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RESPONSE OF VEHICLES TO PAVEMENT UNDULATIONS

THOMAS M. POST
JAMES E. BERNARD

HIGHWAY SAFETY RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN 48109

PREPARED FOR:

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16. Abstract

The ride response of vehicles to long configuration, large amplitude road undulations is simulated at traversing speeds up to 60 mph.

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CONTENTS

1.0 INTRODUCTION

This report presents findings and recommendations developed by The University of Michigan Highway Safety Research Institute for the Federal Highway Administration in a project entitled "Response of Vehicles to Pavement Undulations." The objective of the research was to determine the ride motions of two passenger cars when they traverse two specified pavement undulations at various speeds.

The assumption underlying the potential use of undulations in road surfaces is that ride motions will encourage drivers to traverse them at relatively low speeds.

The research entailed computer simulations of the undulations, vehicles, and traversal speeds. Section 2 presents details of the simulations and the vehicles considered in this study. Section 3 presents the computed results. Conclusions and recommendations are given in Section 4.

2.0 TECHNICAL DETAILS

This section is divided into three subsections concerning the computer simulation used in this research, the road profile, and the simulated vehicles.

2.1 The Computer Simulation

The HSRI "Phase III" computer simulation [1]* was used for the calculation of ride response resulting from the pavement undulations. In this study, a five degree of freedom model was used, facilitating computations of the bounce and pitch motions of the sprung mass, the vertical motions of the front and rear wheels, and the longitudinal position of the vehicle's mass center. Since the road profile and the vehicle are assumed to have lateral symmetry, no rolling motions result, and the left side wheels have identical motions to the right side wheels.

Calculations were made at speeds from 5 to 60 mph (2.2 to 26.4 m/sec) in discrete 5 mph (2.2 m/sec) increments. Two vehicles were simulated on two road configurations at each speed, a total of 48 computer runs. The simulation time for each run depended on the wheelbase of the vehicle, the traversing speed, and the length of the configuration, viz.:

$$t_s = \frac{\ell + W_b}{V_0} + 1 \qquad (1)$$

where

t_s = the simulated time in seconds

ℓ = length of the road undulation

W_b = vehicle wheelbase

V_0 = vehicle speed

*Brackets indicate references.

Thus the simulation is concluded one second after the rear wheels leave the road undulation.

The time histories of the variables computed in the study are:

1) Vertical displacement, velocity, and acceleration of the sprung mass center

2) Pitch angle, velocity, and acceleration of the sprung mass

3) Longitudinal position of the sprung mass center

4) Front and rear suspension forces and deflections

5) Front and rear tire forces and deflections

6) Vertical axle displacement

7) Ground clearance

In addition, key metrics associated with the above time histories were computed during each simulation:

1) Peak positive and negative vertical accelerations of both the front and rear passengers

2) Root mean square accelerations of the front passenger

3) Peak tire forces and tire deflections from the static values for the front and rear

4) Histograms indicating the percent of time in which tire forces (front and rear) are less than certain fractions of the static tire loads. The fractions used here are 0, 1/4, 3/4, 1.

5) Peak positive and negative spring deflections for both the front and rear suspensions

6) Minimum vehicle-ground clearance during traversal.

2.2 The Road Profile

The road profile used in this study is a parabolic shaped bump protruding from the reference road level, as shown in Figure 1.

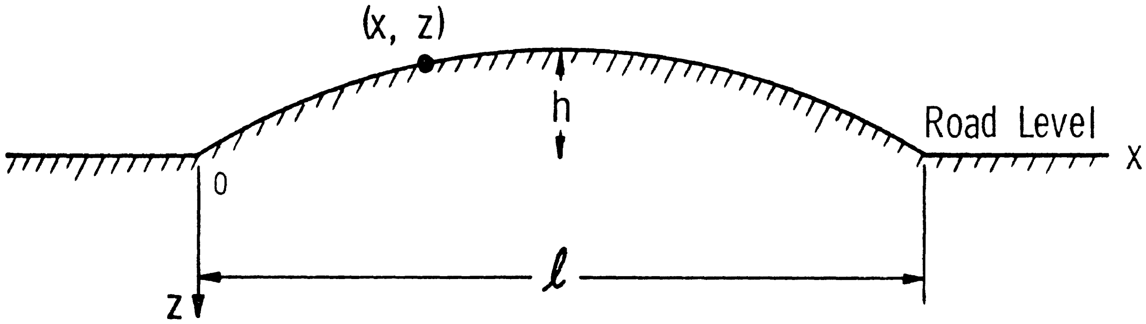


Figure 1. Road Profile.

The road coordinates (x,y), as measured from the beginning of the bump (Point 0), satisfy the relation:

$$
\begin{aligned}
z &= 0 && x < 0 \\
z &= \frac{-4xh}{\ell^2}(\ell - x) && 0 \le x \le \ell \qquad (2) \\
z &= 0 && x > \ell
\end{aligned}
$$

The two road bumps, determined by the parameter set (ℓ,h) employed for this study, are presented in Table 1.

TABLE 1

Bump	ℓ	h
1	12 ft. (2.46 m)	5 in. (12.7 cm)
2	16 ft. (3.28 m)	6 in. (15.24 cm)

2.3 Vehicles

The two vehicles simulated were a 1971 Mustang and a 1973 Buick station wagon. Parametric specifications for each vehicle are listed in Table 2.

The suspensions on both vehicles were modeled in a non-linear fashion to simulate the increased stiffnesses encountered at the bump stops, as shown in Figures 2a and 2b.

The tires were represented by a vertical spring and damper making point contact at the tire-road interface. The road can transmit only vertical forces to the vehicle.

TABLE 2

VEHICLE SPECIFICATIONS

Parameter	Units	1971 Mustang	1973 Buick
Total Weight	lb	3488 (15515N)	4583 (20385N)
Sprung Weight	lb	2836 (12615N)	3770 (16769N)
Suspension Weights			
Front	lb	187 (832N)	247 (1099N)
Rear	lb	305 (1357N)	405 (1801N)
Passenger Weight	lb	160 (712N)	160 (712N)
Static Tire Loads			
Front	lb	1972 (8771N)	2446 (10880N)
Rear	lb	1516 (6743N)	2137 (9505N)
Wheelbase	in	109 (2.77M)	116 (2.95M)
Static C.G. Height Above Ground			
Sprung	in	27.58 (.7M)	28.5 (.724M)
Total	in	25.48 (.647M)	26.3 (.668M)
Pitch Moment of Inertia of Sprung Mass	in-lb/sec^2	11138 (1258.4Nm/sec^2)	31838 (3597Nm/sec^2)
Viscous Damping-Front Axle			
Jounce	lb-sec/in	3.66 (6.41N-s/cm)	1.9 (3.33N-s/cm)
Rebound	lb-sec/in	5.36 (9.39N-s/cm)	5.66 (9.91N-s/cm)
Viscous Damping-Rear Axle			
Jounce	lb-sec/in	4.0 (7N-s/cm)	4.0 (7N-s/cm)
Rebound	lb-sec/in	6.67 (11.68N-s/cm)	15.0 (26.27N-s/cm)

TABLE 2 (Cont.)

Parameter	Unit	1971 Mustang	1973 Buick
Maximum Coulomb Friction			
Front Suspension	lb	36 (160N)	40.0 (178N)
Rear Suspension	lb	50 (222N)	60.0 (267N)
Tire Spring Rate	lb/in	1420 (2487N/cm)	1420 (2487N/cm)
Static Flat Ground Clearance			
Between Axles	in	8.4 (21.34cm)	10.8 (27.43cm)
Aft of Axles	in	12 (30.48cm)	12 (30.48cm)
Passenger Distance Behind C.G.			
Front	in	0	0
Rear	in	24 (60.9cm)	60 (152.4cm)

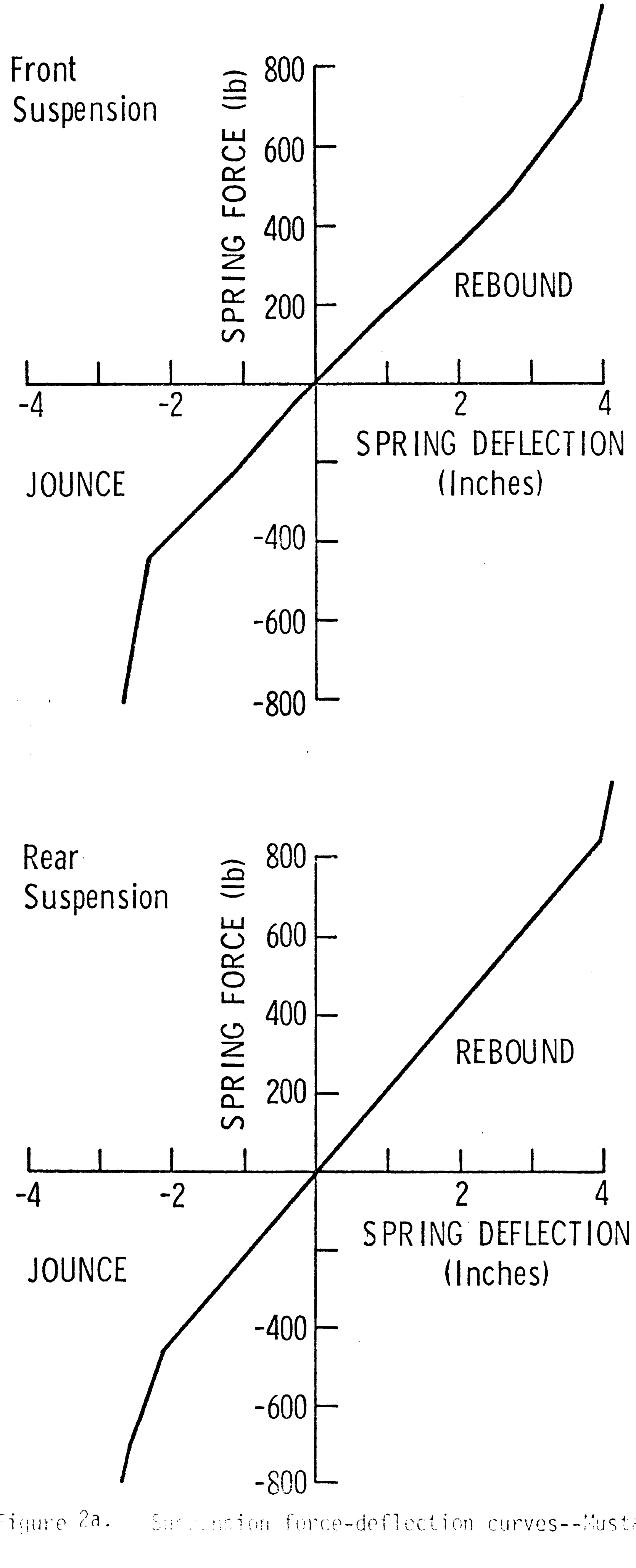
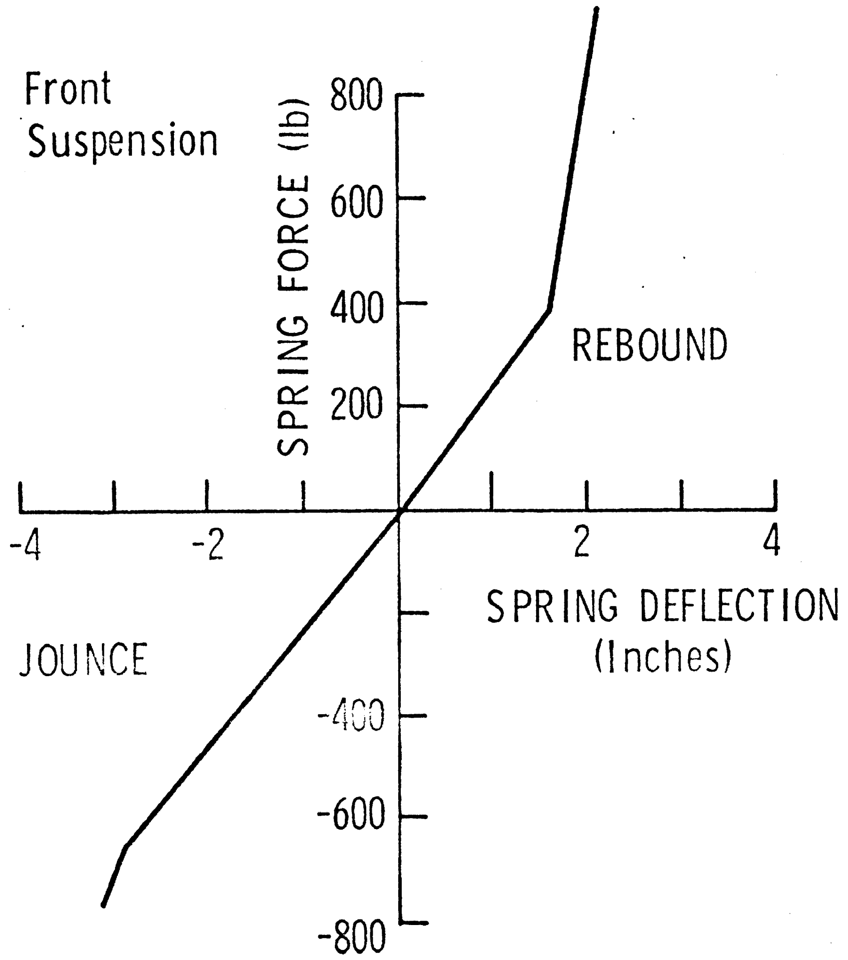


Figure 2a. Suspension force-deflection curves--Mustang



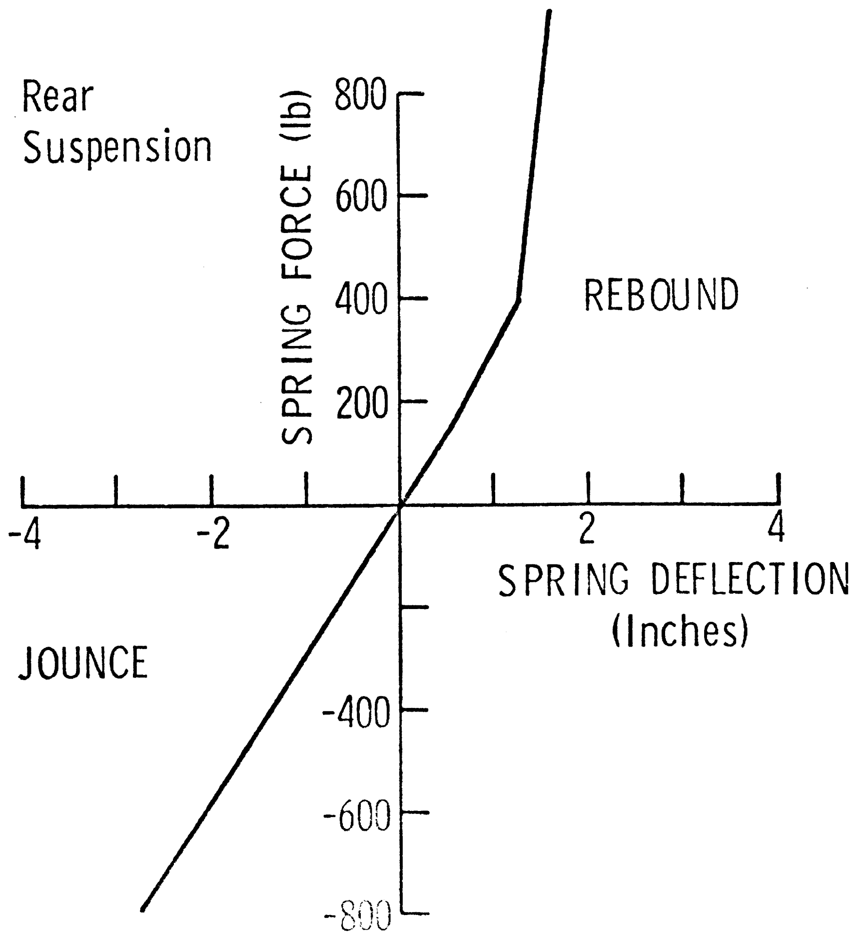


Figure 2b. Suspension force-deflection curves--Buick wagon.

3.0 THE COMPUTED RESULTS

Several calculations were made to summarize the performance of each vehicle on each bump. A summary of these calculations is given in this section.

3.1 Accelerations

The peak passenger vertical accelerations (both positive and negative) achieved during traversal of the two road undulations for each combination of vehicle and speed are shown in Figures 3a to 3d. Simulations were made for a front passenger located at the sprung mass center for each vehicle and at a rearward position located 24 in. (61 cm) behind the mass center for the Mustang and 60 in. (152.4 cm) behind the mass center for the Buick wagon. The difference between these values of accelerations is due to the pitch accelerations encountered.

The peak acceleration values for the front and rear passenger do not necessarily occur simultaneously since the bounce and pitch modes go in and out of phase during traversal. Further, the time of the peaks may occur after the vehicle has completely crossed the bump. This occurs when the vehicle becomes airborne during traversal and impacts the road surface some distance beyond the bump.

The root-mean-square acceleration experienced by the front passenger is an aid in determining the overall severity level of the vertical acceleration. This value is given by

$$\ddot{Z}_{RMS} = \sqrt{\frac{1}{t_s} \int_0^{t_s} \ddot{Z}^2 \, dt} \qquad (3)$$

where $\ddot{Z}$ is vertical acceleration. Root-mean-square acceleration is plotted against vehicle speed in Figure 4.

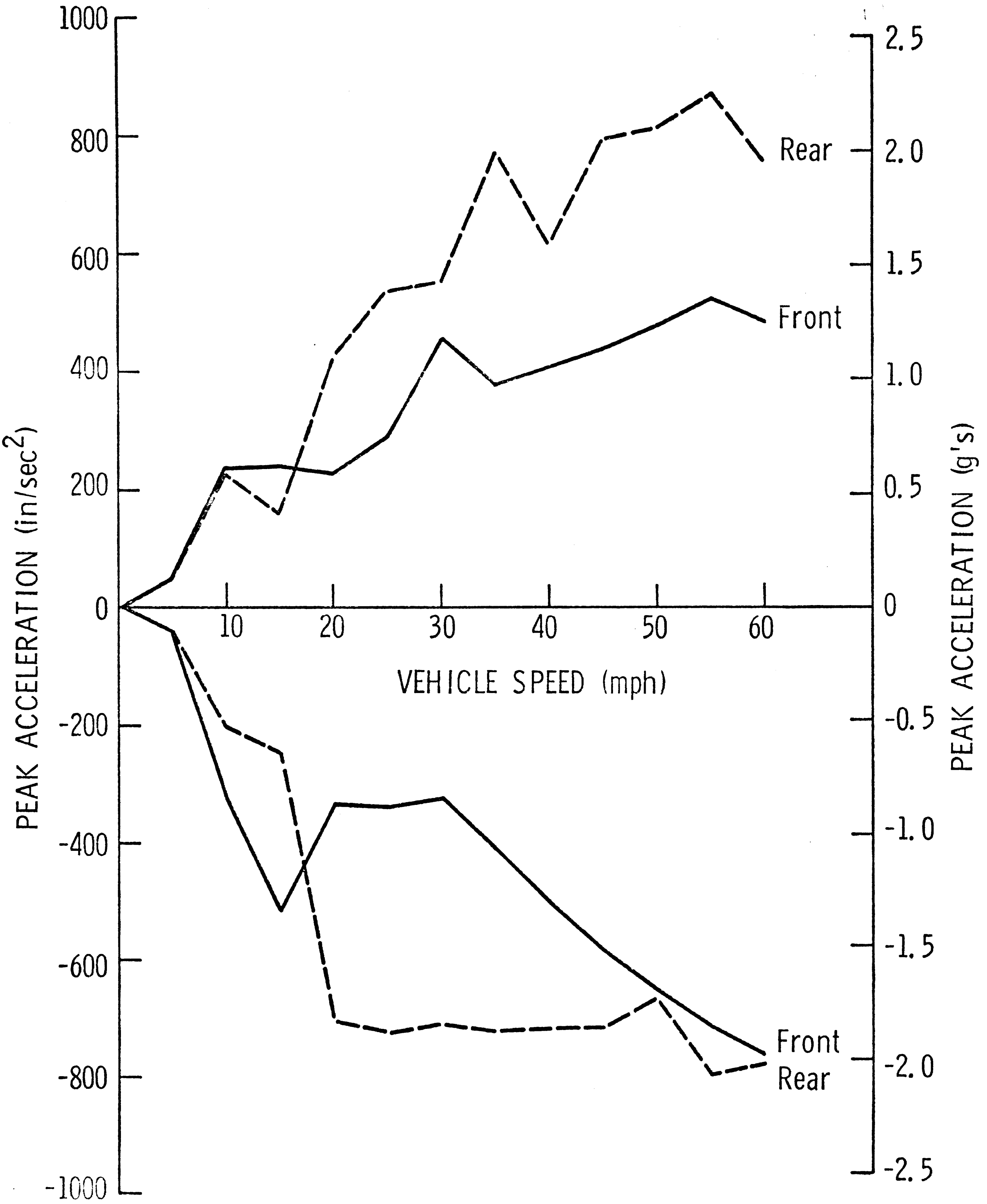


Figure 3a. Peak accelerations of front and rear passengers -- Mustang, 12' x 5" bump.

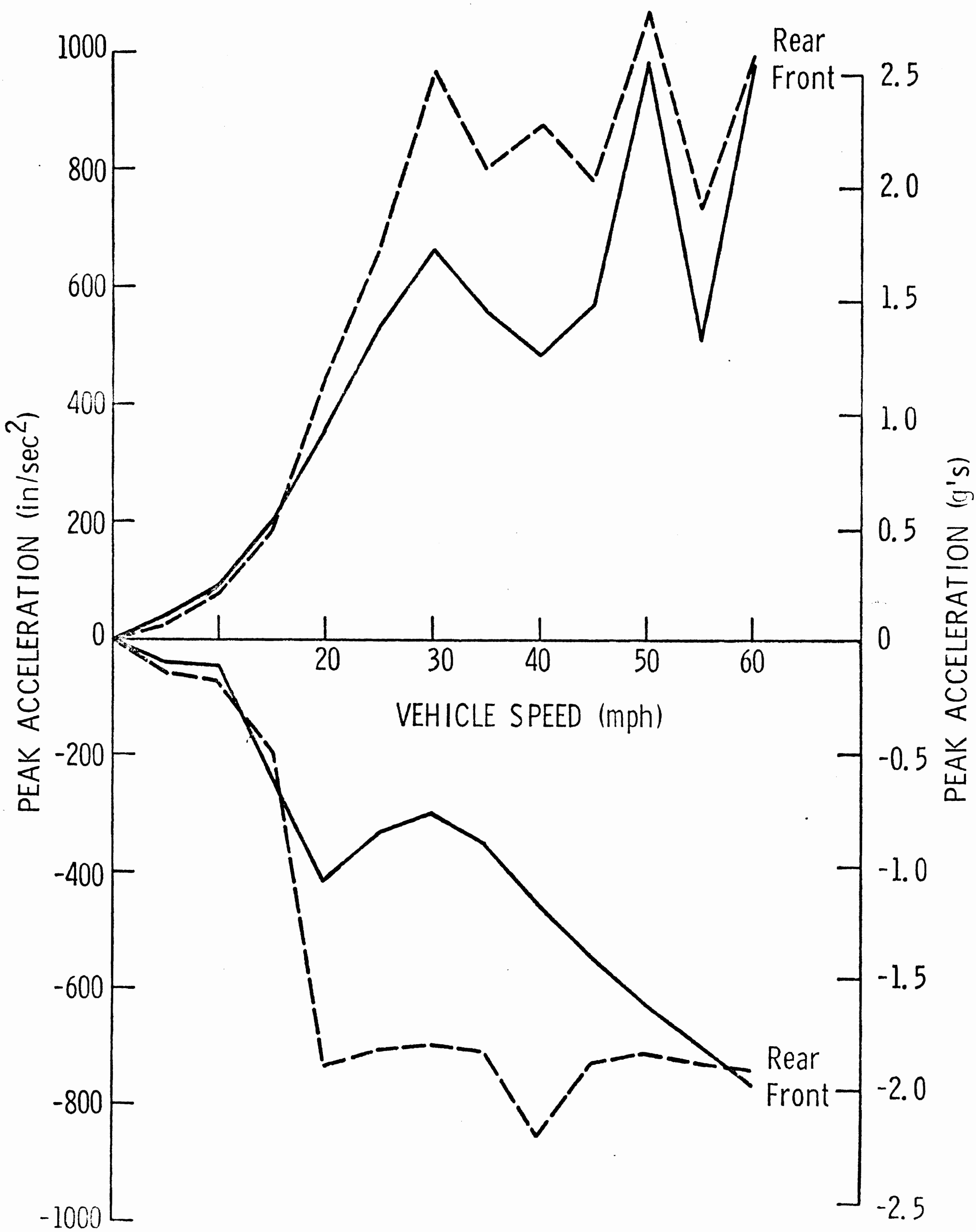


Figure 3b. Peak accelerations of front and rear passengers -- Mustang, 16' x 6" bump.

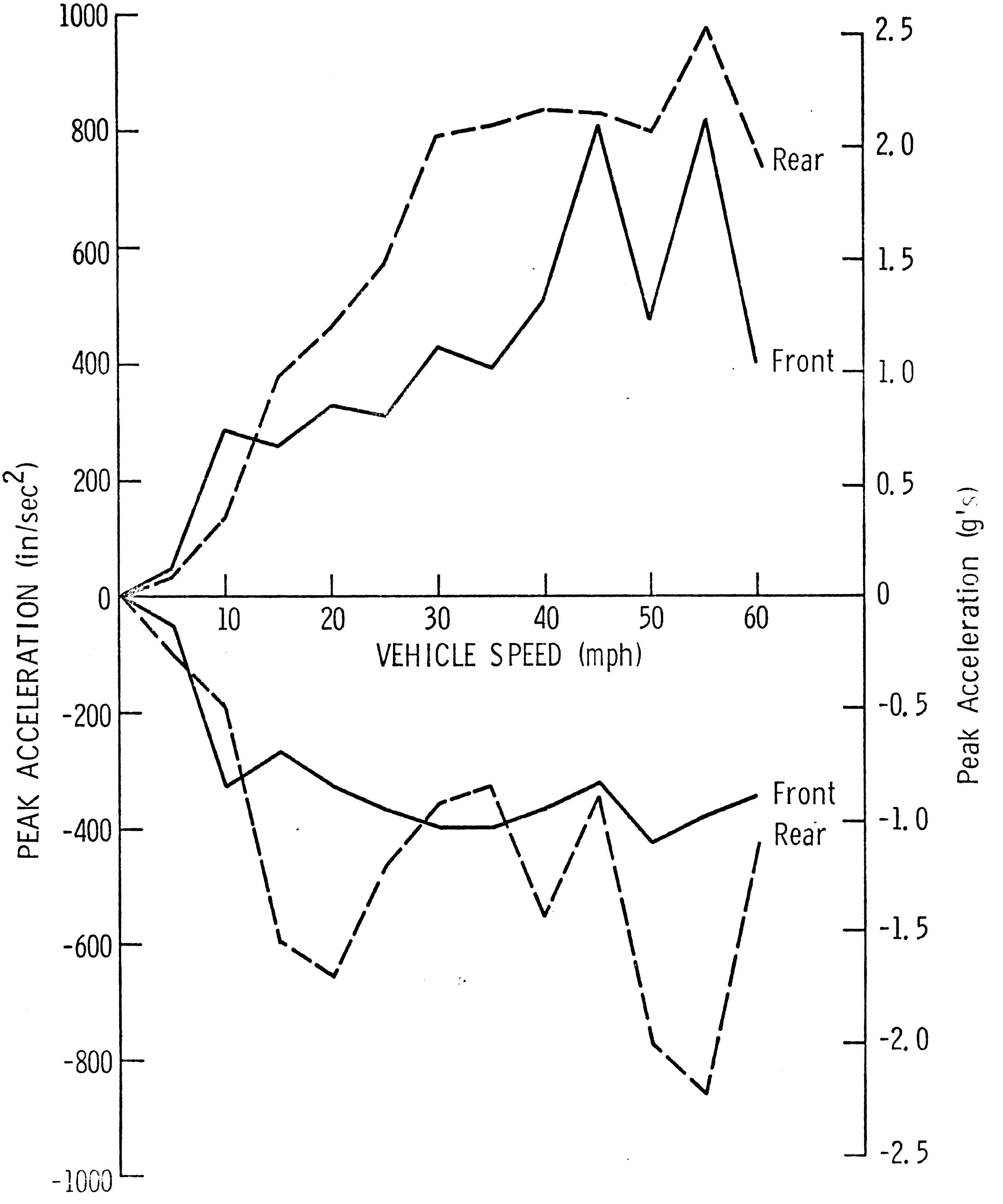


Figure 3c.. Peak accelerations of front and rear passengers -- Buick wagon, 12' x 5" bump.

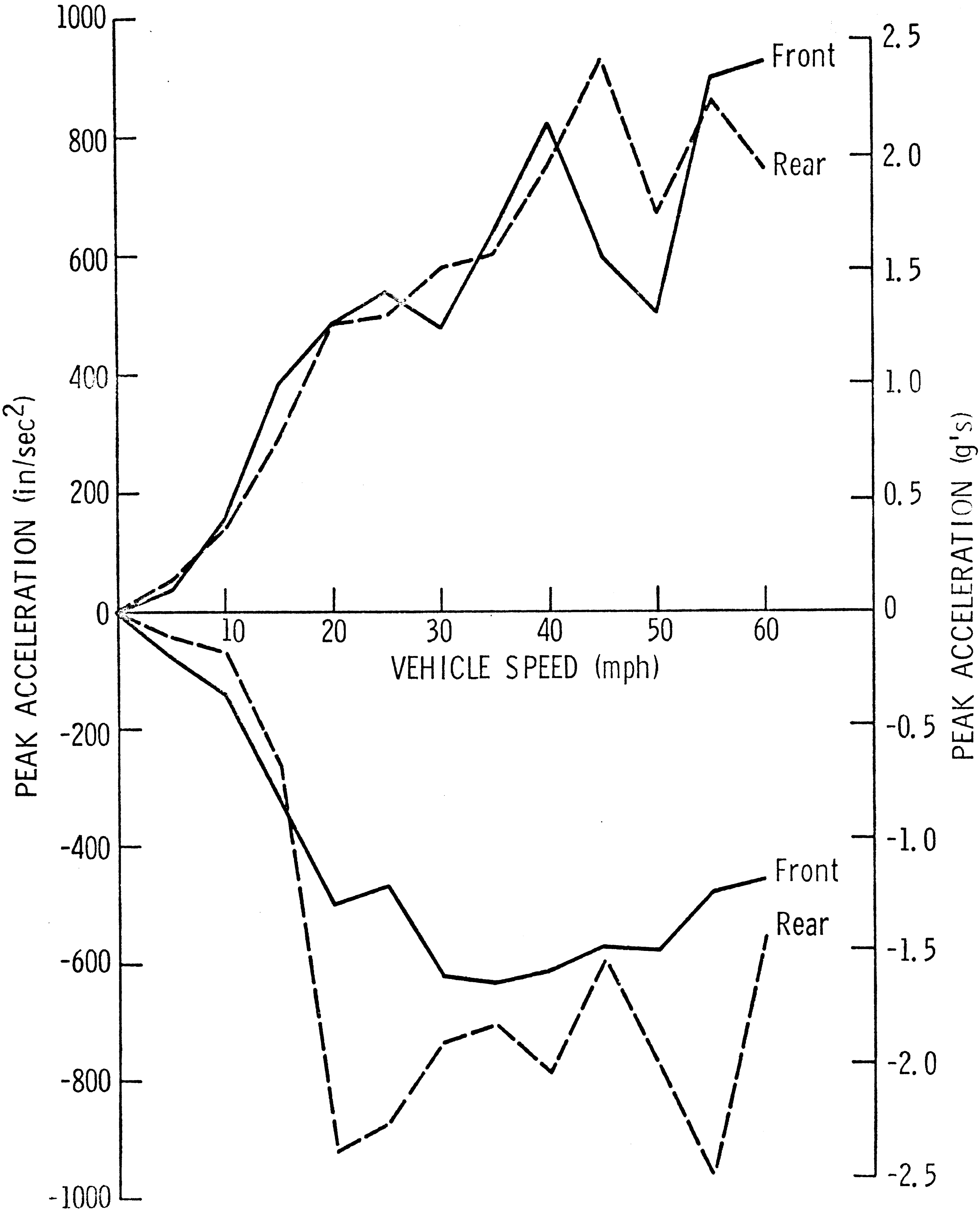


Figure 3d. Peak accelerations of front and rear passengers -- Buick wagon, 10' x 16" bump.

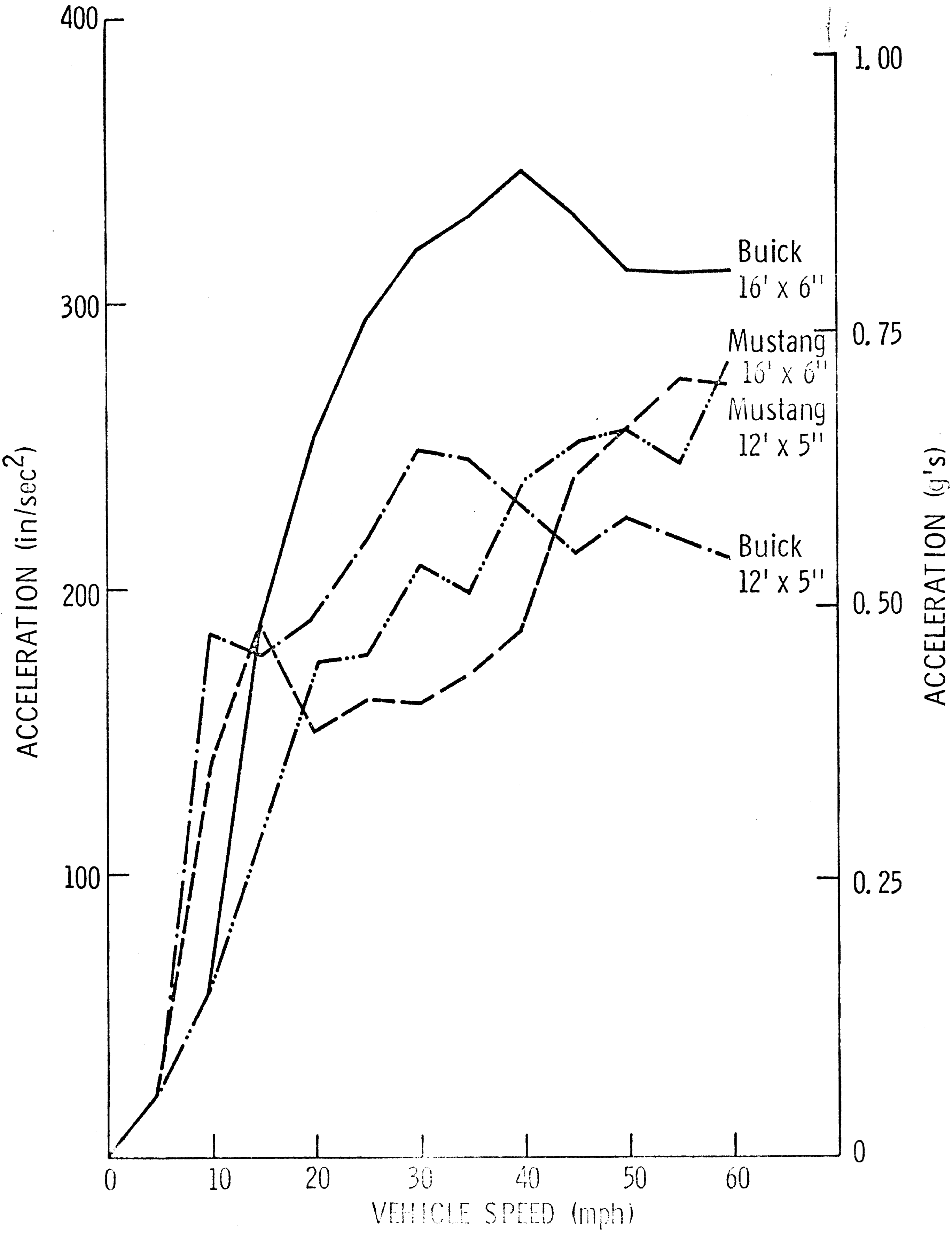


Figure 4. Root mean square acceleration of front passenger

A factor which has a significant influence on this computation is the percent of the time, t_s, in which the front and rear tires are off the ground. This facet of ride will be discussed later.

3.2 Tire Forces and Deflections

The tires for each vehicle are modeled as a linear spring-damper system. The tire spring constant is 1420 lb/in (2487 N/cm) or 2840 lb/in (4974 N/cm) for the axle. The tire damping constant is two percent of critical damping value determined from the suspension weight and the tire spring rate.

Figures 5a to 5d show the peak dynamic tire forces and deflections above the static conditions occurring during traversal. These calculations give the total tire load increase above the static condition for either the front axle or the rear axle. These calculations are rather rough approximations at the extremes as nonlinear phenomena should be expected to be important under such high loads.

3.3 Tire Force Histograms

The use of the histograms may best be explained through a detailed example. Figure 6 shows the time history of the vertical rear tire force for the Mustang traversing the 12' x 5" undulation at 20 mph (8.8 m/sec). The static axle load, NS, is 1516 lb (6743 N). The length of the arrowed lines indicate the elapsed time in which the tire force is less than the indicated force level. For the purpose of the histograms, these times may be normalized to the simulation time, t_s, which here is 1.72 sec (0.72 sec for bump traversal and 1 second additional). The percent time values for this run are shown in Table 3. Note that the table indicates that the rear tires are off the ground 18.7 percent of the time.

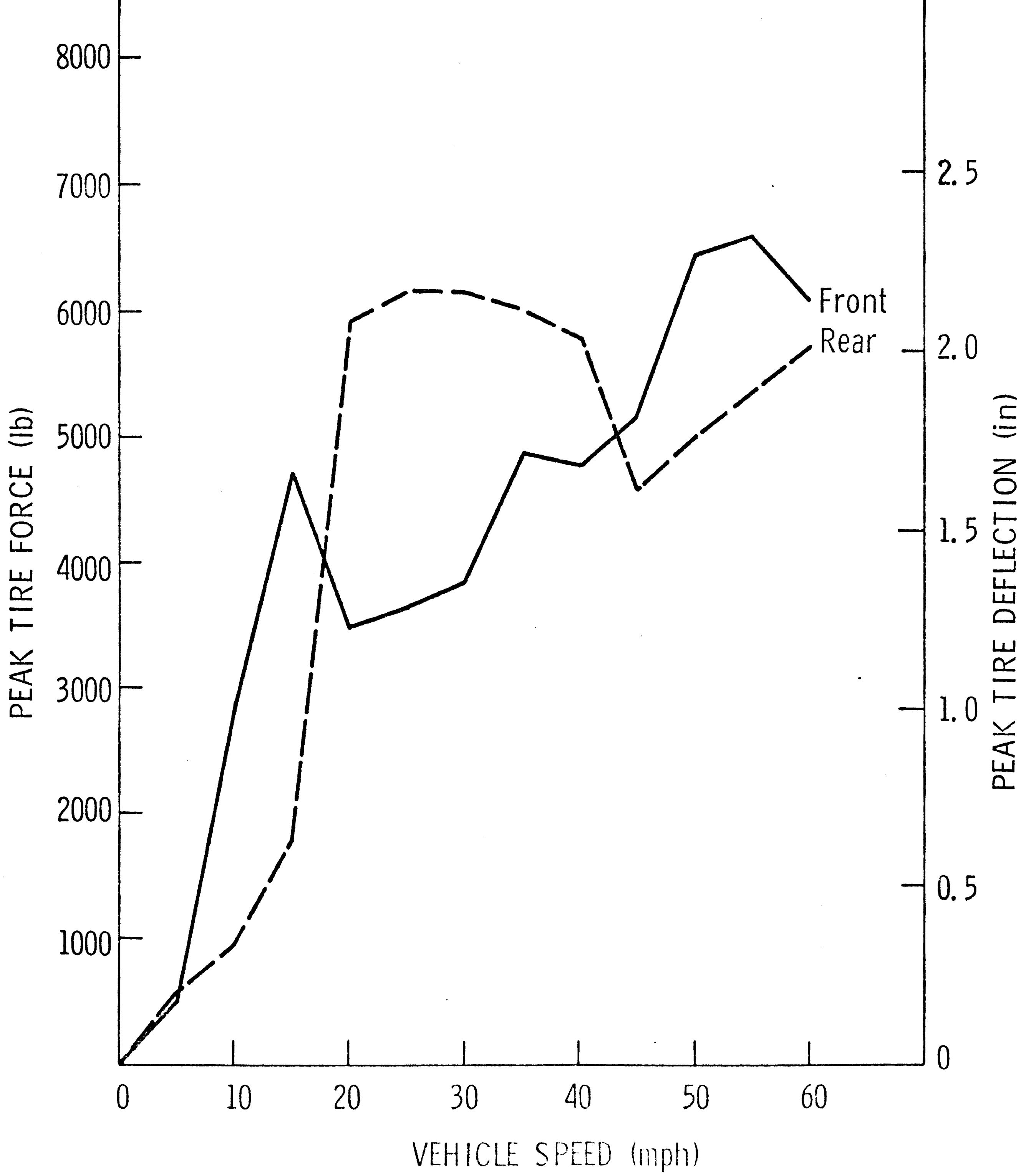


Figure 5a. Peak tire forces and deflections -- Mustang, 12' x 5" bump.

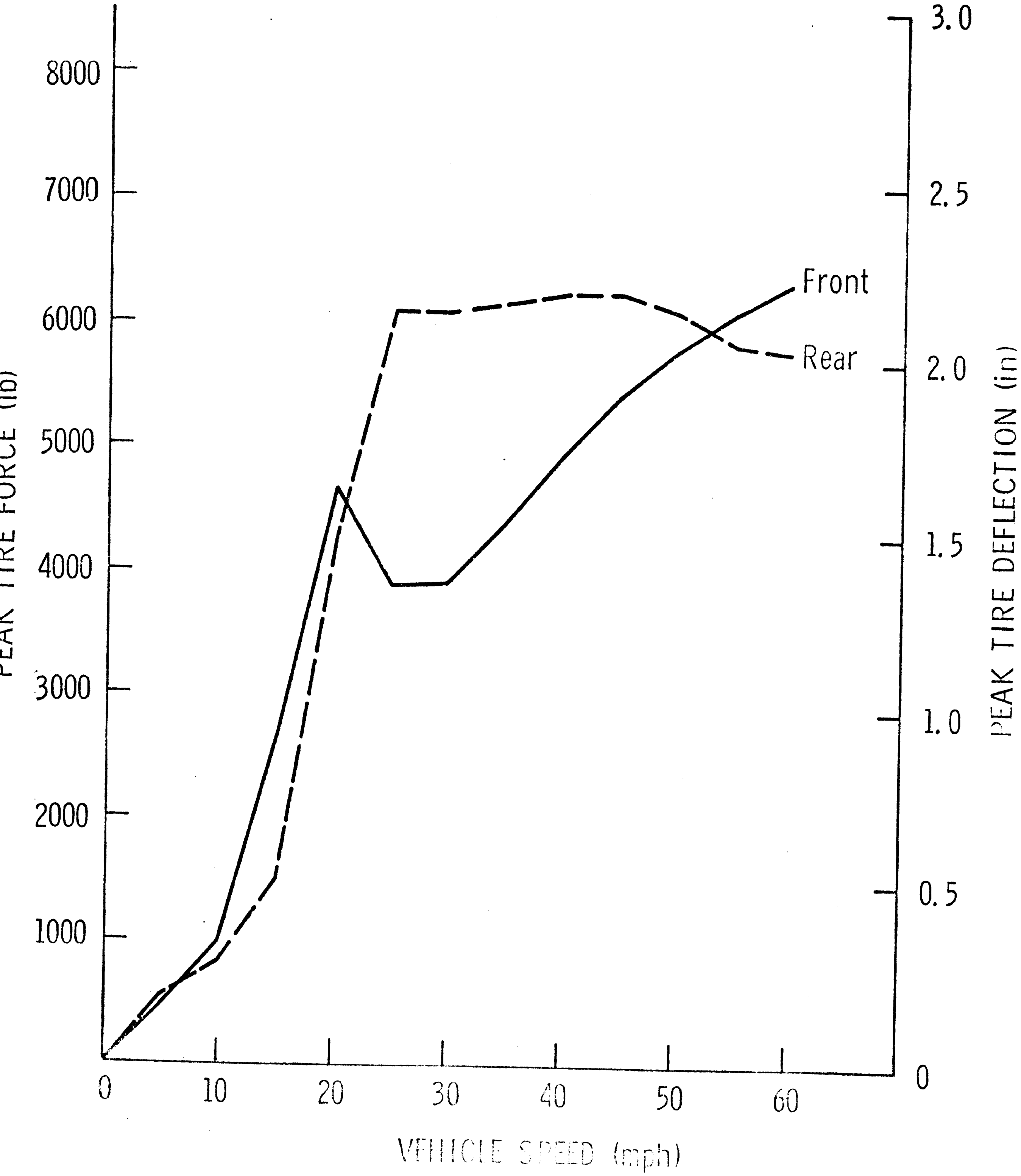


Figure 5b. Peak tire forces and deflections -- Mustang, 16' x 6" bump.

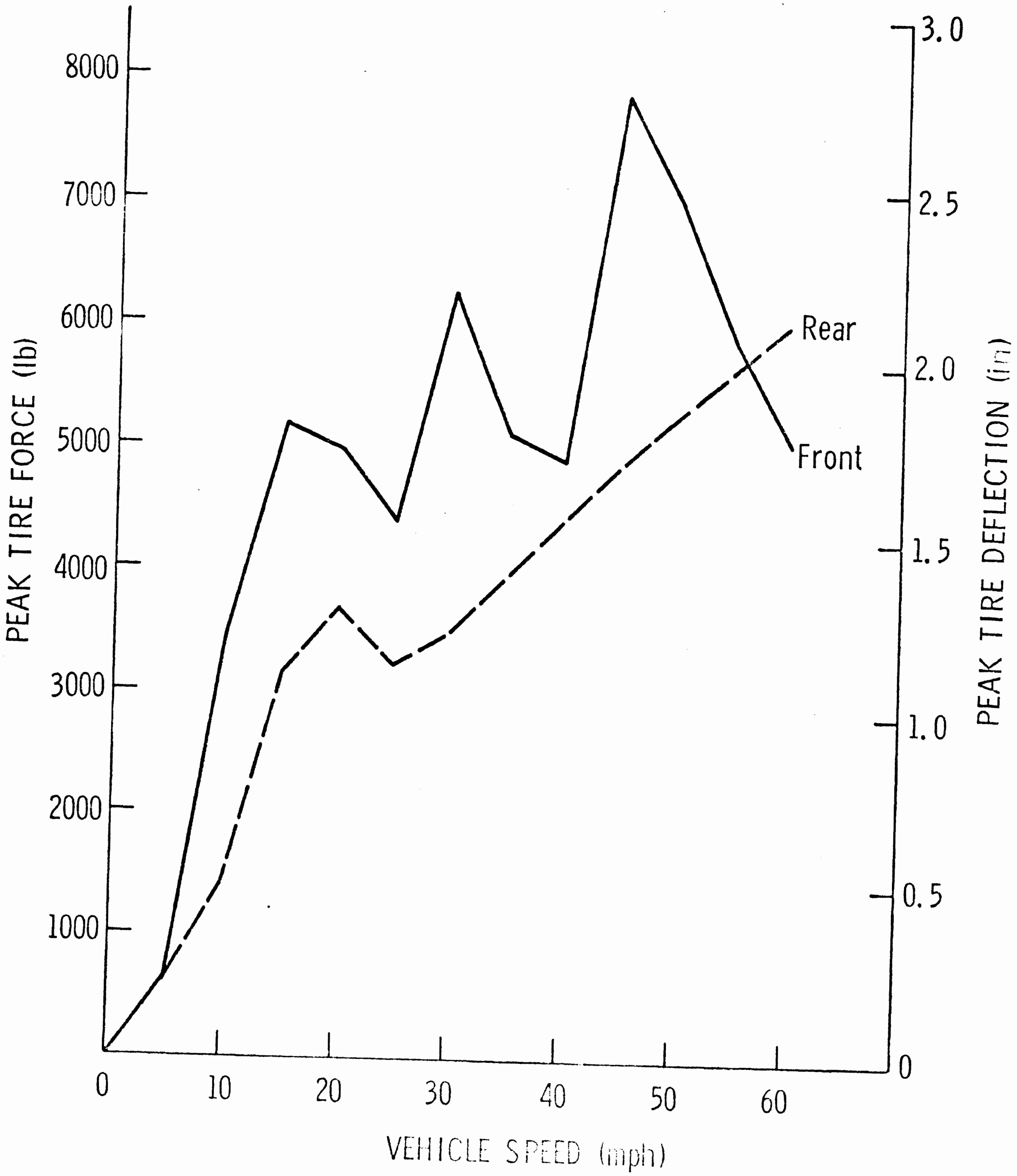


Figure 5c. Peak tire forces and deflections -- Buick wagon, 12' x 5" bump.

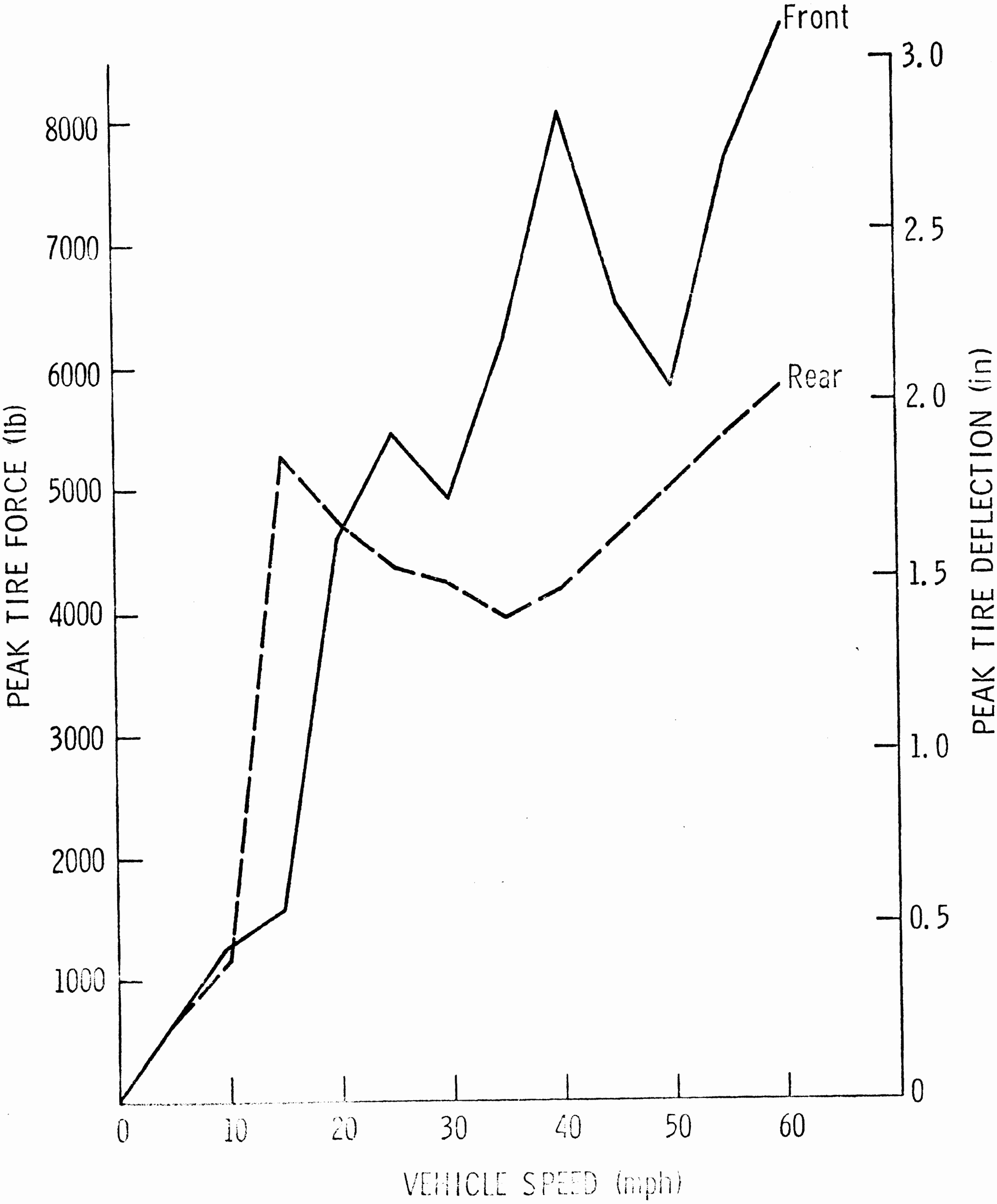


Figure 5d. [illegible] and deflections -- Buick wagon, [illegible]

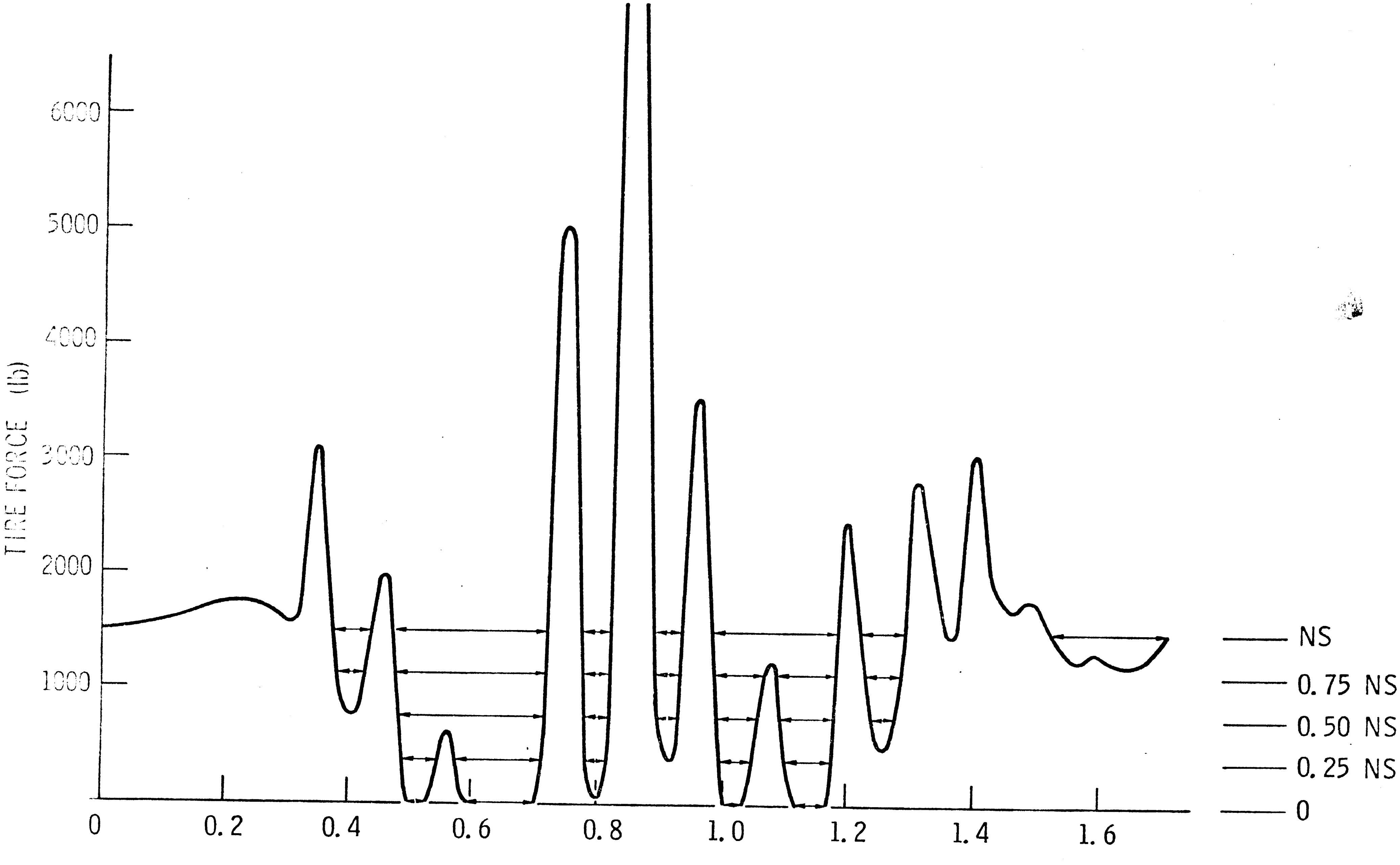


Figure 6. Tire force time history -- Mustang rear tire, 12' x 5" bump, 20 mph.

TABLE 3

A HISTOGRAM FOR THE REAR TIRES OF THE MUSTANG
ON THE 12' x 5" BUMP AT 20 MPH

Tire Load	% Time
NS	50.5
.75NS	34.7
.50NS	29.1
.25NS	22.7
0	18.7

The force histograms are shown in Figures 7a to 7h which illustrate the calculated percentages for the front and rear tires of each vehicle for each road undulation as a function of speed.

3.4 Suspension Deflections

The peak suspension deflections have a bearing on both the vehicle accelerations and the ground clearance. Peak jounce and rebound spring deflections for the front and rear suspensions are shown in Figures 8a to 8d for each vehicle-undulation-speed combination.

3.5 Minimum Vehicle-Ground Clearance

A most important consideration of the design of the road undulation is whether the vehicle can traverse the bump without "bottoming out." The road bump may obstruct the vehicle between the axles, at either axle or at either bumper. Figure 9 shows a simulated vehicle profile. The numbers 0-4 designate the possible obstruction points.

Figure 10 shows the simulation results of each combination of vehicle-road undulation in which the minimum clearance, δ, is plotted against vehicle speed. The numbers along these curves indicate the corresponding vehicle position of the minimum clearance.

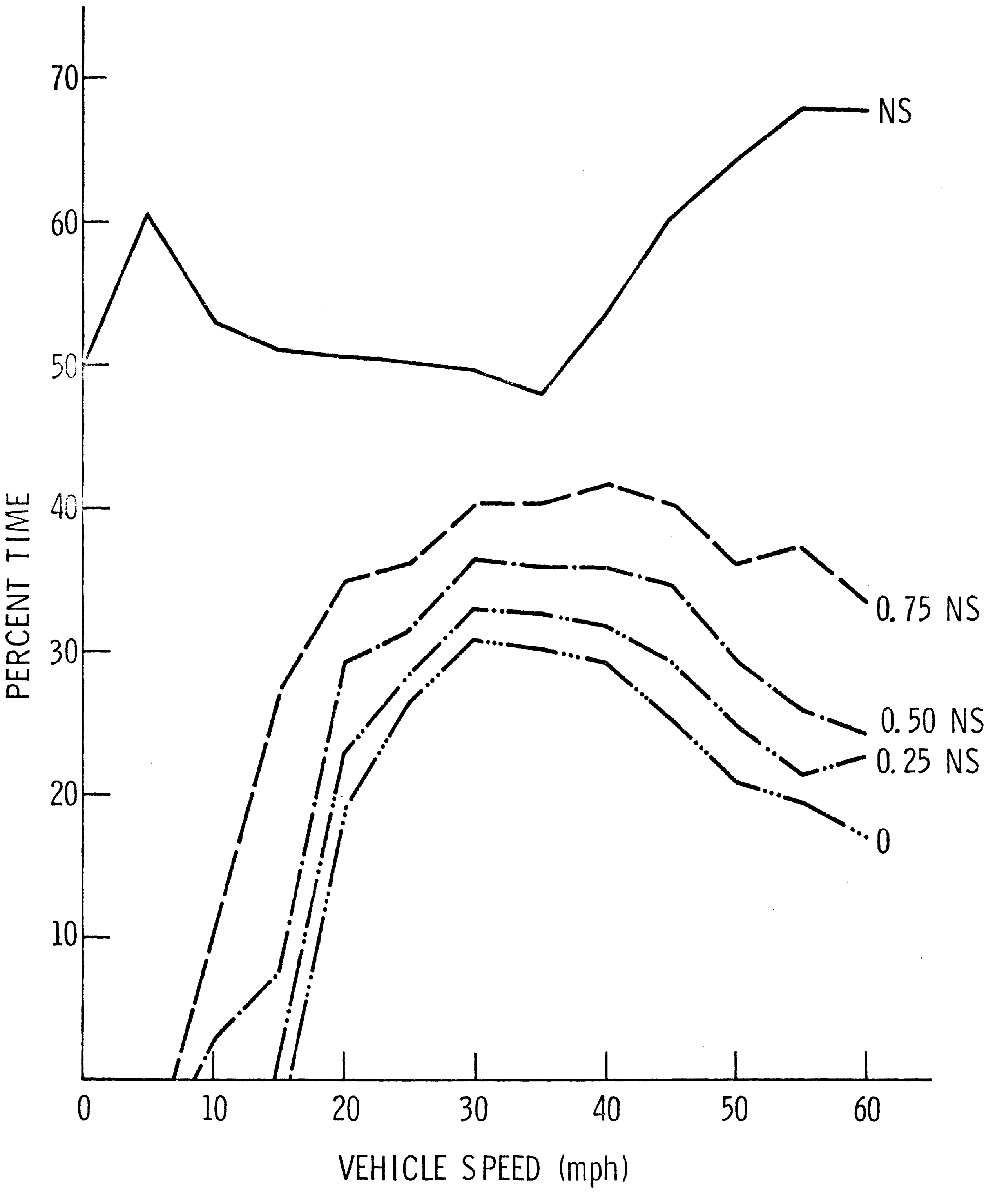


Figure 7a. Tire force histograms -- Mustang front, 12' x 5" bump.

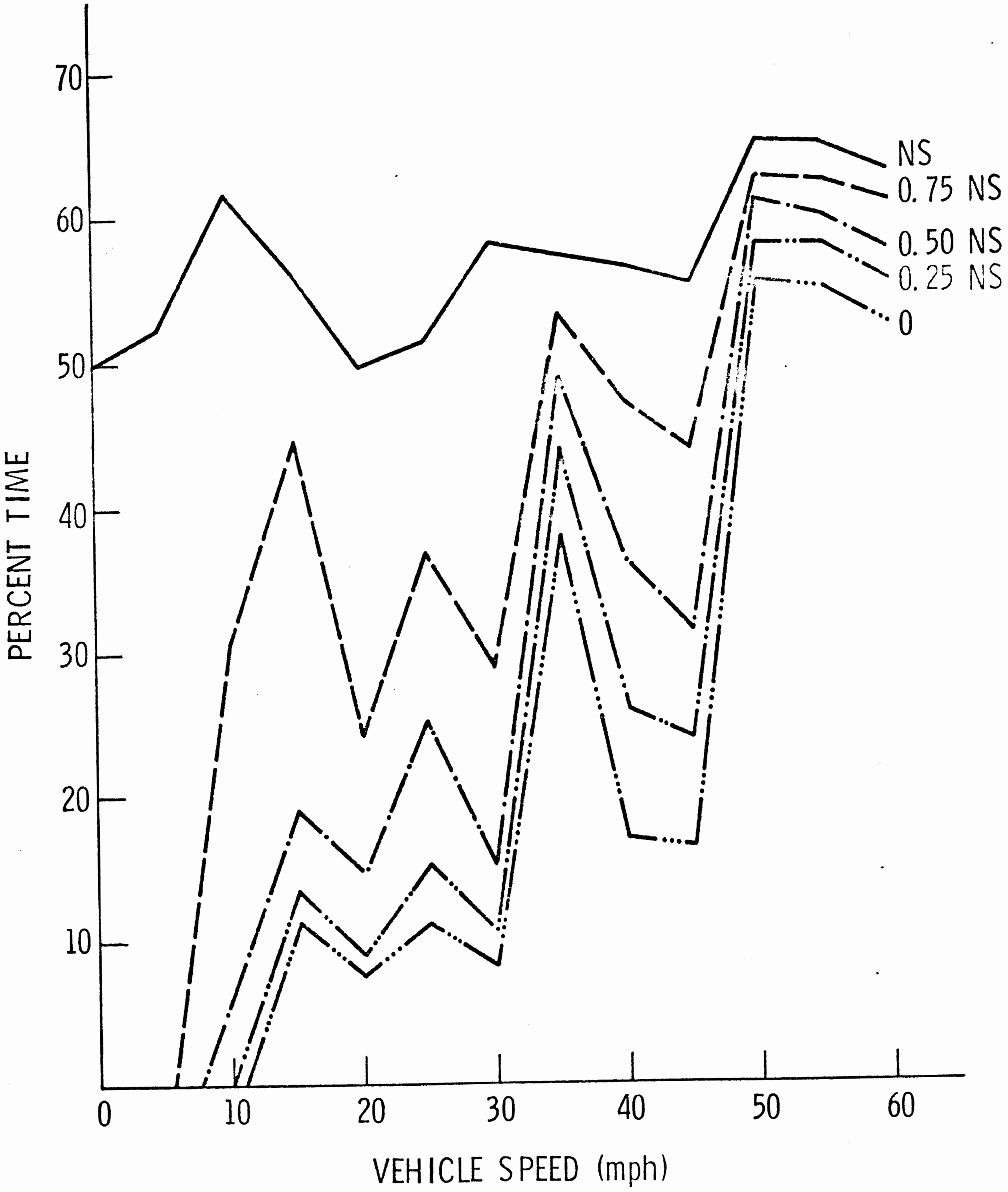


Figure 7b. Tire force histograms -- Mustang rear, 12' x 5" bump.

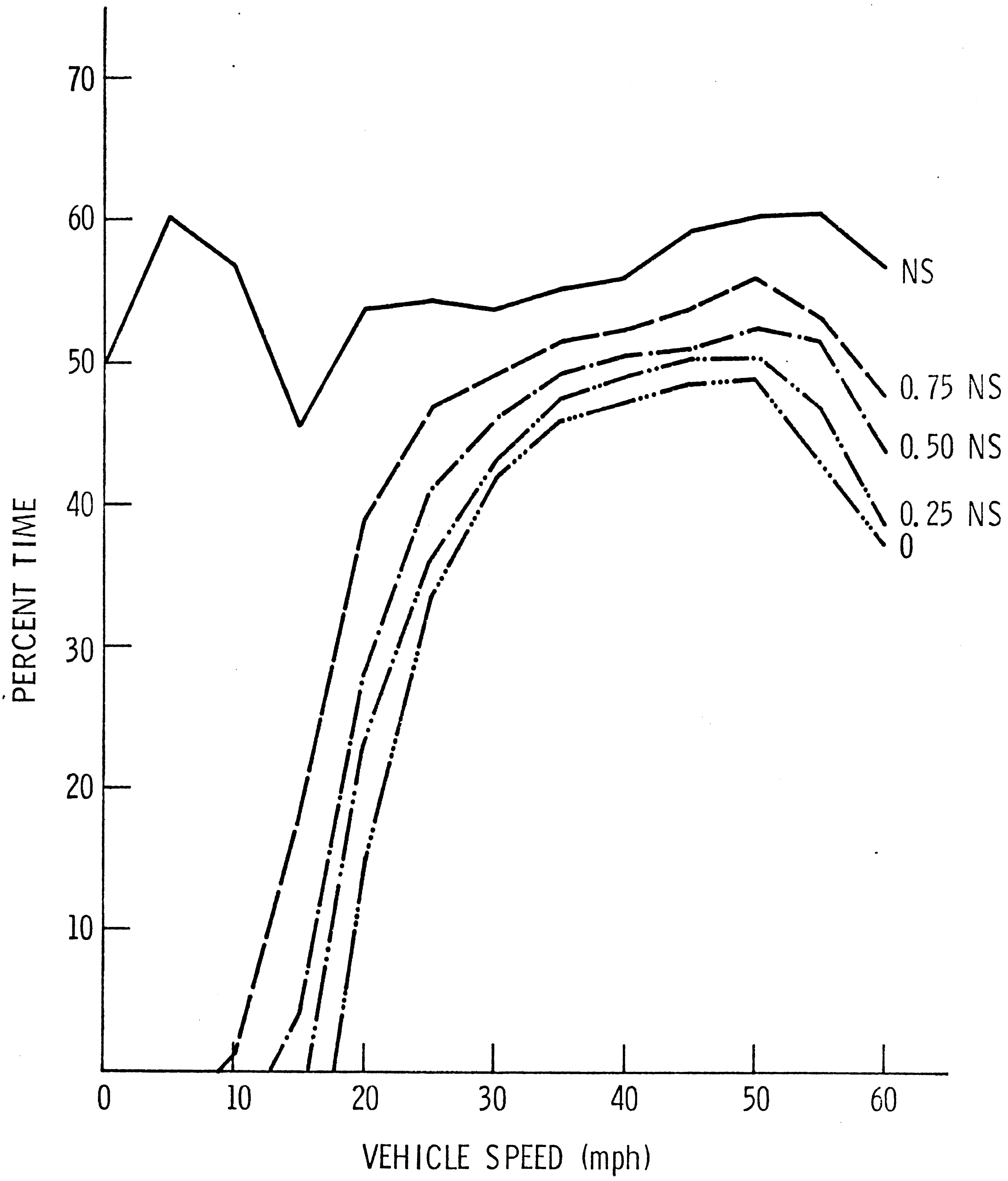


Figure 7c. Tire force histograms -- Mustang front, 16' x 6" bump.

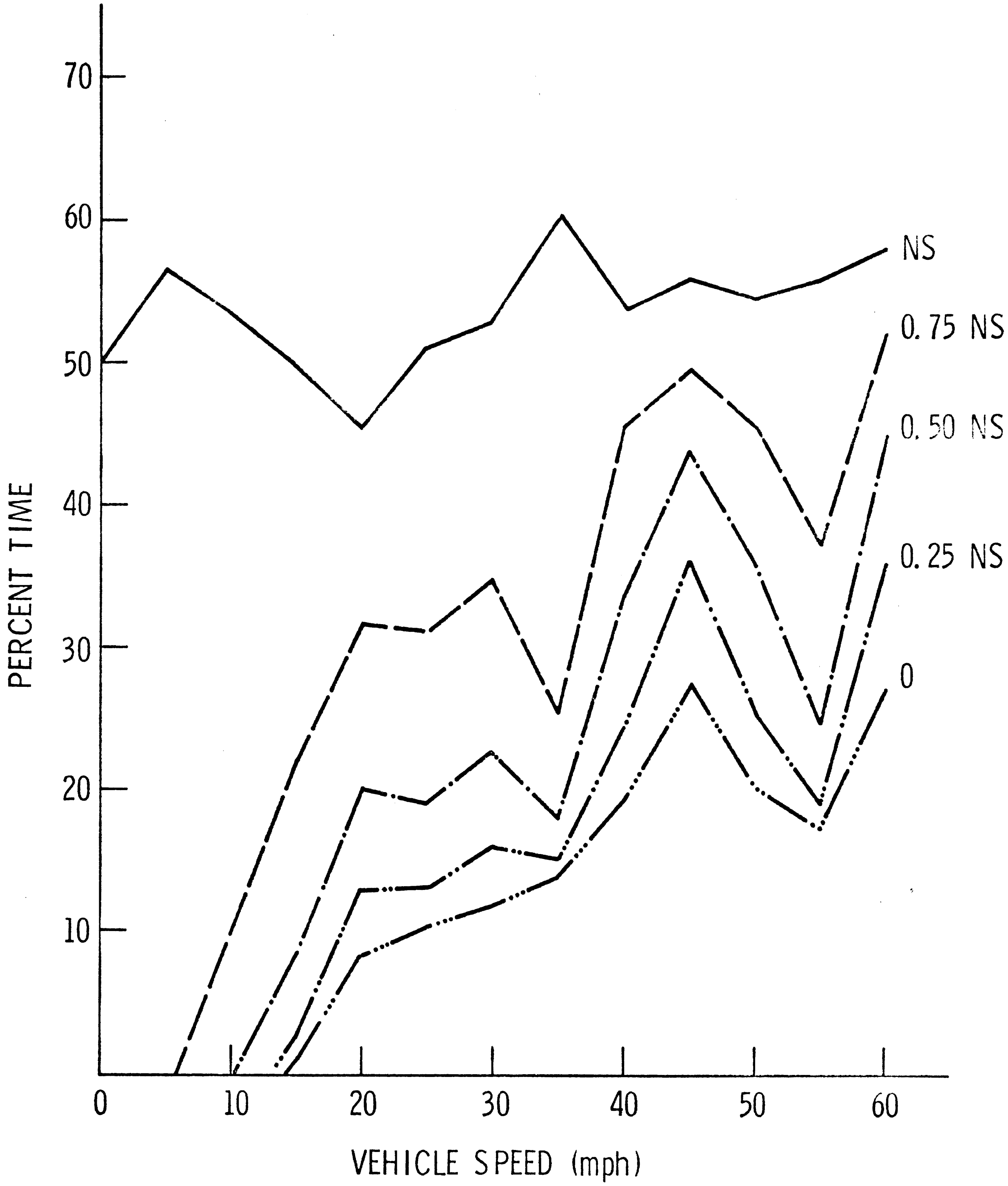


Figure 7d. Tire force histograms -- Mustang rear, 16' x 6" bump.

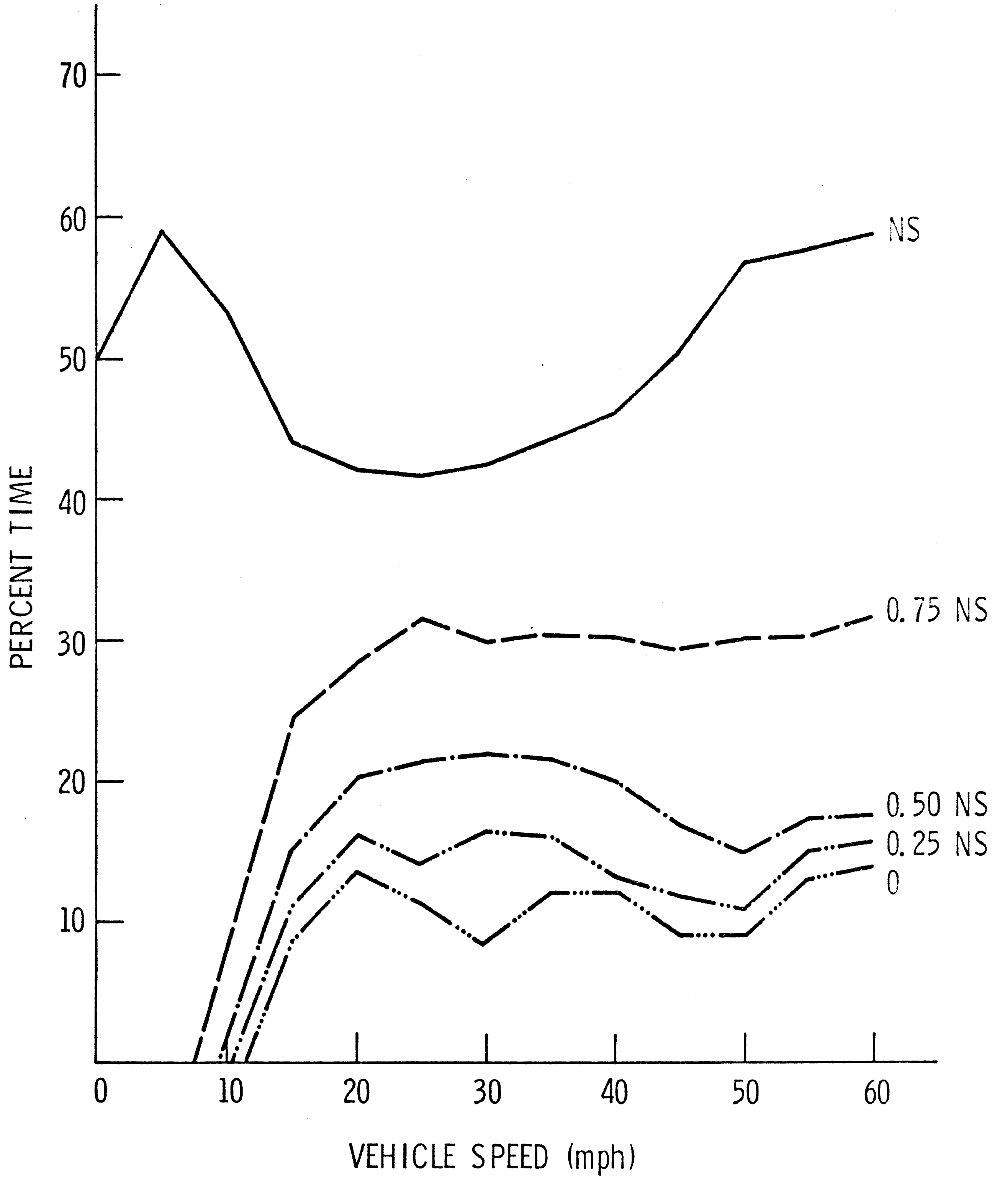


Figure 7e. Tire force histograms -- Buick front, 12' x 5" bump.

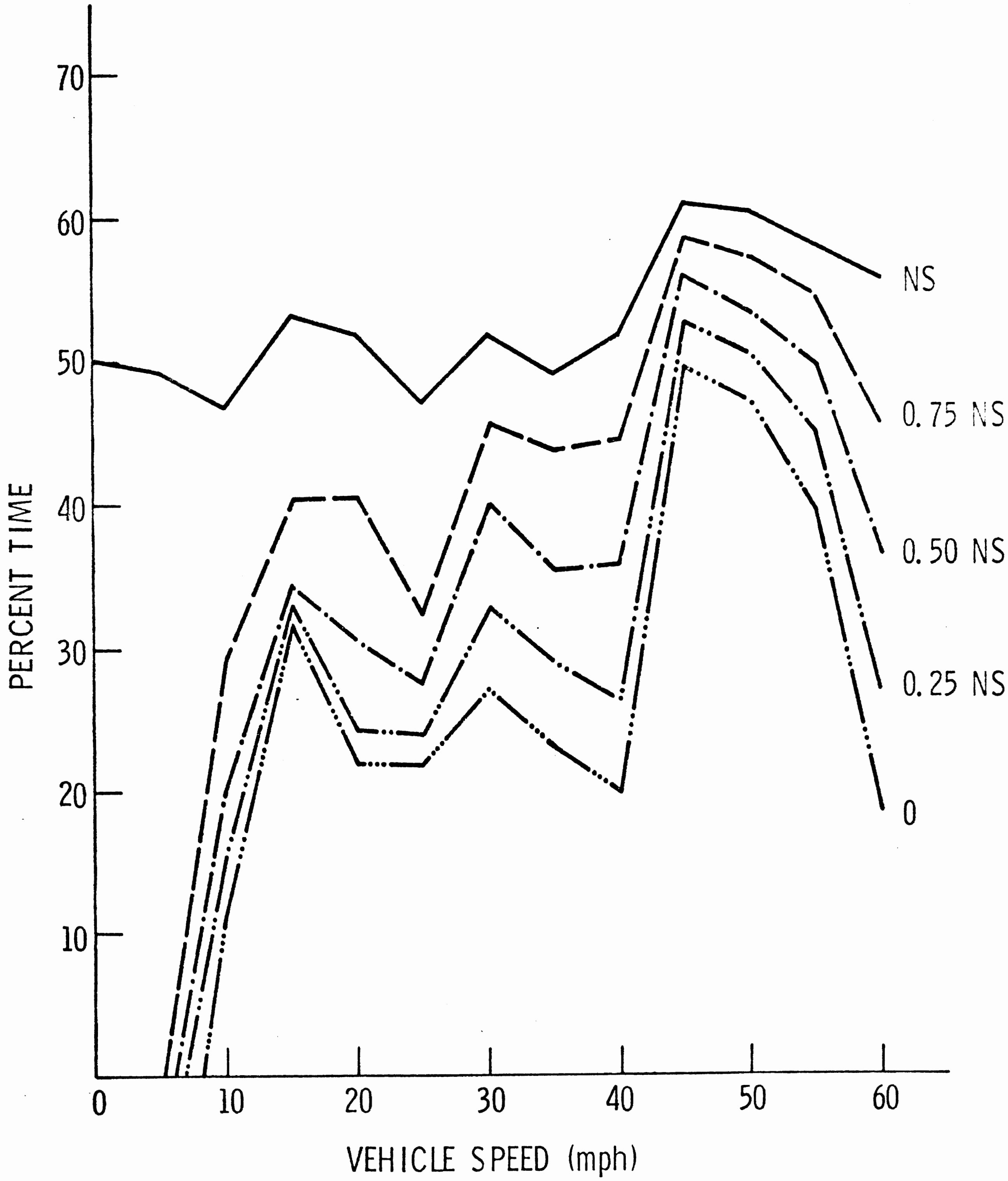


Figure 7f. Tire force histograms -- Buick rear, 12' x 5" bump.

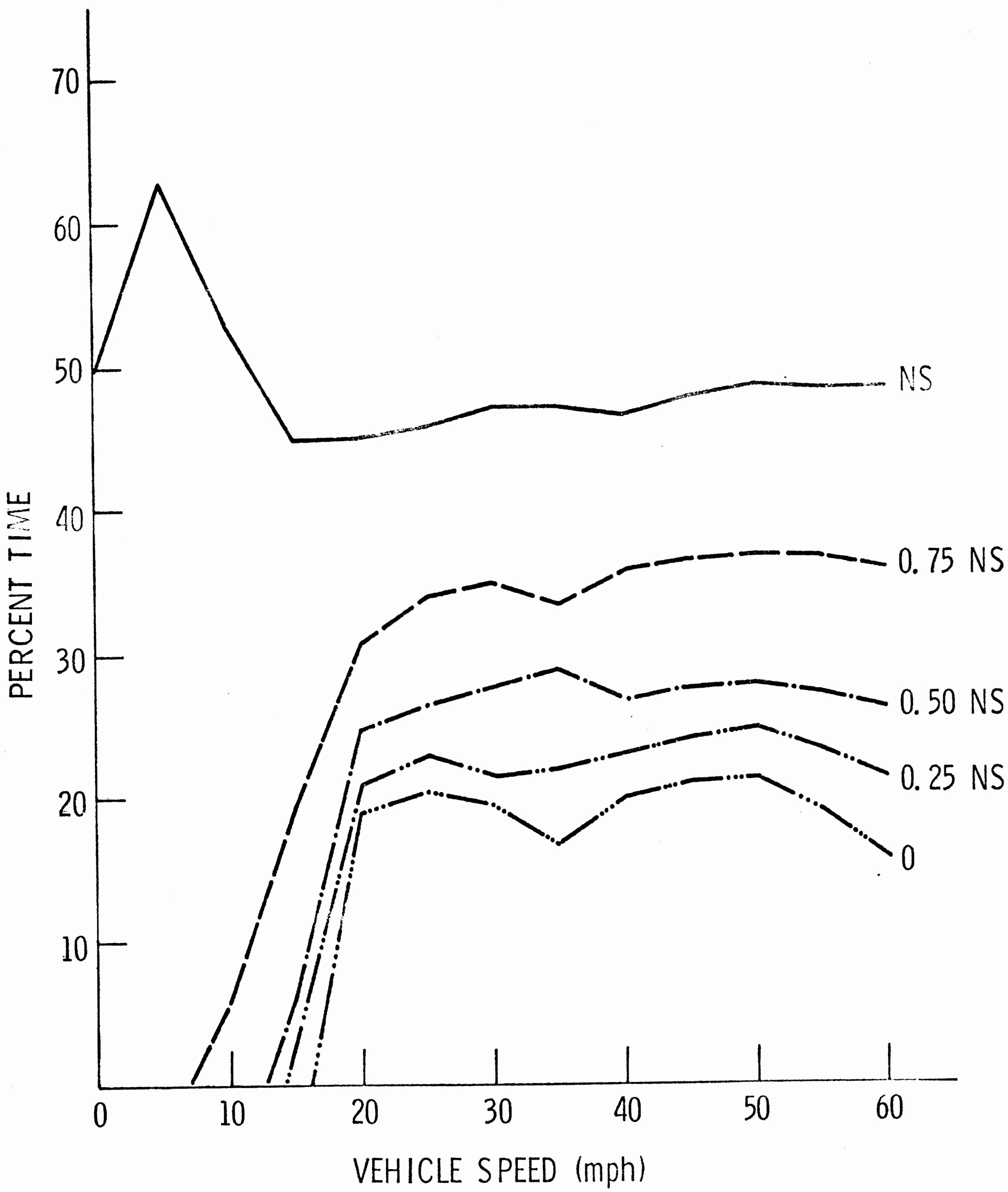


Figure 7g. Tire force histograms -- Buick front, 16' x 6" bump.

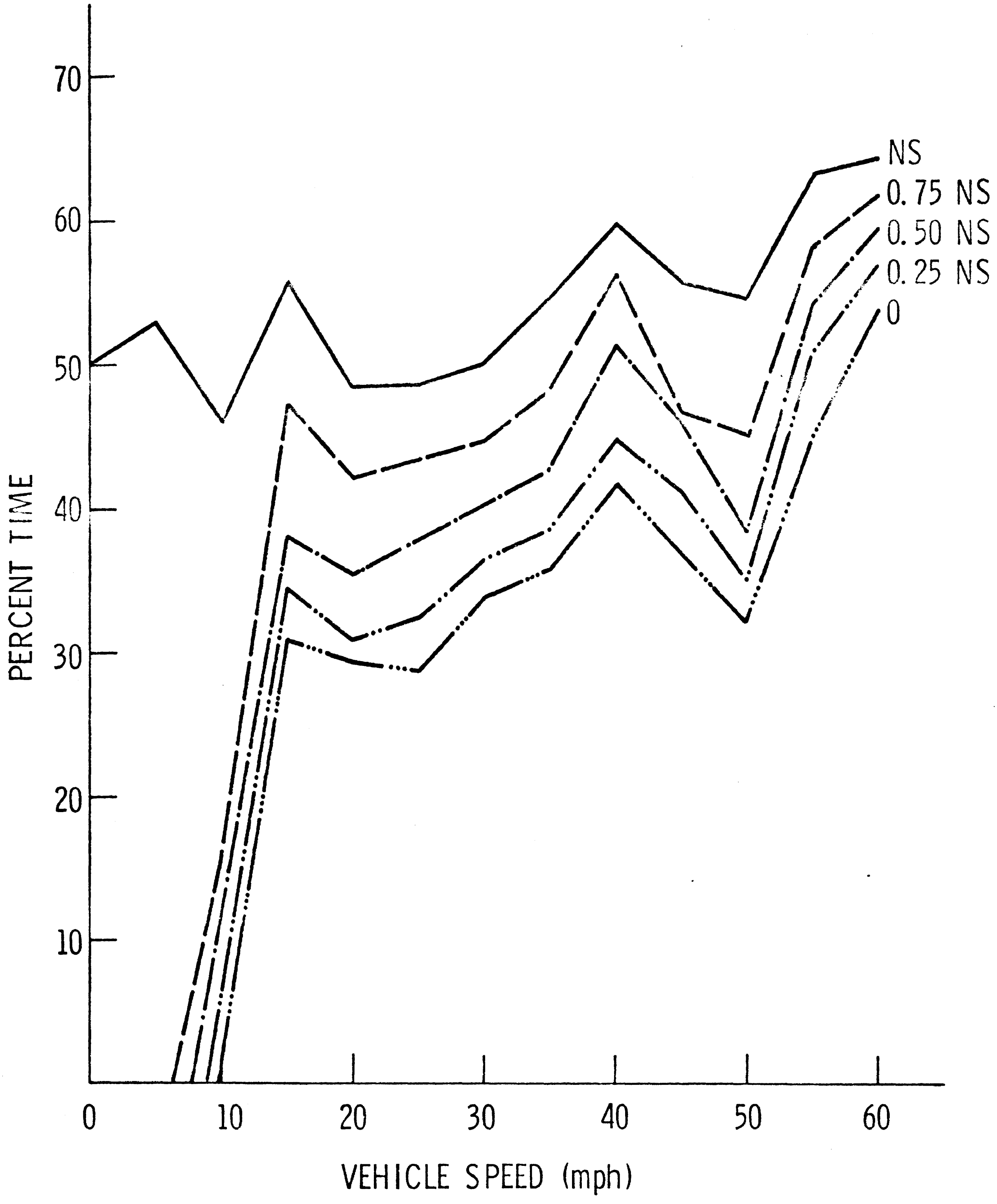


Figure 7h. Tire force histograms -- Buick rear, 16' x 6" bump.

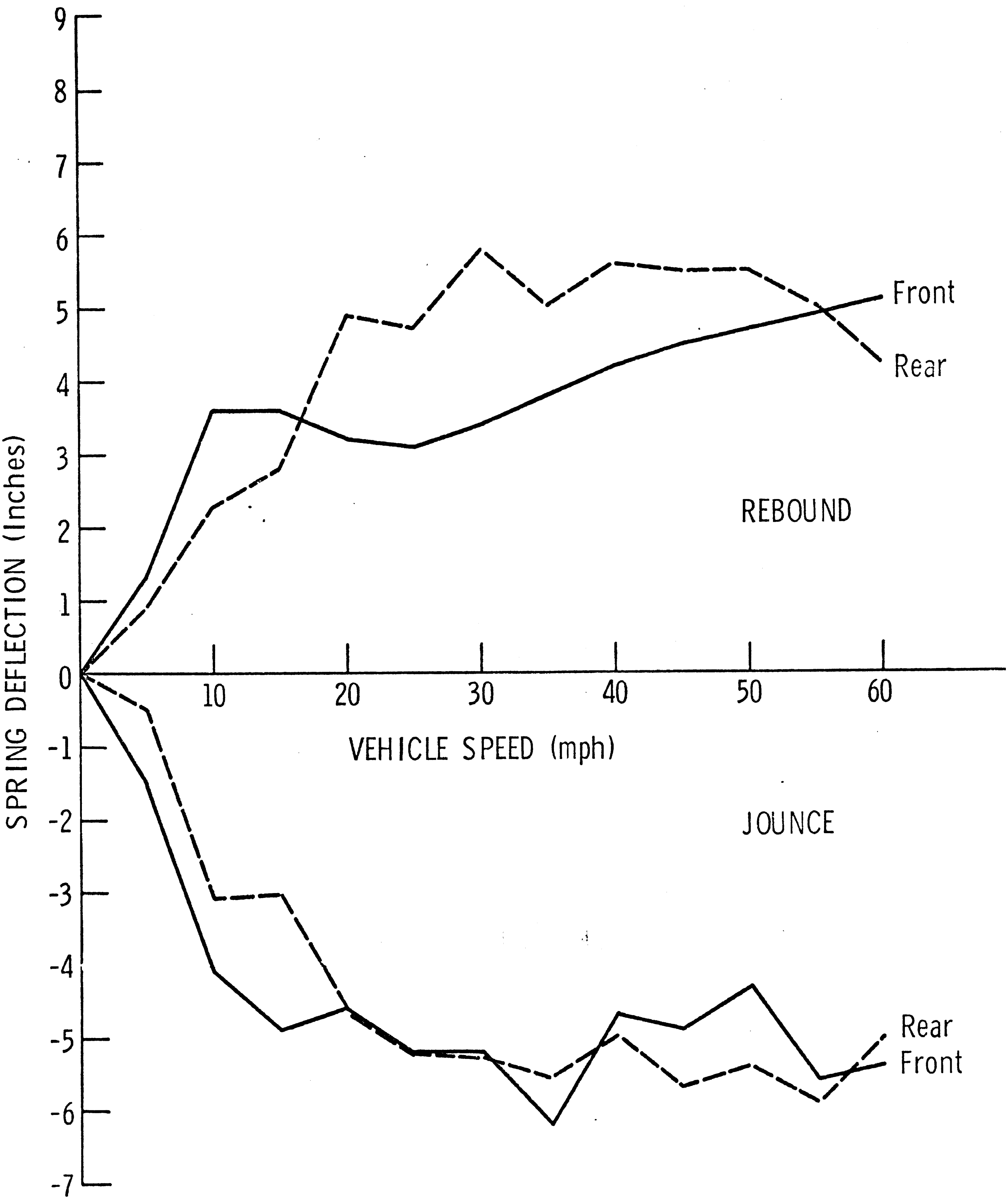


Figure 8a. Peak suspension spring deflections -- Mustang, 12' x 5" bump.

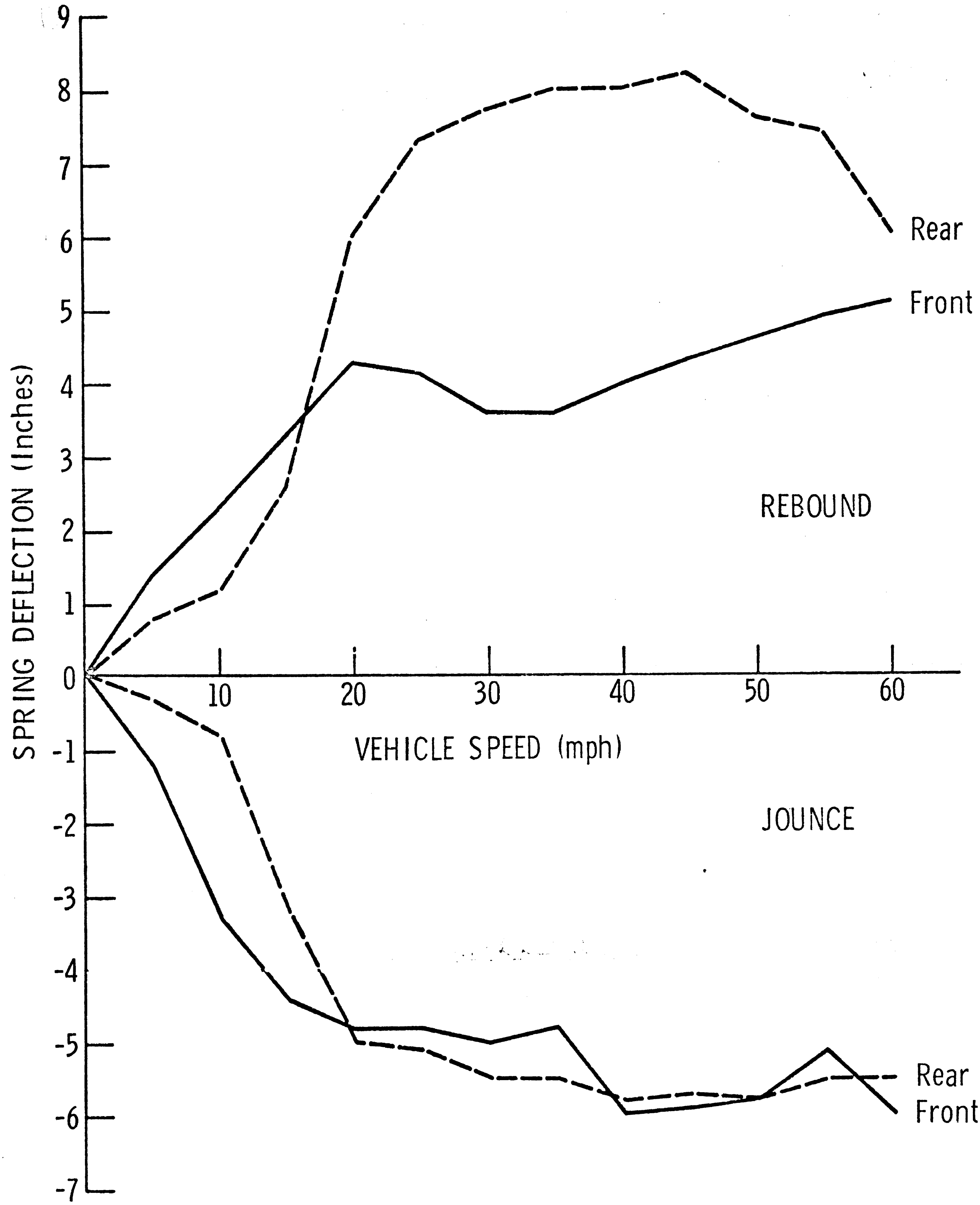


Figure 8b. Peak suspension spring deflections -- Mustang, 16' x 6" bump.

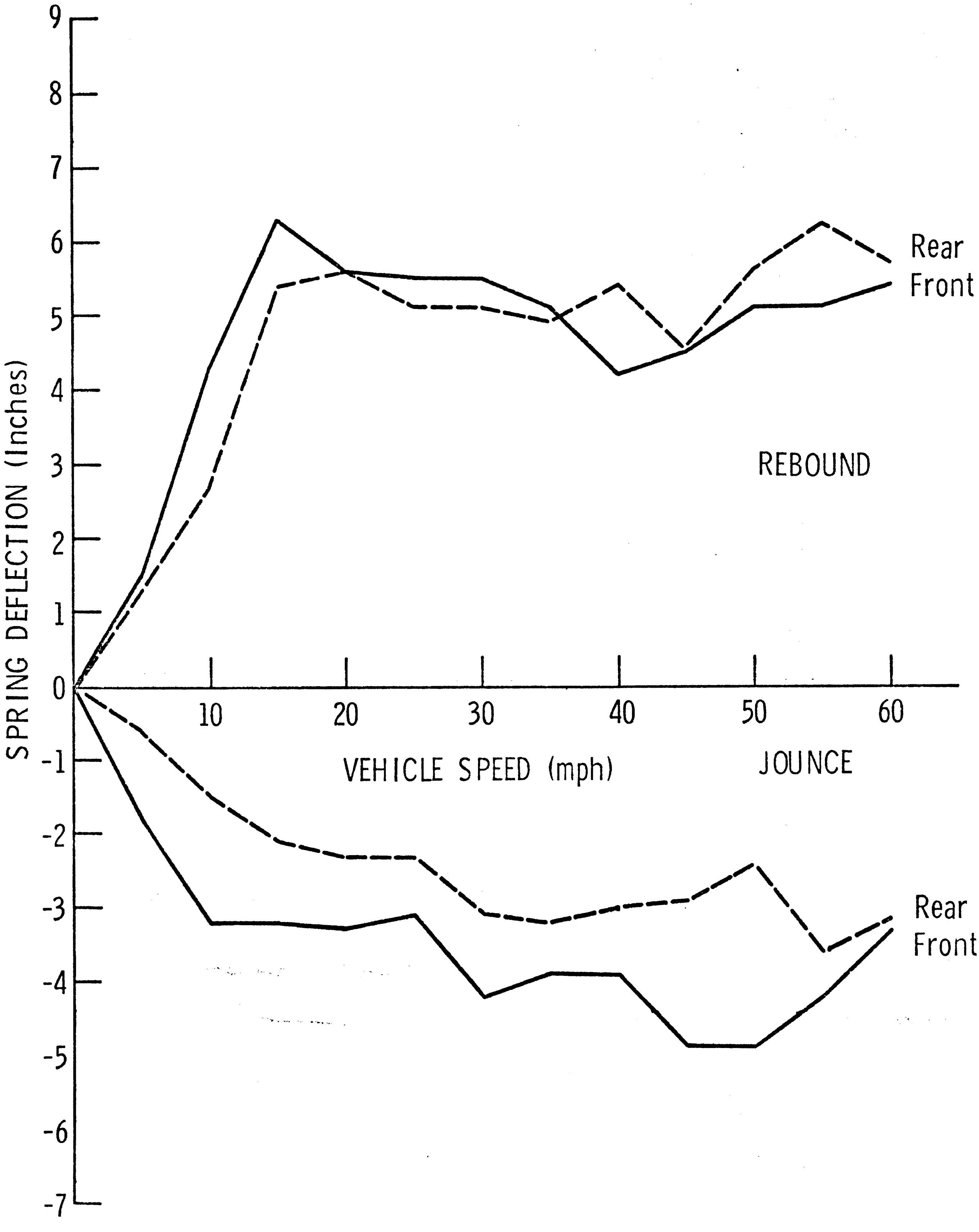


Figure 8c. Peak suspension spring deflections -- Buick wagon, 12' x 5" bump.

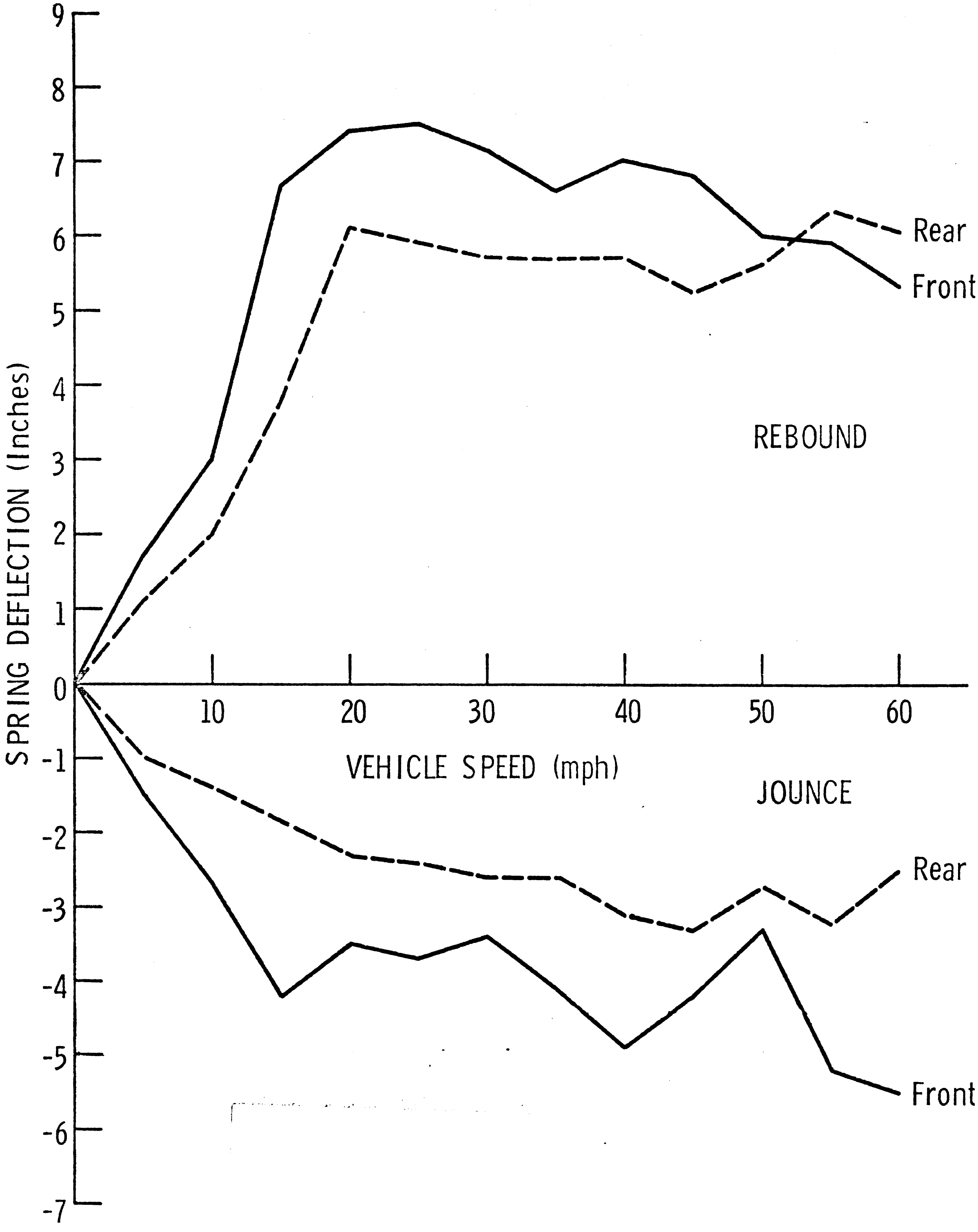


Figure 8d. Peak suspension spring deflections -- Buick wagon, 16' x 16" bump.

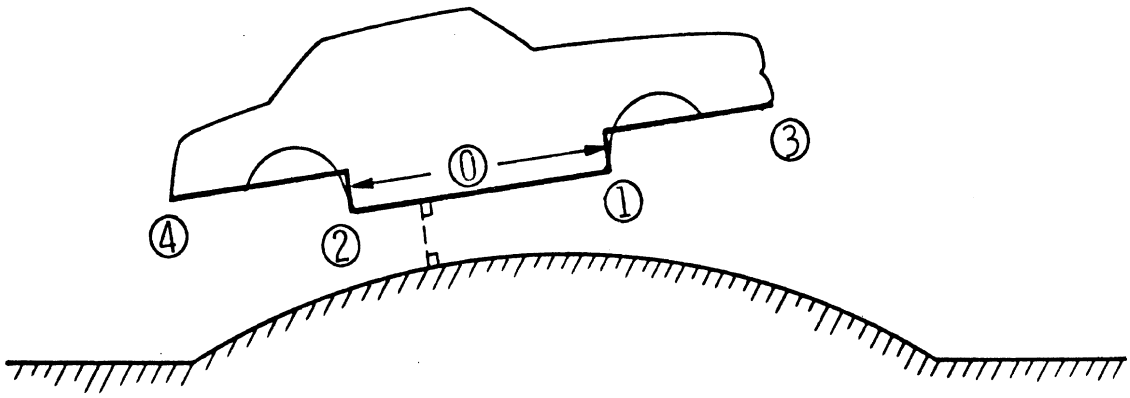


Figure 9. Vehicle profile.

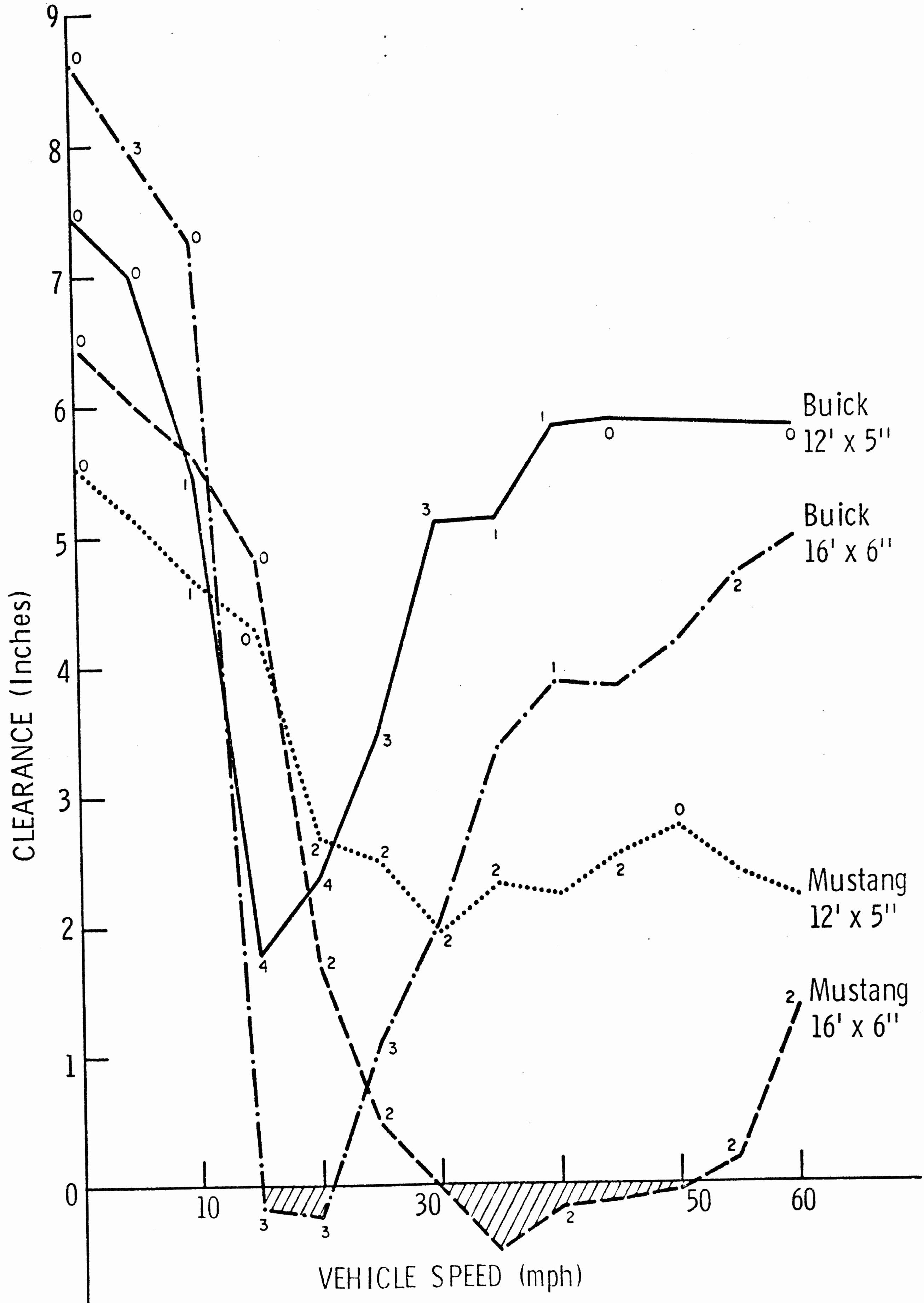


Figure 10. Minimum vehicle-road clearance.

Negative values of clearance (shaded area) indicate obstruction would have occurred, however, the dynamic vehicle behavior derived from the obstruction is beyond the scope of the simulation.

Figure 10 shows evidence of obstruction of each vehicle while traversing the 16' x 6" undulation. Although no obstruction is apparent for the 12' x 5" undulation, each vehicle came within 2 in. of the road bump at relatively low speed.

4.0 FINDINGS AND RECOMMENDATIONS

The simulation results indicate that significant discomfort will be experienced by passengers riding in either vehicle during a traversal of the five- or six-inch undulation at speeds in excess of 20 mph. We use "indicate" rather than a stronger word since the computed results are an approximate representation of the physical world. The model of the vehicle employed in the simulation is a rigid-body representation of an entity that has finite flexibility and thus the influence of the bending motions of the car body on the accelerations felt by the passengers has been ignored. Nevertheless, the calculated accelerations are sufficiently large that it seems reasonable to conclude that the undulations, as designed, will cause typical drivers to decrease their speed substantially either to avoid discomfort or to prevent structural damage. Clearly, the calculations show that the 16' x 6" undulation may cause the traversing vehicle to be damaged as a result of physical interference between road and vehicle.

On balance, it appears that the long-wavelength undulations examined in this study should not be introduced as speed-reduction devices without giving this matter careful, further thought and without examining additional undulation geometrics. Some of our reservations derive from a concern about the driver who may be inclined to seek a thrill from traversing these undulations at high speed. As indicated in Figures 7a to 7h, a high speed of traversal will result in the vehicle being airborne for a significant amount of time. In our judgment, this lack of tire-road contact is hazardous from a directional control point of view. It is also conceivable that the undulations examined in this study can cause structural failures during a high-speed traversal. Without information relative to the maximum loadings that can be withstood by the structure of the vehicle, it is not possible to draw substantive conclusions with respect to the issue of structural integrity.

It is clear that long wave undulations cannot be thwarted by traversing them at high speeds and consequently it is desirable to find the minimum disturbance which will avoid the disastrous consequences mentioned above and yet create sufficient discomfort to serve its intended purpose. Accordingly, HSRI recommends that an undulation of somewhat lesser severity be installed for a pilot study in which traffic would be monitored over a reasonable length of time.

REFERENCES

1. Winkler, C.B., et al., A Computer Program for Predicting the Braking Performance of Trucks and Tractor-Trailers to be published by the Highway Safety Research Institute, Univ. of Michigan, Report No. UM-HSRI-PF-75-5.