle 3
2.6 Hz
16000
12000
8000
4000
Tire Force (lbs)
Left Wheel Axle 2
2.6 Hz
14000
12000
10000
8000
6000
4000
2000
0
Tire Force (lbs)
Left Wheel Axle 1
1.9Hz
1.8 Hz
01 MAR 74 PLOT NO. 4 19.24.32.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
HORIZONTAL DISTANCE (IN.)

Fig 5.

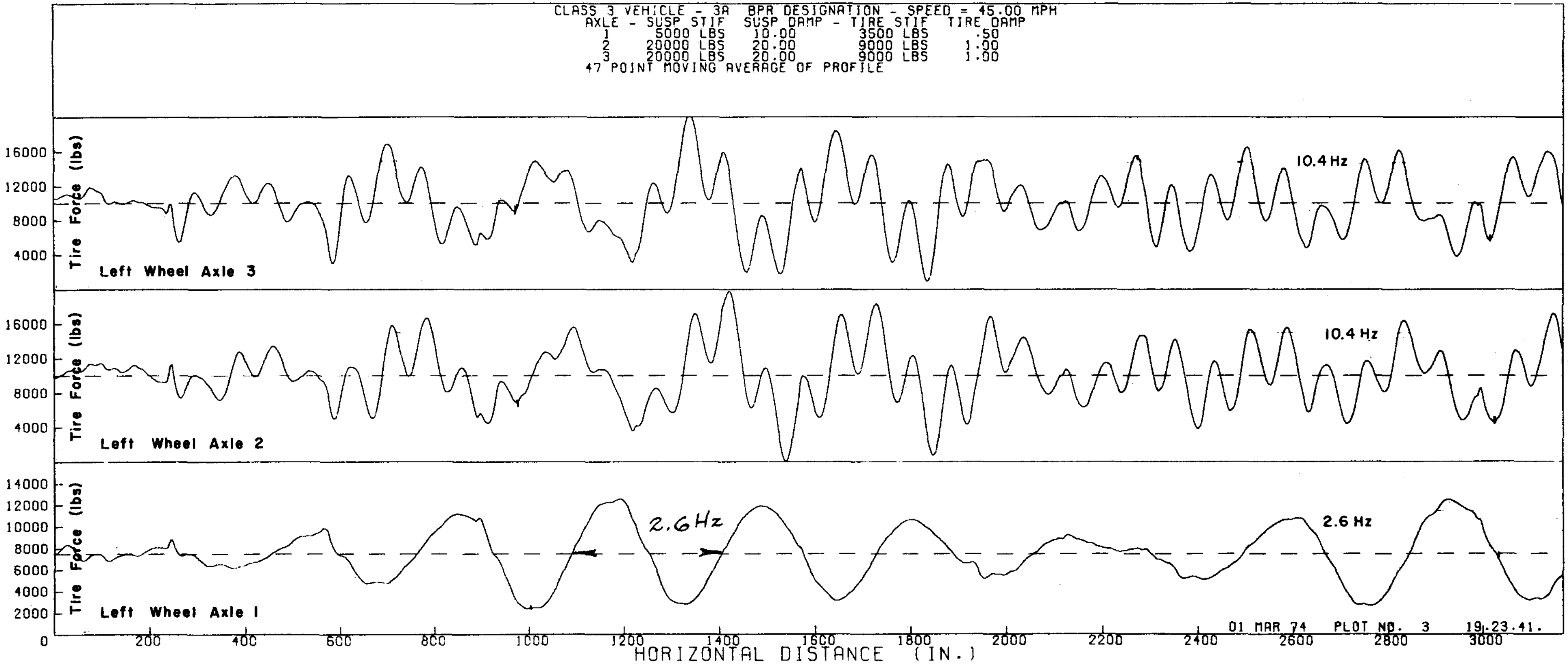

CLASS 3 VEHICLE - 3A BPR DESIGNATION - SPEED = 45.00 MPH
AXLE - SUSP STIF SUSP DAMP - TIRE STIF TIRE DAMP
1 5000 LBS 10.00 3500 LBS .50
2 20000 LBS 20.00 9000 LBS 1.00
3 20000 LBS 20.00 9000 LBS 1.00
47 POINT MOVING AVERAGE OF PROFILE
Tire Force (lbs)
16000
12000
8000
4000
Left Wheel Axle 3
10.4 Hz
Tire Force (lbs)
16000
12000
8000
4000
Left Wheel Axle 2
10.4 Hz
Tire Force (lbs)
14000
12000
10000
8000
6000
4000
2000
0
Left Wheel Axle 1
2.6 Hz
2.6 Hz
01 MAR 74 PLOT NO. 3 19.23.41.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
HORIZONTAL DISTANCE (IN.)

Fig 6.

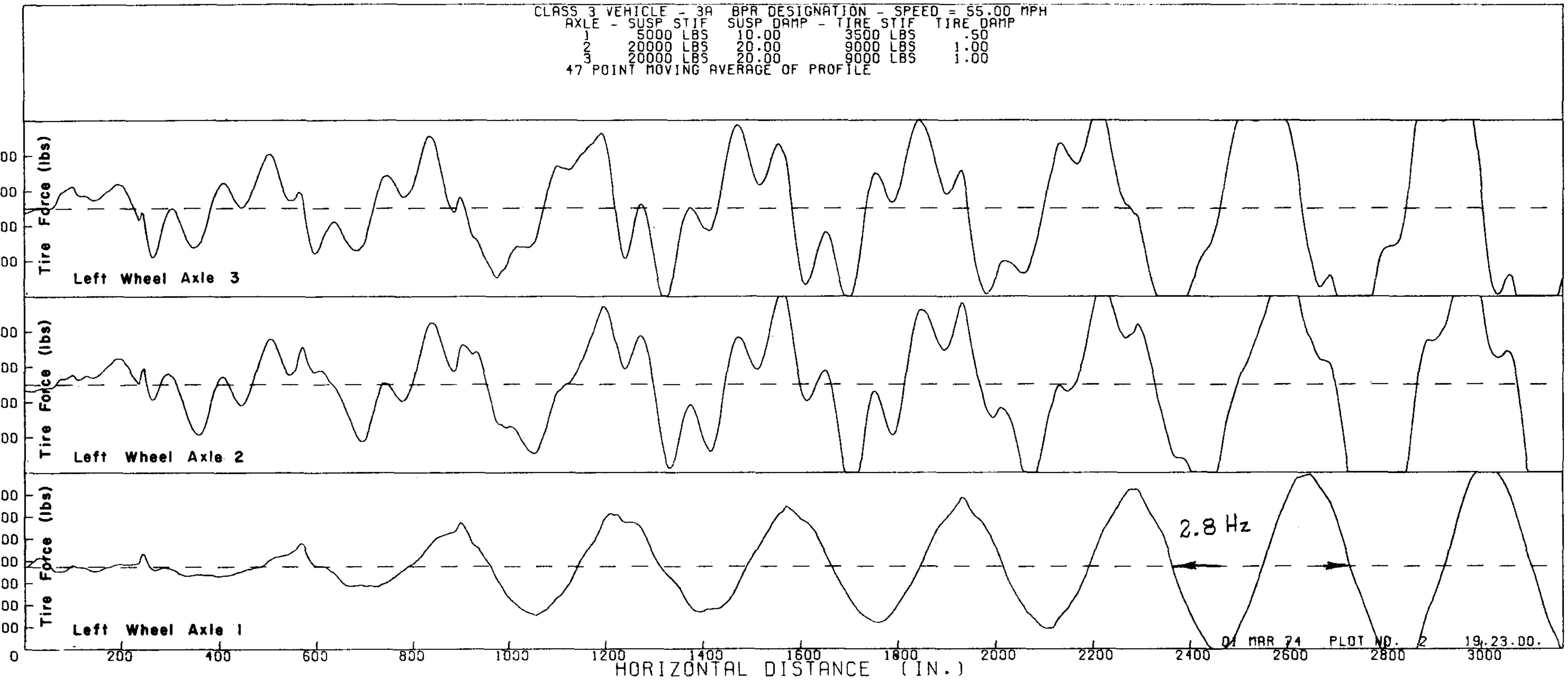
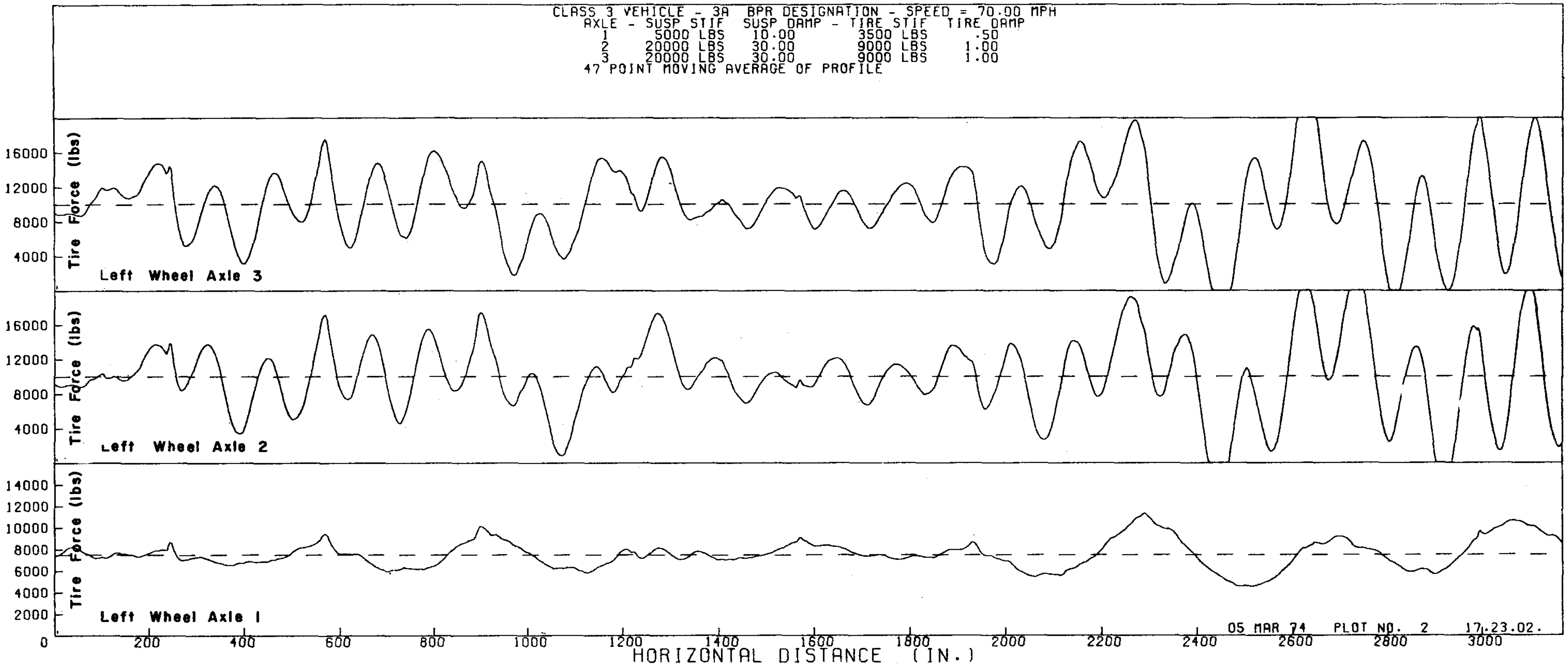

CLASS 3 VEHICLE - 3A BPR DESIGNATION - SPEED = 55.00 MPH
AXLE - SUSP STIF SUSP DAMP - TIRE STIF TIRE DAMP
1 5000 LBS 10.00 3500 LBS .50
2 20000 LBS 20.00 9000 LBS 1.00
3 20000 LBS 20.00 9000 LBS 1.00
47 POINT MOVING AVERAGE OF PROFILE
Tire Force (lbs)
16000
12000
8000
4000
Left Wheel Axle 3
Tire Force (lbs)
16000
12000
8000
4000
Left Wheel Axle 2
Tire Force (lbs)
14000
12000
10000
8000
6000
4000
2000
0
Left Wheel Axle 1
2.8 Hz
04 MAR 74 PLOT NO. 2 19.23.00.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
HORIZONTAL DISTANCE (IN.)

Fig 7.


CLASS 3 VEHICLE - 3A BPR DESIGNATION - SPEED = 70.00 MPH

| AXLE - | SUSP STIF | SUSP DAMP - | TIRE STIF | TIRE DAMP |
|---|---|---|---|---|
| 1 | 5000 LBS | 10.00 | 3500 LBS | .50 |
| 2 | 20000 LBS | 30.00 | 9000 LBS | 1.00 |
| 3 | 20000 LBS | 30.00 | 9000 LBS | 1.00 |

47 POINT MOVING AVERAGE OF PROFILE

05 MAR 74 PLOT NO. 2 17.23.02.

Fig 8.

loads from the rear wheels resulted from the oscillations of the wheel masses at about 10 Hz.

As speed increases up to a certain point, dynamic wheel forces increase, and the causeway profile with its 30-foot-long waves interacts increasingly with the sprung mass (body and load) of the vehicle. Excitation of the sprung mass is evidenced in the wheel force diagrams, Figs 5 through 8, by the periodic nature of the dynamic wheel forces at frequencies of about 2 to 3 Hz.

Variations in wheel forces at these frequencies are of particular concern since the natural frequency of many bridge structures lies in this same range. When the natural frequency of the vehicle and of the structure coincide, extremely large dynamic forces can be created and structural damage can result.

Figure 7 indicates that at a speed of 55 mph the simulated transit-mix truck is excited by the undulating causeway profile at near its natural frequency. The pattern of gradually increasing tire forces at regular intervals shows this. Oscillations of the vehicle are violent, and tire forces go from zero to more than double the static weight. Figure 8 shows that at a speed of 70 mph, significant cancellation of the low frequency vehicle oscillations is caused by the 30-foot-long profile waves and that the dynamic wheel forces are smaller than those at 55 mph.

Even though the dynamic deflections of the structure were not included in the simulation analysis, the effects of speed on dynamic wheel forces have been demonstrated. It is expected that the critical speed will still be in the range of 50 to 60 mph if live load deflections of the structure are included.

## CONCLUSIONS AND RECOMMENDATIONS

The simulation study shows that the magnitude of dynamic loads which can be produced on the Port Isabel causeway by a loaded transit-mix concrete truck are more than double the static weight of the vehicle. At speeds of 30 mph and above, the sagging bridge spans excite the vehicle in such a way that tire forces vary cyclically at about 2 to 3 Hz and range in magnitude from nearly zero to over twice the static weight. The speed at which the simulated vehicle experienced maximum excitation near its apparent natural frequency of approximately 2.8 Hz was 55 mph. Since the natural frequency of the causeway spans is in the range of 3 to 5 Hz, vehicle oscillations of this order should be avoided if feasible.

A speed limit of 20 mph is recommended for trucks on the causeway. The 30-foot-long undulations in the road surface profile caused by the sagging spans do not induce low frequency oscillations in heavy vehicles operating at or below this speed. The high frequency dynamic loads caused by oscillation of the wheel masses at vehicle speeds below 20 mph are partially counteracted by the inertial resistance of the structure and will therefore not be likely to produce critical stresses in the girders.

Speed-zoning on the causeway will help to reduce the dynamic loads caused by heavy vehicles and thereby prolong the service life of the structure. Small delays to traffic resulting from the reduced truck speeds will probably save extensive investments in maintenance and repair during the coming months.

# REFERENCES

1. Al-Rashid, Nasser I., Clyde E. Lee, and William P. Dawkins, "A Theoretical and Experimental Study of Dynamic Highway Loading," Research Report No. 108-1F, Center for Highway Research, The University of Texas at Austin, May 1972.

2. General Motors Corporation, "Dynamic Pavement Loads of Heavy Highway Vehicles," National Cooperative Highway Research Program Report 105, Highway Research Board, 1970.