TANK TRAILER STABILITY ANALYSIS

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Technical Memorandum

Prepared for:

The Fruehauf Corporation

by

The Highway Safety Research Institute
The University of Michigan

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FRUEHAUF DIVISION / FRUEHAUF CORPORATION

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Dear Mr. Fancher:

This letter is in reply to your request of June 30, 1982 to place a copy of Technical Memorandum "Tank Trailer Stability Analysis" in the HSRI Library.

We agree that this memorandum should be made available to the public through HSRI's normal channels.

Yours truly,

A. F. Hulverson,
Vice President -
Engineering

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1.0 INTRODUCTION

This report presents results of directional stability and rollover threshold calculations for various articulated vehicle configurations incorporating tank trailers manufactured by the Fruehauf Corporation. The vehicles examined include three tractor-semitrailers, one truck/full-trailer, and two double tankers.

The directional stability and rollover analyses were performed by the Highway Safety Research Institute (HSRI) of The University of Michigan. To initiate the study, parameters describing the trailers and their suspension (or spring) characteristics were derived from drawings and measurements supplied by Mr. Stan Sadlocha of the Fruehauf Corporation. Typical tractor and tire parameters from previous HSRI research studies were used to complete the descriptions of the vehicles analyzed. The analysis employed computerized vehicle models originally developed in a previous HSRI research program entitled "Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers" [1].

This analysis was proposed to Fruehauf by HSRI in response to a letter from Mr. Larry Botkin of Fruehauf to Mr. R.D. Ervin of HSRI. Subsequently, the HSRI proposal was revised according to communications with the Research and Development Division of Fruehauf. Once the proposal was accepted, Messrs. John Getz and Stan Sadlocha of the R & D Division provided liaison between HSRI and the Fruehauf Corporation.

A concise summary of the findings of this study is presented in the next section. Section 3 provides a technical description of the vehicles and loading configurations examined. Sections 4 and 5 describe the methods used and the results obtained in the directional and roll analyses, respectively. Several appendices (A through F) provide detailed information concerning (1) the meanings and values of the parameters needed in the computerized models, (2) the results of pertinent calculations, and (3) the new suspension (spring) models implemented in this study.

2.0 SUMMARY

The findings of the directional stability and rollover threshold calculations for various tank trailer configurations are summarized in this section.

2.1 Directional Stability

The directional performance and stability were evaluated using the linear yaw plane model described in Reference [1]. Each vehicle was analyzed in the fully loaded, empty and partial loading conditions. The directional performance measures itemized below were used as the basis for quantifying the directional stability of each vehicle configuration.

1) Natural frequencies and damping ratios of the natural modes of yaw motion at 50 mph (eigenvalues).

2) Lateral acceleration frequency response of the vehicle at 50 mph.

3) The transient response exhibited by the vehicle during a two-second, emergency-type lane-change maneuver executed at 50 mph. (This maneuver was found to be very close to a worst case situation for these vehicles.)

Numerics based on performance measures (2) and (3) were found to be the most useful in characterizing the directional behavior of the vehicles, especially the tendency of the rear-most trailers of multi-articulated vehicles to exhibit an amplified and weakly damped directional response. The following results were obtained from the directional stability calculations.

1) All of the three tractor-semitrailer combinations that were analyzed exhibited well-damped and attenuated semi-trailer motions.

2) Vehicles with typical, unmodified dollies (i.e., the full trailer of the truck/full-trailer, and the pup trailers of the conventional double tanker configurations) were found to exhibit lightly damped, amplified lateral motions in an emergency lane-change maneuver at 50 mph. The amplification in the lateral acceleration response was found to range from

1.5 to 3.0 in the emergency lane-change maneuver.

3) Rigidizing the pintle hook connection in yaw and roll was found to increase the damping and decrease the amplifying tendency in the double tanker configurations. The amplification in an emergency lane change was reduced by 21% for the five-axle double tanker and by 30% for the nine-axle double tanker.

2.2 Rollover Thresholds

Calculations were performed for each vehicle in the fully loaded condition. A modified version of the nonlinear roll model described in Reference [1] was used for computing the rollover thresholds for steady turning and emergency lane-change-type maneuvers.

The results obtained from the rollover threshold calculations were as follows:

1) The steady turning rollover threshold was found to range from 0.37 g to 0.46 g for all of the vehicles analyzed.

2) Vehicles equipped with Fruehauf T-type air suspensions exhibited higher rollover thresholds as compared to those equipped with conventional leaf springs because (a) the air springs do not have free-play and (b) the air suspensions have roll stiffnesses which are roughly comparable to the roll stiffnesses of the leaf spring suspensions.

3) The rollover threshold during emergency maneuvers (dynamic rollover threshold) was found to vary over a very wide range. The tractor-semitrailers and the double tankers equipped with rigidized pintle hooks were found to possess a dynamic rollover threshold which was higher (in the range of 0.46 to 0.64 g) than the rollover threshold in a steady turn. The conventional double tanker and the truck-full trailer configuration, on the other hand, exhibited a much lower dynamic rollover threshold (in the range of 0.18 to 0.28 g).

4) Rigidizing the pintle hook of a double tanker resulted, approximately, in a twofold increase in the dynamic rollover threshold.

5) The presence of backlash in the suspensions was found to lower the rollover threshold during steady turning and emergency maneuvers. (The influence of suspension backlash on the rollover threshold of the pup trailer of a double tanker is illustrated in Figure 18.)

The directional response and rollover results for the vehicles studied in this program are presented in summary form in two bar charts, specifically, Figure 11, entitled "Lateral Acceleration Gain During Emergency Maneuvers," and Figure 17, entitled "Static and Dynamic Rollover Thresholds." The relative performance of the vehicles studied may be compared by examining Figures 11 and 17.

3.0 VEHICLE DESCRIPTION

Directional and roll response calculations were performed for six vehicles. The vehicles included three tractor-semitrailers, a truck/full-trailer and two double tanker-type vehicles. Table 1 presents schematic diagrams of the vehicles, along with other relevant information.

For each vehicle, directional response calculations were performed in the fully loaded, empty and partial loading conditions, making a total of 38 cases, which are defined in Table 2. It should be noted that the influence of roll on directional behavior is neglected in the yaw plane analysis. Hence, configurations with identical layout, but different suspension properties (e.g., Ia with Ib, IIa with IIb, IIc with IId, and VIa with VIb) are lumped together for the purposes of evaluating their directional behavior.

Calculations of rollover thresholds in steady turns and rapid lane-change maneuvers were performed for the 13 configurations (Ia through VIc) listed in Table 1. Vehicle parameters corresponding to a fully loaded condition were used in the roll analysis.

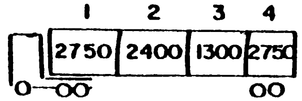
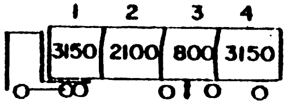
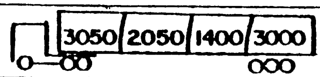
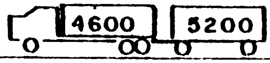
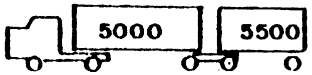
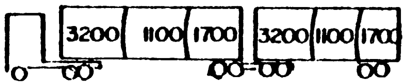
Fruehauf Model	Schematic Diagram	Total Tank Capacity (gal)	Region of Operation	Payload Capacity at Rated Axle Loads (gal)	Tires	Configuration no. and description
BKY8499		9200	Interstate	8844	Fruehauf 10x20 duals	Ia. 4 leaf spring (UxBO2OI) suspension Ib. T-type air ride suspension
BKD-0065		9200	Michigan and Ohio	9000 8385		<u>All three axles on ground</u> IIa. T-type air ride suspension on front axle, F2W rear suspension IIb. T-type air ride suspension on add axles <u>Front axle lifted</u> IIc. T-type air ride suspension on 2 rear axles IId. F2W suspension on 2 rear axles
BKY-9450-1		9550	Michigan	9000		III. With three leaf spring (U-CDO5II) suspension
BLY 2714		9800	California	9347		IV. With four leaf spring (UxBO2OI) suspension
BLY 2985		10500	California	9020		<u>With four leaf spring (UxBO2OI) suspension</u> Va. Pintle type conventional drawbar Vb. Drawbar rigidly connected to semi-trailer
BKD 0067		12000	—	12114	Uniroyal 11x22.5 singles	<u>With single leaf spring (UCD9637) suspension</u> VIa. Single tires and wide spring centers, with conventional drawbar VIb. Single tires and standard spring centers, with conventional drawbar VIc. Single tires and standard spring centers, with rigid type drawbar

TABLE I: VEHICLE CONFIGURATIONS

Table 2. Loading Conditions for Which Directional Response Calculations Were Performed.

Data Set # and Case #	Configuration
	#Ia and Ib - Tractor-Semi BKY8499
1	Fully loaded
2	Empty
3	Compartment #1 full
4	Compartment #4 full
	#IIa and IIb - Tractor-Semi BKD0065
5	Fully loaded
6	Compartment #1 full
7	Compartment #4 full
	#IIc and IId - Tractor-Semi BKD0065
8	Empty
9	Compartment #1 full
10	Compartment #4 full
	#III - Tractor-Semi BKY940-1
11	Fully loaded
12	Empty
13	Compartment #1 full
14	Compartment #4 full
	#IV - Truck/Full-Trailer BLY2714
15	Fully loaded
16	Empty
17	Semi loaded, pup empty
18	Semi empty, pup loaded
	#Va - 5-Axle Double Tanker BLY2985
19	Fully loaded
20	Empty
21	Semi loaded, pup empty
22	Semi empty, pup loaded

Table 2. (Cont.)

Data Set # and Case #	Configuration
	#Vb - Modified 5-Axle Double BLY2985
23	Fully loaded
24	Empty
25	Semi loaded, pup empty
26	Semi empty, pup loaded
	#VIa and VIb - 9-Axle Double BKD0067
27	Fully loaded
28	Empty
29	Semi loaded, pup empty
30	Semi empty, pup loaded
31	Semi loaded, pup comp. #3 full
32	Semi loaded, pup comp. #2 & 3 full
	#VIc - Modified 9-Axle Double BKD0067
33	Fully loaded
34	Empty
35	Semi loaded, pup empty
36	Semi empty, pup loaded
37	Semi loaded, pup comp. #3 full
38	Semi loaded, pup comp. #2 & 3 full

4.0 DIRECTIONAL BEHAVIOR

A linear yaw plane model (a model in which all motions of the vehicle are restricted to the horizontal plane) was used for examining the directional performance of the vehicles. Numerics based on the directional performance measures itemized below have been used for quantifying the directional stability and performance of the vehicles in each of the loading conditions listed in Table 2:

1) natural frequencies and damping ratios of the natural modes of yaw motion (eigenvalues) at 50 mph,

2) lateral acceleration frequency response of the vehicle (by frequency response, we mean the directional response of the vehicle to sinusoidal steer inputs at 50 mph), and

3) the transient response exhibited by the vehicle during a 2-second emergency-type lane-change maneuver executed at 50 mph.

4.1 The Directional Response Model

The mathematical model used in this study is the same as the one developed by HSRI for the double-bottom tanker study [1] in 1978. The important simplifying assumptions made in the process of deriving the equations of motion are as follows:

1) Cornering forces and aligning moments generated at the tire-road interface are linear functions of the sideslip angle.

2) Pitch and roll motions of the sprung mass may be neglected.

3) There are no significant tire forces present in the longitudinal direction, and the vehicle is assumed to have a constant forward velocity.

4) Articulation angles are small such that the approximations $\sin \Gamma = \Gamma$ and $\cos \Gamma = 1.0$ hold.

5) Steering system dynamics are left out of the model and the steering input is assumed to be given directly to the front wheels.

6) The liquid in the tanks is assumed to take part in the yawing motion without sloshing.

Figure 1 shows the representation of a double tanker in the yaw model. The vehicle parameters used to describe the 38 loading conditions defined in Table 2 are listed in Appendix A. All major dimensions and weight distributions were obtained using drawings supplied by the Fruehauf Corporation, while yaw moments of inertia were estimated based on the size and mass of each unit. Tire characteristics corresponding to a Fruehauf 10 x 20 rib tire were used for all vehicles expect BKD0067, where data for an 11 x 22.5 Uniroyal Fleetmaster tire were used.

The complete set of linear differential equations which describe the directional motion of the vehicle is given in Appendix A of Reference [1]. These equations, when written in matrix notation, are of the form

$$[A]\{\dot{x}\} = [B]\{x\} + \{C\}\delta \qquad (1)$$

where [A], [B] and {C} are matrices whose elements are functions of the vehicle parameters, δ is the front-wheel angle, and {x} is the vector of state variables. The state variables for a tractor-semitrailer, for example, are

v_1 - lateral velocity of tractor

r_1 - yaw rate of tractor

r_2 - yaw rate of trailer

Γ - articulation angle

Eigenvalues, frequency response functions, and time histories of vehicle behavior during transient maneuvers were evaluated by the application of suitable numerical algorithms to this set of equations. Flow diagrams for calculations of eigenvalues and transient responses are given in Appendix A of Reference [1]. The method adopted for the calulation of frequency response functions will be discussed in Section 4.3.

4.2 Eigenvalues

The number of natural modes of yaw motion exhibited by an articulated vehicle depends upon the number of independent articulated units constituting the vehicle configuration. For example, a tractor-semitrailer

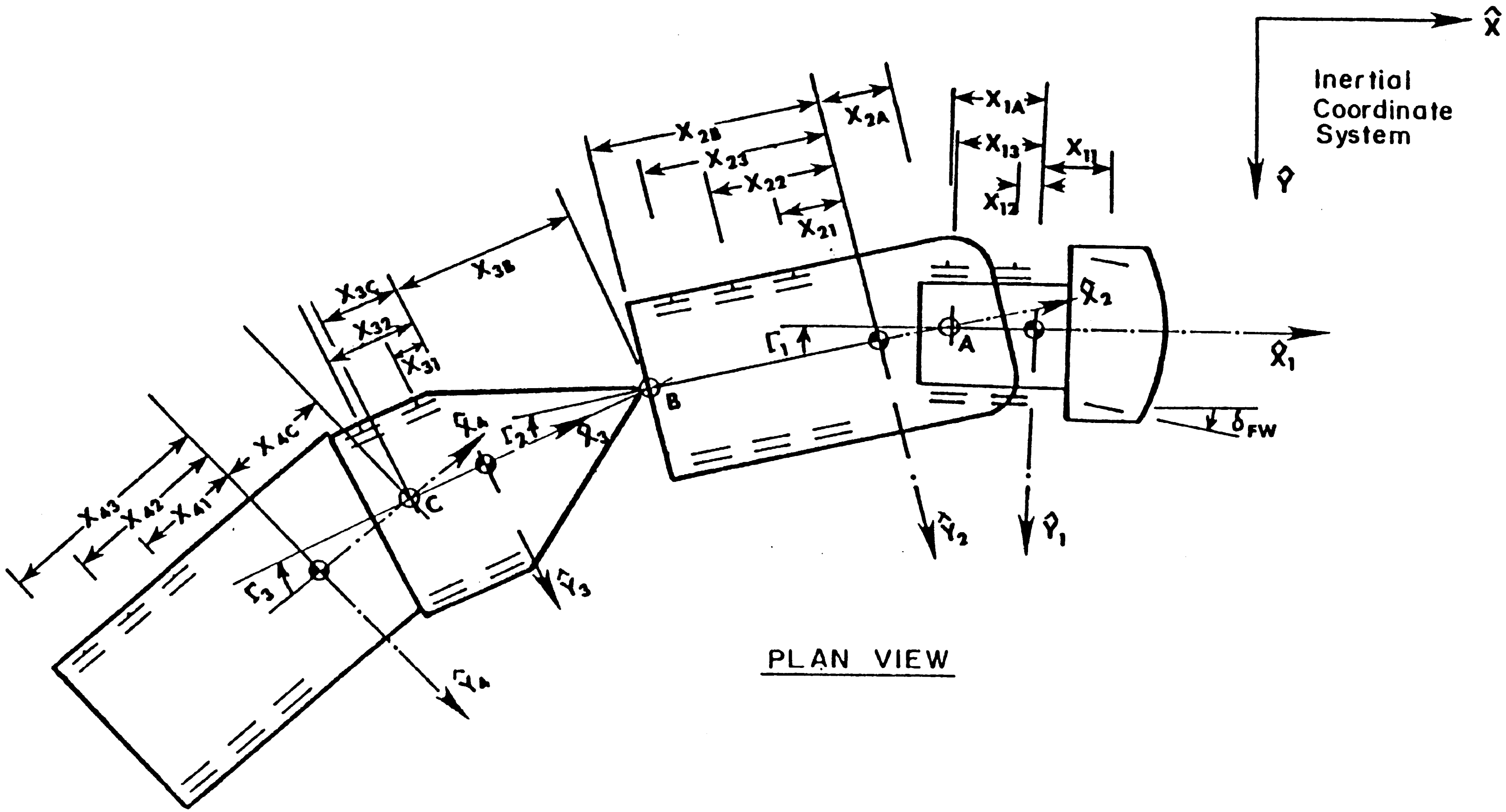


Figure 1. Definition of coordinate systems and important parameters of a double tanker.

(composed of two units) has two modes of motion and a corresponding set of two pairs of complex eigenvalues, while a conventional double tanker (consisting of a tractor, semitrailer, dolly and pup trailer) has a set of four pairs of eigenvalues. For a vehicle to be directionally stable, it is necessary that all the natural modes of yaw motion be positively damped (that is, for stability, the damping ratio, ζ , must be greater than zero). Small values of damping ratio indicate that transient motions generated during a maneuver will consist of slowly decaying oscillations occurring at frequencies close to the natural frequencies of the lightly damped modes of motion. The natural frequencies and damping ratios of the eigenvalues are primarily influenced by vehicle design, payload distribution, and forward speed. Appendix B contains a tabulation of the natural frequencies and damping ratios for a forward speed of 50 mph for each of the cases listed in Table 2.

The influence of payload distribution on the damping ratio of the least damped mode of each vehicle is summarized in Figure 2. Improvements in the damping of a double tanker when fitted with a rigidized pintle hook are evident from this figure. With one exception, the tractor-semitrailer vehicles, as a class, exhibit much higher damping levels than the tanker/full-trailer and double tanker-type vehicles. The damping ratio of 0.51 exhibited by tractor-semitrailer BKD0065 with compartment #3 loaded (see Fig. 2 and Case 7 in Appendix B) results because the c.g. of the semitrailer, in this loading condition, is shifted rearward to a point where it almost lies on top of the mid-axle of the three-axle suspension.

For simple dynamical systems such as a single degree of freedom spring-mass-damper system, the eigenvalues furnish us with enough information about the response of the system to external forcing functions, but for multiple degree of freedom systems, such as a tractor-semitrailer or a double tanker, the information gained from the eigenvalues is insufficient to predict their directional behavior. Eigenvalues do not, for example, reveal the problem of rearward amplification of directional response that is peculiar to multi-articulated vehicles. A frequency response analysis or an analysis of the transient response of the vehicle during emergency maneuvers such as a lane change, on the other hand, provides much more information. (These methods of analysis, of course, involve a greater amount of computation than an eigenvalue analysis.)

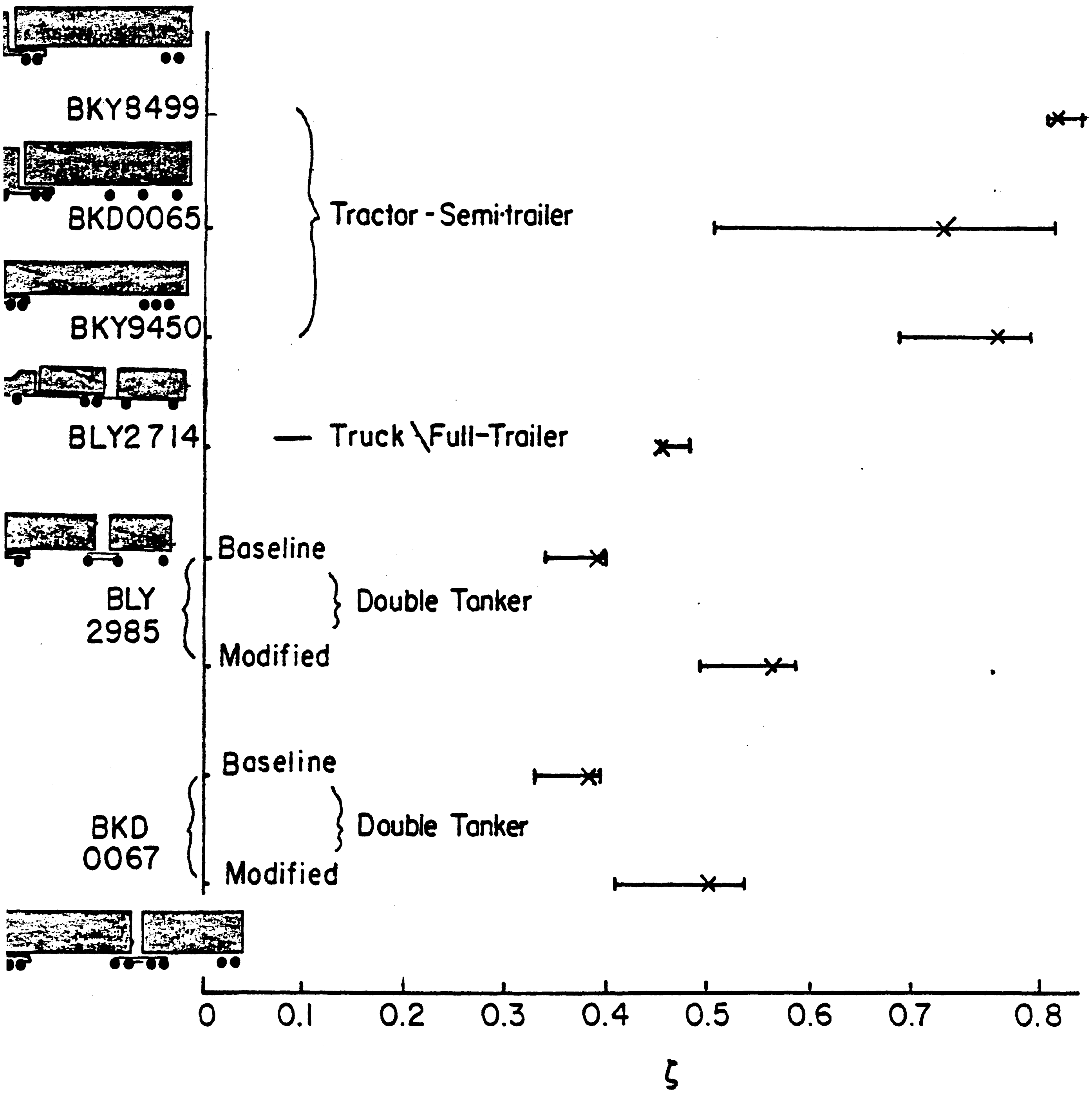


Figure 2. The range of variation, with load, of the damping ratio of the least damped mode for each vehicle. Fully loaded condition is marked with the symbol x.

Results obtained from the frequency response and transient response analyses are presented in the next two sections.

4.3 Frequency Response

The frequency response of a multi-articulated vehicle can be obtained from the differential equations of motion (1) as follows:

A sinusoidal steer input of unit amplitude and frequency ω can be written as

$$\delta = 1 \cdot e^{i\omega t} \tag{2}$$

Since the system of equations are linear, the response of the vehicle is also harmonic and is of the form

$$\{x\} = \{\overline{x}\}e^{i\omega t} \tag{3}$$

where $\{\overline{x}\}$ is the vector of complex quantities which define the magnitude and phase of each state variable. Therefore, upon substitution of (2) and (3) into Equation (1) and rearranging, we get

$$[[A]i\omega - [B]]\ \{\overline{x}\} = \{C\} \tag{4}$$

and

$$\{\overline{x}\} = [[A]i\omega - [B]]^{-1}\{C\} \tag{5}$$

The right-hand side of (5) can be evaluated for any given input frequency, ω.

The lateral acceleration response of each unit of an articulated vehicle is related to the state variables by the following relationships:

$$\begin{aligned}
&\text{Tractor} && a_{y_1} = \dot{v}_1 + u\ r_1 \\
&\text{Semi} && a_{y_2} = \dot{v}_1 + u\ r_1 - x_{1A}\dot{r}_1 - x_{2A}\dot{r}_2 \\
&\text{Dolly} && a_{y_3} = \dot{v}_1 + u\ r_1 - x_{1A}\dot{r}_1 - (x_{2A}+x_{2B})\dot{r}_2 - x_{3B}\dot{r}_3 \\
&\text{Pup Trailer} && a_{y_4} = \dot{v}_1 + u\ r_1 - x_{1A}\dot{r}_1 - (x_{2A}+x_{2B})\dot{r}_2 \\
& && \qquad - (x_{3B}+x_{3C})\dot{r}_3 - x_{4C}\dot{r}_4
\end{aligned} \tag{6}$$

where

a_y's are the lateral accelerations

u is the forward velocity

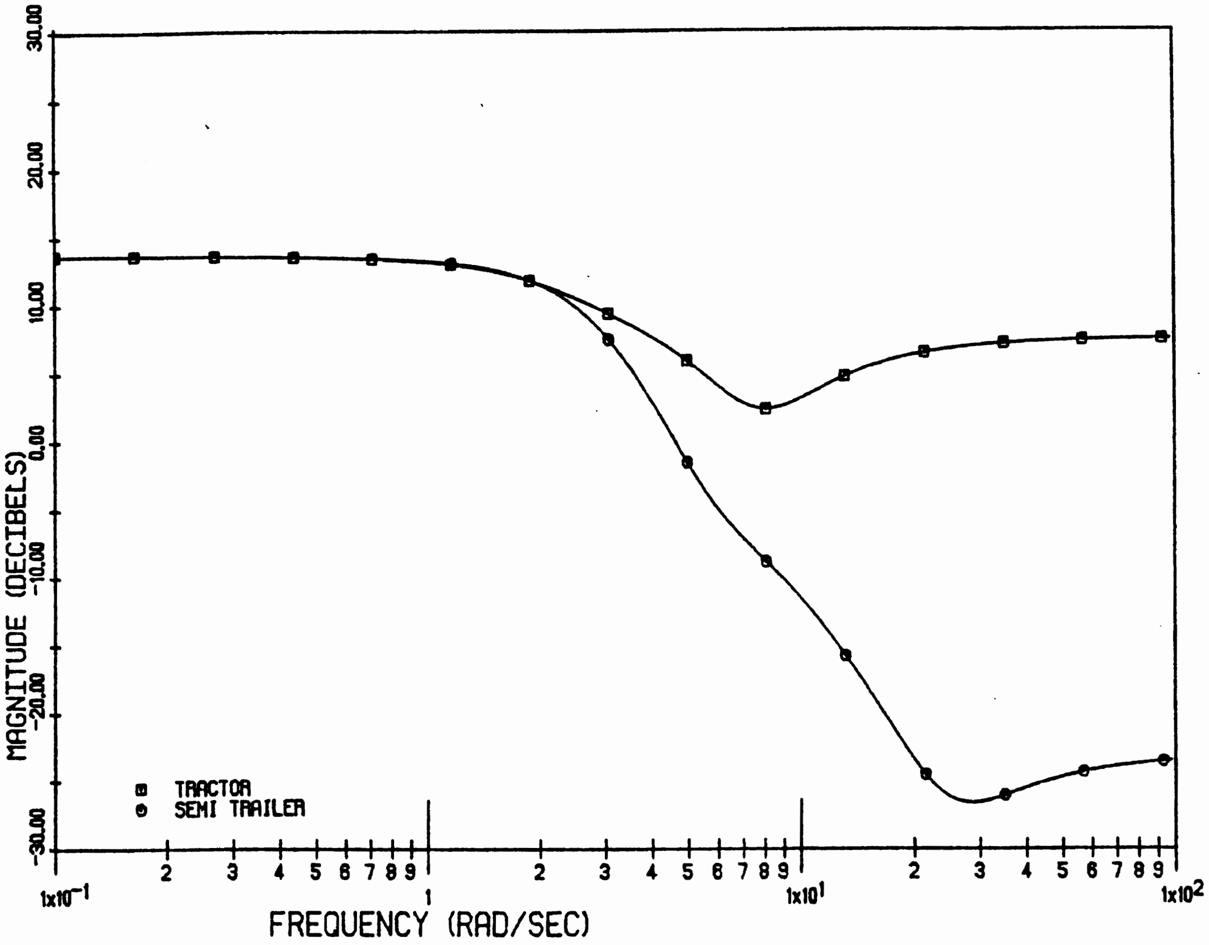
x_{1A}, x_{2A}, etc. are dimensions defined in Appendix A.

Hence, the frequency response of the lateral acceleration of each element of an articulated vehicle can be obtained by combining (6) with (5).

Examples of the lateral acceleration frequency response of a tractor-semitrailer (BKD0065), truck/full-trailer (BLY2719) and a double tanker (BLY2985) in the baseline and modified conditions are shown in Figures 3, 4, and 5, respectively. The ordinate in these plots is the amplitude of the lateral acceleration (ft/sec^2) response in decibels for a front-wheel input amplitude of one degree. (Note: a quantity x when expressed in the decibel scale is $20 \log_{10}(x)$.) A complete set of plots for each of the 38 cases listed in Table 2 are included in Appendix C.

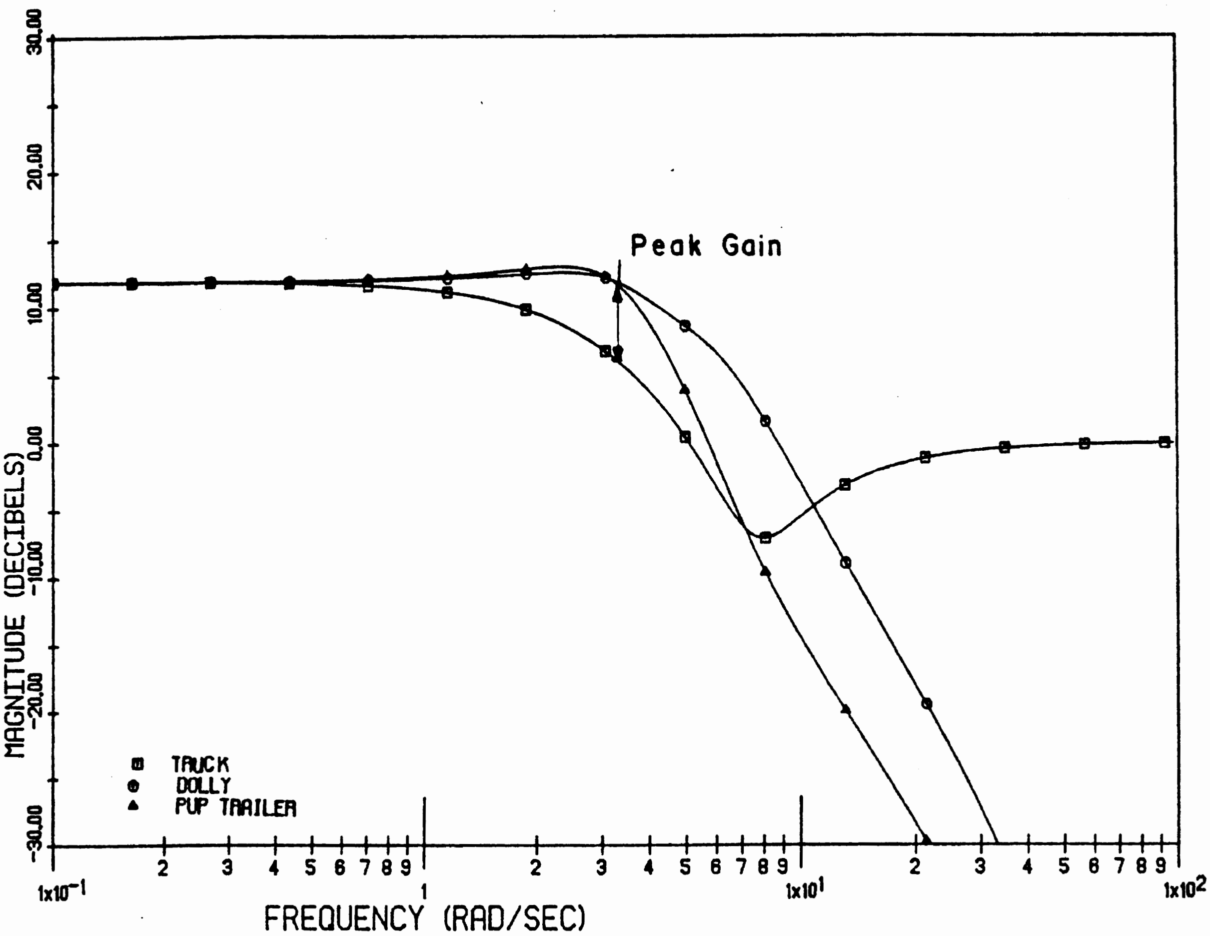
Figure 3, which is representative of the response exhibited by most commercial tractor-semitrailer configurations, indicates an attenuated semitrailer response (by attenuation we mean a trailer response which is smaller than the tractor response) for frequencies greater than 2 rad/sec. Certain unfavorable loading conditions in which the rearmost compartment of the semitrailer is loaded, such as Case #7 in Table 2, result in a semitrailer response which is only slightly larger than that of the tractor, in the 1 to 2 rad/sec range. (See the results for Data Set #7 in Appendix C.) The full trailer of a truck/full-trailer combination (Fig. 4) or the pup trailer of a conventional double tanker (Fig. 5a), on the contrary, exhibit considerable amplification of the lateral acceleration response in the 1 to 6 rad/sec frequency range. Comparison of Figure 5a with Figure 5b reveals the attenuating influence of the rigidized pintle hook on the lateral motion of the pup trailer.

The maximum amplification exhibited by the rearmost trailer, over the entire frequency range, serves as a convenient measure of the directional performance of multi-articulated vehicles. As shown in Figure 4, the maximum amplification can be computed in the decibel scale simply by finding the maximum difference, in db, between the frequency response of the rearmost trailer and the tractor.



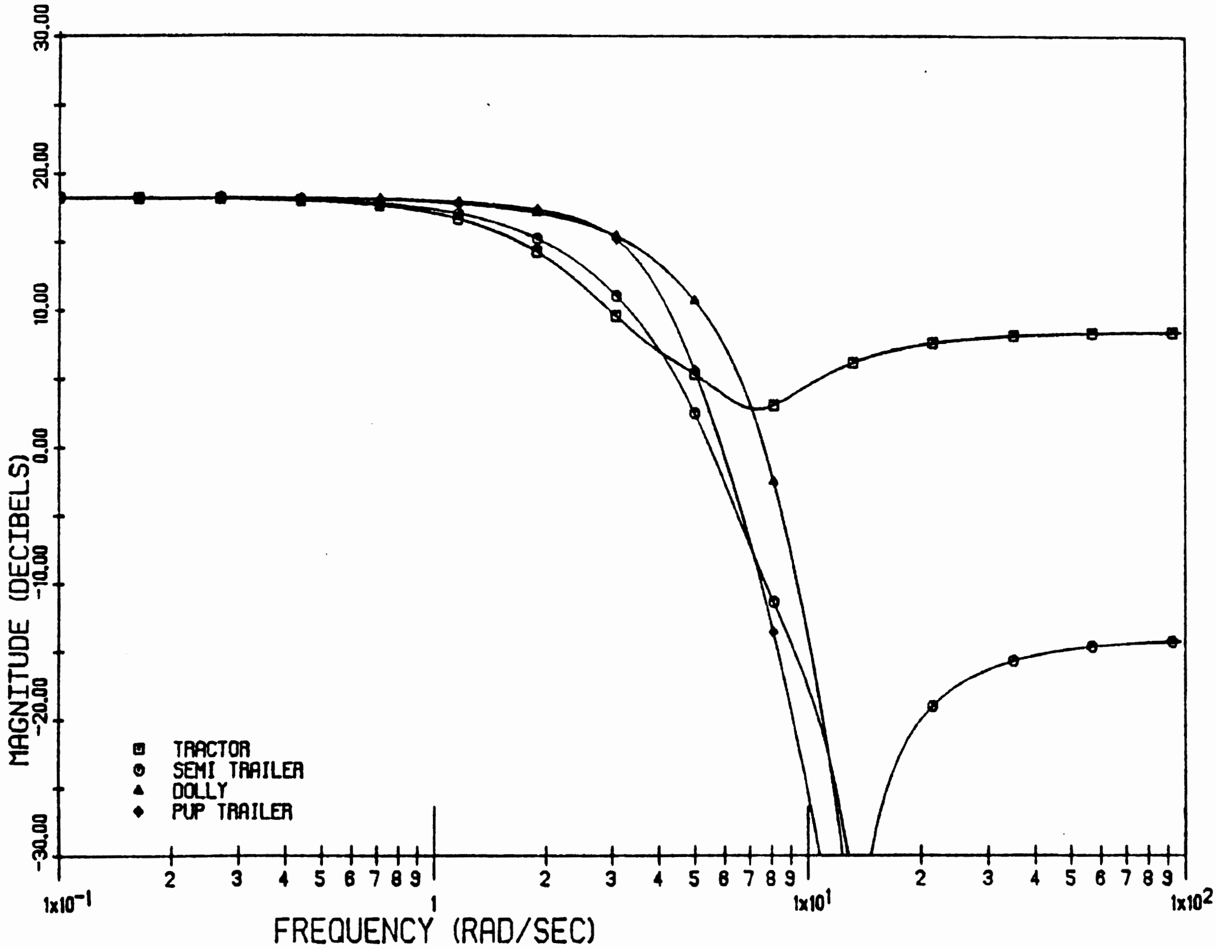
TRACTOR-SEMI BKD-0065 FULLY LOADED DATASET#5

Figure 3



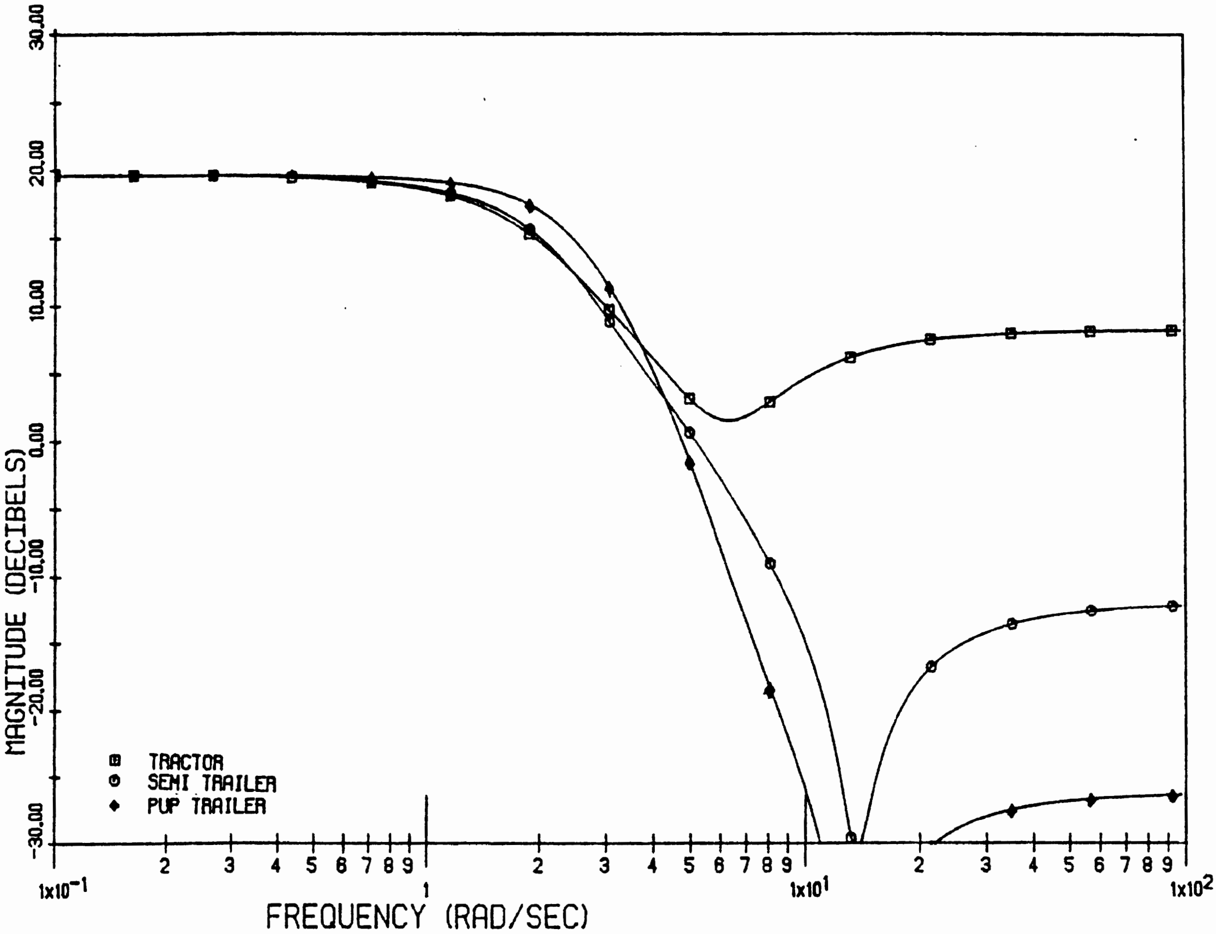
TRUCK/ FULL-TRAILER BLY-2714 FULLY LOADED .DATASET#15

Figure 4



DOUBLE TANKER BLY-2985 FULLY LOADED . DATASET#19

Figure 5a



MODIFIED DOUBLE BLY-2985 FULLY LOADED .DATASET#23

Figure 5b

The peak amplification factor of each of the 38 cases analyzed are plotted in Figure 6 in a histogram format, using the decibel scale. A scale containing the actual peak gain is also superimposed on the x axis of this diagram.

4.4 Transient Response During Emergency Maneuvers

The behavior of articulated vehicles during emergency maneuvers at normal highway speeds serves as a good indicator of their directional and roll stability. An emergency-type lane-change maneuver, for example, causes the rear trailers of a multi-articulated vehicle to experience higher levels of lateral acceleration than the tractor, thereby making the rear trailers more susceptible to a rollover. This type of amplifying behavior is primarily influenced by vehicle design and operating parameters such as speed and payload distribution.

A steer input of the form shown in Figure 7 was used for the purpose of examining the directional response of various vehicles in a lane-change (or obstacle avoidance) type of maneuver at a forward speed of 50 mph. For example, as can be seen in Figure 8, the semitrailer of a tractor-semitrailer combination does not exhibit an amplification of the peak lateral acceleration experienced by the tractor in the simulated lane-change maneuver. The pup trailers of the truck/full-trailer (Fig. 9) and the double tanker (Fig. 10a), on the contrary, exhibit considerable amplification of the lateral acceleration response. Comparison of Figure 10b with Figure 10a shows the reduction of the peak pup trailer lateral acceleration produced by rigidizing the pintle hook of the double tanker.

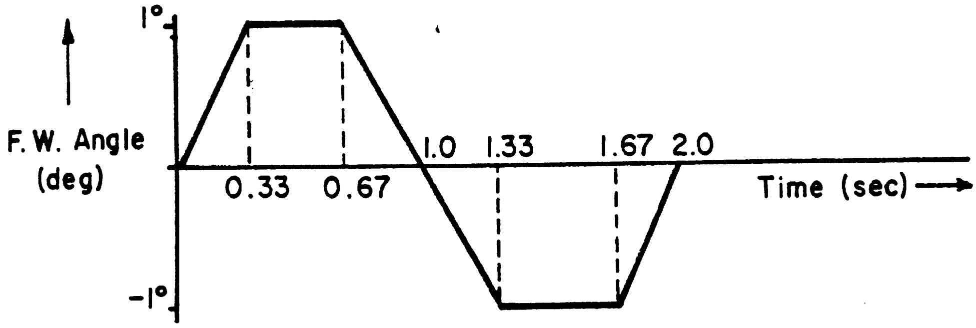
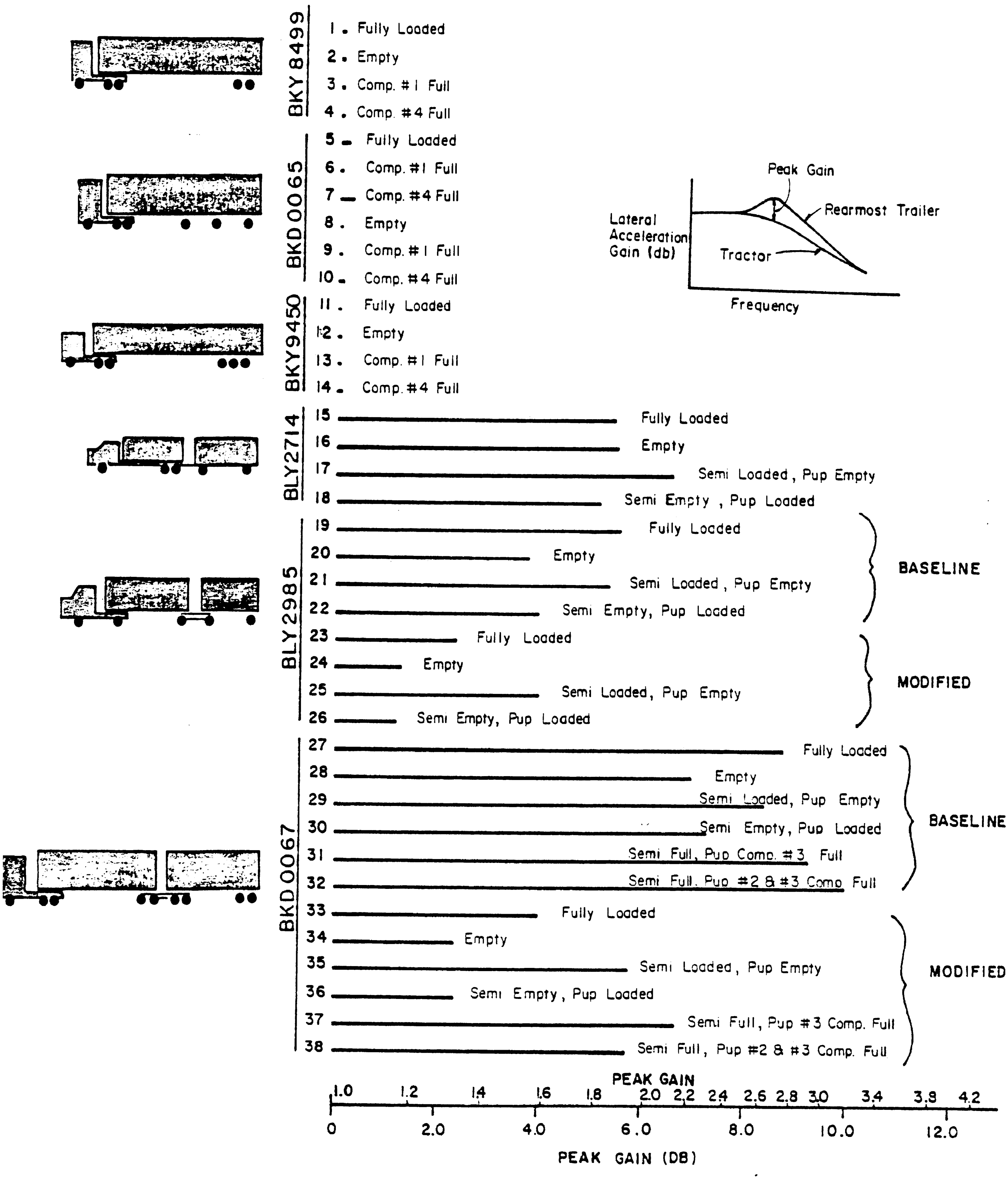
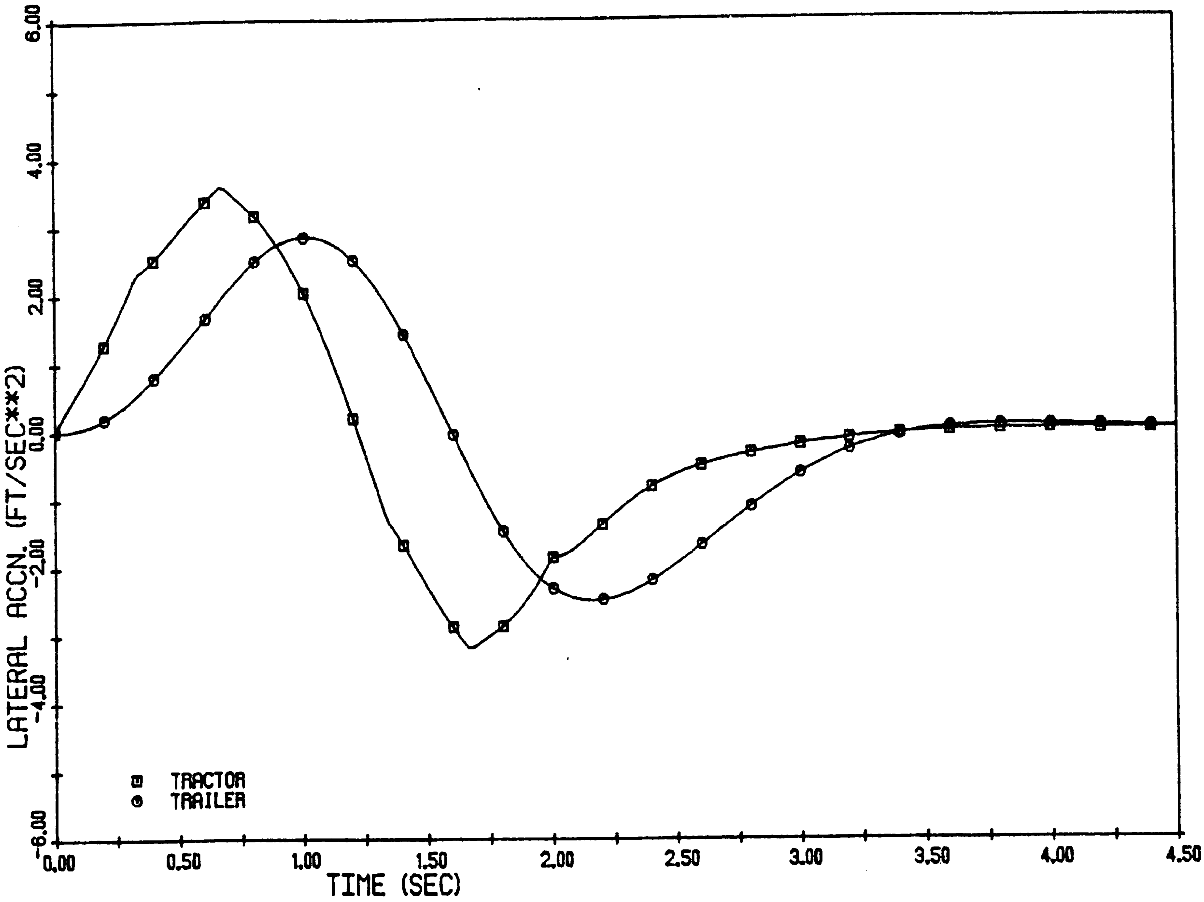


Figure 7



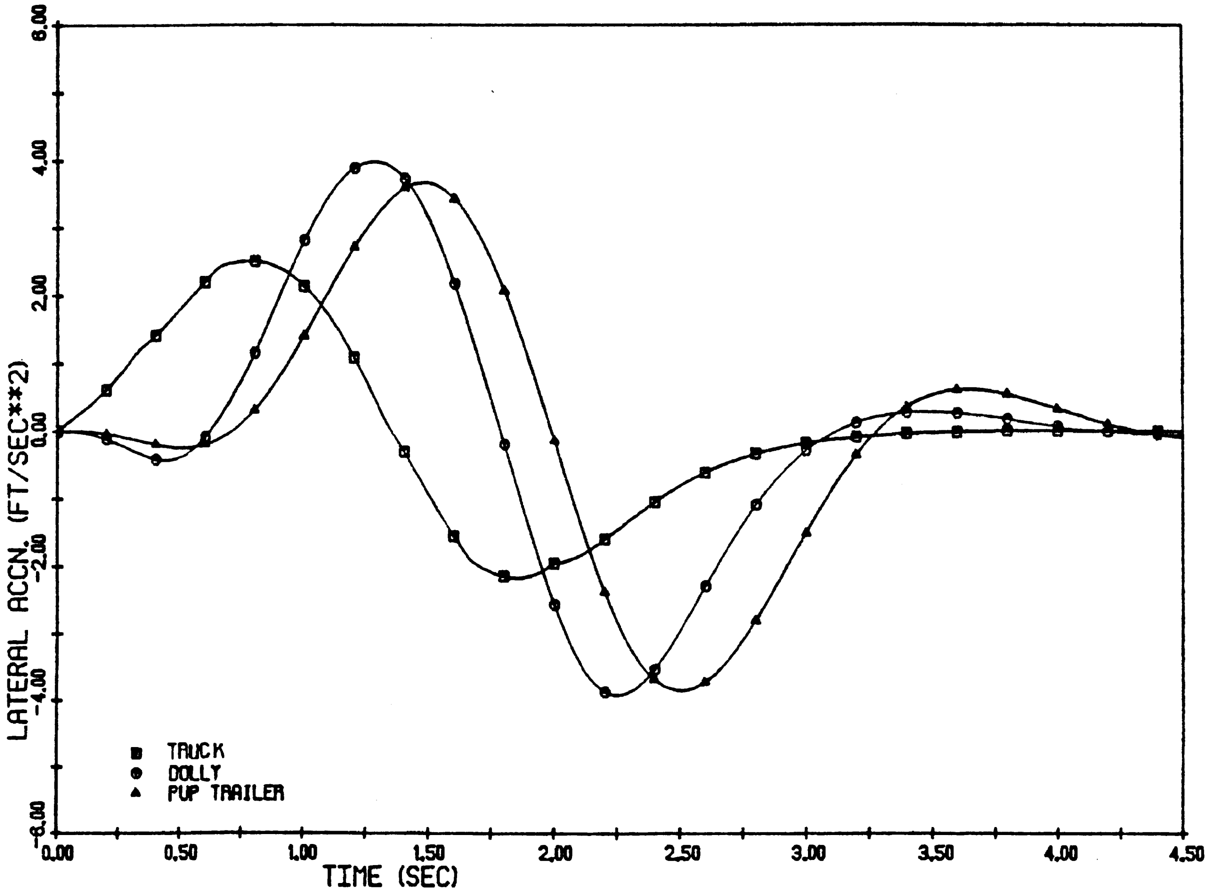
PEAK GAINS OF LATERAL ACCELERATION RESPONSE

Figure 6



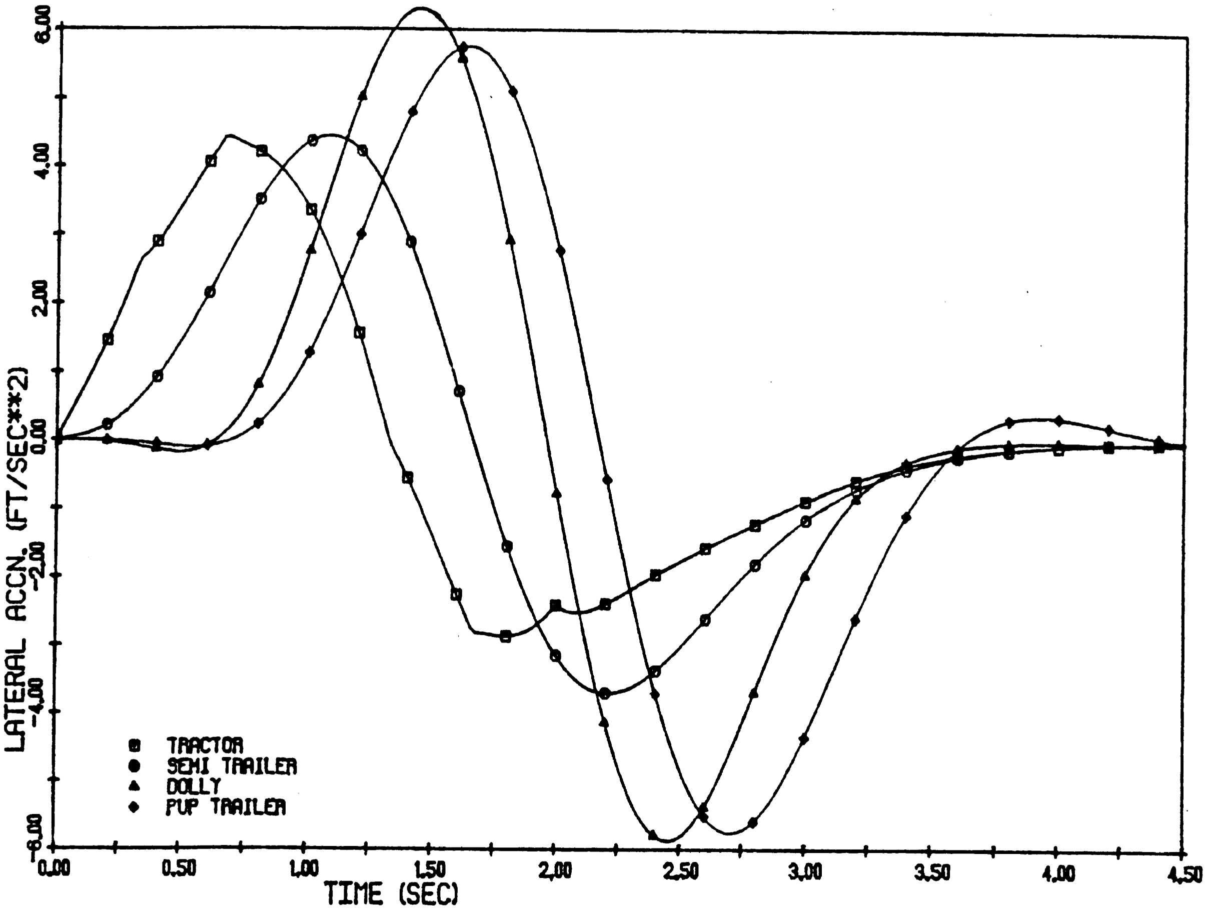
TRACTOR-SEMI BKD-0065 LOADED , DATASET#5

Figure 8



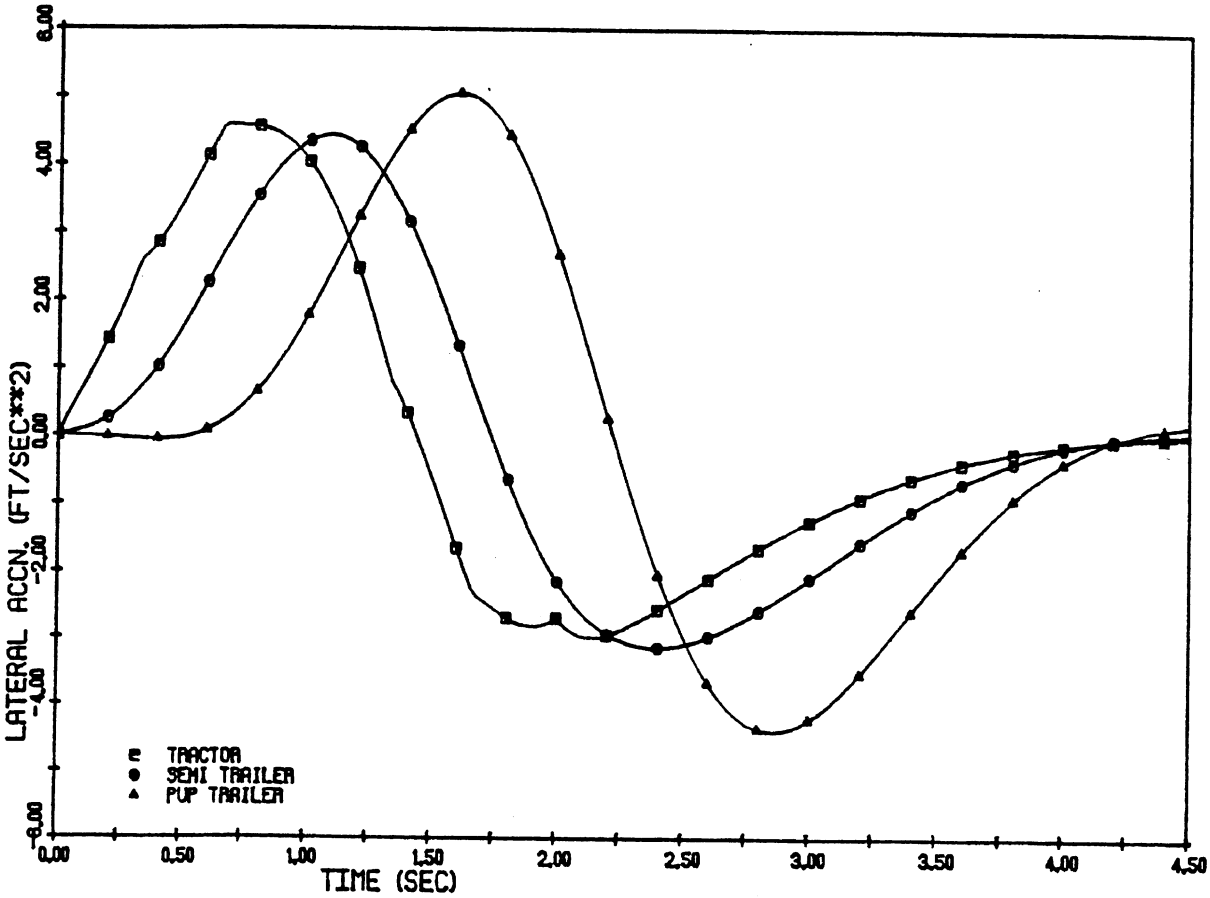
TRUCK/FULL-TRAILER BLY-2714 , LOADED , DATASET#15

Figure 9



DOUBLE-TANKER-BLY-2985, FULLY LOADED DATASET#19

Figure 10a



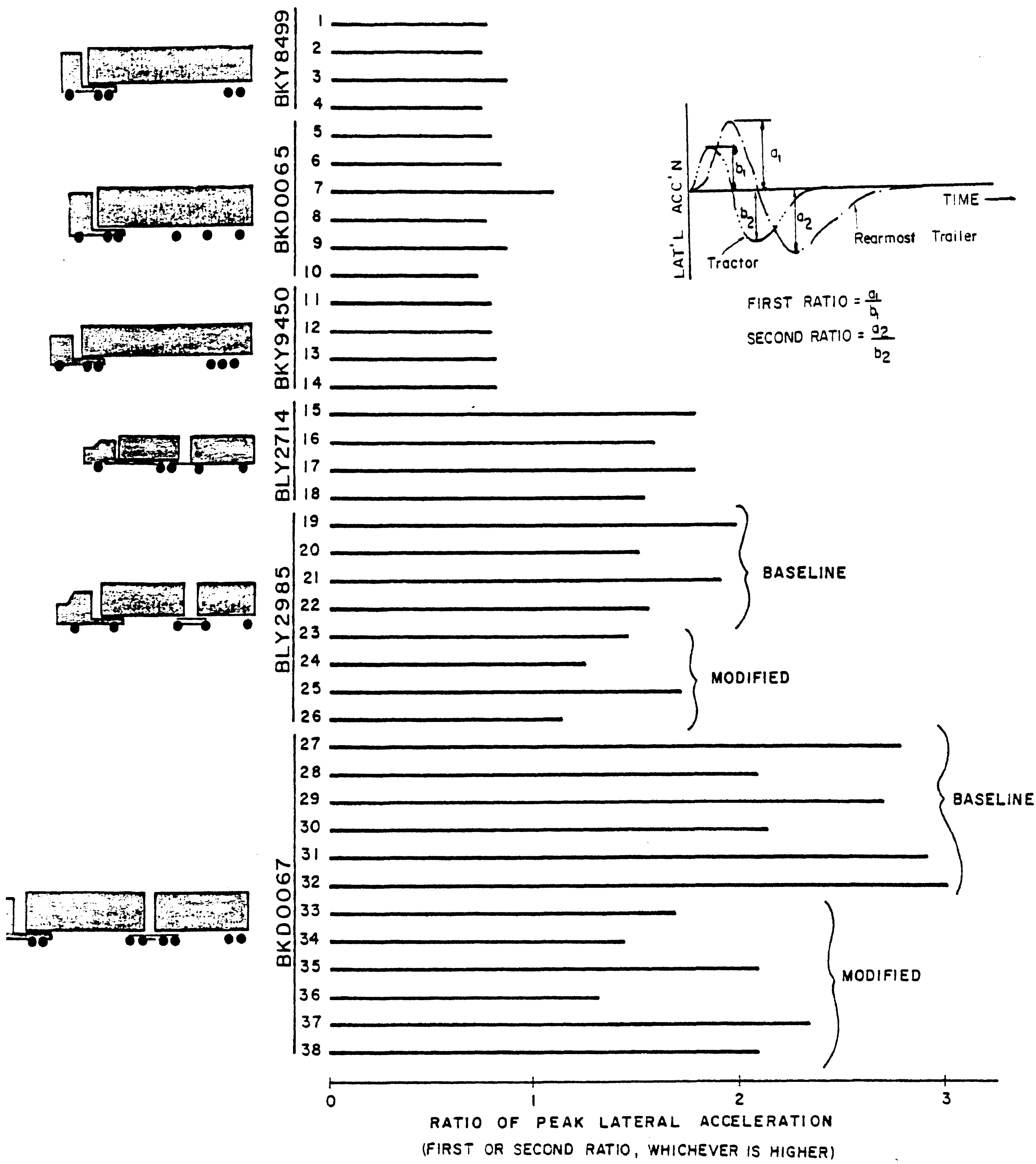
MODIFIED-DOUBLE-BLY-2985, FULLY LOADED DATASET#23

Figure 10b

The ratio between the peak lateral acceleration of the rearmost trailer and that of the tractor serves as a good index of directional stability and also of the extent to which the rear trailers are susceptible to a rollover during emergency maneuvers. Figure 11 presents a summary of the peak lateral acceleration ratios (gains) for the 38 cases analyzed in this study. An inspection of Figure 11 shows that all the three semi-trailers (except Case #7) have peak lateral acceleration gains which are less than 1.0. Both the truck/full-trailer (BLY2714) and the baseline five-axle double tanker (BLY2985) exhibit amplification levels which lie in the range of 1.5 to 2.0.

Modification of the pintle hook reduced the average peak lateral acceleration gain of the five-axle double tanker (BLY2985) by 21 percent—from 1.77 to 1.39. (By average we mean the average for all the four loading conditions.)

A larger reduction of 30 percent (from 2.82 to 1.83) was produced by rigidizing the pintle hook of the nine-axle double tanker (BKD0067).



LATERAL ACCELERATION GAIN DURING EMERGENCY MANUEVERS

Figure 11

5.0 ROLL RESPONSE

The methodology used, and the results obtained, from rollover threshold calculations are presented in this chapter. A dynamic roll model was used in simulating the roll behavior of the vehicles during (1) steady turns and (2) two-second emergency-type lane-change maneuvers. Table 1 defines the thirteen vehicle configurations for which calculations were performed. Results from an investigation of the influence of suspension backlash on the rollover threshold are also included in this chapter.

5.1 Roll Model

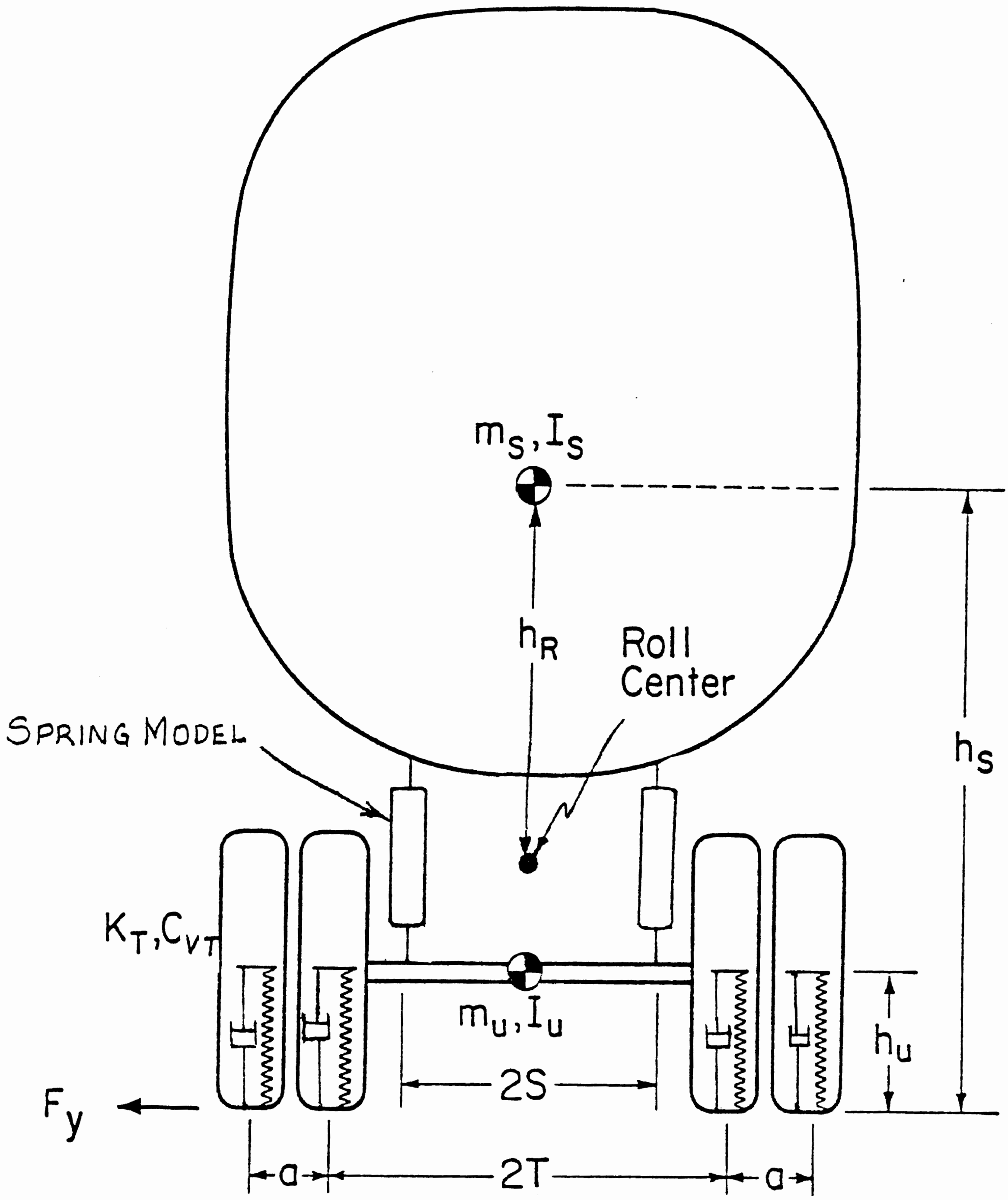
The roll model used in these calculations was a modified version of the dynamic roll model which was developed for the Michigan double tanker study [1]. All motions of the vehicle are restricted to the roll plane in this five-degree-of-freedom nonlinear roll model. The representation of the vehicle in the roll model is shown in Figure 12. The five degrees of freedom permitted in the model are:

1) lateral displacement of the unsprung mass c.g.
2) vertical displacement of the unsprung mass c.g.
3) roll of the unsprung mass with respect to the ground
4) roll of the sprung mass with respect to the unsprung mass
5) vertical motion of the sprung mass with respect to the unsprung mass.

Itemized below are the important simplifying assumptions made in the process of modeling the vehicle.

1) All sprung and unsprung mass characteristics which are distributed along the length of the vehicle are lumped together and are assumed to be present in a single roll plane.

Multi-articulated vehicles in which all units are rigidly coupled in roll (such as tractor-semitrailers and double tankers with a rigidized pintle hook) are represented in the model by combining all sprung mass, unsprung mass, and suspension characteristics. In the case of vehicles



REPRESENTATION OF THE VEHICLE IN THE DYNAMIC ROLL MODEL

Figure 12

such as a conventional double tanker, where very little roll coupling exists between the pup trailer and the rest of the vehicle, the pup trailer alone is represented and analyzed.

2) The time history of the lateral force at the tire-road interface is assumed to be a known quantity and is used as input for simulating the roll response of the vehicle (see Section 3.2).

3) Vertical stiffness and damping of the tires are represented by linear springs and viscous dampers, as shown in Figure 12.

4) The sprung mass is assumed to roll about a roll axis which is at a fixed height beneath the sprung mass c.g., permitting both vertical and roll motion of the sprung mass with respect to the unsprung mass.

5) Two suspension spring models are available as options:

a) a suspension represented by linear springs and coulomb friction elements, with a dead zone (which is used to represent suspension backlash), and

b) a suspension spring model which can be used to fit measured force-deflection characteristics.

The complete set of differential equations which describe the roll dynamics are presented in Reference [1]. A listing of the computer program along with a description of the spring models is given in Appendix E. Roll parameters of all the vehicle configurations along with spring data are listed in Appendix F. Vehicle parameters such as sprung and unsprung masses and c.g. height were estimated from drawings supplied by the Fruehauf Corporation. The roll moments of inertia were estimated based on the size and weight of the sprung and unsprung masses. The suspensions were represented by parameters which gave a best fit to the spring data supplied by the Fruehauf Corporation.

5.2 Time Histories of Lateral Force

Time histories of the lateral force at the tire-road interface were used as input for the simulation of roll response. The rollover threshold for each vehicle was computed by conducting a series of simulations. The lateral force level was increased in small steps, until the rollover limit was reached. The critical force level needed to roll the vehicle over was then used to compute the rollover threshold in g's.

A forcing function of the form shown in Figure 13 was used for simulating steady turns. The smooth, but rapidly rising, shape of the curve was chosen so as to keep the roll transients small while at the same time avoiding long simulation times.

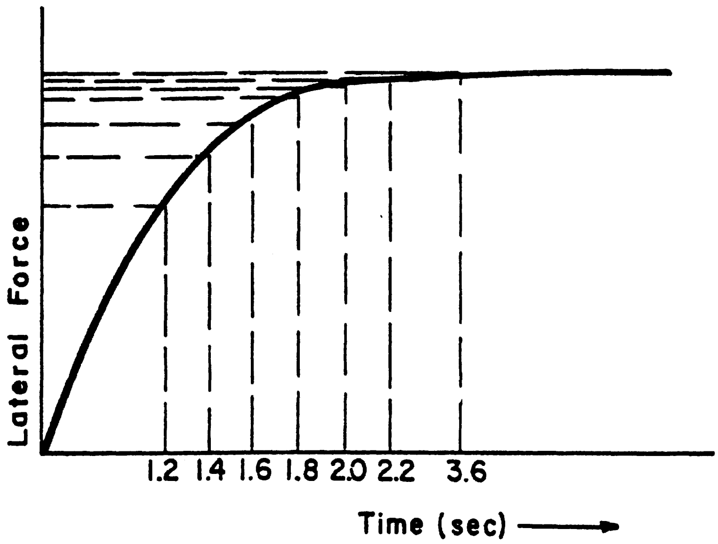
Since the shape and magnitude of the lateral force time history is not known for a lane-change maneuver, it was obtained by an indirect method which is described below:

First the directional response of the vehicle during a two-second lane-change maneuver was simulated using the linear yaw model described in Section 4.1. It was not possible to directly use the lateral force time history (from the directional response calculation) as input for the roll simulation due to the fact that its shape differed considerably from the nonlinear response observed during experiments of emergency lane-change maneuvers at the rollover limit. (See Reference [1].) At the rollover limit, it was found that the lateral acceleration response (and hence the lateral force) was of the shape shown in Figure 14a. The vehicles, moreover, exhibited a tendency to rollover during the second peak in the lateral acceleration time history. Hence, in order to make a more realistic estimate of the rollover threshold, the lateral force time history obtained from the linear model was modified. As shown in Figure 14c, a dwell (or flat top) of 0.4 sec. was added to the second peak of the lateral force time history obtained from the linear model.

5.3 Simulation Results

Results of rollover threshold computations are presented in this section. First, examples of roll response during simulations of steady turning and lane-change-type maneuvers are shown. Then, a summary of the rollover threshold levels is presented for all the vehicle configurations analyzed.

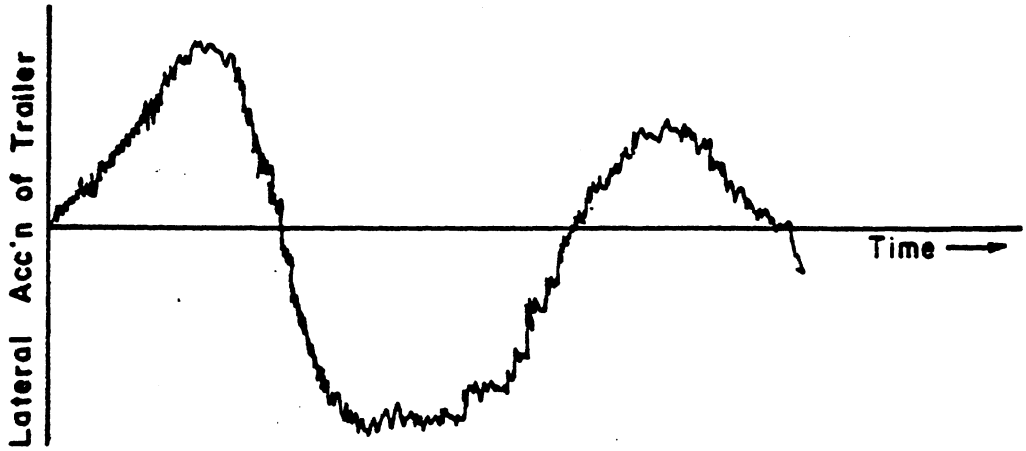
5.3.1 Roll Response During Simulation of Steady Turn. A lateral force time history which rises smoothly to the steady-state level was used for simulating steady turns. The force inputs and the roll responses shown in Figures 15a and 15b are for the modified nine-axle double (BKD0067).



TIME	FORCE
0.0	0.0
1.2	600
1.4	685
1.6	750
1.8	810
2.0	855
2.2	890
2.4	920
2.6	945
2.8	965
3.0	978
3.2	986
3.4	994
3.6	1000
6.0	1000

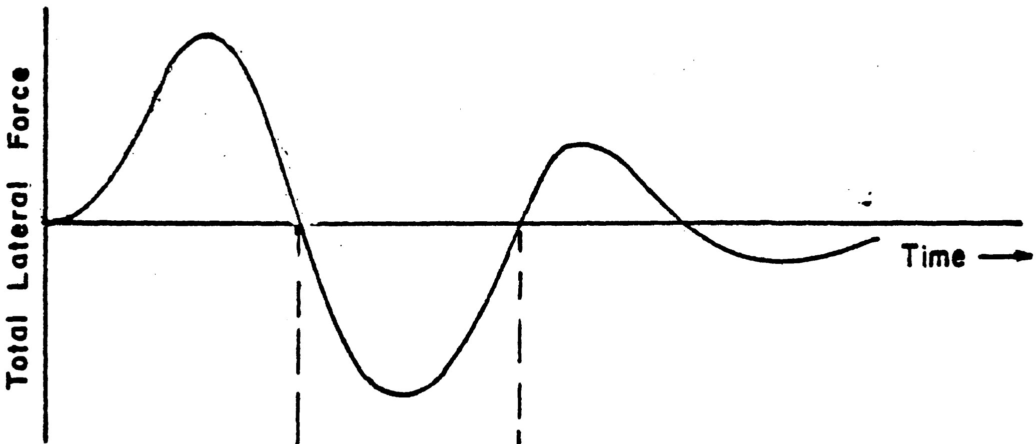
LATERAL FORCE TIME HISTORY USED FOR SIMULATING STEADY TURNS

Figure 13



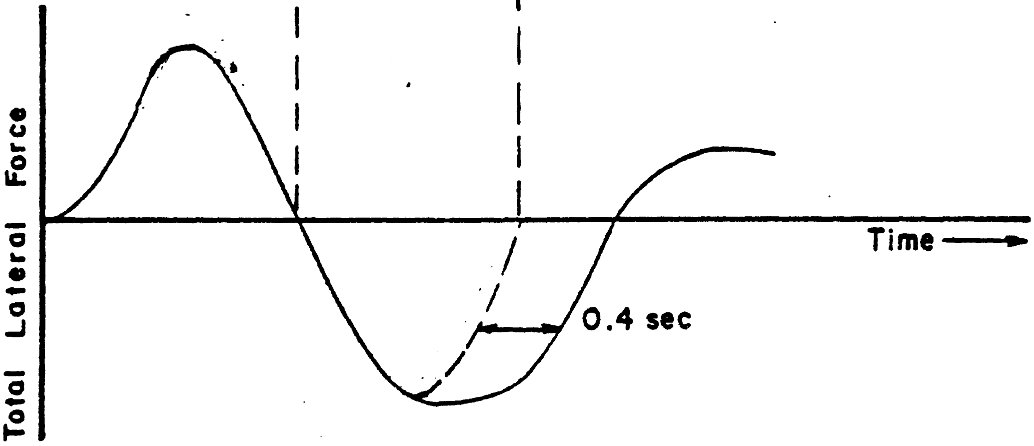
Lateral Acceleration Time History Observed During Experiment

Figure 14a



Lateral Force Time History Obtained From Linear Model

Figure 14b



Lateral Force Used as Input For Roll Simulation

Figure 14c

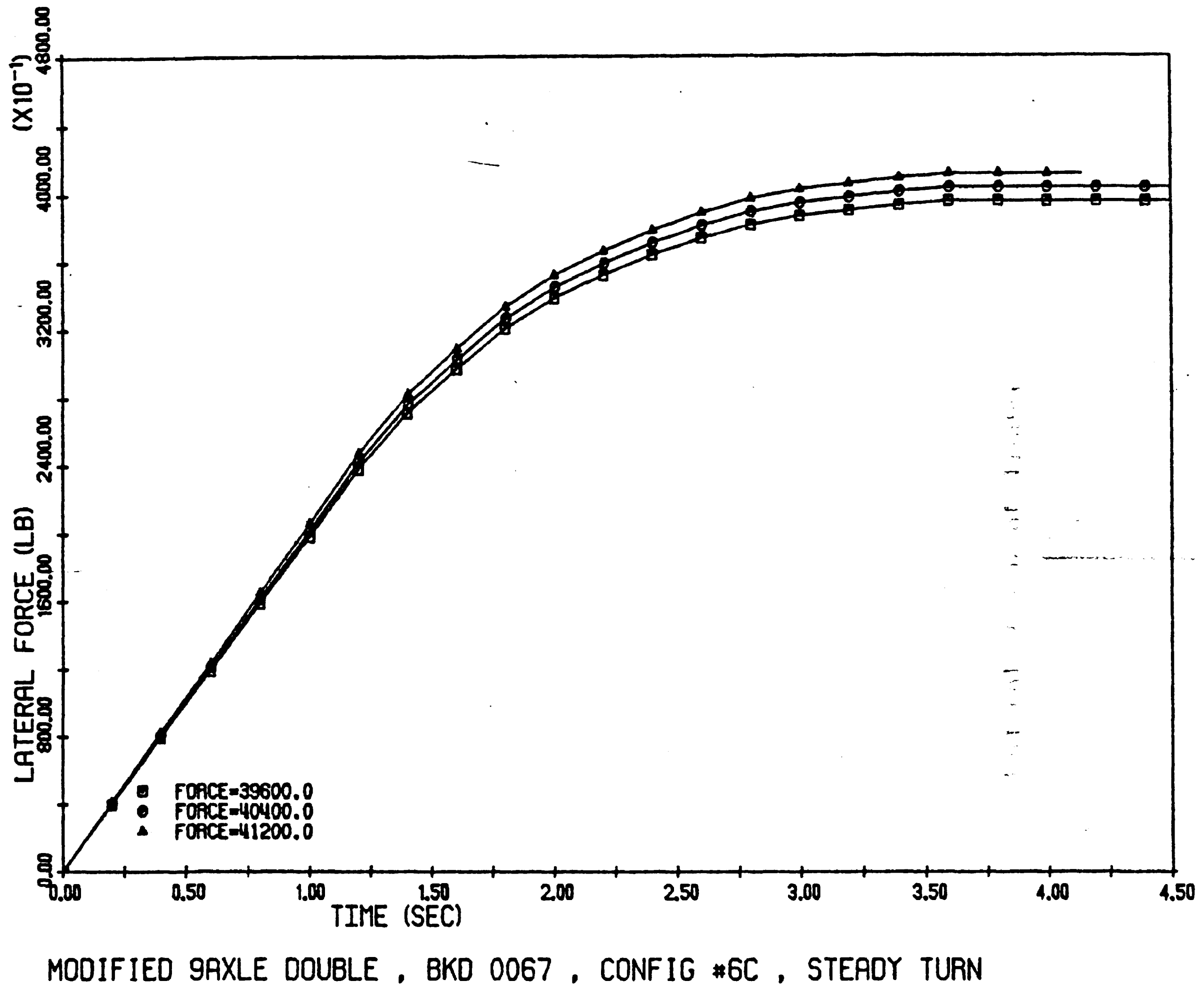


Figure 15a

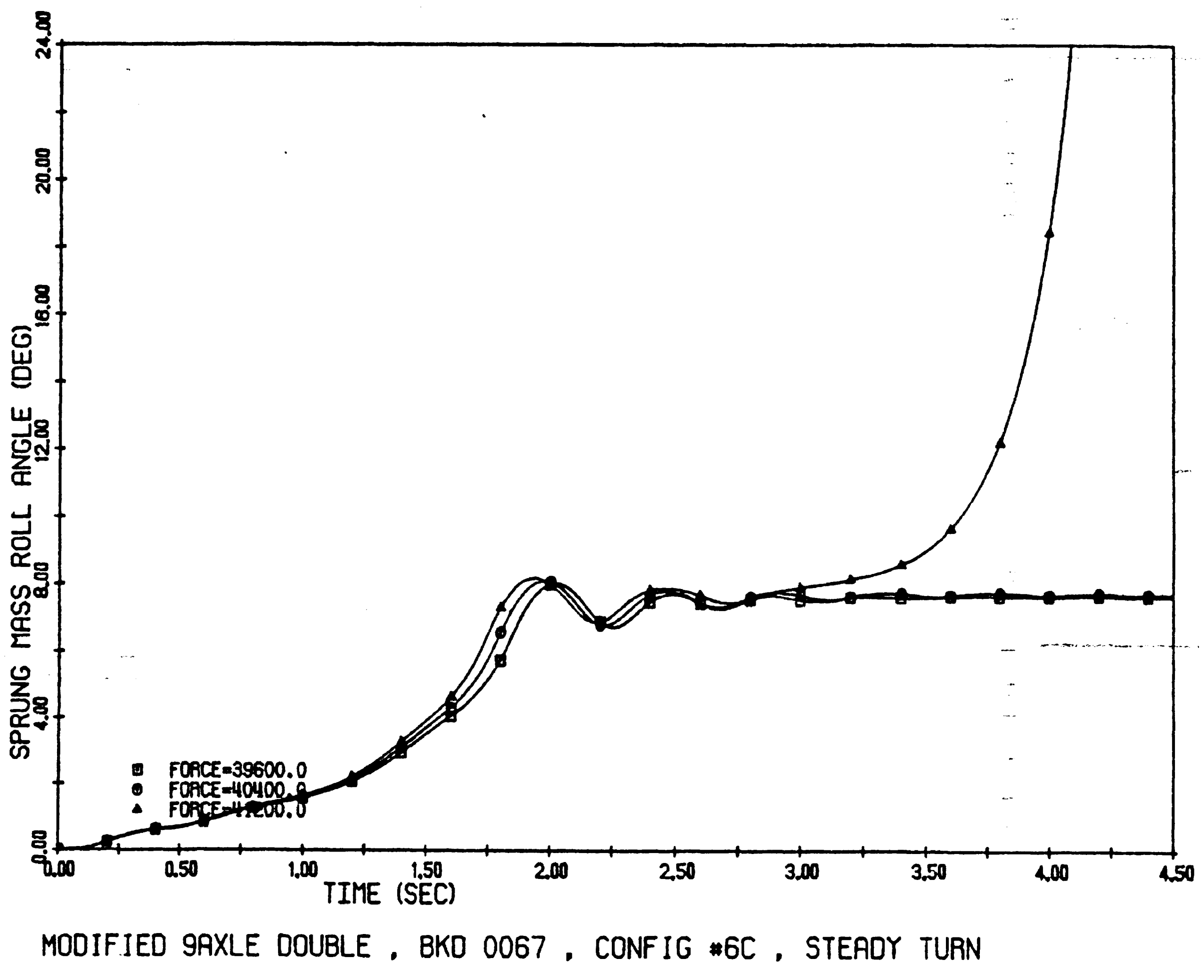


Figure 15b

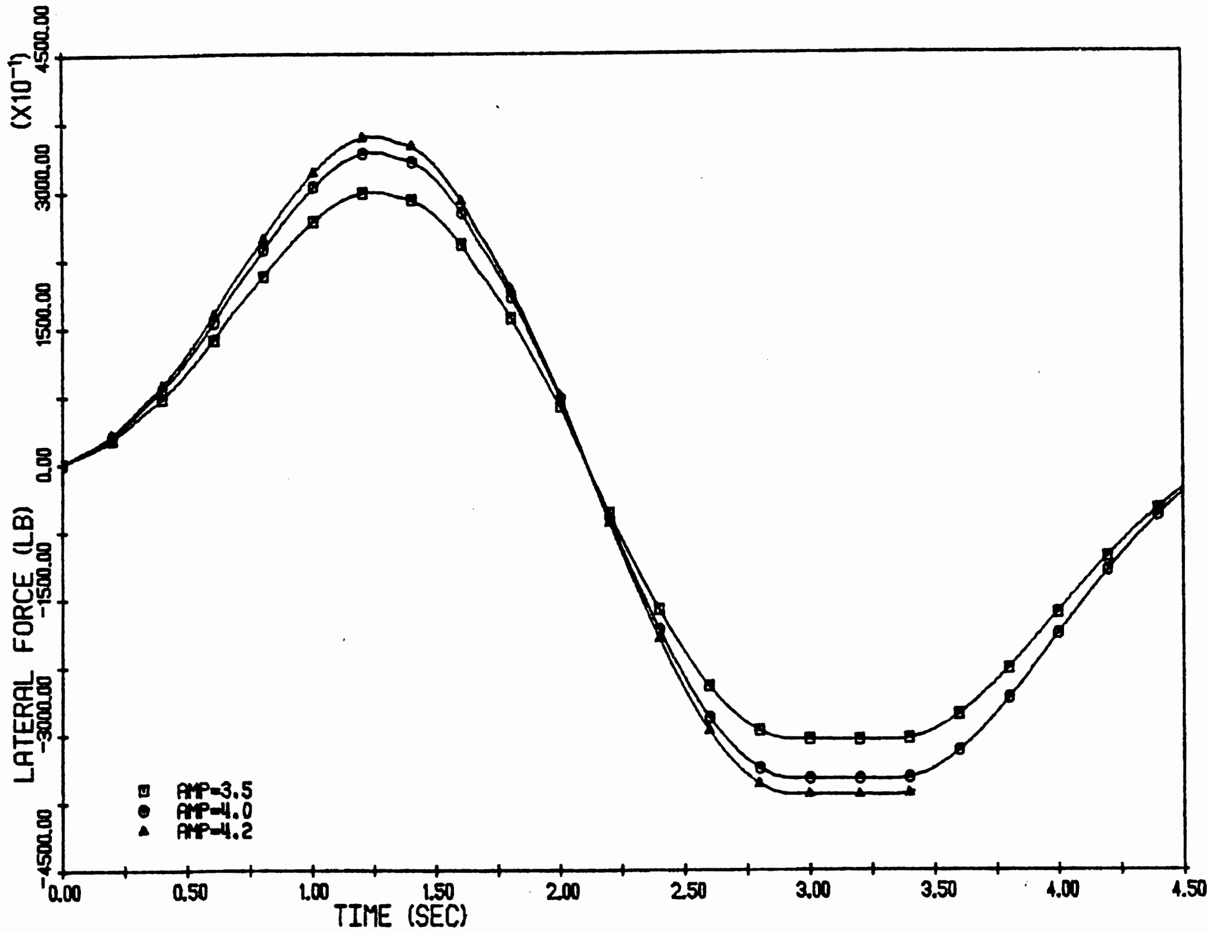
As can be seen in Figure 15b, the vehicle rolled over when a lateral force level of 41,200 lbs was applied. This lateral force of 41,200 lbs, when translated to g units, gives a rollover threshold of 0.39 g's.

Despite the use of a smoothly increasing lateral force input, some oscillatory roll transients in the sprung mass motion (see Fig. 15b) were found to occur. The small errors in rollover threshold calculations, which result from such an oscillatory roll motion, result in rollover threshold estimates which are on the conservative side. (By conservative, we mean that the estimated rollover threshold will, if at all, be slightly lower than the actual threshold level during an ideal steady turn.)

5.3.2 Roll Response During Simulation of Lane-Change Maneuvers. The lateral force inputs and the simulated roll responses for two-second lane-change maneuvers of increasing levels of severity are shown in Figures 16a and 16b. Initially, the time history of the lateral force input was obtained from the directional response simulation for a steering input of one degree amplitude at the front wheels. The severity of the maneuver is then indicated by the amount by which the lateral force time history obtained from the directional response simulation is amplified. Typical amplification factors are labeled "AMP" in the lower left-hand corner of these figures. Figure 16b indicates that the roll response is highly nonlinear, especially at maneuver levels which approach a rollover.

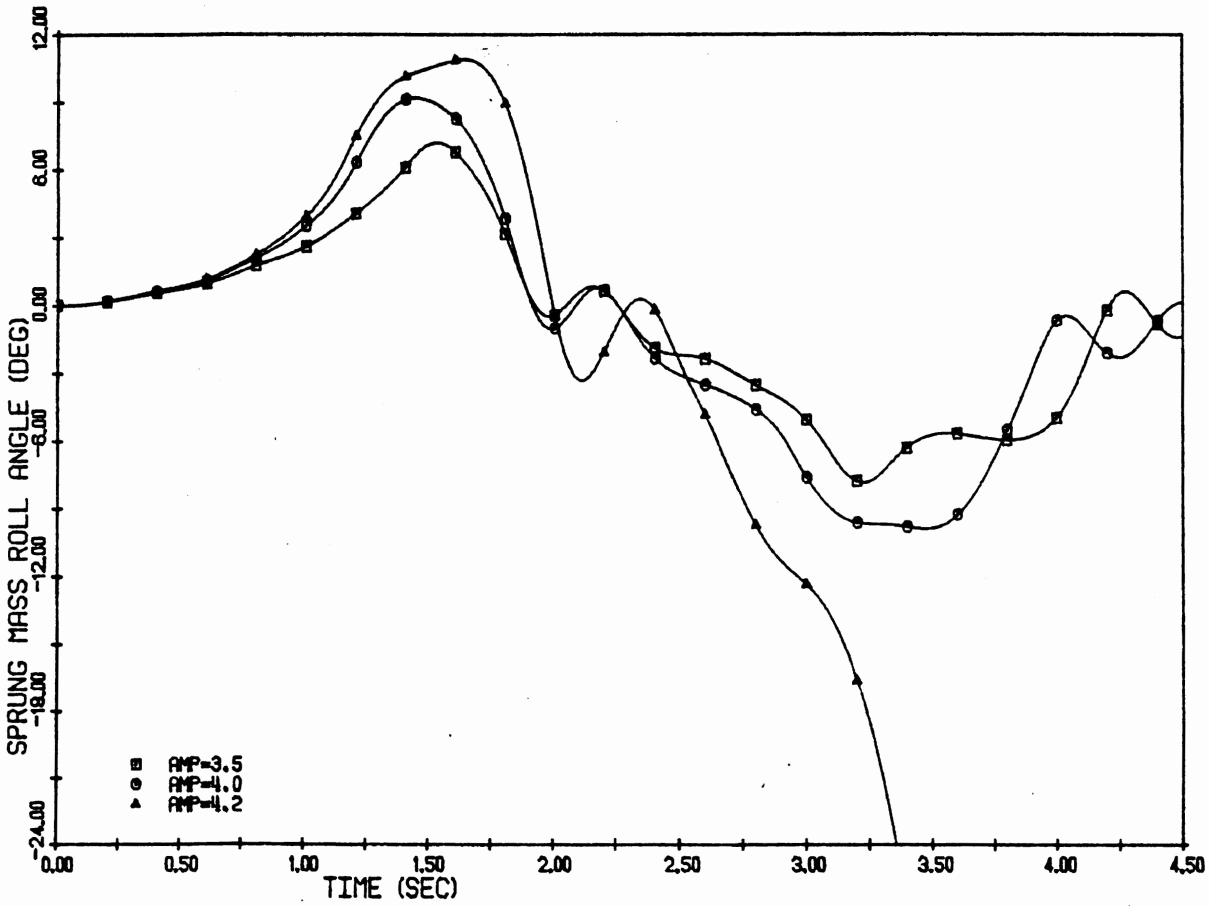
The force generated by the suspension spring model during the lane-change maneuver is shown in Figure 16c. As can be seen in this figure, the spring goes through a cycle of tension and compression during the maneuver. A comparison of Figure 16c with Figure F.1 reveals the accuracy with which the spring model can be made to fit measured spring data. The variation of vertical forces at tires on the left and right side of the vehicle are plotted in Figure 16d for a maneuver which is slightly below the rollover threshold. Wheel lift-off is indicated in this figure at points A and B.

The peak lateral acceleration level experienced by the tractor during a rollover was computed using the amplification factor (AMP). This type of calculation is illustrated as follows for Configuration 6c.



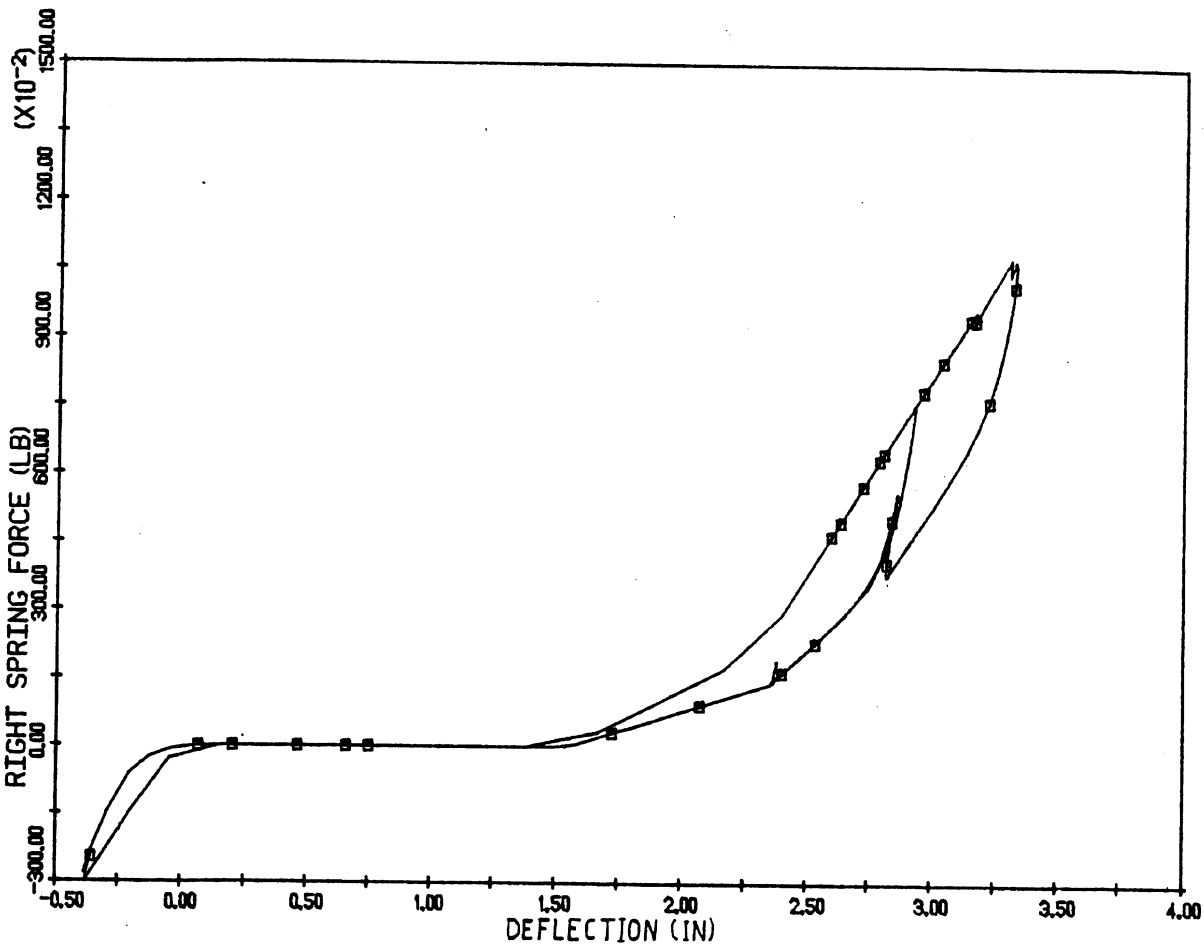
MODIFIED 9AXLE DOUBLE , BKD 0067 , CONFIG #6C

Figure 16a



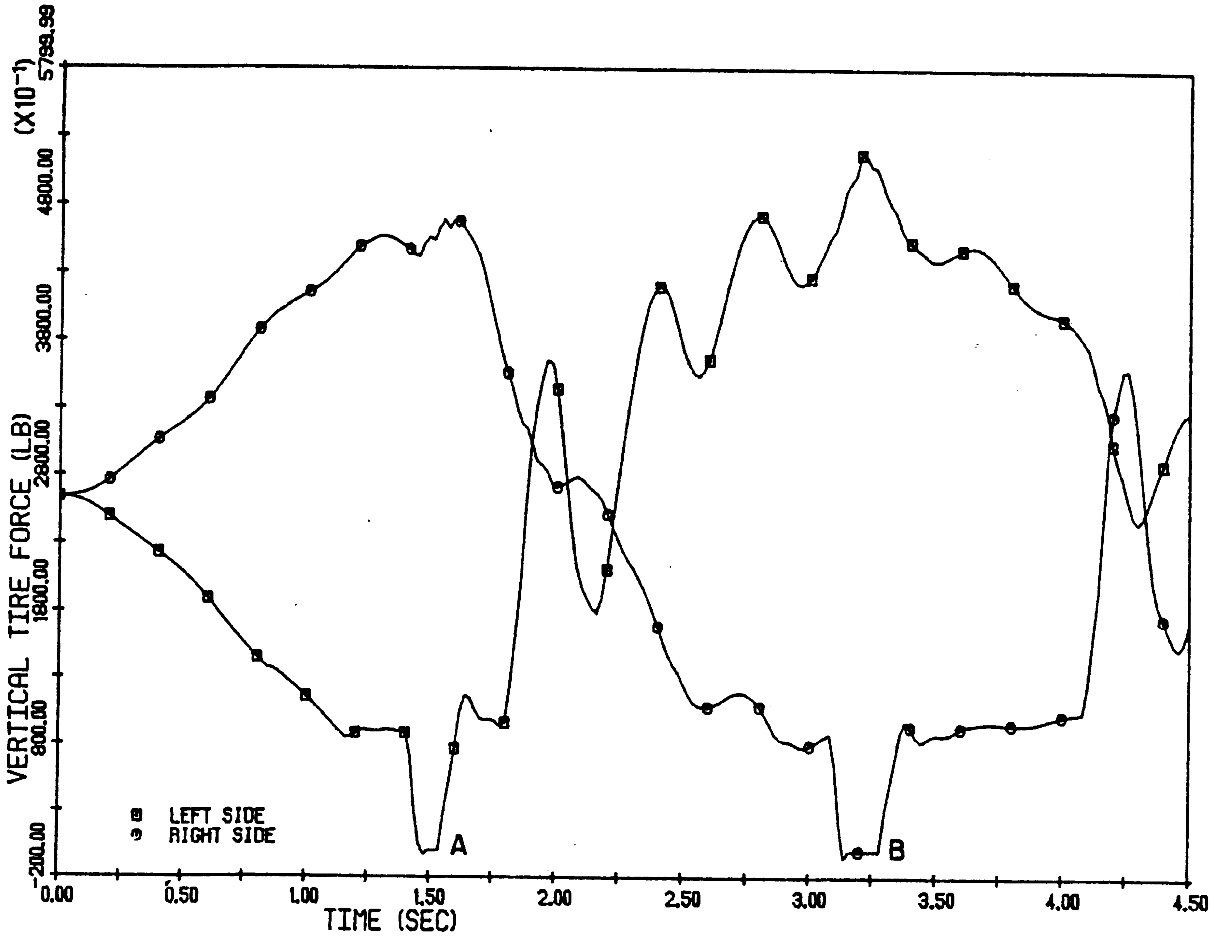
MODIFIED 9AXLE DOUBLE , BKD 0067 , CONFIG #6C

Figure 16b



MODIFIED 9AXLE DOUBLE , BKD 0067 , CONFIG #6C

Figure 16c



MODIFIED 9AXLE DOUBLE , BKD 0067 , CONFIG #6C

Figure 16d

1) The peak lateral acceleration experienced by the tractor was determined during the directional response simulation of a lane-change maneuver with a steering input of one degree amplitude at the front wheels (for Configuration 6c it was found to be 3.52 ft/sec^2 or 0.11 g).

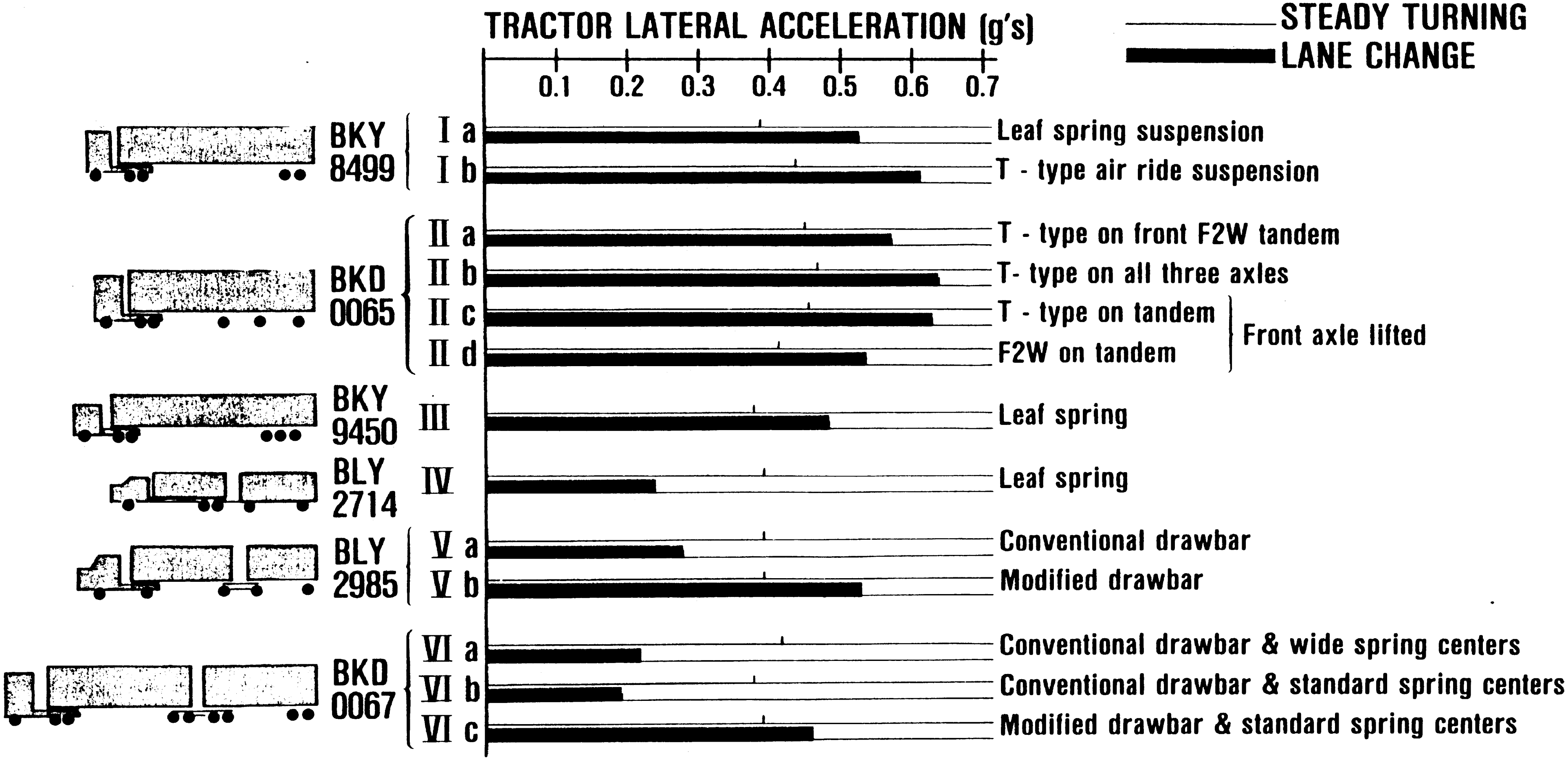
2) The tractor rollover threshold in g's was then computed as the product of the amplification factor (AMP) and the peak g level determined in (1) (for this configuration AMP = 4.2; therefore, the rollover threshold is 4.2 x 0.11 or 0.46 g).

5.3.3 Summary of Rollover Threshold Level. The rollover threshold levels are summarized in Figure 17 in a bar chart format. This figure shows the maximum lateral acceleration levels experienced by the tractor during rollover in steady turning and lane-change maneuvers.

For the vehicles analyzed, the rollover threshold levels during steady turns were found to range from 0.370 g for Configuration 6b (nine-axle double, BKD0067, with standard spring spacing and single tires) to 0.463g for Configuration 2b (six-axle tractor-semitrailer, with air suspension on all three trailer axles). Tractor-semitrailers equipped with air suspensions were found to exhibit higher rollover threshold levels than the vehicles equipped with conventional springs. This can be attributed primarily to the absence of backlash in the air suspensions.

As can be seen in Figure 17, the rollover thresholds in lane-change-type maneuvers were found to vary over a wider range. For all of the tractor-semitrailer configurations and the two modified double tanker configurations (Vb and VIc), the rollover threshold in the lane-change maneuver was found to be higher (ranging from 0.46 to 0.64 g) than in the steady turning maneuver. On the other hand, the tractor-full trailer (IV) and the conventional doubles (Va, VIa, and VIb) exhibit much lower rollover threshold levels (ranging from 0.18 g to 0.28 g) in the lane-change-type maneuver. The modification of the draw bar is seen to result approximately in a twofold increase in the rollover threshold level (compare Va with Vb and VIb with VIc). These results indicate that vehicles incorporating conventional dollies tend to have low rollover thresholds in lane-change (obstacle-avoidance) maneuvers.

ROLL STABILITY STUDY - LATERAL ACCELERATION LIMITS

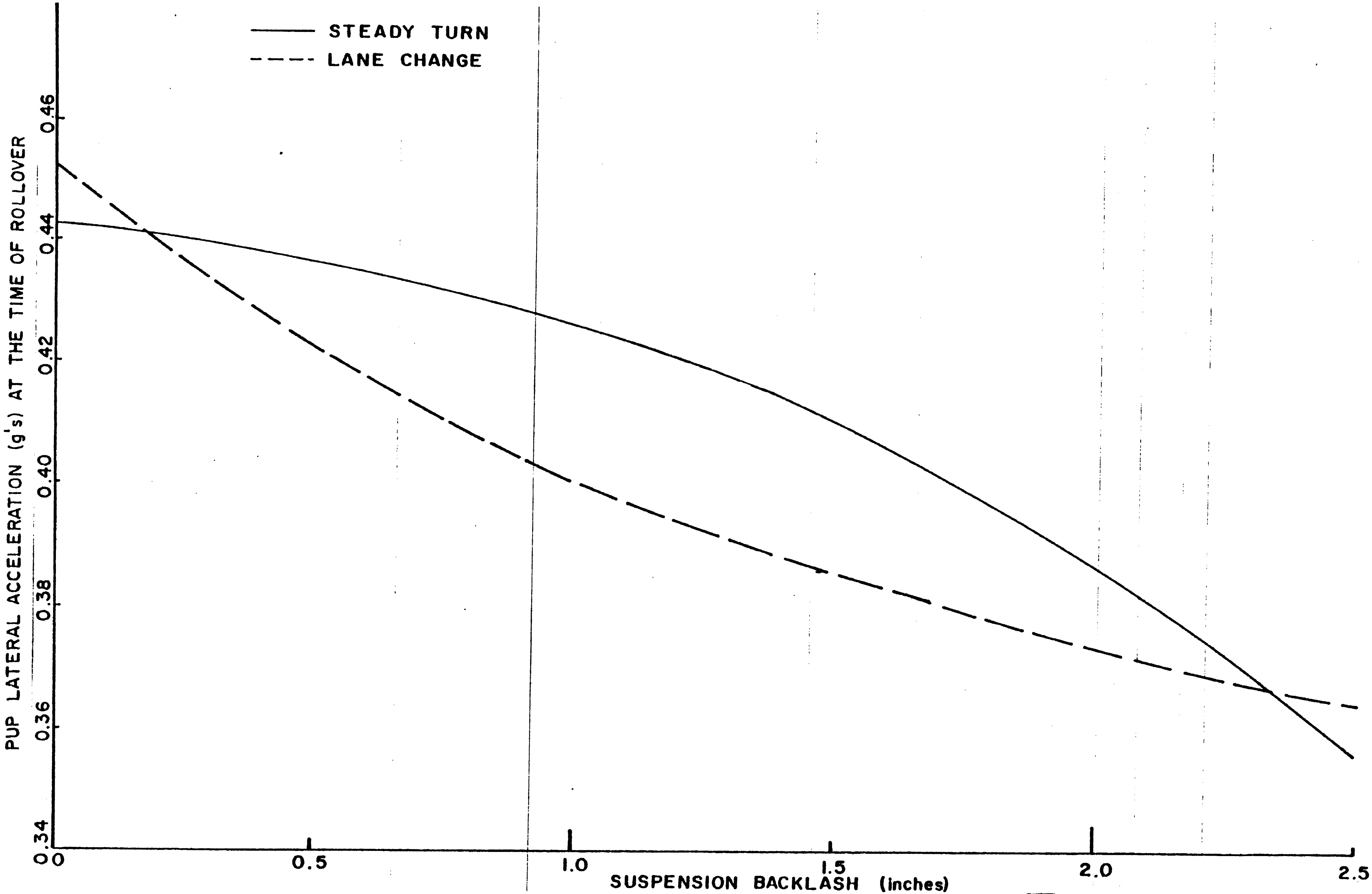


MAXIMUM LATERAL ACCELERATIONS WHEN FULLY LOADED

Figure 17

5.3.4 Influence of Suspension Backlash. The influence of suspension backlash on rollover threshold was studied for the pup trailer of the nine-axle double, BKD0067 (Configuration VIa). The results of these calculations are plotted in Figure 18 with the suspension backlash as the abscissa and the rollover threshold level of the pup trailer as the ordinate.

Suspension backlash is found to decrease the rollover threshold for both steady turning and lane-change maneuvers. For backlash values of up to 1.5 in., the decrease in the lane-change rollover threshold is found to be more rapid than the decrease in the steady turning rollover threshold. Elimination of a backlash of 1.5 in. is seen to increase the lane-change rollover threshold by 18% and the rollover threshold in a steady turn by 8.3%.



INFLUENCE OF SUSPENSION BACKLASH ON ROLLOVER THRESHOLD (for BKD0067, configuration VI a in the fully loaded condition)

Figure 18

REFERENCES

1. Ervin, R.D., et al. "Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers." Final Report prepared for Office of Highway Safety Planning, Michigan Department of State Police, Contract No. MPA-78-0D2A, Highway Safety Research Institute, University of Michigan, Report No. UM-HSRI-78-18, May 7, 1978.

APPENDIX A

PARAMETERS FOR DIRECTIONAL RESPONSE CALCULATIONS

Listed in this appendix are vehicle parameters which were used in the directional response calculations. The parameters for the 38 cases (see Table 2 for the description of each case) are listed in Tables A.1 through A.3. Table A.4 defines the symbols used in these tables. The cornering force and aligning torque data for a Fruehauf 10x20 and a Uniroyal Fleetmaster 11x22.5 tire are plotted in Figures A.1 and A.2, respectively. The Fruehauf 10x20 tire data was used on all vehicles except BKD0067, where the Uniroyal 11x22.5 data was used.

Table A.1

PARAMETER	1	2	3	4	5	6	7	8	9	10	11	12	13	14
X_{11}	90	90	90	90	78	78	78	78	78	78	78	78	78	78
X_{12}	64.5	64.5	64.5	64.5	53	53	53	53	53	53	53	53	53	53
X_{13}	115.5	115.5	115.5	115.5	103	103	103	103	103	103	103	103	103	103
X_{21}	161.0	90.7	246.1	44.06	0.2	81.7	-107.7	58.64	190.7	1.3	91.77	28.44	165.43	-14.62
X_{22}	210	139.7	295.1	93.06	109.2	190.7	1.3	167.64	299.7	110.3	140.77	77.44	214.43	34.38
X_{23}	–	–	–	–	218.2	299.7	110.3	–	–	–	189.77	126.44	263.43	83.38
X_{1A}	71.5	71.5	71.5	71.5	55.5	55.5	55.5	55.5	55.5	55.5	49.5	49.5	49.5	49.5
X_{2A}	217	287.3	131.9	333.94	214.3	132.8	322.2	264.86	132.8	322.2	200.23	263.56	126.57	306.62
W_1	15000	15000	15000	15000	16000	16000	16000	16000	16000	16000	15000	15000	15000	15000
I_1	265019	265019	265019	265019	233466	233466	233466	233466	233466	233466	233466	233466	233466	233466
W_2	63050	9550	26325	26325	67750	32065	32065	12850	32065	32065	66590	11690	30295	29990
I_2	3021888	541998	1573080	764837	3561061	1762617	1358704	655025	1762617	1358704	2935002	509175	1538829	705194
C_{11}	1296	1090	1214	1104	1336	1306	1112	1156	1320	1166	1396	1110	1320	1114
C_{12}	2308	908	1840	1051	2020	1872	740	1030	1932	1100	2140	884	1928	910
C_{13}	2308	908	1840	1051	2020	1872	740	1030	1932	1100	2140	884	1928	910
C_{21}	2308	621	788	1760	2132	801	1740	821	1028	2012	1972	486	668	1568
C_{22}	2308	621	788	1760	2132	801	1740	821	1028	2012	1972	486	668	1568
C_{23}	–	–	–	–	2132	801	1740	–	–	–	1972	486	668	1568
N_{11}	256	186	224	190	276	262	192	206	266	210	306	190	266	194
N_{12}	408	97	280	112	328	284	79	110	300	117	356	94	268	97
N_{13}	408	97	280	112	328	284	79	110	300	117	356	94	268	97
N_{21}	408	664	84	248	360	86	240	88	110	324	304	52	71	192
N_{22}	408	664	84	248	360	86	240	88	110	324	304	52	71	192
N_{23}	–	–	–	–	360	86	240	–	–	–	304	52	71	192
C_{S12}	35697	12440	28650	14400	31360	29180	10140	14110	30260	15060	33090	12090	28800	12470
C_{S13}	35697	12440	28650	14400	31360	29180	10140	14110	30260	15060	33090	12090	28800	12470
C_{S21}	35697	8510	10790	27300	33057	10970	26610	11250	14080	31284	30395	6650	9150	22470
C_{S22}	35697	8510	10790	27300	33057	10970	26610	11250	14080	31284	30395	6650	9150	22470
C_{S23}	–	–	–	–	33057	10970	26610	–	–	–	30395	6650	9150	22470
Y_{12}, Y_{13}	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Y_{21}, Y_{22}, Y_{23}	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5

Table A.2

	15	16	17	18	19	20	21	22	23	24	25	26
X_{11}	176.3	118.9	176.3	118.9	41	41	41	41	41	41	41	41
X_{12}	32.7	90.1	32.7	90.1	77	77	77	77	77	77	77	77
X_{13}	84.7	142.1	84.7	142.1	–	–	–	–	–	–	–	–
X_{21}	0.0	0.0	0.0	0.0	98.4	68.9	98.4	68.9	83.8	12.0	83.8	12.0
X_{22}	–	–	–	–	–	–	–	–	203.95	132.15	203.95	132.15
X_{31}	103.55	47.4	47.4	103.55	0.0	0.0	0.0	0.0	111.9	69.0	69.0	111.9
X_{41}	–	–	–	–	111.9	69.0	69.0	111.9	–	–	–	–
X_{1A}	161.7	219.1	161.7	219.1	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0
X_{2A}	148.0	148	148	148	120.1	149.6	120.1	149.6	134.7	206.5	134.7	206.5
X_{2B}	0.0	0.0	0.0	0.0	130.15	100.65	130.15	100.65	203.95	132.15	203.95	132.15
X_{3B}	118.95	175.1	175.1	118.95	88.4	88.4	88.4	88.4	128.6	171.5	171.5	128.6
X_{3C}	–	–	–	–	0.0	0.0	0.0	0.0	–	–	–	–
X_{4C}	–	–	–	–	128.6	171.5	171.5	128.6	–	–	–	–
W_1	42000	16100	42000	16100	11800	11800	11800	11800	11800	11800	11800	11800
I_1	1018054	462985	1018054	462985	168720	168720	168720	168720	168720	168720	168720	168720
W_2	2465	2465	2465	2465	32575	5400	32575	5400	34900	7725	34900	7725
I_2	6750	6750	6750	6750	535606	108606	535606	108606	810888	265838	810888	265838
W_3	35535	4410	4410	35535	2325	2325	2325	2325	33300	5400	5400	33300
I_3	622195	68987	68987	622195	6750	6750	6750	6750	650391	111377	111377	650391
W_4	–	–	–	–	33300	5400	5400	33300	–	–	–	–

Table A.2 (Cont.)

	15	16	17	18	19	20	21	22	23	24	25	26
I_4	–	–	–	–	650391	111377	111377	650391	–	–	–	–
C_{11}	1294	1004	1294	1004	1164	1096	1164	1096	1164	1096	1164	1096
C_{12}	2200	743	2200	743	2368	1038	2368	1038	2368	1038	2368	1038
C_{13}	2200	743	2200	743	–	–	–	–	–	–	–	–
C_{21}	2452	621	621	2452	2380	675	2380	675	2380	675	2380	675
C_{22}	–	–	–	–	–	–	–	–	2372	707	707	2372
C_{31}	2452	634	634	2452	2372	707	707	2372	2368	703	703	2368
C_{41}	–	–	–	–	2368	703	703	2368	–	–	–	–
N_{11}	256	190	256	190	210	188	210	188	210	188	210	188
N_{12}	376	79	376	79	428	111	428	111	428	111	428	111
N_{13}	376	79	376	79	–	–	–	–	–	–	–	–
N_{21}	460	66	66	460	416	72	416	72	416	72	416	72
N_{22}	–	–	–	–	–	–	–	–	428	76	76	428
N_{31}	460	68	68	460	428	76	76	428	428	75	75	428
N_{41}	–	–	–	–	428	75	75	428	–	–	–	–
C_{s12}	34057	10180	34057	10180	36746	14220	36746	14220	36746	14220	36746	14220
C_{s13}	34057	10180	34057	10180	–	–	–	–	–	–	–	–
C_{s21}	38380	8510	8510	38380	36916	9240	36916	9240	36916	9240	36916	9240
C_{s22}	–	–	–	–	–	–	–	–	36910	9685	9685	36910
C_{s31}	38380	8680	8680	38380	36910	9685	9685	36910	36746	9630	9630	36746
C_{s41}	–	–	–	–	36746	9630	9630	36746	–	–	–	–
12, y_{13}	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
, y_{22}	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
y_{41}	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5

Table A.3

	27	28	29	30	31	32	33	34	35	36	37	38
X_{11}	67.9	67.9	67.9	67.9	67.9	67.9	67.9	67.9	67.9	67.9	67.9	67.9
X_{12}	51.6	51.6	51.6	51.6	51.6	51.6	51.6	51.6	51.6	51.6	51.6	51.6
X_{13}	100.6	100.6	100.6	100.6	100.6	100.6	100.6	100.6	100.6	100.6	100.6	100.6
X_{21}	75.37	38.44	75.37	38.44	75.37	75.37	57.8	-28.9	57.8	-28.9	57.8	57.8
X_{22}	124.37	87.44	124.37	87.44	124.37	124.37	106.8	20.1	106.8	20.1	106.8	106.8
X_{23}	–	–	–	–	–	–	202.8	116.1	202.8	116.1	202.8	202.8
X_{24}	–	–	–	–	–	–	251.8	165.1	251.8	165.1	251.8	251.8
X_{31}	-24.5	-24.5	-24.5	-24.5	-24.5	-24.5	76.56	38.44	38.44	76.56	5.8	18.36
X_{32}	24.5	24.5	24.5	24.5	24.5	24.5	125.56	87.44	87.44	125.56	54.8	67.36
X_{41}	76.56	38.44	38.44	76.56	5.8	18.36	–	–	–	–	–	–
X_{42}	125.56	87.44	87.44	125.56	54.8	67.36	–	–	–	–	–	–
X_{1A}	54.1	54.1	54.1	54.1	54.1	54.1	54.1	54.1	54.1	54.1	54.1	54.1
X_{2A}	117.13	154.06	117.13	154.06	117.13	117.13	134.7	221.4	134.7	221.4	134.7	134.7
X_{2B}	148.87	111.94	148.87	111.94	148.87	148.87	227.3	140.6	227.3	140.6	227.3	227.3
X_{3B}	96.0	96.0	96.0	96.0	96.0	96.0	117.94	156.06	156.06	117.94	188.7	176.14
X_{3C}	0.0	0.0	0.0	0.0	0.0	0.0	–	–	–	–	–	–
X_{4C}	117.94	156.06	156.06	117.94	188.7	176.14	–	–	–	–	–	–
W_1	14000	14000	14000	14000	14000	14000	14000	14000	14000	14000	14000	14000
I_1	227532	227532	227532	227532	227532	227532	227532	227532	227532	227532	227532	227532
W_2	44000	7100	44000	7100	44000	44000	47400	10500	47400	10500	47400	47400
I_2	874342	143699	874342	143699	874342	874342	1379071	415691	1379071	415691	1379071	1379071
W_3	3400	3400	3400	3400	3400	3400	44100	7100	7100	44100	17470	24180
I_3	14457	14457	14457	14457	14457	14457	815119	143699	143699	815119	207183	246925
W_4	44100	7100	7100	44100	17470	24180	–	–	–	–	–	–
I_4	815119	143699	143699	815119	207183	246925	–	–	–	–	–	–

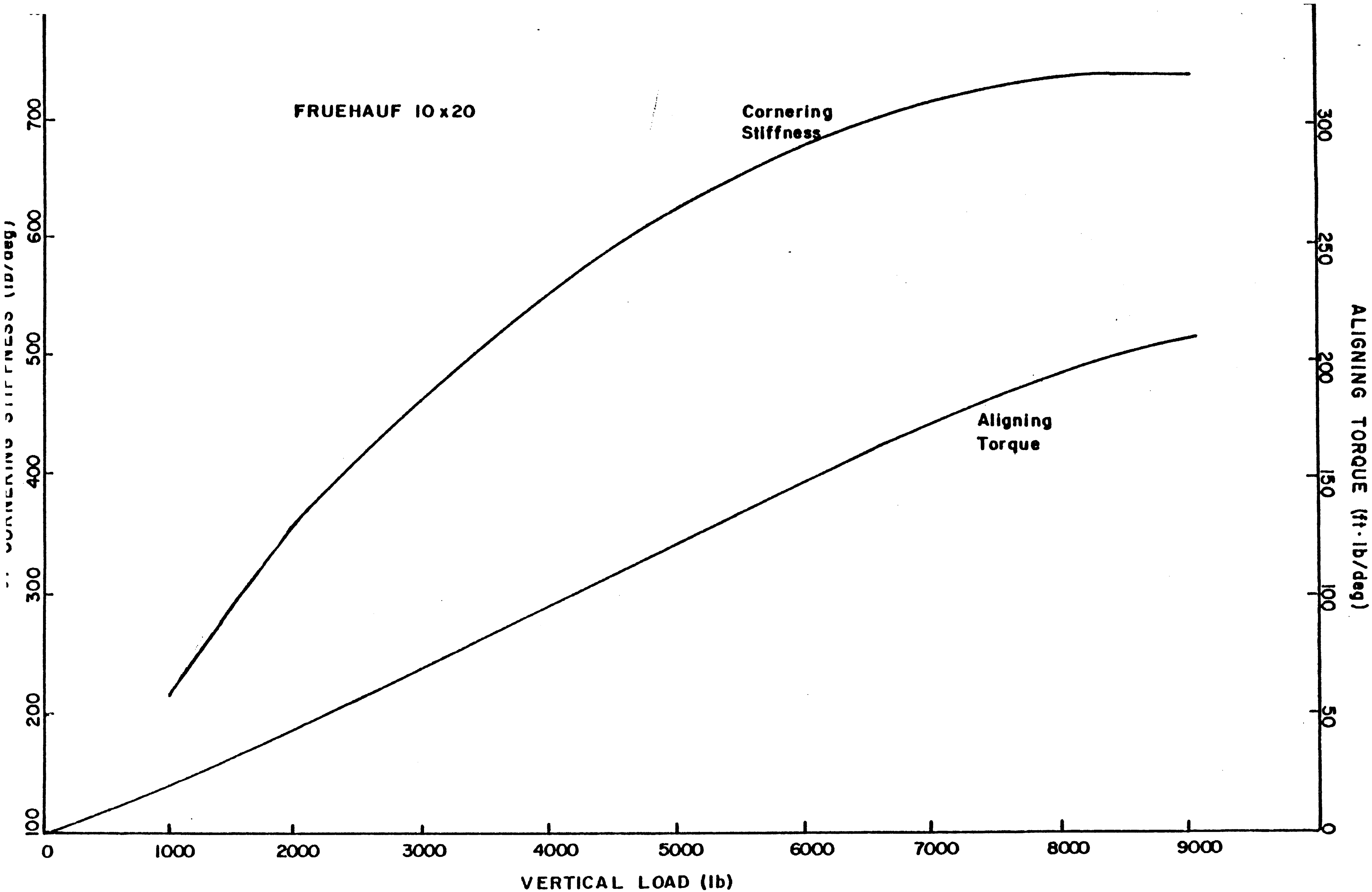
Table A.3 (Cont.)

	27	28	29	30	31	32	33	34	35	36	37	38
C_{11}	1080	880	1080	880	1080	1080	1080	880	1080	880	1080	108
C_{12}	1160	570	1160	570	1160	1160	1160	570	1160	570	1160	116
C_{13}	1160	570	1160	570	1160	1160	1160	570	1160	570	1160	116
C_{21}	1160	370	1160	370	1160	1160	1160	370	1160	370	1160	116
C_{22}	1160	370	1160	370	1160	1160	1160	370	1160	370	1160	116
C_{23}	–	–	–	–	–	–	1160	400	400	1160	420	55
C_{24}	–	–	–	–	–	–	1160	400	400	1160	420	55
C_{31}	1160	400	400	1160	420	554	1160	370	370	1160	864	103
C_{32}	1160	400	400	1160	420	554	1160	370	370	1160	864	103
C_{41}	1160	370	370	1160	864	1030	–	–	–	–	–	–
C_{42}	1160	370	370	1160	864	1030	–	–	–	–	–	–
N_{11}	180	126	180	126	180	180	180	126	180	126	180	18
N_{12}	206	56	206	56	206	206	206	56	206	56	206	20
N_{13}	206	56	206	56	206	206	206	56	206	56	206	20
N_{21}	206	30	206	30	206	206	206	30	206	30	206	20
N_{22}	206	30	206	30	206	206	206	30	206	30	206	20
N_{23}	–	–	–	–	–	–	206	34	34	206	36	54
N_{24}	–	–	–	–	–	–	206	34	34	206	36	54
N_{31}	206	34	34	206	36	54	206	30	30	206	122	166
N_{32}	206	34	34	206	36	54	206	30	30	206	122	166
N_{41}	206	30	30	206	122	166	–	–	–	–	–	–
N_{42}	206	30	30	206	122	166	–	–	–	–	–	–

Table A.4. Definition of Vehicle Parameters

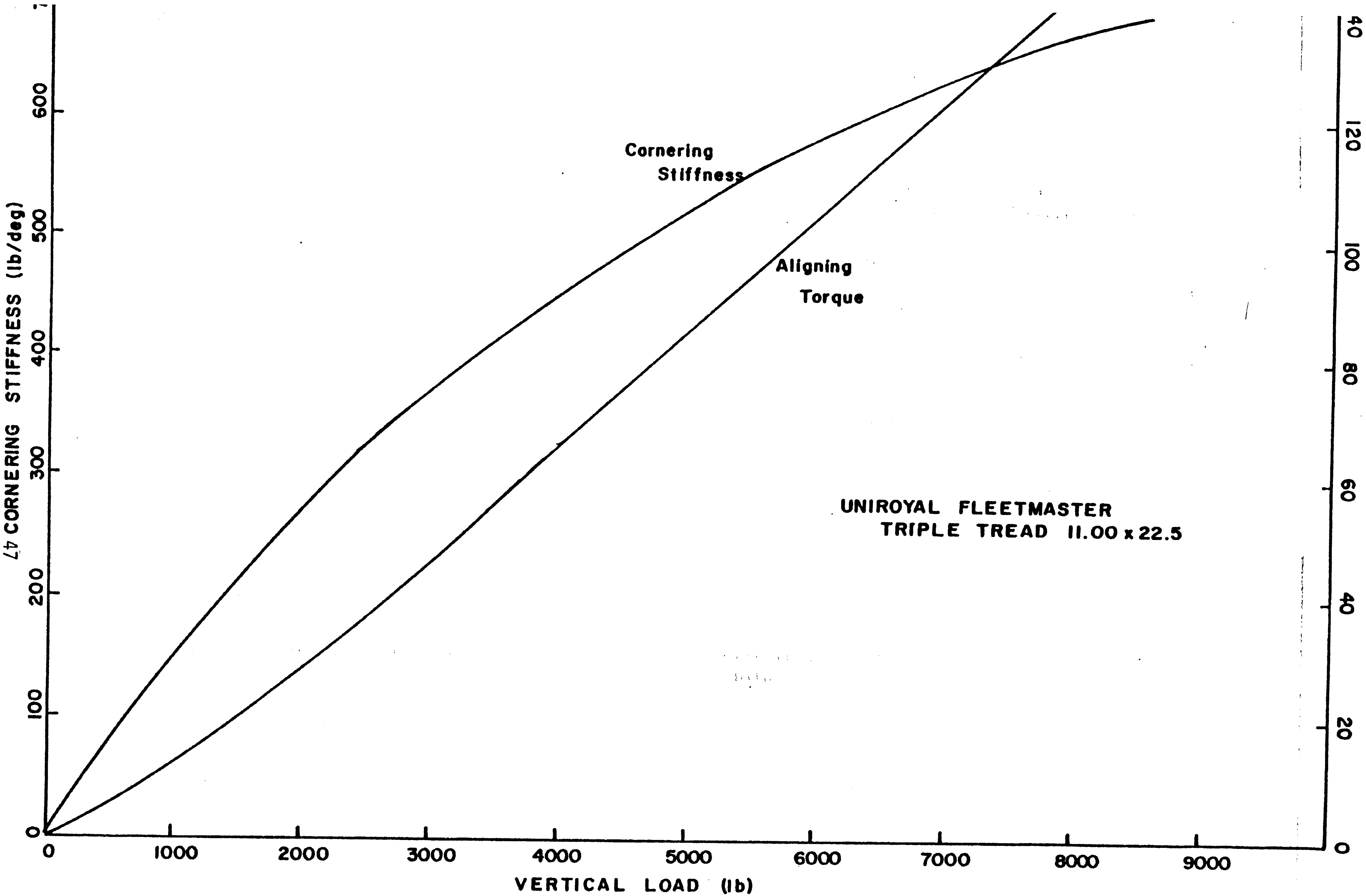
<u>Note:</u> A double subscript notation has been used when referring to the axles on the articulated vehicle train. An axle with subscript ij denotes the j^{th} axle on the i^{th} element of the train. For example, the third axle of the semitrailer (the semitrailer is the second element of the train) is referred to as axle "23."

W_i	weight of the i^{th} element of the train (lbs)
I_i	yaw moment of inertia of the i^{th} element of the train ($lb \cdot in \cdot sec^2$)
C_{ij}	sum of the cornering stiffness of all tires mounted on axle ij (lb/deg)
N_{ij}	sum of aligning moments/unit slip angle of all the tires mounted on axle ij (ft•lb/deg)
C_{sij}	longitudinal stiffness of one tire on axle ij (lb)
X_{ij}	distance of axle ij from the mass center of the i^{th} element (in)
X_{1A}	distance of tractor fifth wheel from mass center of tractor (in)
X_{2A}	distance of tractor fifth wheel from mass center of semitrailer (in)
X_{2B}	distance of pintle hook from mass center of semitrailer (in)
X_{3B}	distance of pintle hook from mass center of dolly (in)
X_{3C}	distance of dolly fifth wheel from mass center of dolly (in)
X_{4C}	distance of dolly fifth wheel from mass center of pup trailer (in)
y_{ij}	spacing distance between the dual tires on axle ij (in)



FRUEHAUF 10 x 20
Cornering Stiffness
Aligning Torque
100
200
300
400
500
600
700
0
50
100
150
200
250
300
ALIGNING TORQUE (ft·lb/deg)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
VERTICAL LOAD (lb)

Figure A.1


CORNERING STIFFNESS (lb/deg)
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
VERTICAL LOAD (lb)
Cornering
Stiffness
Aligning
Torque
UNIROYAL FLEETMASTER
TRIPLE TREAD 11.00 x 22.5
Figure A.2

APPENDIX B

EIGENVALUES AT 50 MPH

Natural Frequency and Damping Ratios of the Eigenvalues at a Forward Speed of 50 mph.

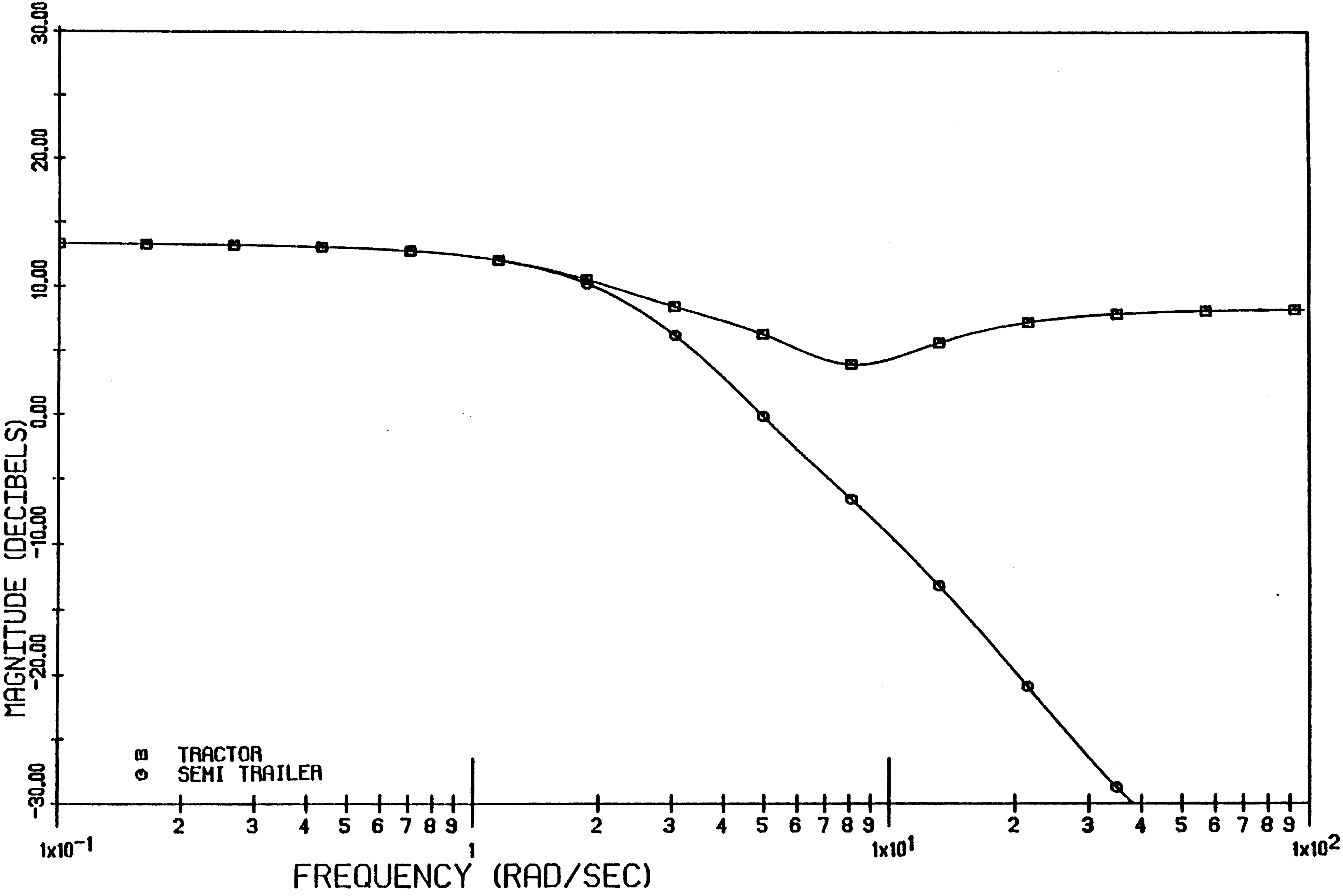
VEHICLE	CASE NO.	ROOT #1		ROOT #2		ROOT #3		ROOT #4	
		ω_1	ξ_1	ω_2	ξ_2	ω_3	ξ_3	ω_4	ξ_4
BKY 8499	1	6.685	0.821	2.798	0.915	–	–	–	–
BKY 8499	2	3.289	0.832	5.574	0.840	–	–	–	–
BKY 8499	3	5.829	0.843	3.449	0.920	–	–	–	–
BKY 8499	4	6.166	0.811	2.968	0.841	–	–	–	–
BKD 0065	5	2.925	0.736	5.854	0.831	–	–	–	–
BKD 0065	6	3.530	0.807	5.790	0.823	–	–	–	–
BKD 0065	7	2.274	0.510	5.140	0.922	–	–	–	–
BKD 0065	8	5.803	0.803	3.297	0.831	–	–	–	–
BKD 0065	9	6.022	0.815	3.482	0.893	–	–	–	–
BKY 9450-1	10	2.840	0.696	5.634	0.826	–	–	–	–
BKY 9450-1	11	3.285	0.788	6.571	0.796	–	–	–	–
BKY 9450-1	12	3.279	0.687	5.292	0.834	–	–	–	–
BKY 9450-1	13	3.667	0.794	6.061	0.815	–	–	–	–
BKY 9450-1	14	3.289	0.728	5.384	0.824	–	–	–	–
BLY 2714	15	3.401	0.460	6.195	0.479	3.772	0.927	–	–
BLY 2714	16	5.547	0.465	4.146	0.522	5.052	0.877	–	–
BLY 2714	17	5.628	0.471	4.133	0.526	3.885	0.922	–	–
BLY 2714	18	6.219	0.483	3.399	0.483	4.786	0.869	–	–
BLY 2985 BASELINE	19	7.342	0.394	3.644	0.498	5.618	0.563	2.789	0.941
BLY 2985 BASELINE	20	6.452	0.341	5.033	0.567	4.207	0.587	3.794	0.815
BLY 2985 BASELINE	21	6.882	0.354	4.196	0.571	5.711	0.574	2.772	0.950
BLY 2985 BASELINE	22	7.272	0.400	3.426	0.497	4.851	0.533	3.930	0.809
BLY 2985 MODIFIED	23	5.729	0.590	2.607	0.660	3.121	0.918	–	–
BLY 2985 MODIFIED	24	5.099	0.614	3.064	0.647	4.135	0.809	–	–
BLY 2985 MODIFIED	25	5.490	0.599	4.002	0.625	2.612	0.989	–	–
BLY 2985 MODIFIED	26	2.348	0.496	5.526	0.600	4.252	0.843	–	–

VEHICLE	CASE No.	ROOT #1		ROOT #2		ROOT #3		ROOT #4	
		ω_1	ξ_1	ω_2	ξ_2	ω_3	ξ_3	ω_4	ξ_4
BKD 0067 BASELINE	27	3.134	0.383	5.841	0.384	4.059	0.499	2.859	0.988
	28	4.777	0.363	4.504	0.475	4.039	0.512	3.512	0.842
	29	5.622	0.360	3.960	0.474	4.068	0.512	2.824	0.992
	30	3.019	0.330	5.822	0.465	4.016	0.467	3.588	0.845
	31	5.661	0.359	3.382	0.418	4.136	0.508	2.825	0.992
	32	6.494	0.394	3.221	0.402	4.082	0.508	2.829	0.992
BKD 0067 MODIFIED	33	4.471	0.499	2.209	0.517	-3.408*	-2.710*	–	–
	34	4.301	0.534	2.813	0.593	3.713	0.839	–	–
	35	4.331	0.531	3.427	0.571	-3.581*	-1.930*	–	–
	36	2.051	0.410	4.431	0.499	3.853	0.865	–	–
	37	3.139	0.498	4.084	0.543	-3.587*	-1.959*	–	–
	38	2.749	0.521	4.650	0.536	-3.660*	-1.989*	–	–

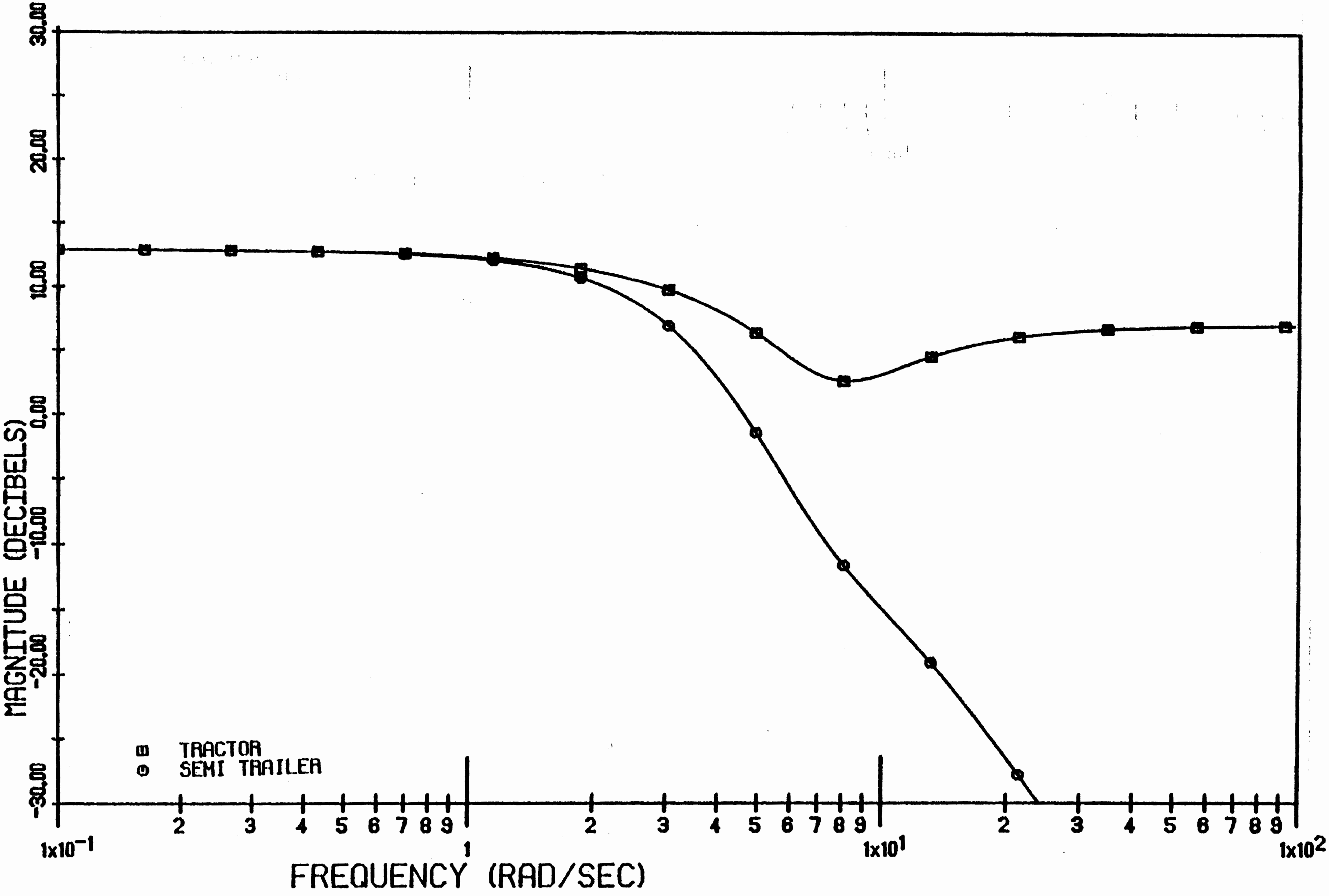
* REAL ROOTS

APPENDIX C

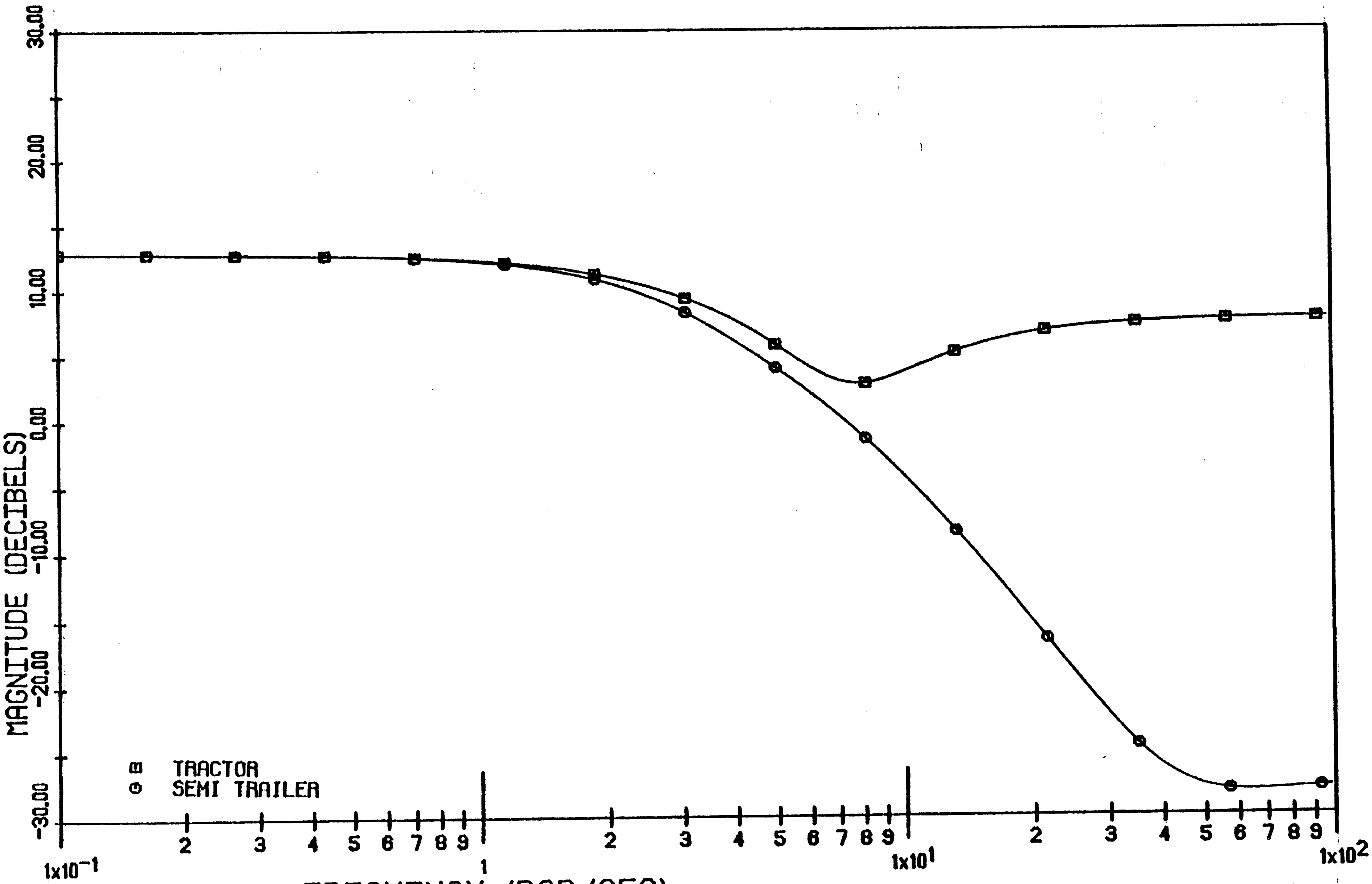
LATERAL ACCELERATION FREQUENCY RESPONSE PLOTS



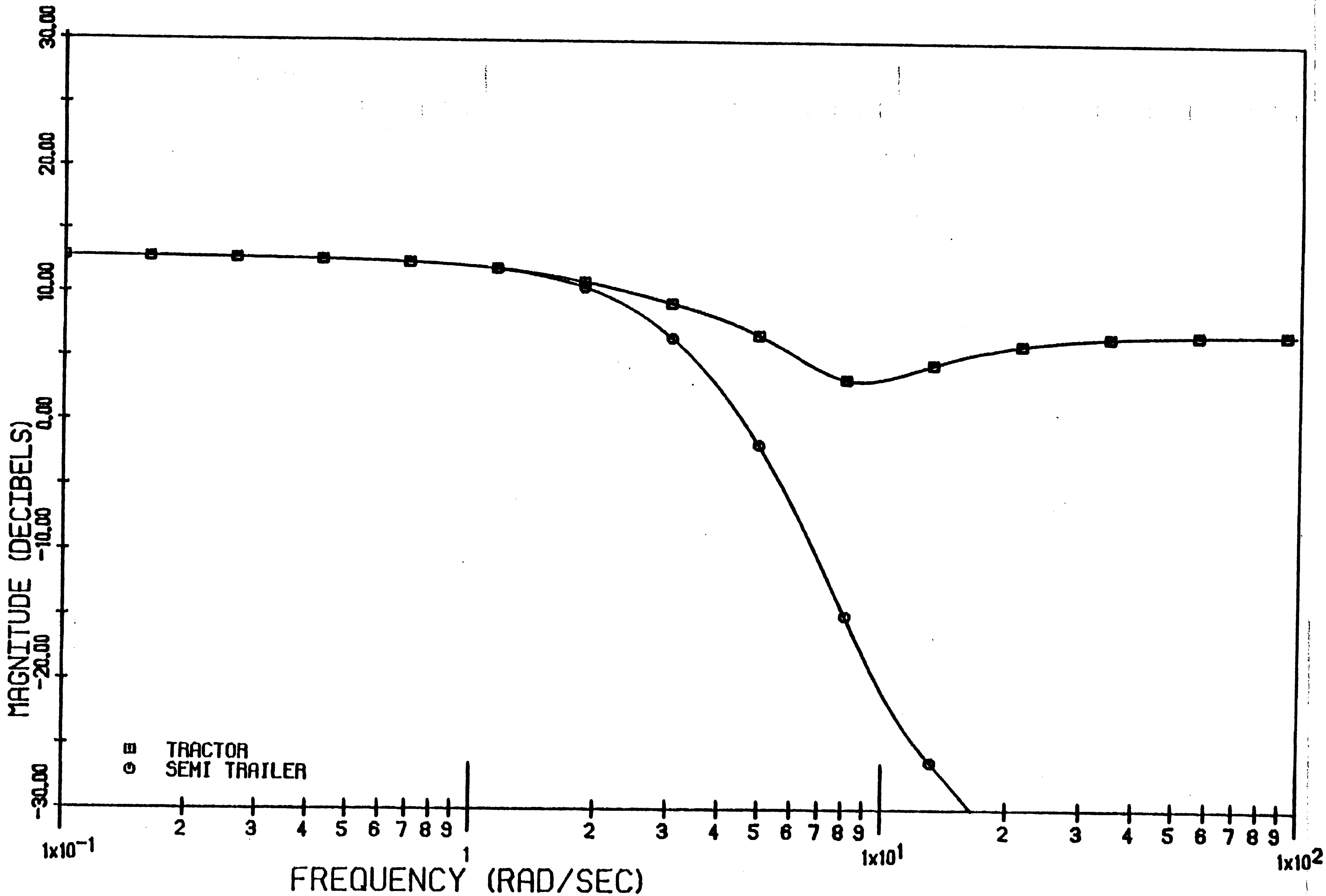
TRACTOR-SEMI BKY-8499 FULLY LOADED . DATASET#1



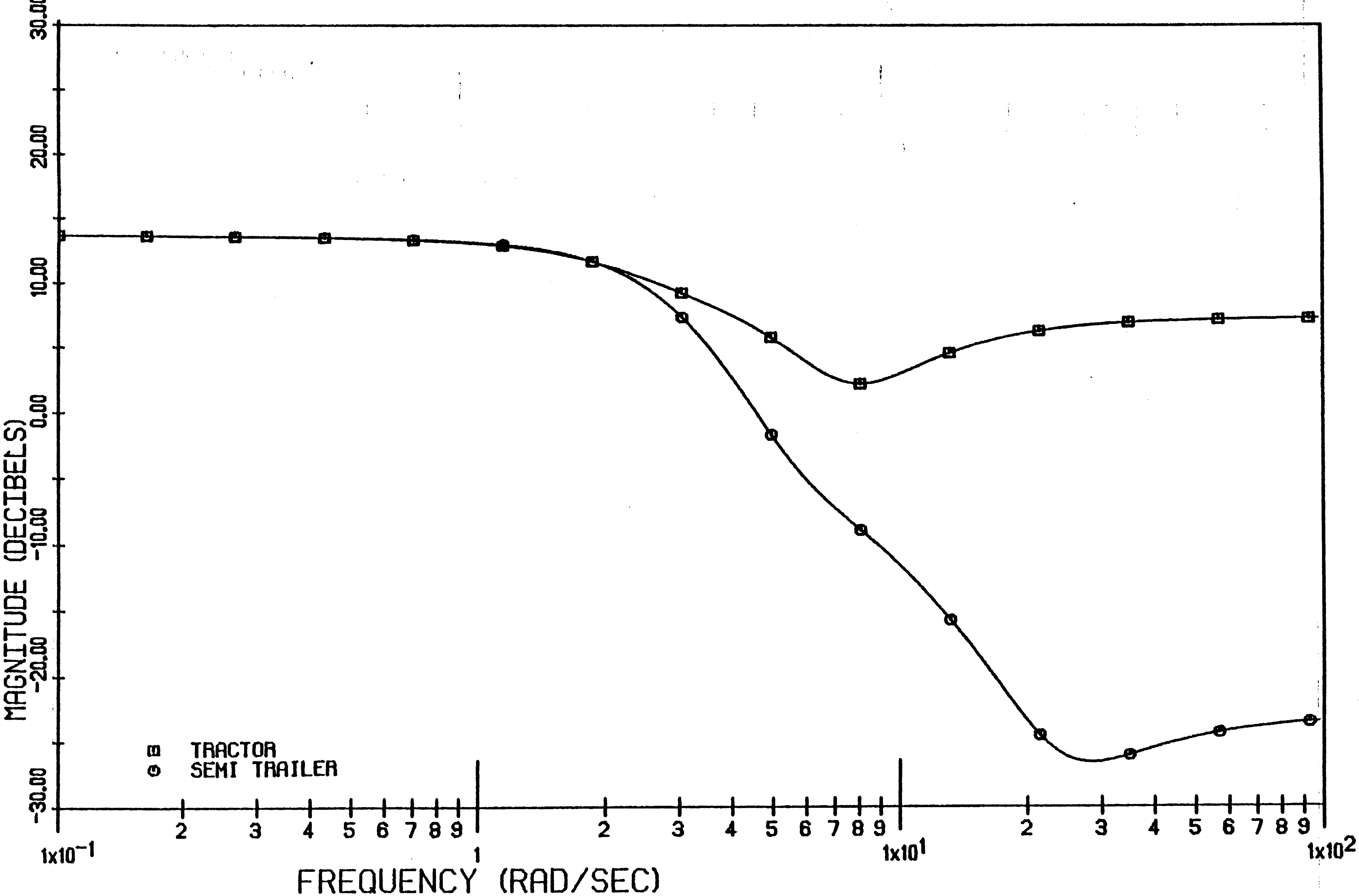
TRACTOR-SEMI BKY-8499 EMPTY . DATASET#2



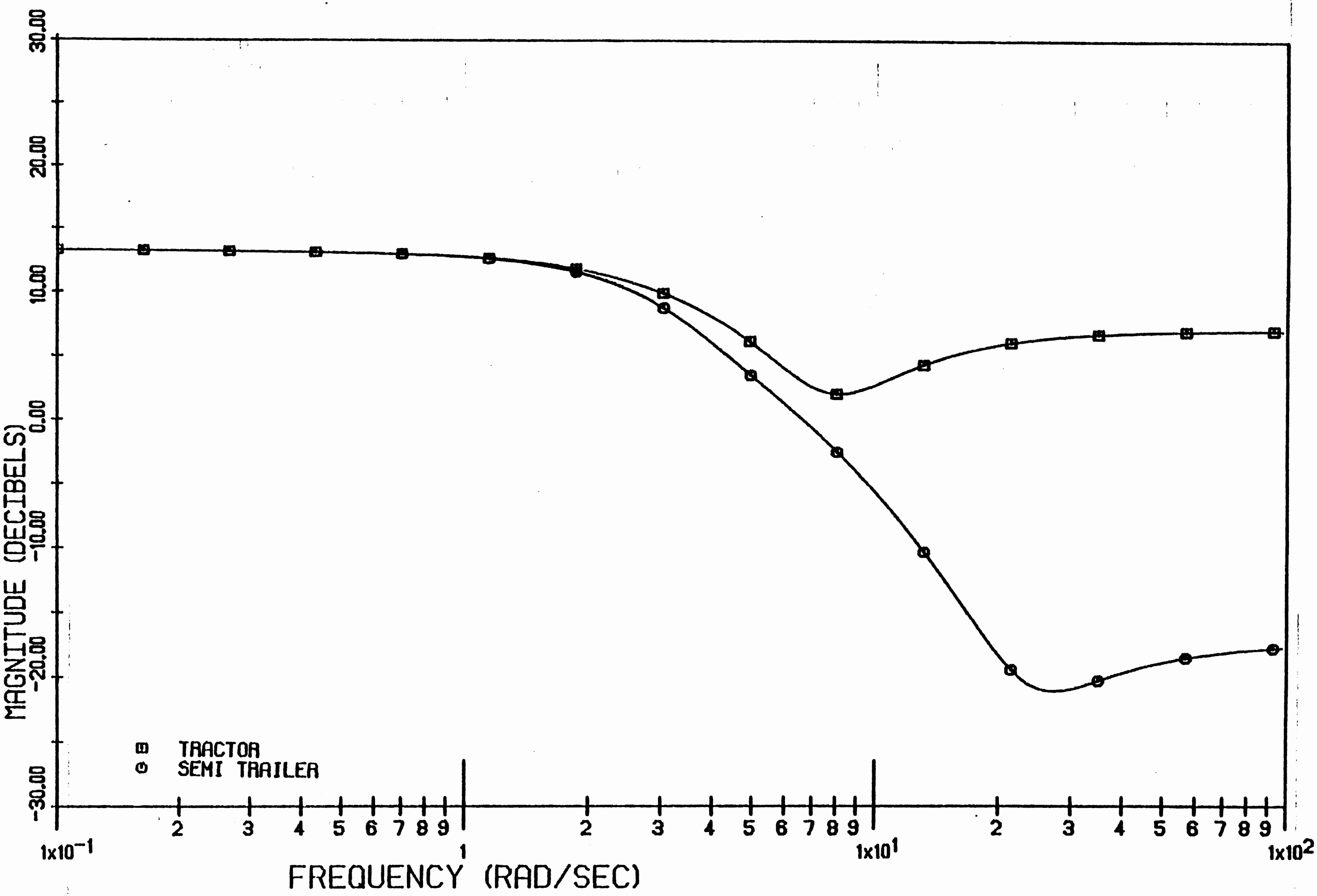
TRACTOR-SEMI BKY-8499 COMP #1 FULL . DATASET#3



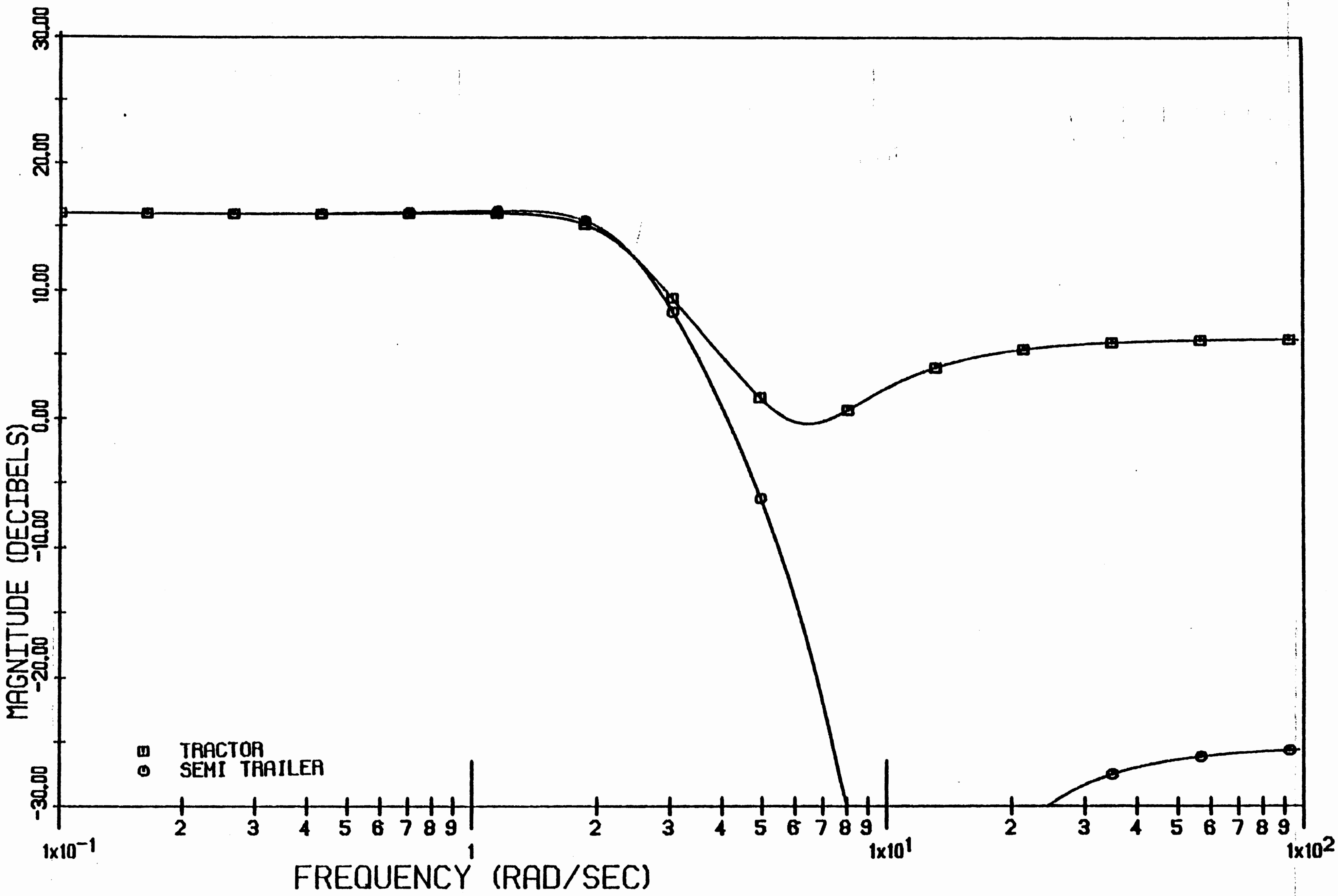
TRACTOR-SEMI BKY-8499 COMP #4 FULL . DATASET#4



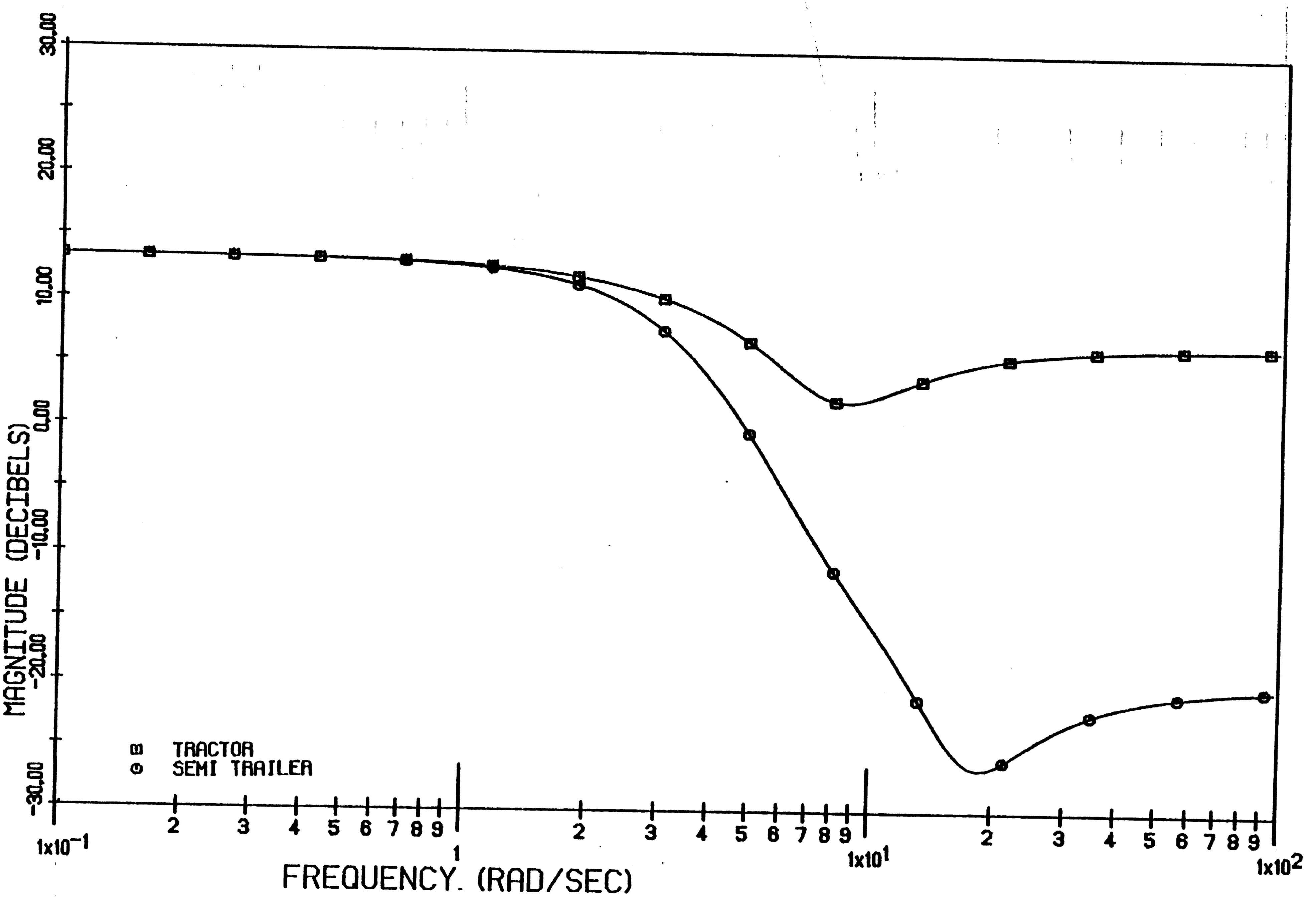
TRACTOR-SEMI BKD-0065 FULLY LOADED DATASET#5



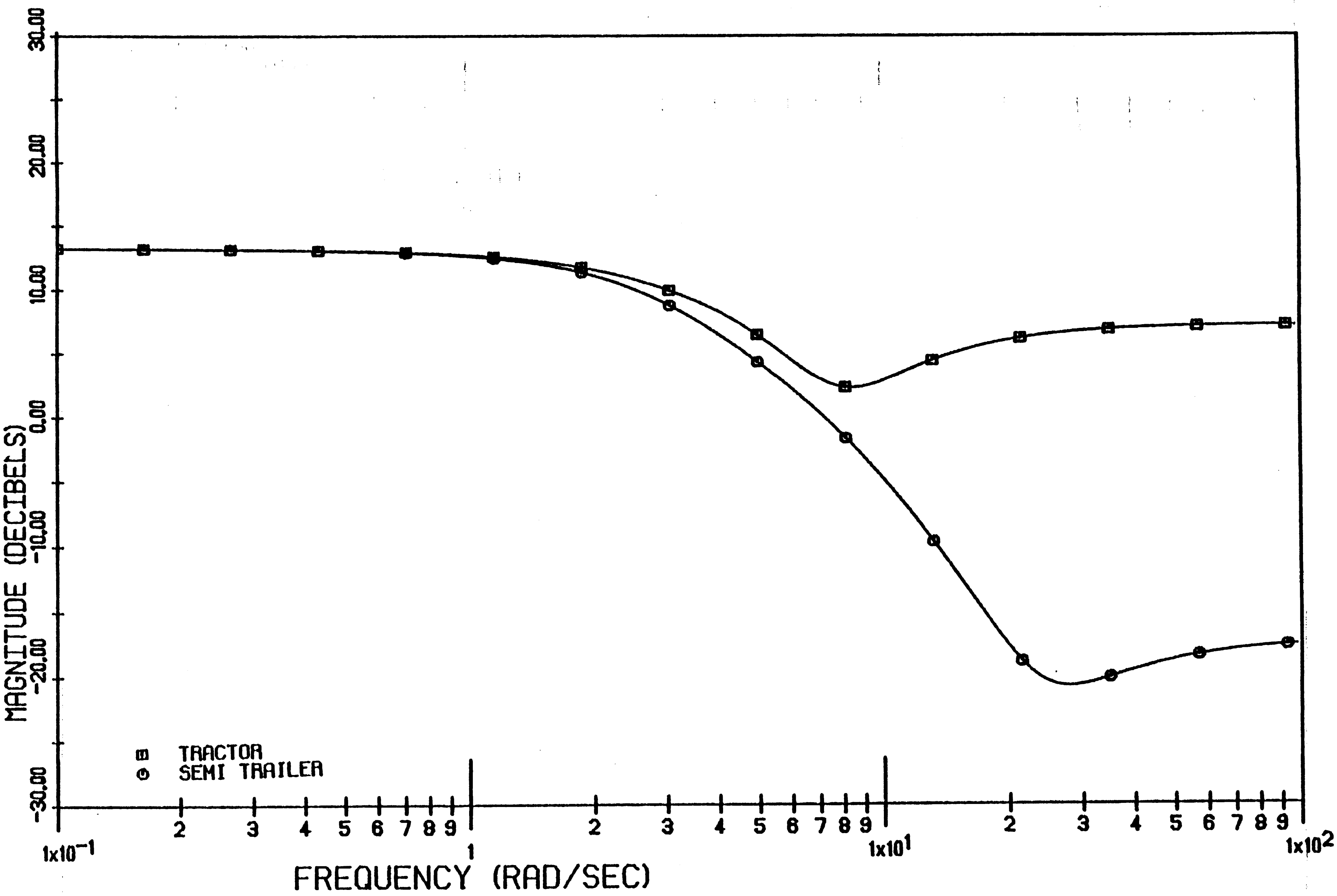
TRACTOR-SEMI BKD-0065 COMP#1 FULL DATASET#6



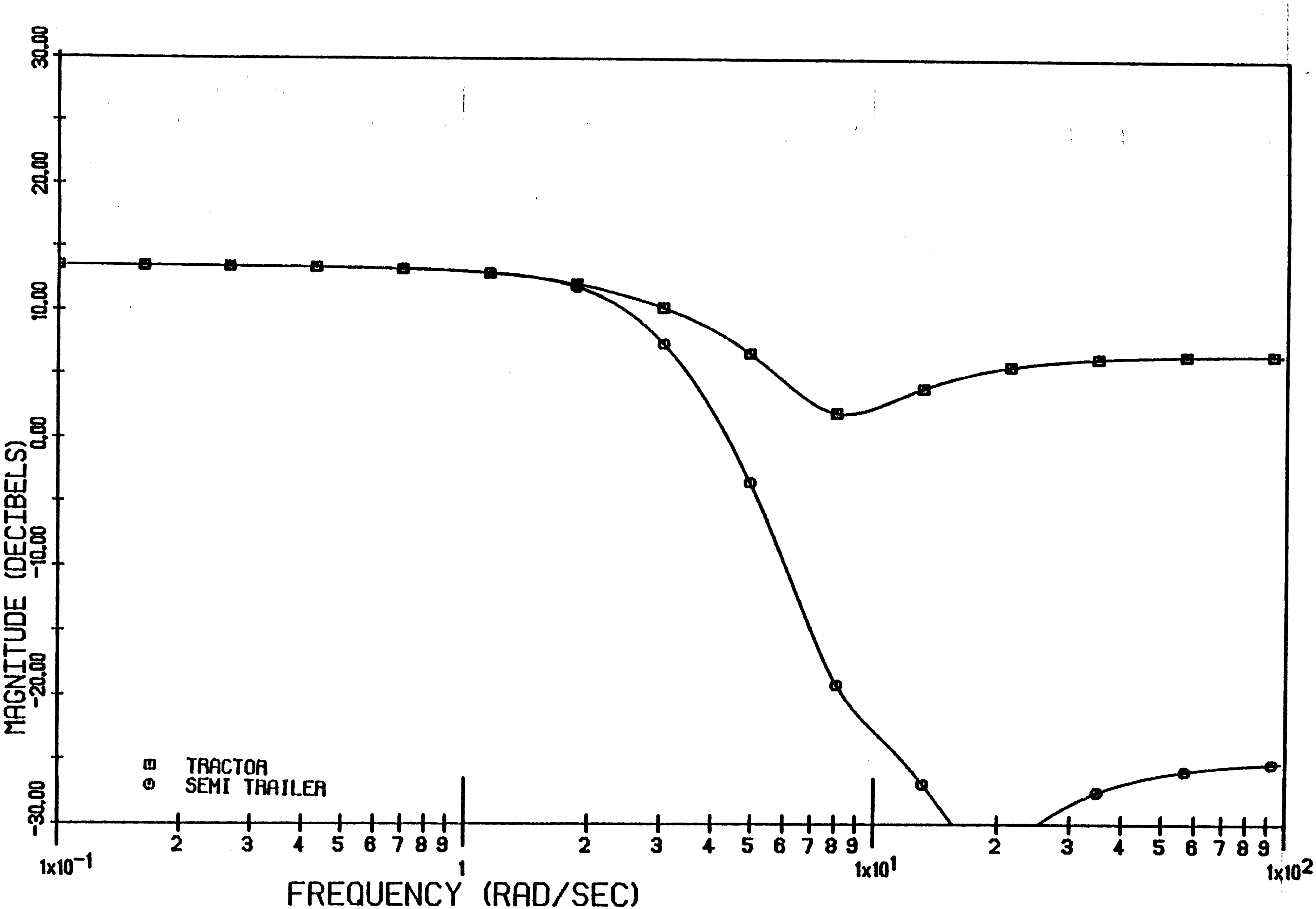
TRACTOR-SEMI BKD-0065 COMP#4 FULL DATASET#7



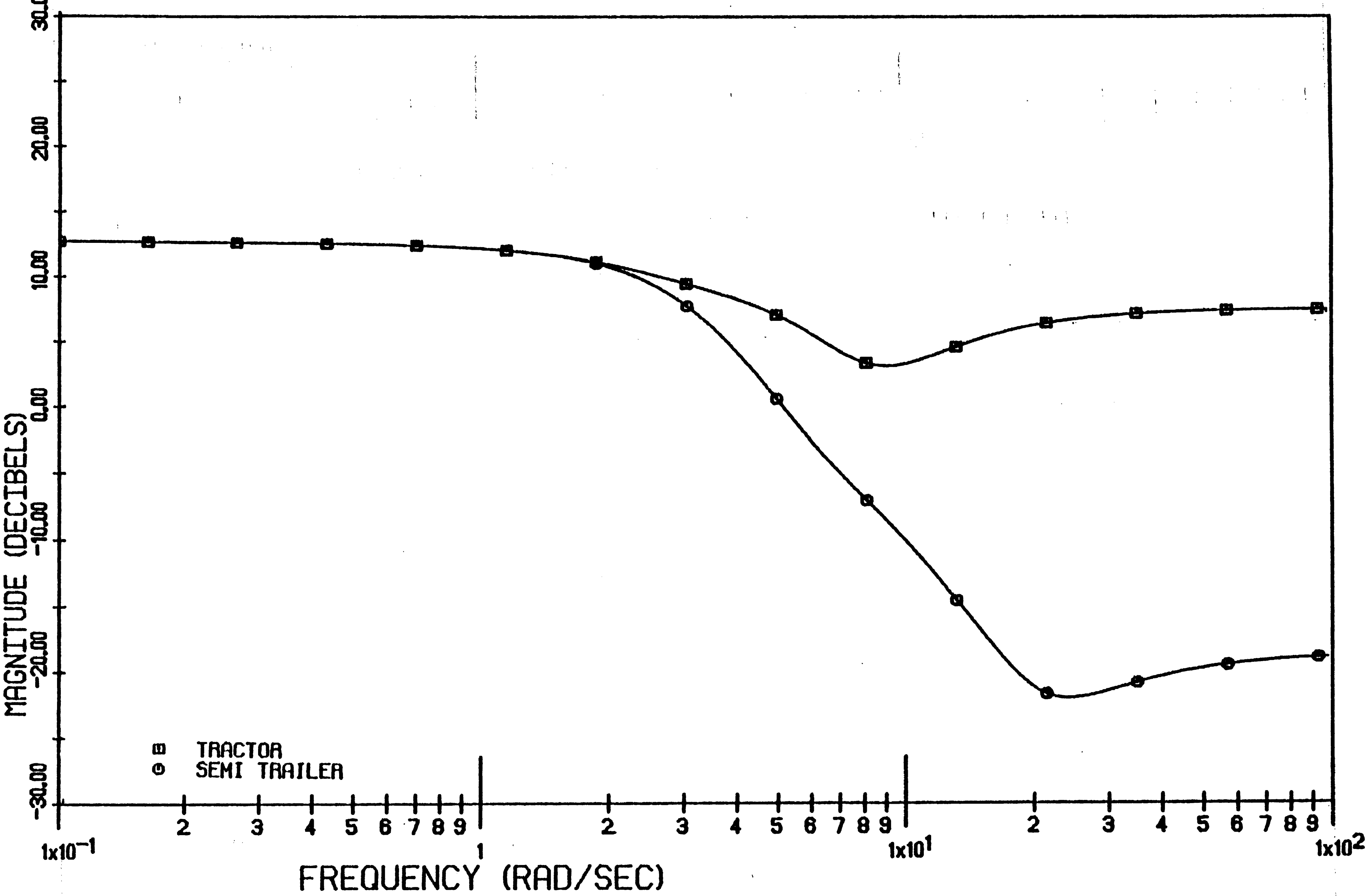
TRACTOR-SEMI BKD-0065 EMPTY.AXLE LIFTED. DATASET#8



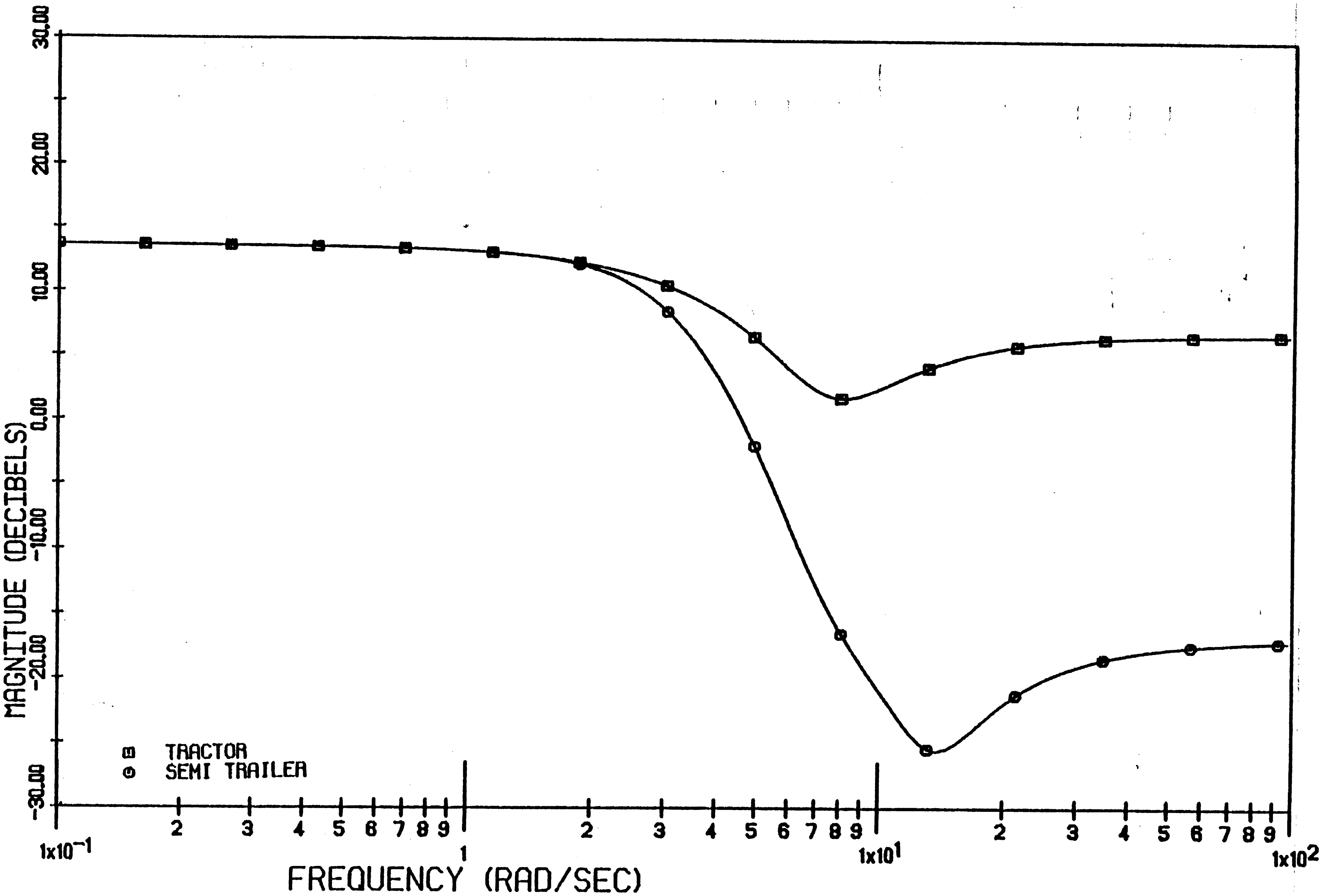
TRACTOR-SEMI BKD-0065 COMP#1 FULL, AXLE LIFTED, DATASET#9



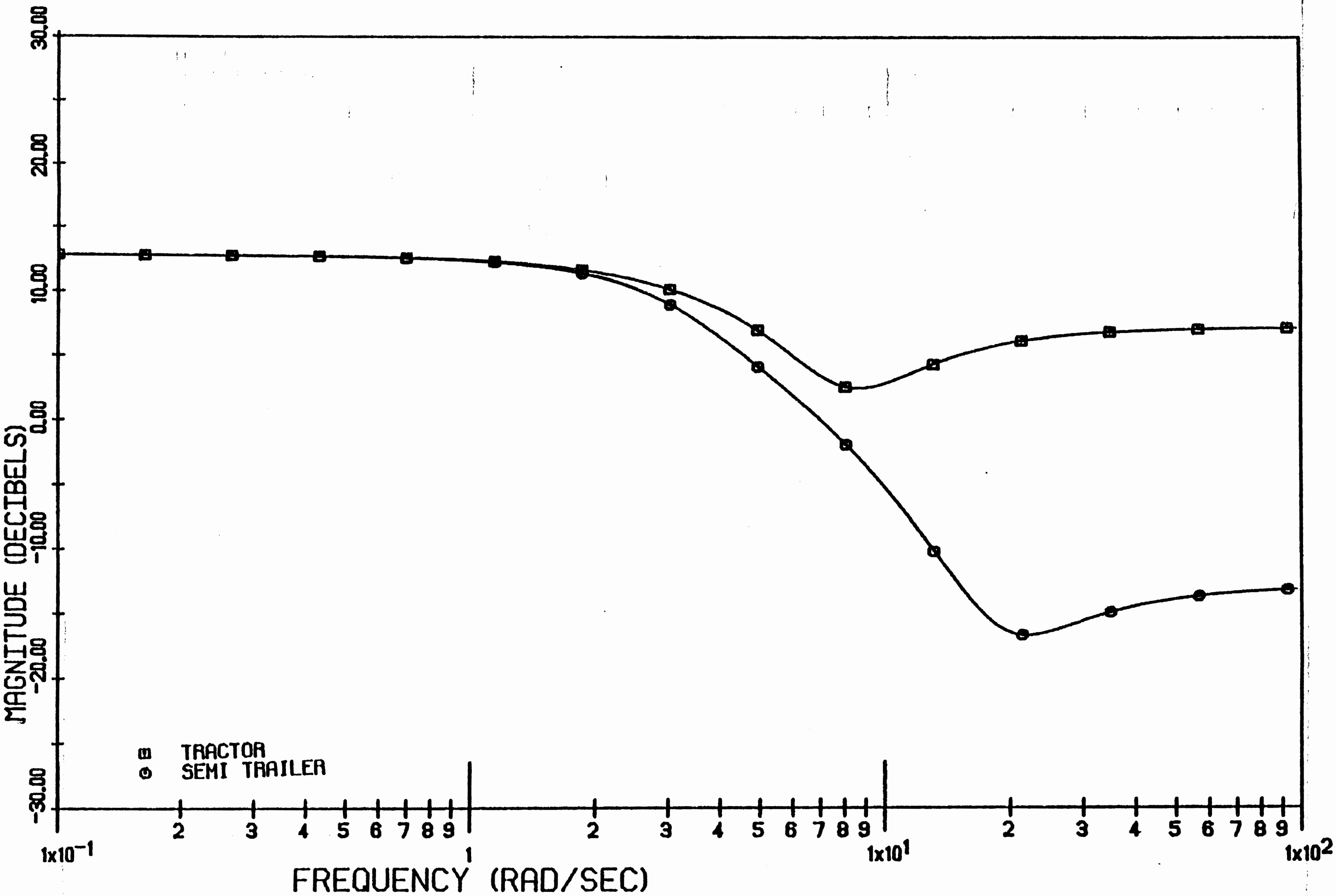
TRACTOR-SEMI BKD-0065 COMP#4 FULL,AXLE LIFTED, DATASET#10



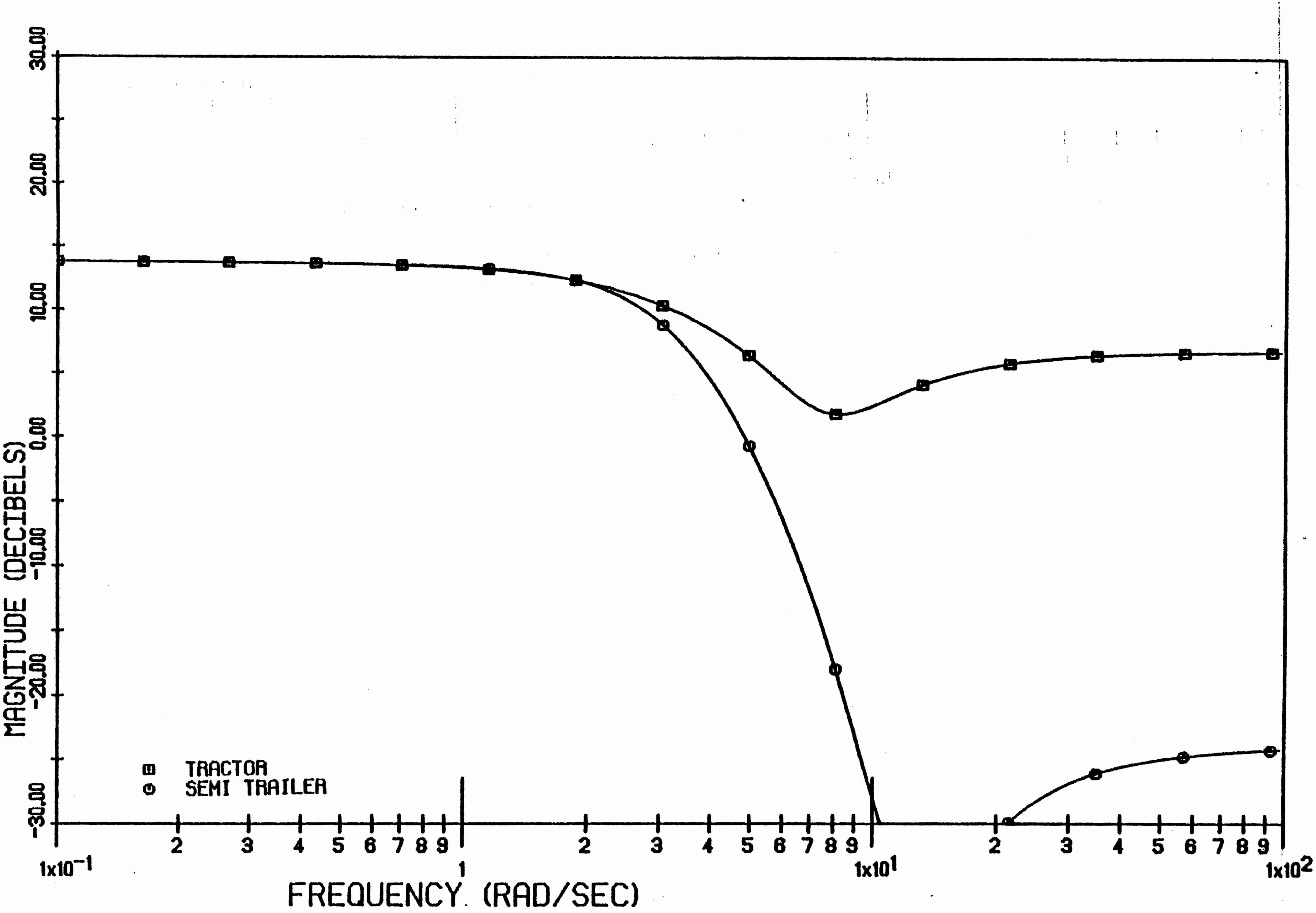
TRACTOR-SEMI BKY-9450-1 FULLY LOADED DATASET#11



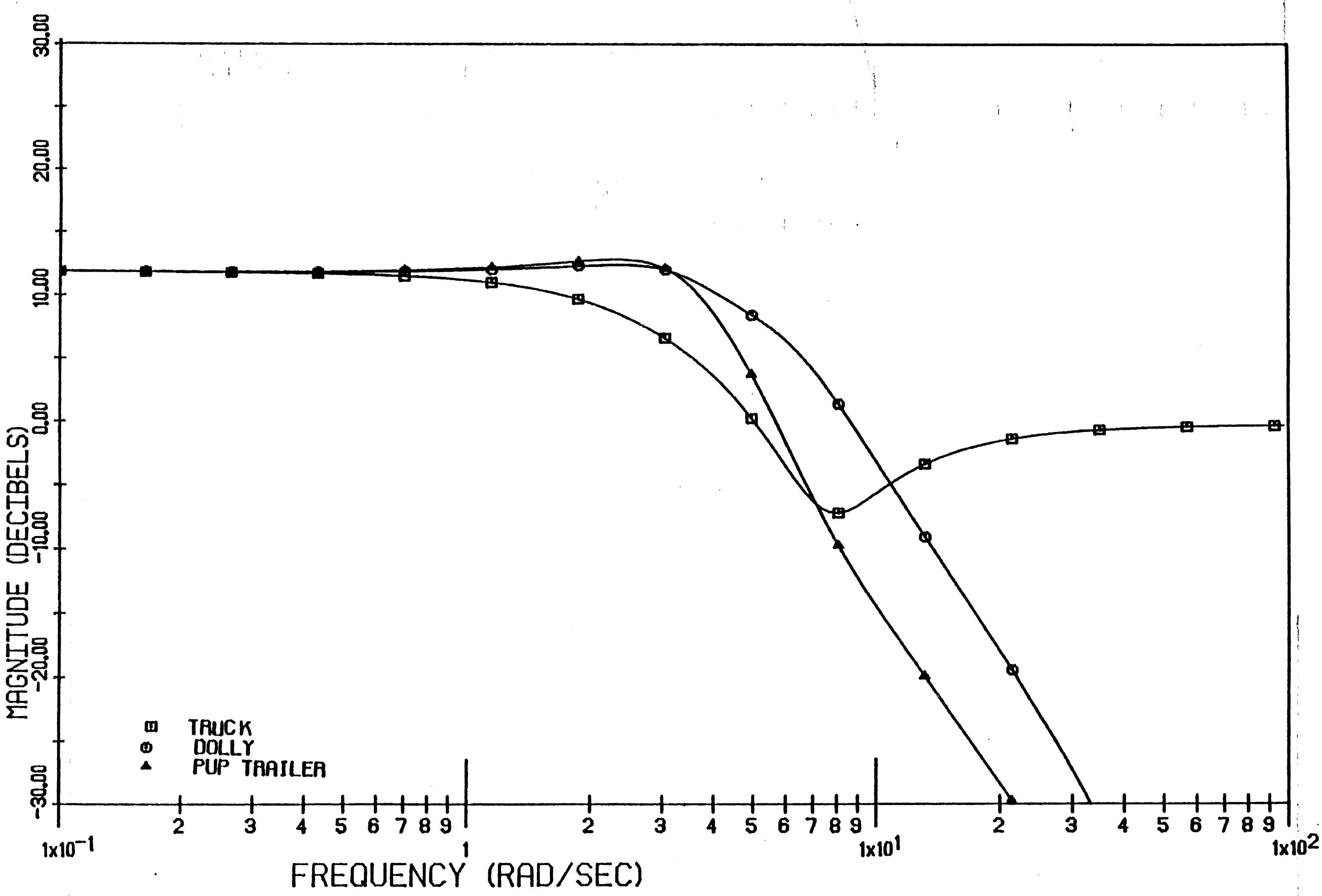
TRACTOR-SEMI BKY-9450-1 EMPTY DATASET#12



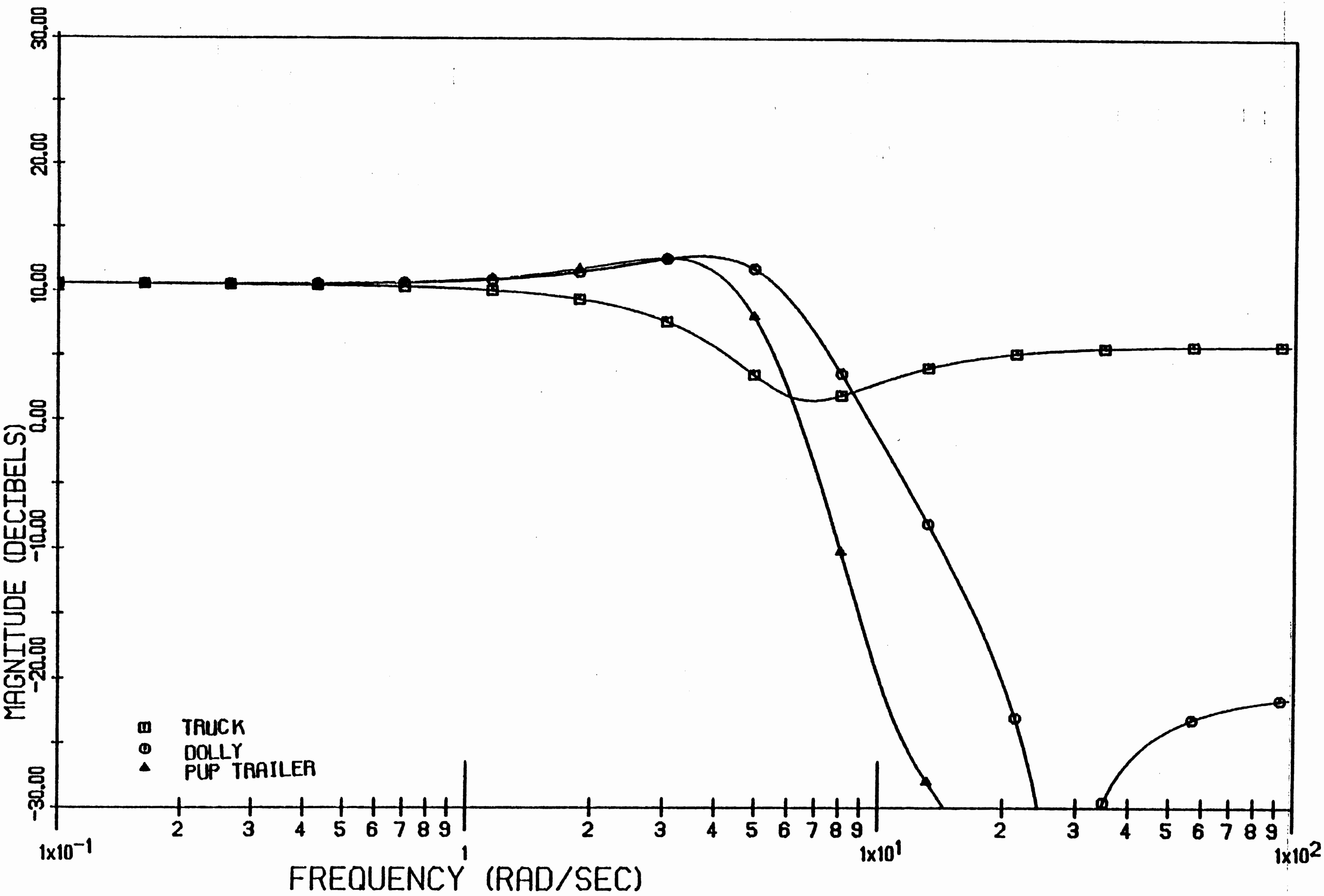
TRACTOR-SEMI BKY-9450-1 COMP#1 FULL DATASET#13



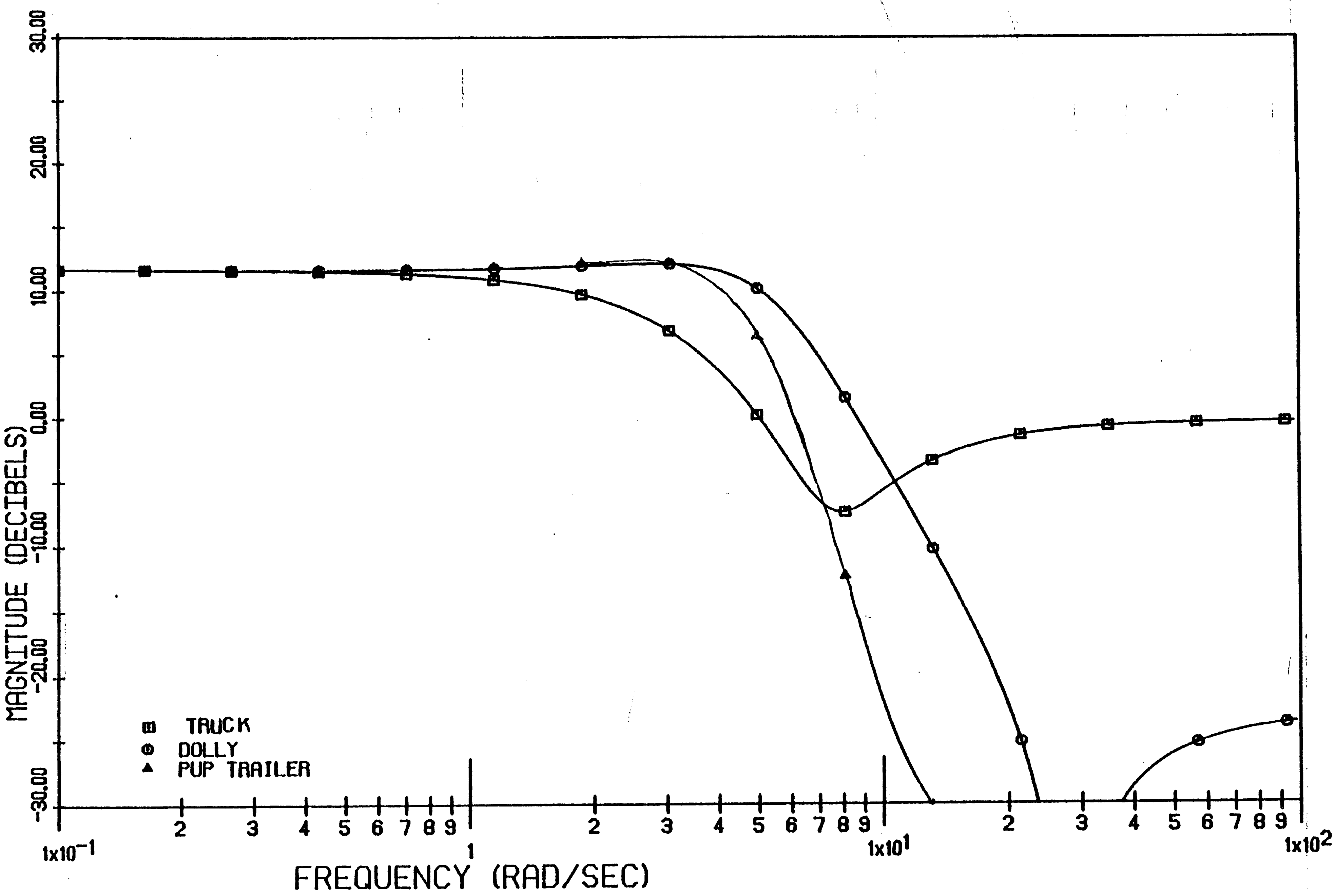
TRACTOR-SEMI BKY-9450-1 COMP#4 FULL DATASET#14



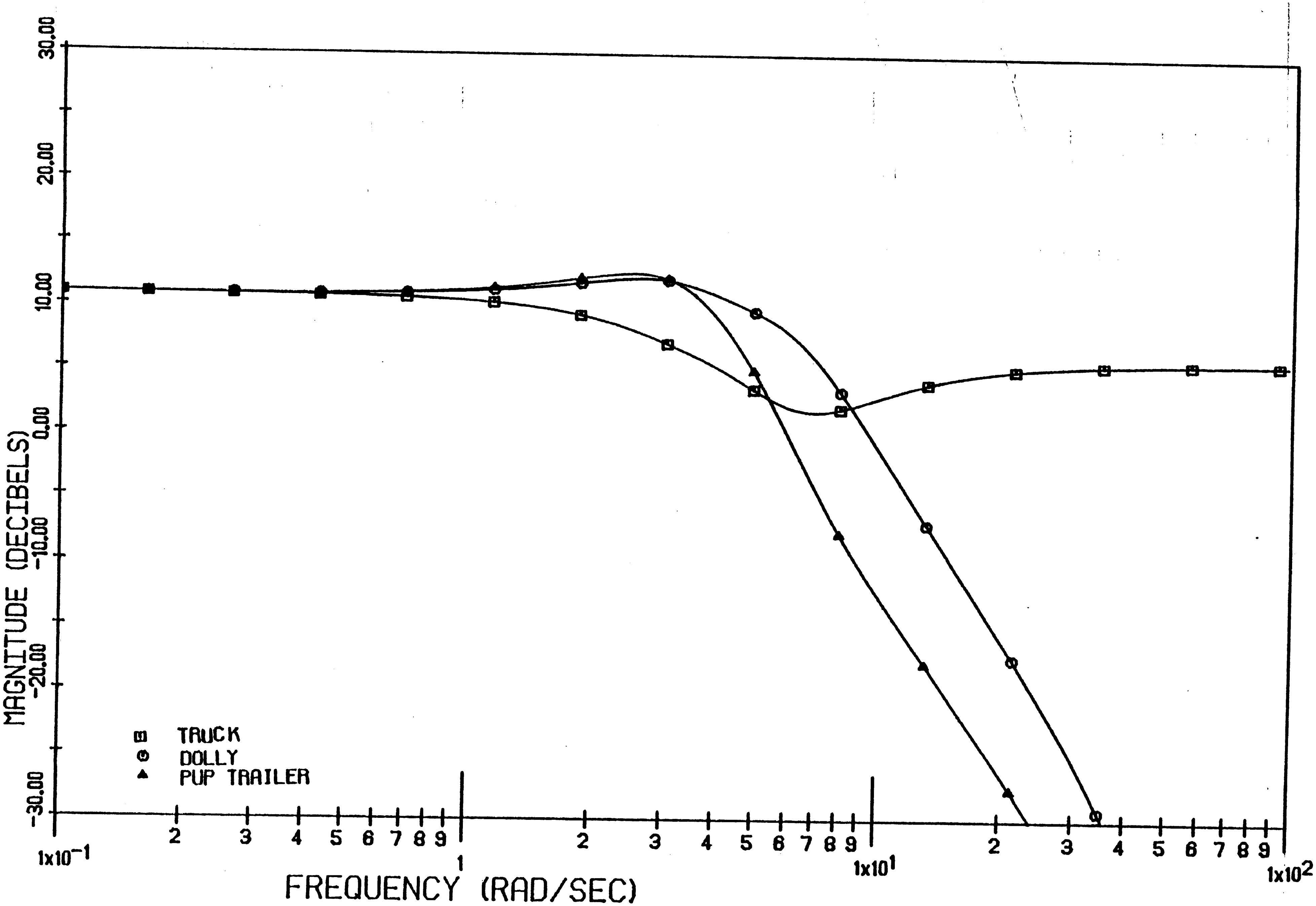
TRUCK/ FULL-TRAILER BLY-2714 FULLY LOADED .DATASET#15



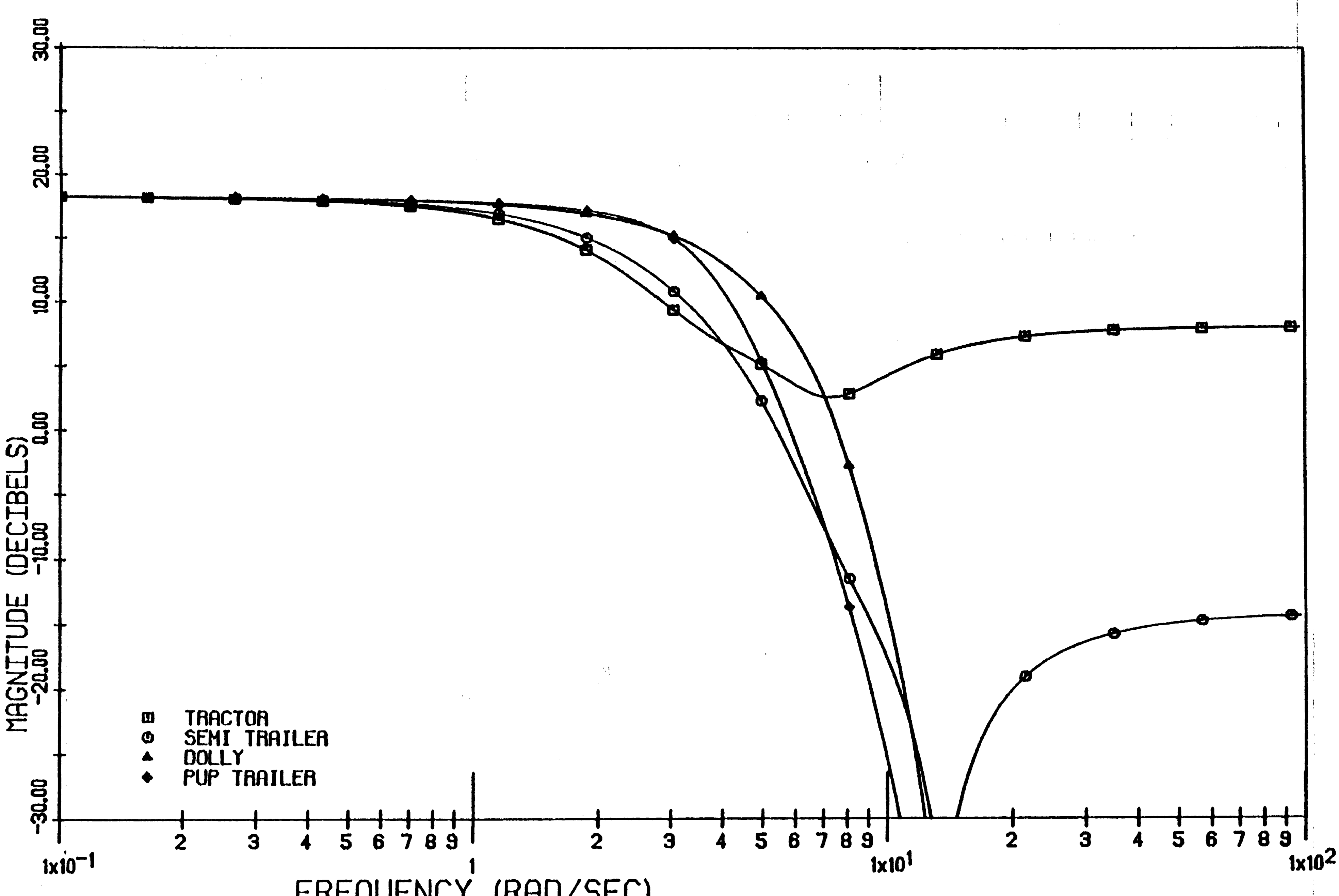
TRUCK/FULL-TRAILER BLY-2714 EMPTY .DATASET#16



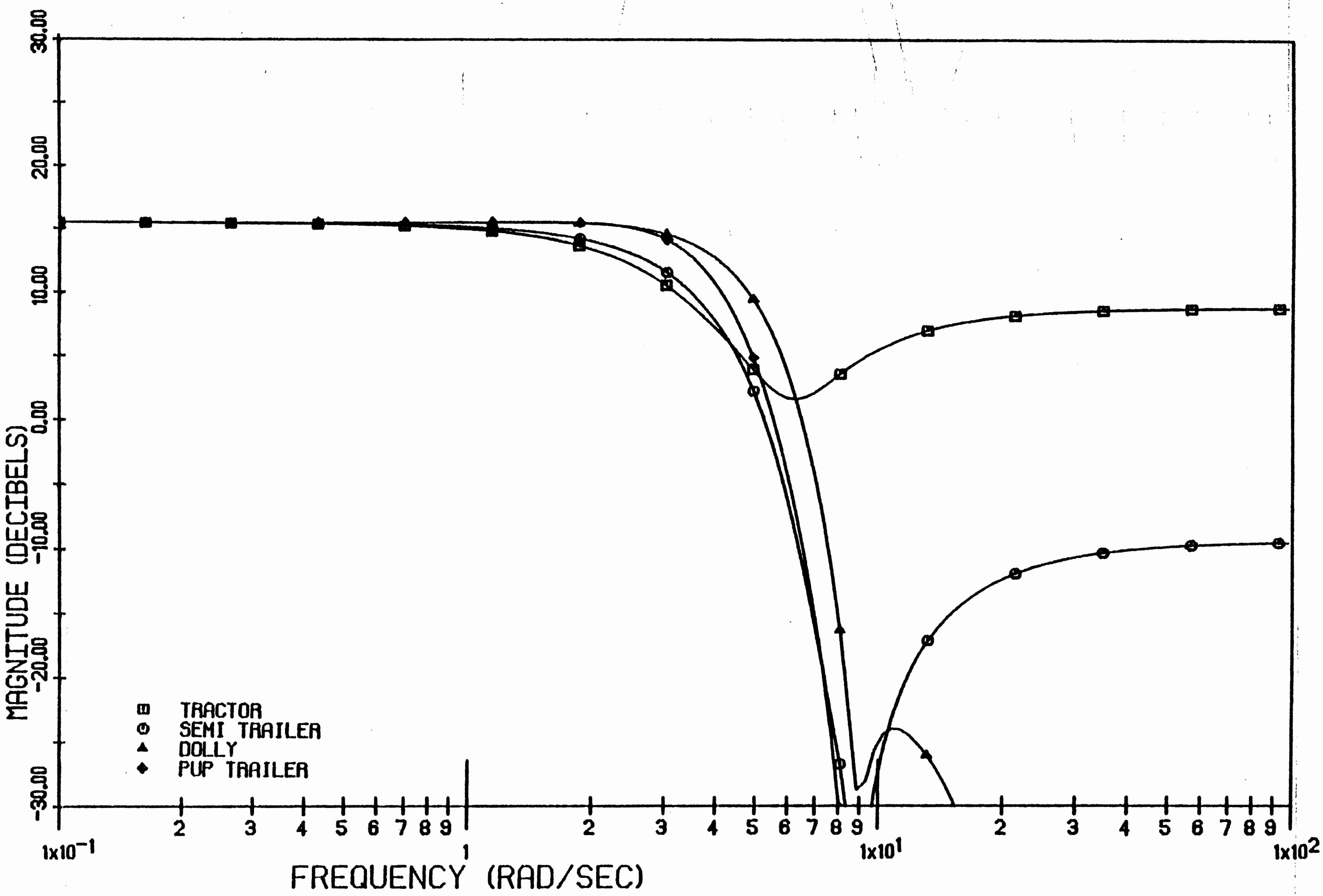
TRUCK/FULL-TRAILER BLY-2714 SEMI LOADED PUP EMPTY .DATASET#17



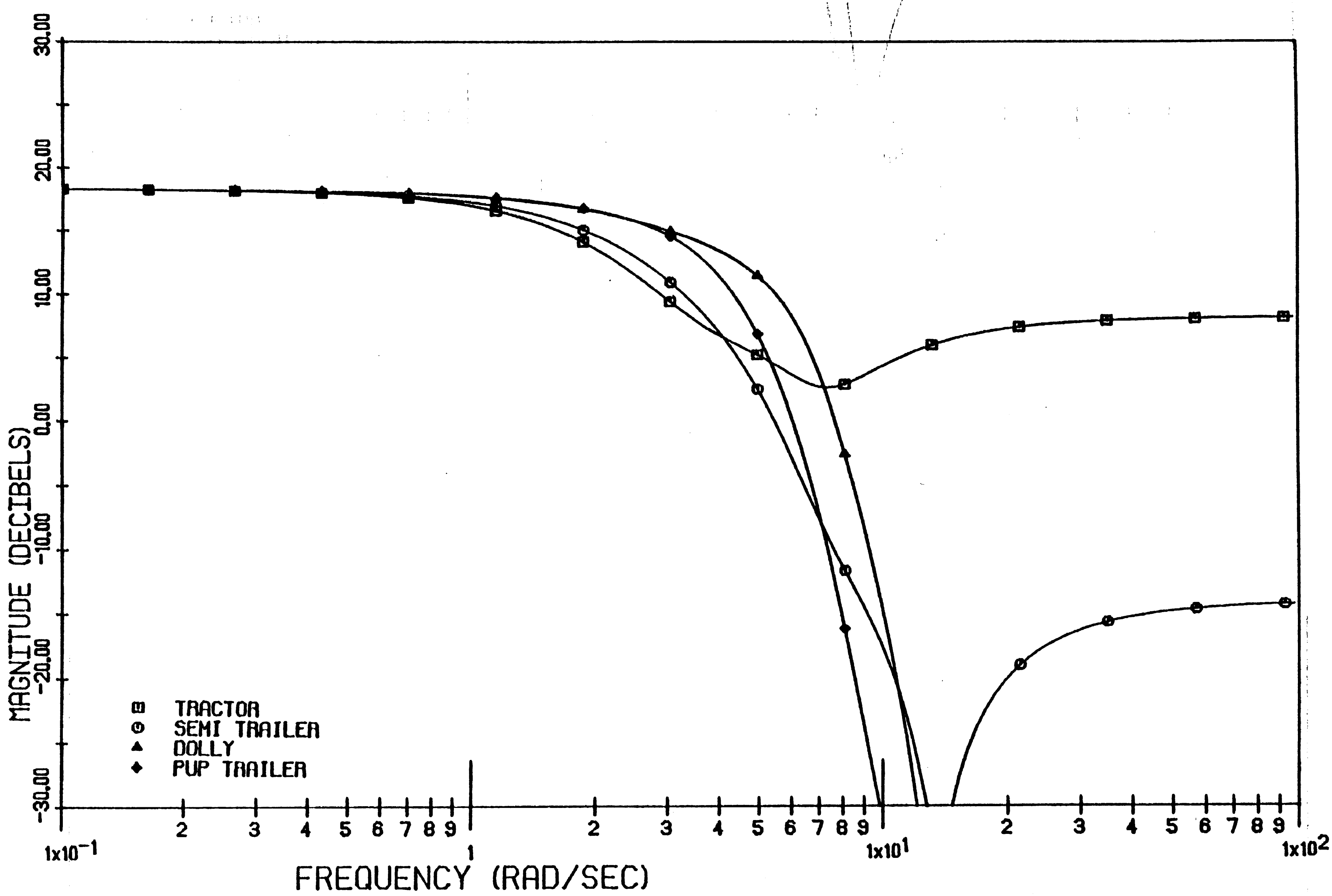
TRUCK/ FULL-TRAILER BLY-2714 SEMI EMPTY PUP LOADED .DATASET#18



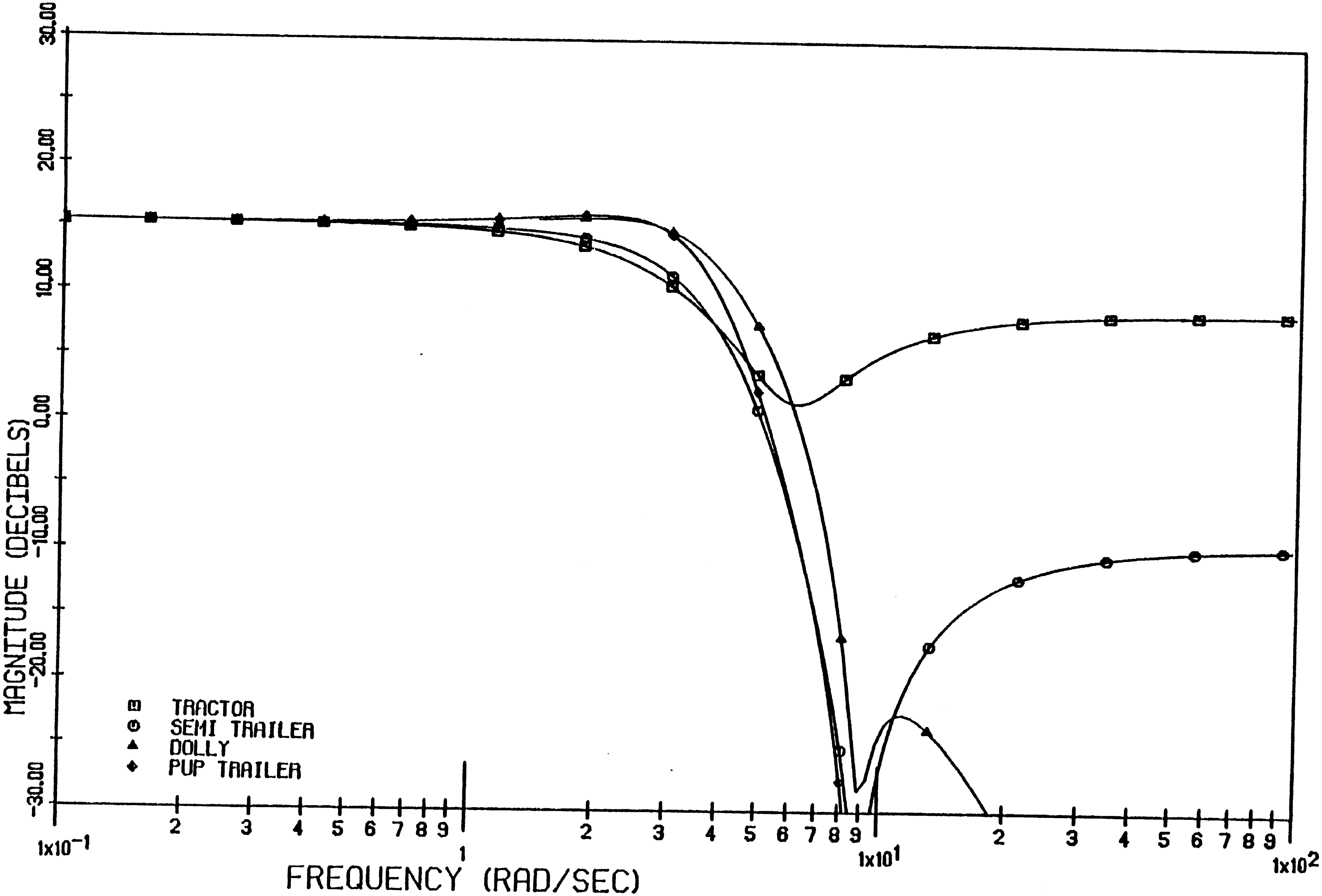
DOUBLE TANKER BLY-2985 FULLY LOADED . DATASET#19



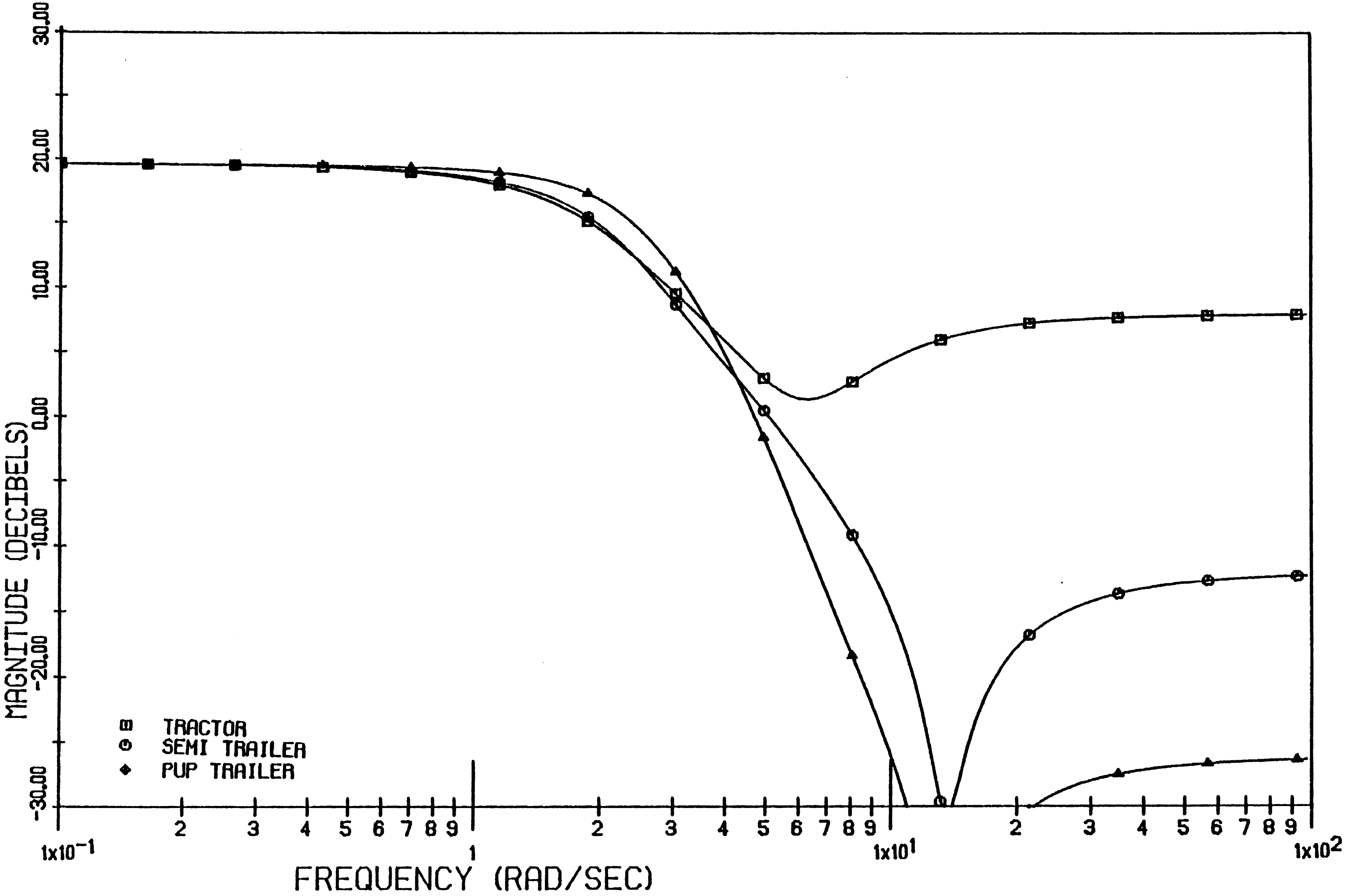
DOUBLE TANKER BLY-2985 EMPTY .DATASET#20



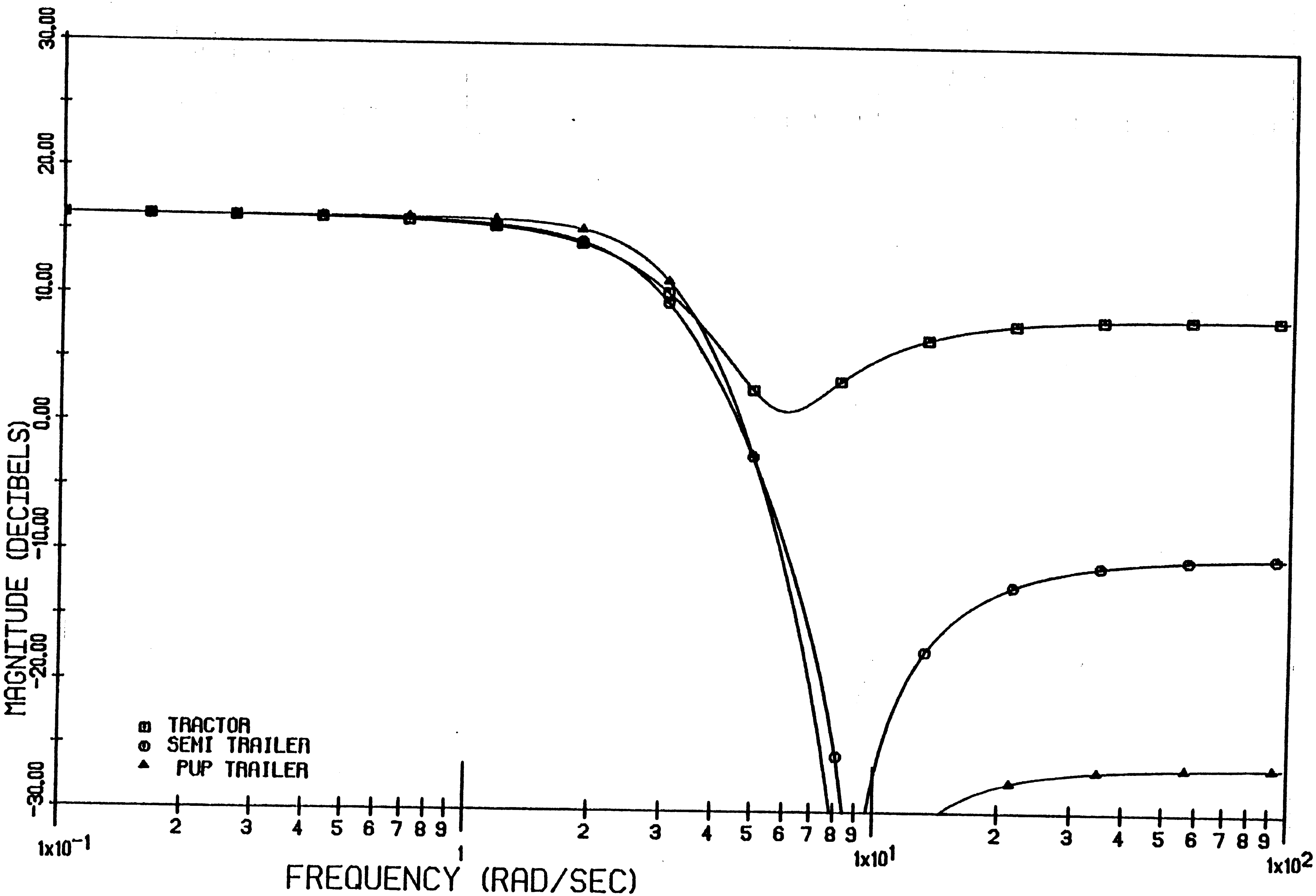
DOUBLE TANKER BLY-2985 SEMI LOADED PUP EMPTY .DATASET#21



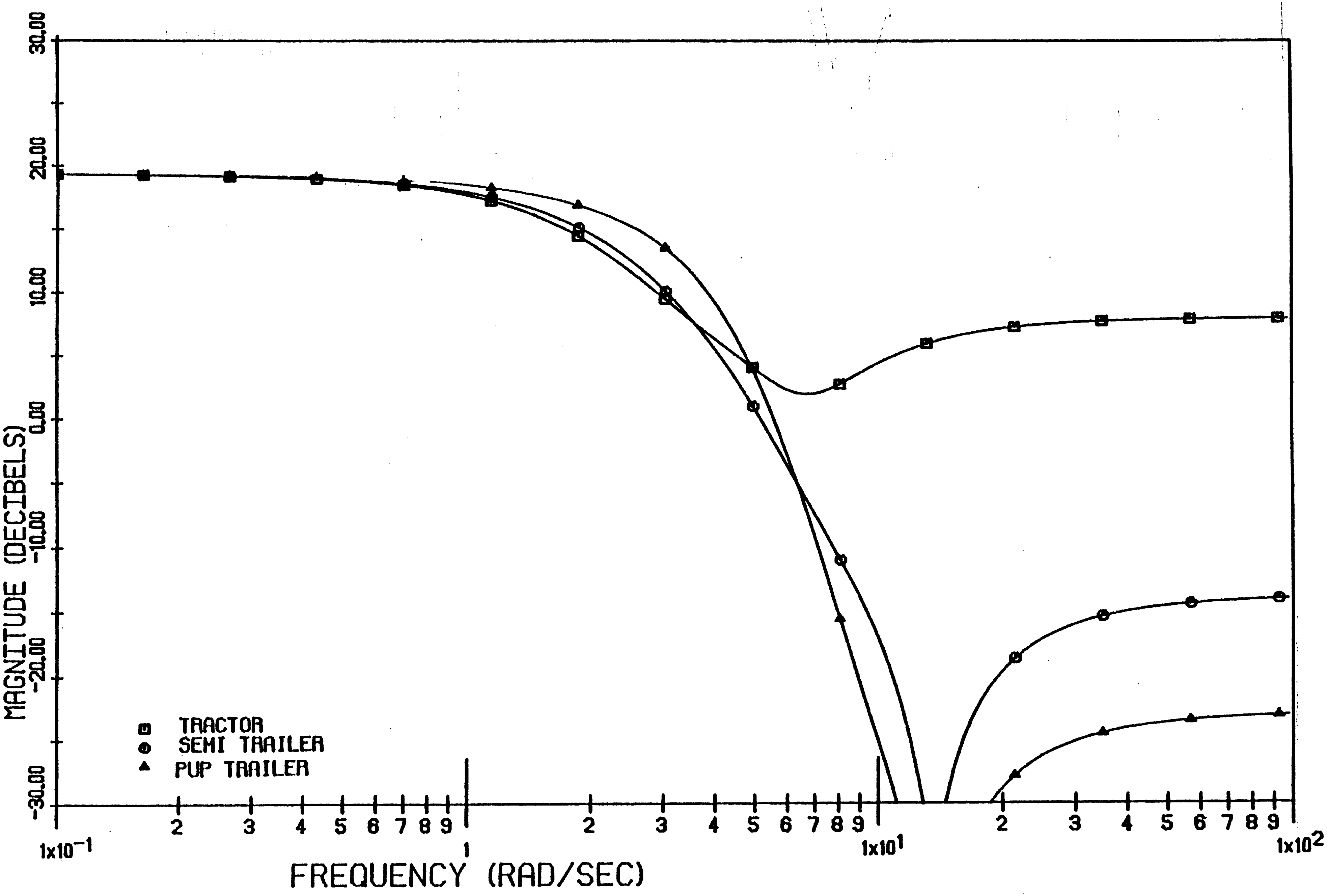
DOUBLE TANKER BLY-2985 SEMI EMPTY PUP LOADED .DATASET#22



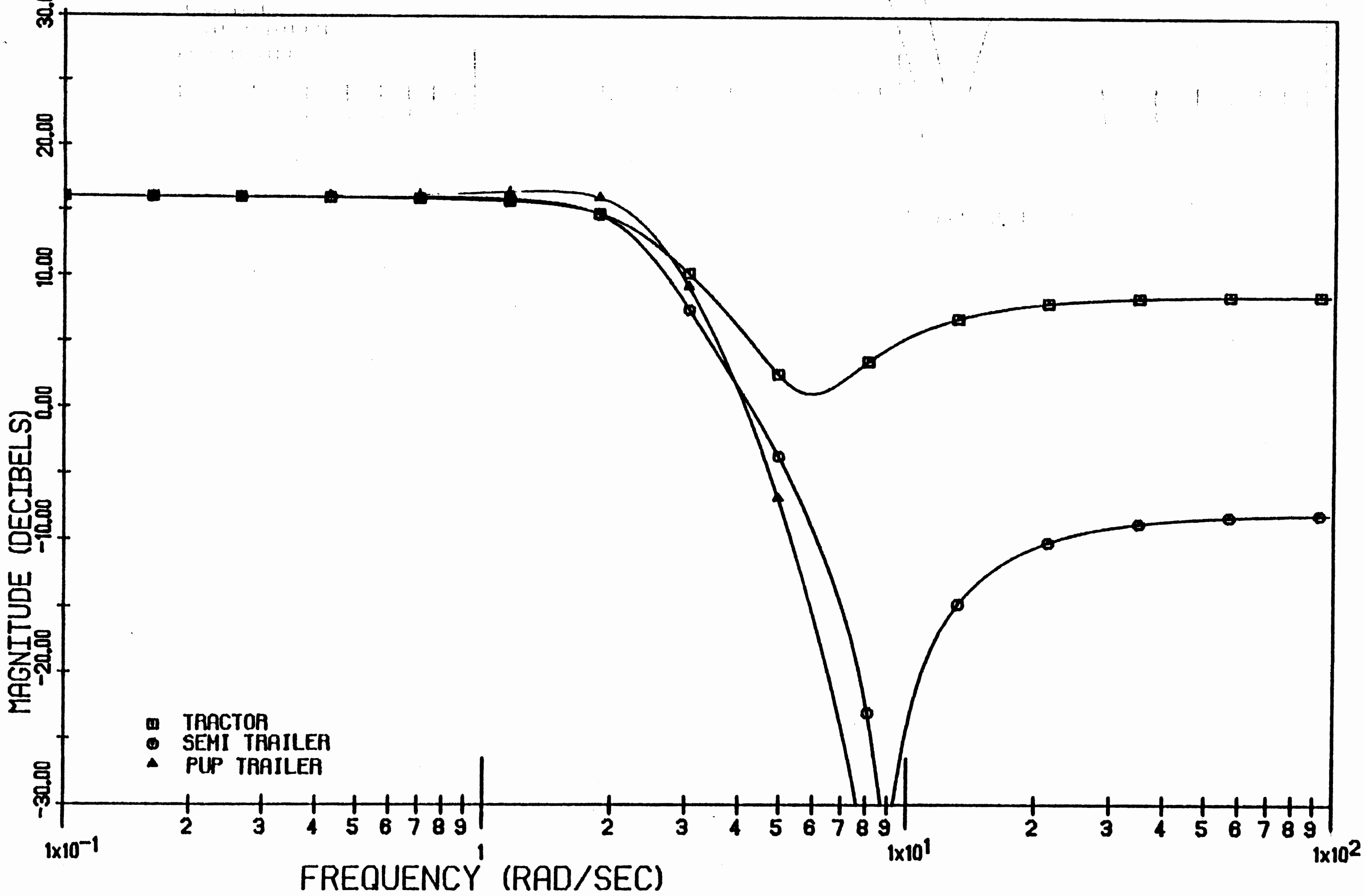
MODIFIED DOUBLE BLY-2985 FULLY LOADED .DATASET#23



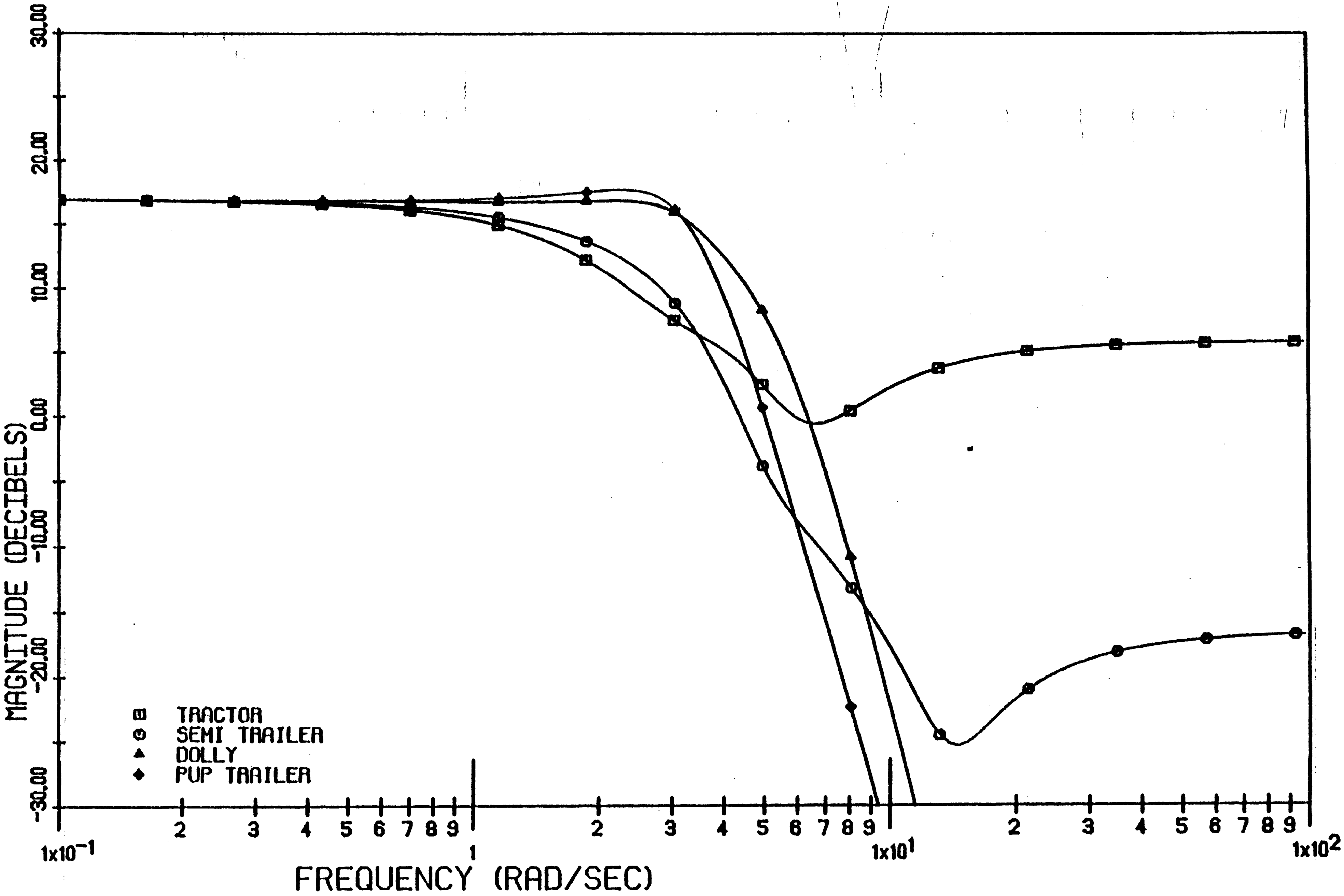
MODIFIED DOUBLE BLY-2985 EMPTY .DATASET#24



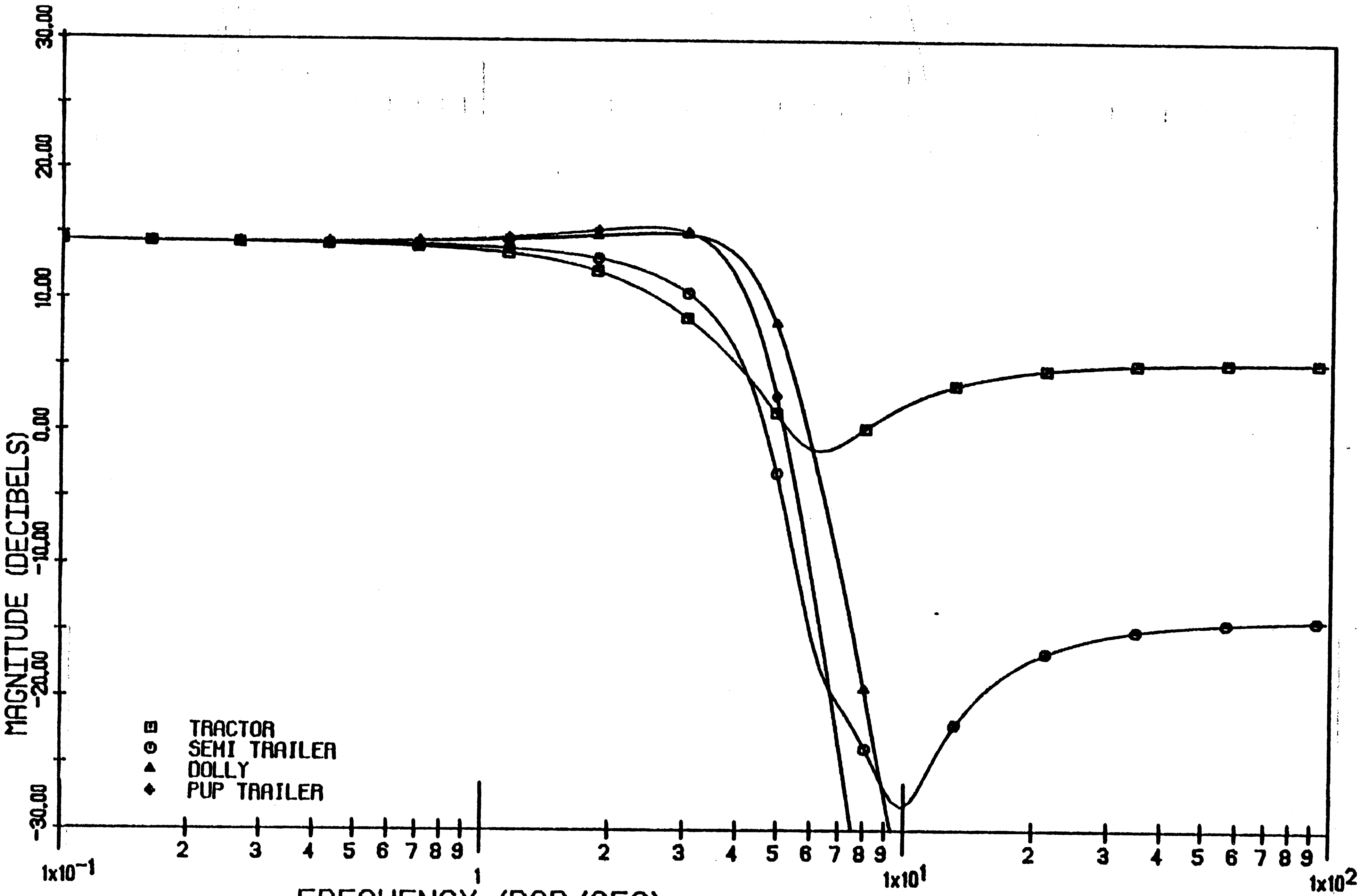
MODIFIED DOUBLE BLY-2985 SEMI LOADED PUP EMPTY .DATASET#25



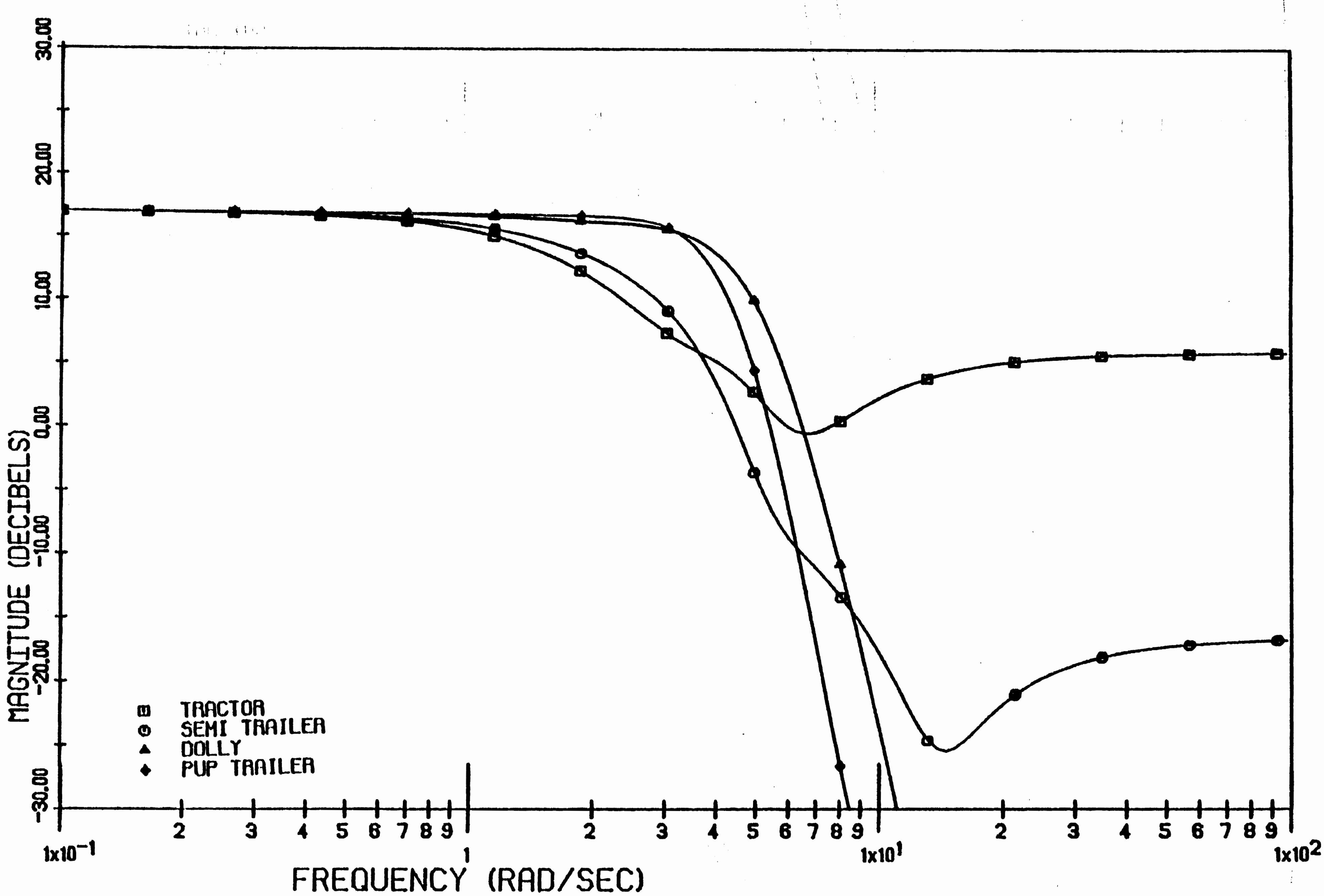
MODIFIED DOUBLE BLY-2985 SEMI EMPTY PUP LOADED .DATASET#26



DOUBLE TANKER BKD-0067 FULLY LOADED DATASET#27

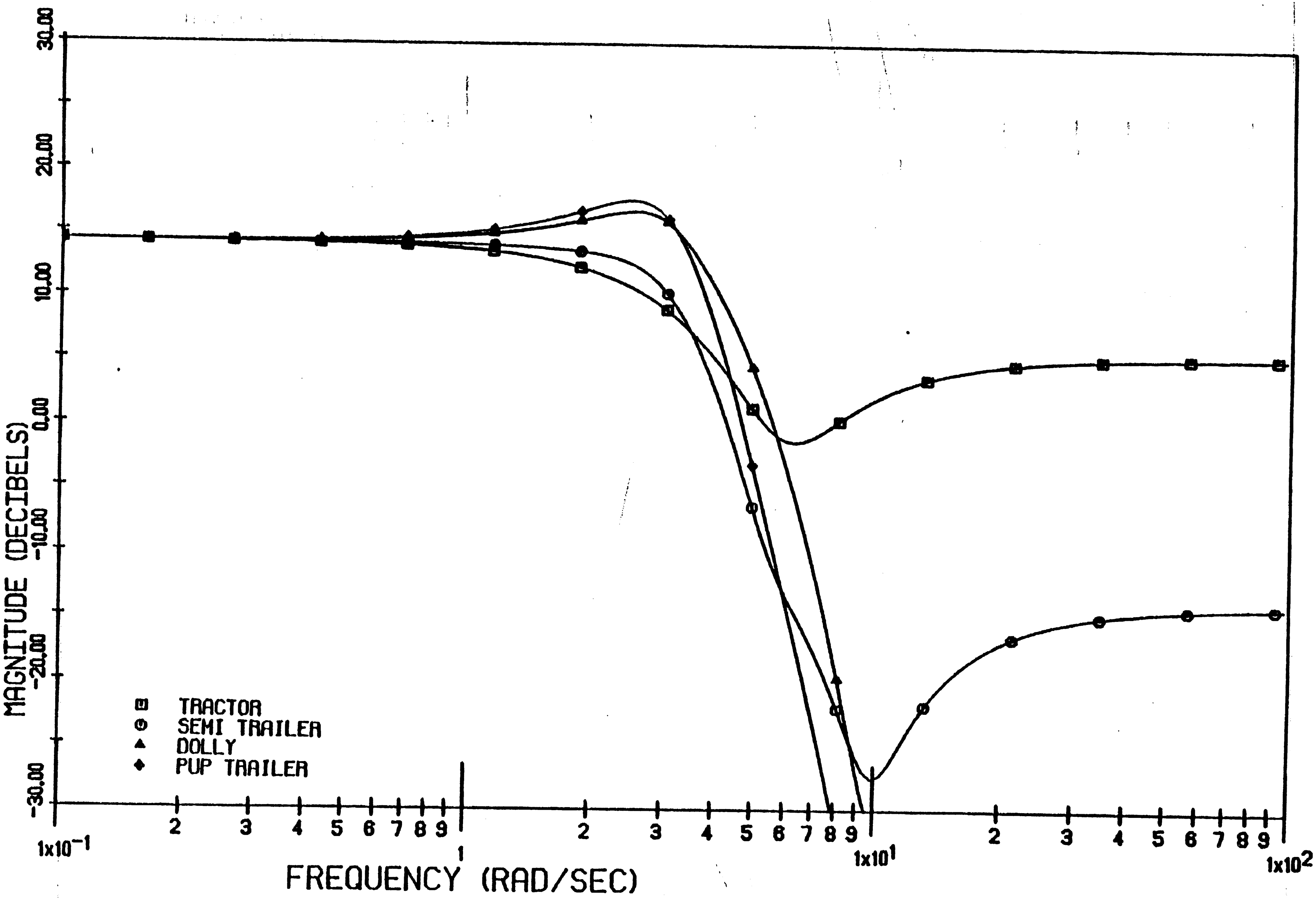


DOUBLE TANKER BKD-0067 EMPTY DATASET#28

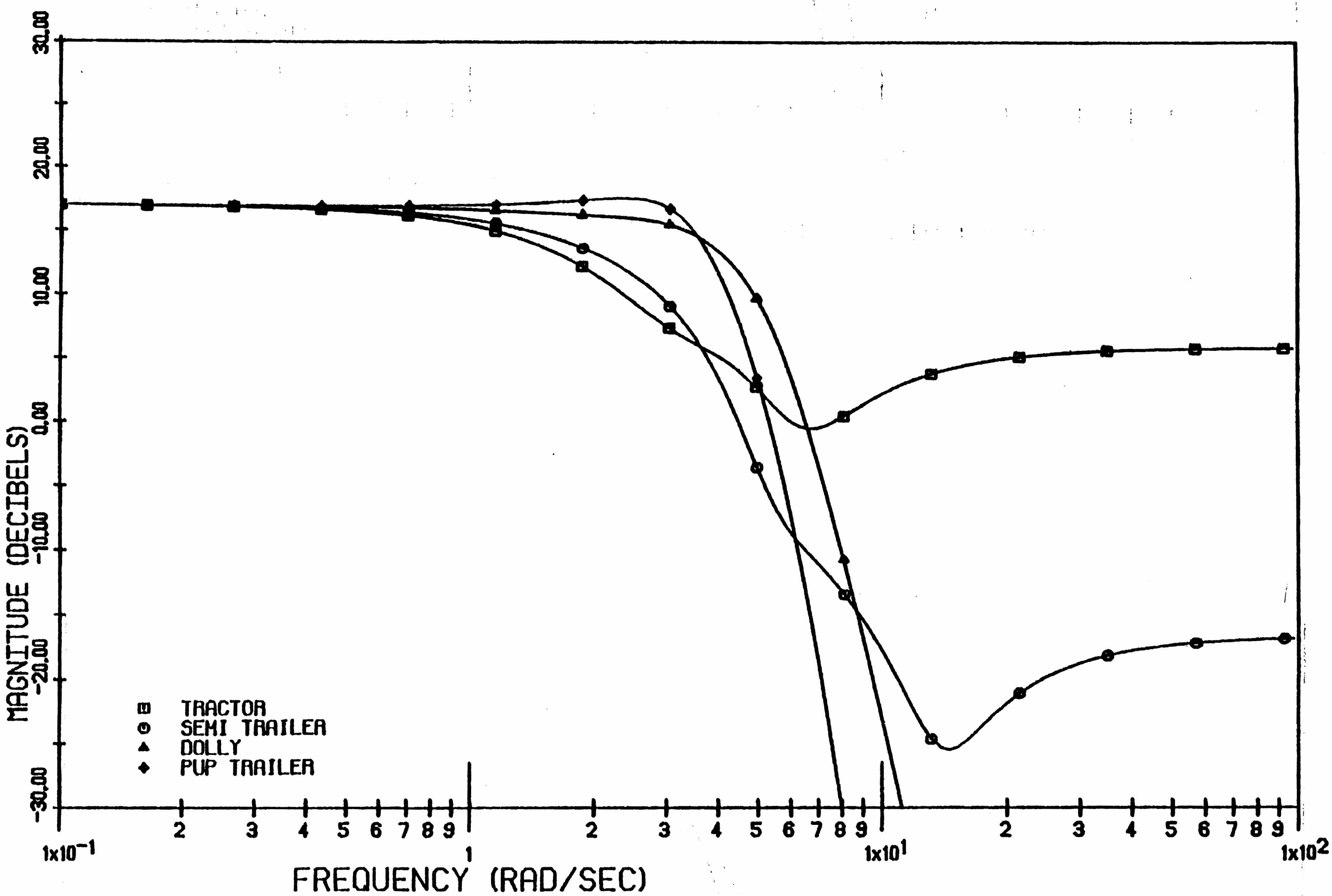


DOUBLE TANKER BKD-0067 ,SEMI LOADED PUP EMPTY, DATASET#29

08



DOUBLE TANKER BKD-0067 . SEMI EMPTY PUP FULL . DATASET#30



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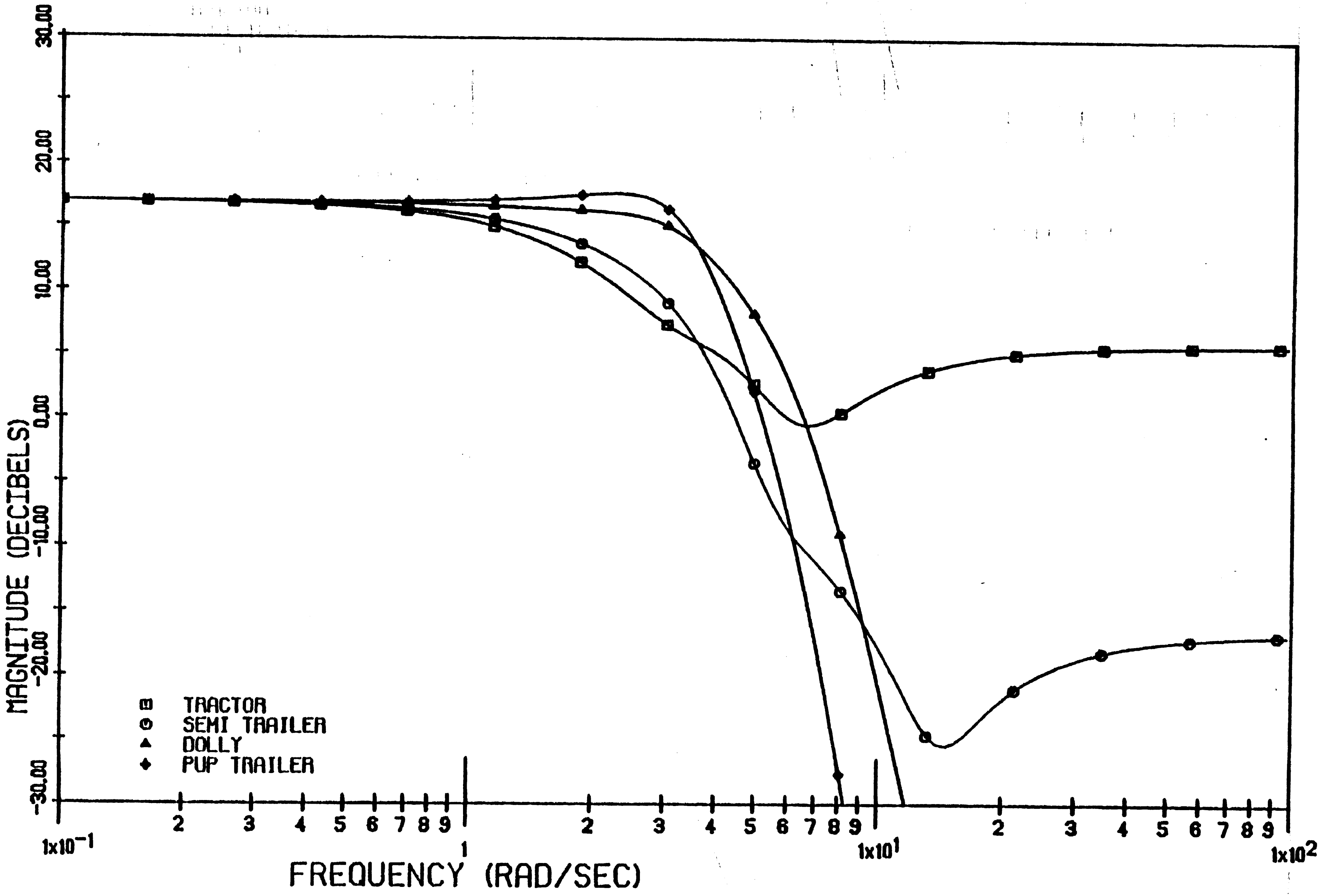
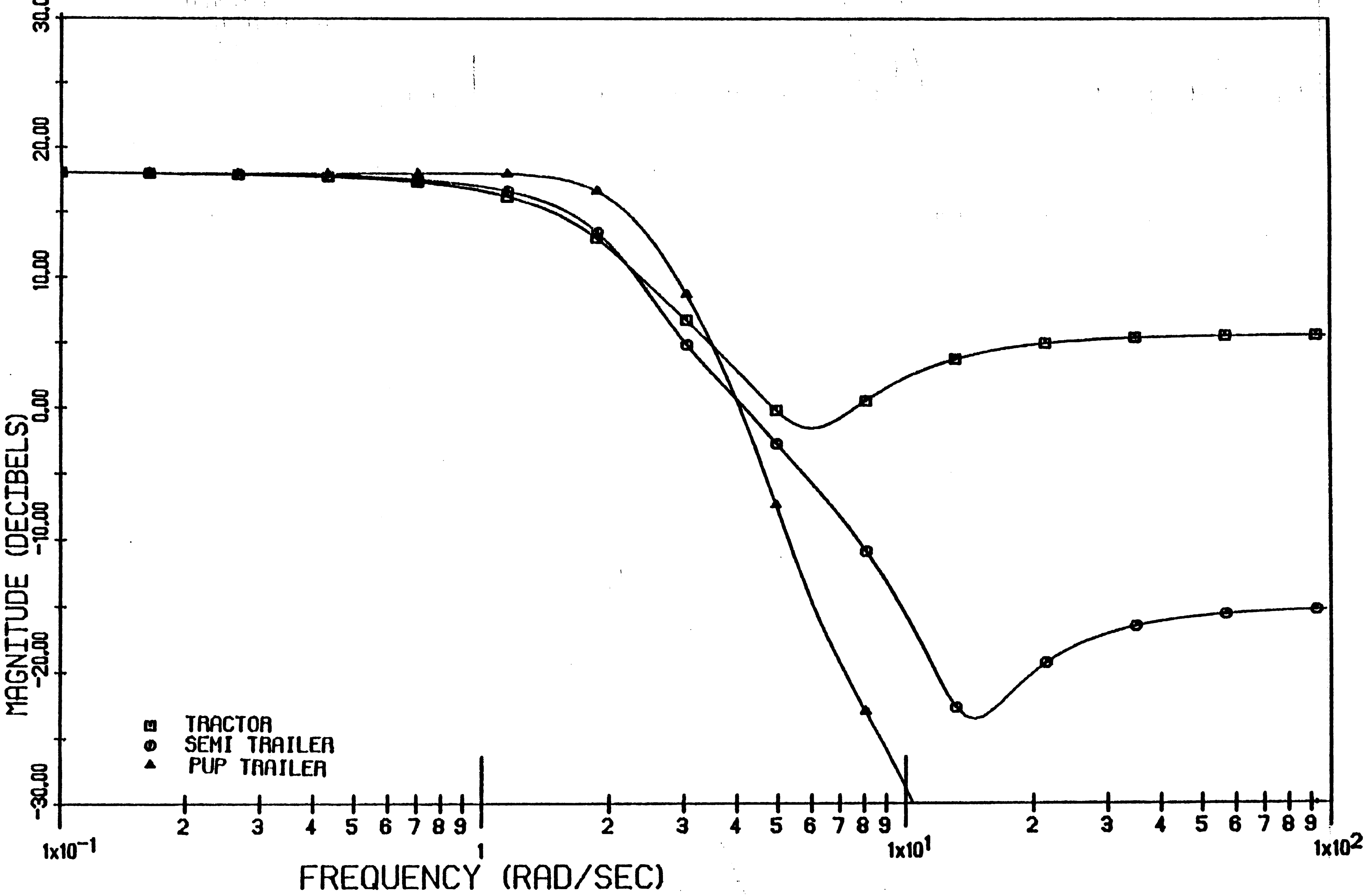
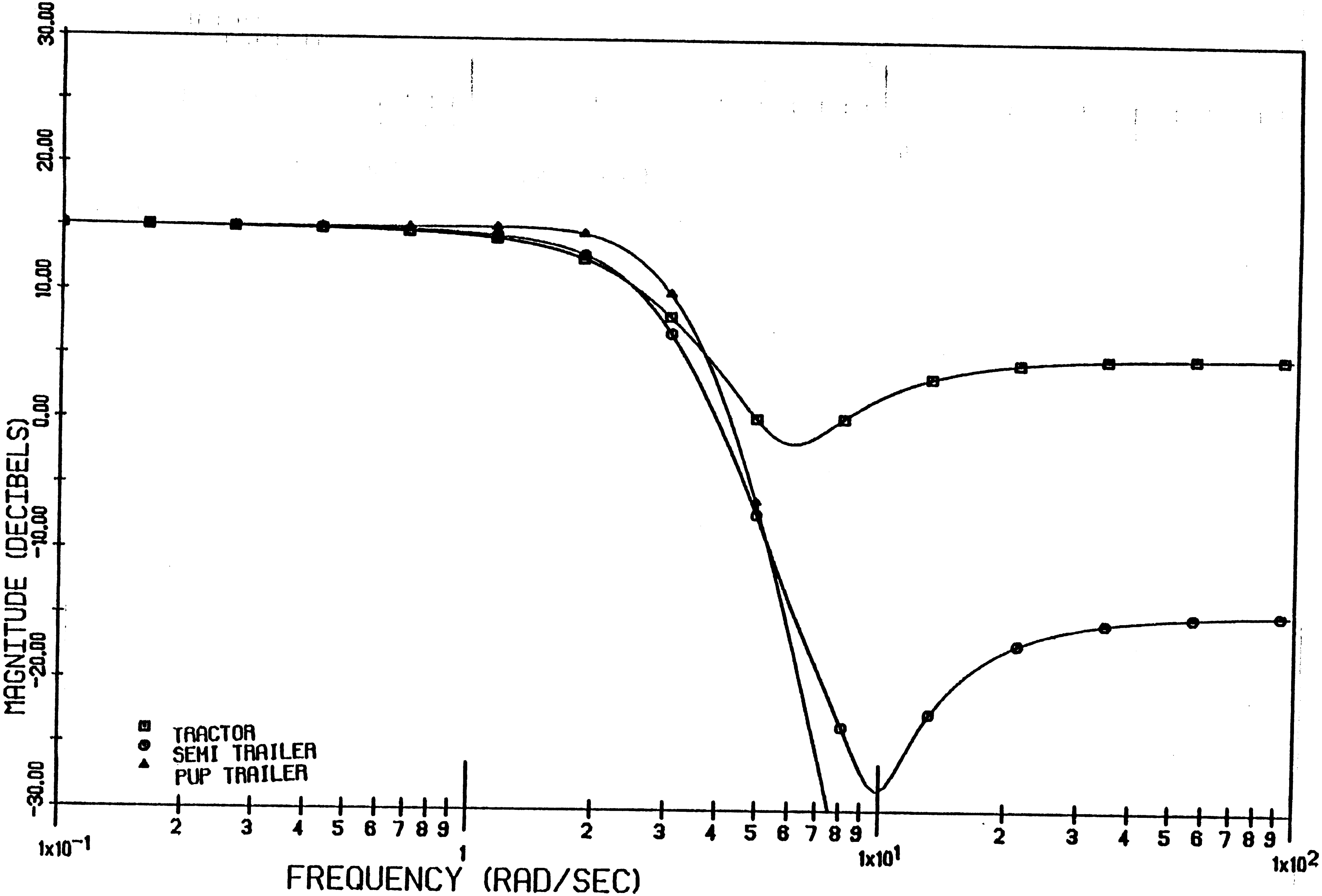


DOUBLE TANKER BKD-0067 , SEMI FULL PUP-COMP#2&3 FULL , DATASET#32



MODIFIED DOUBLE BKD-0067 FULLY LOADED DATASET#33



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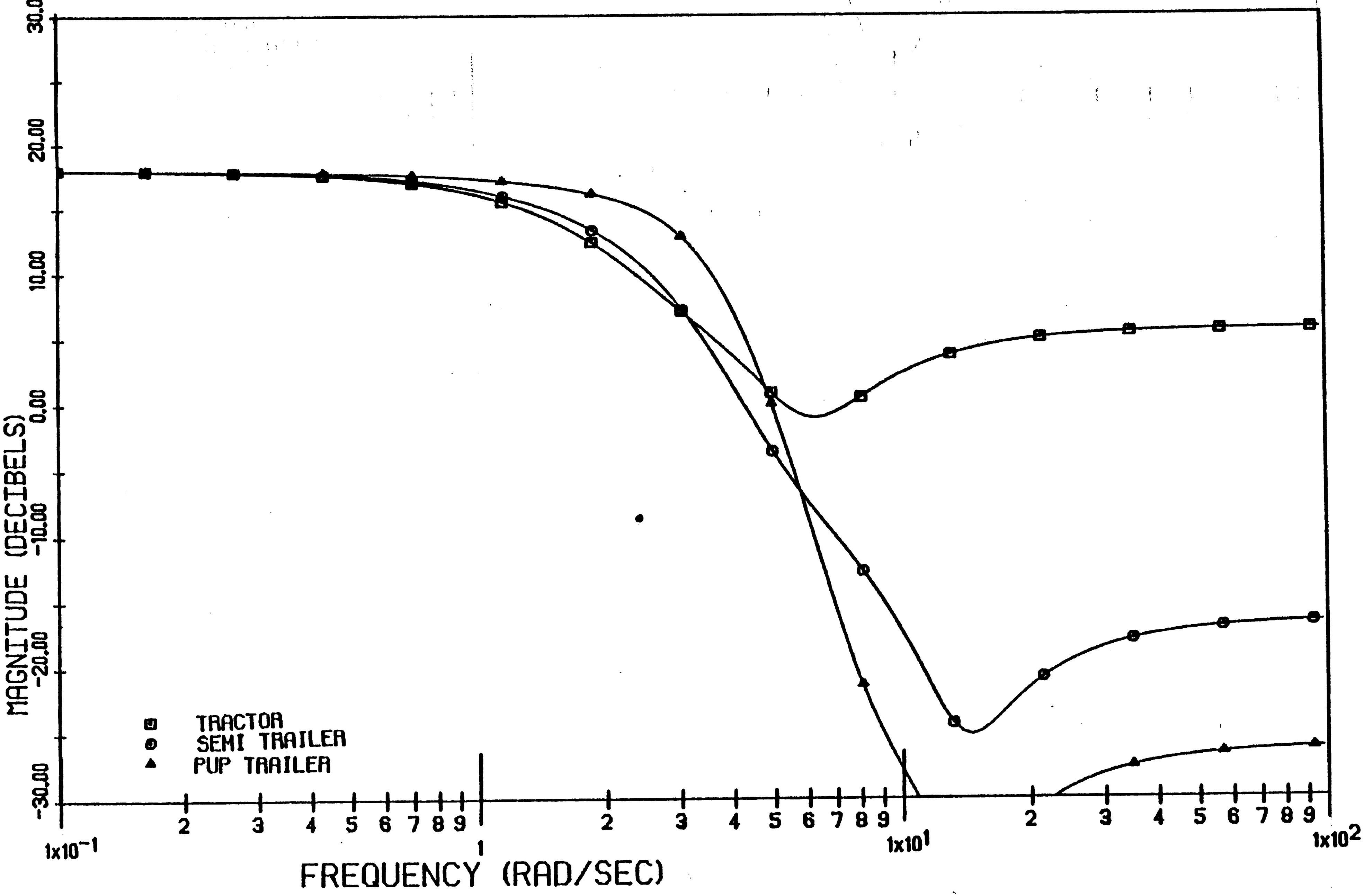

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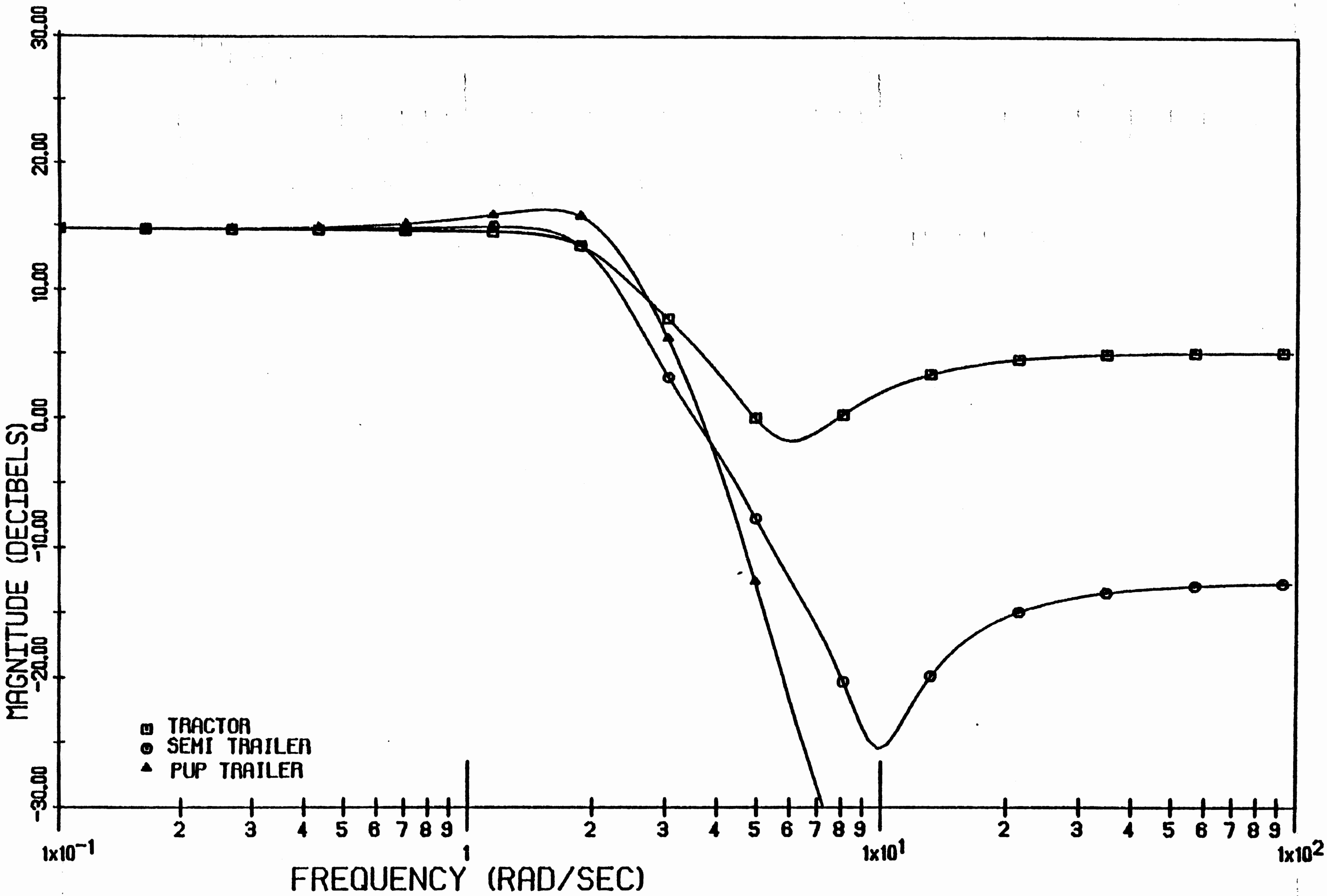

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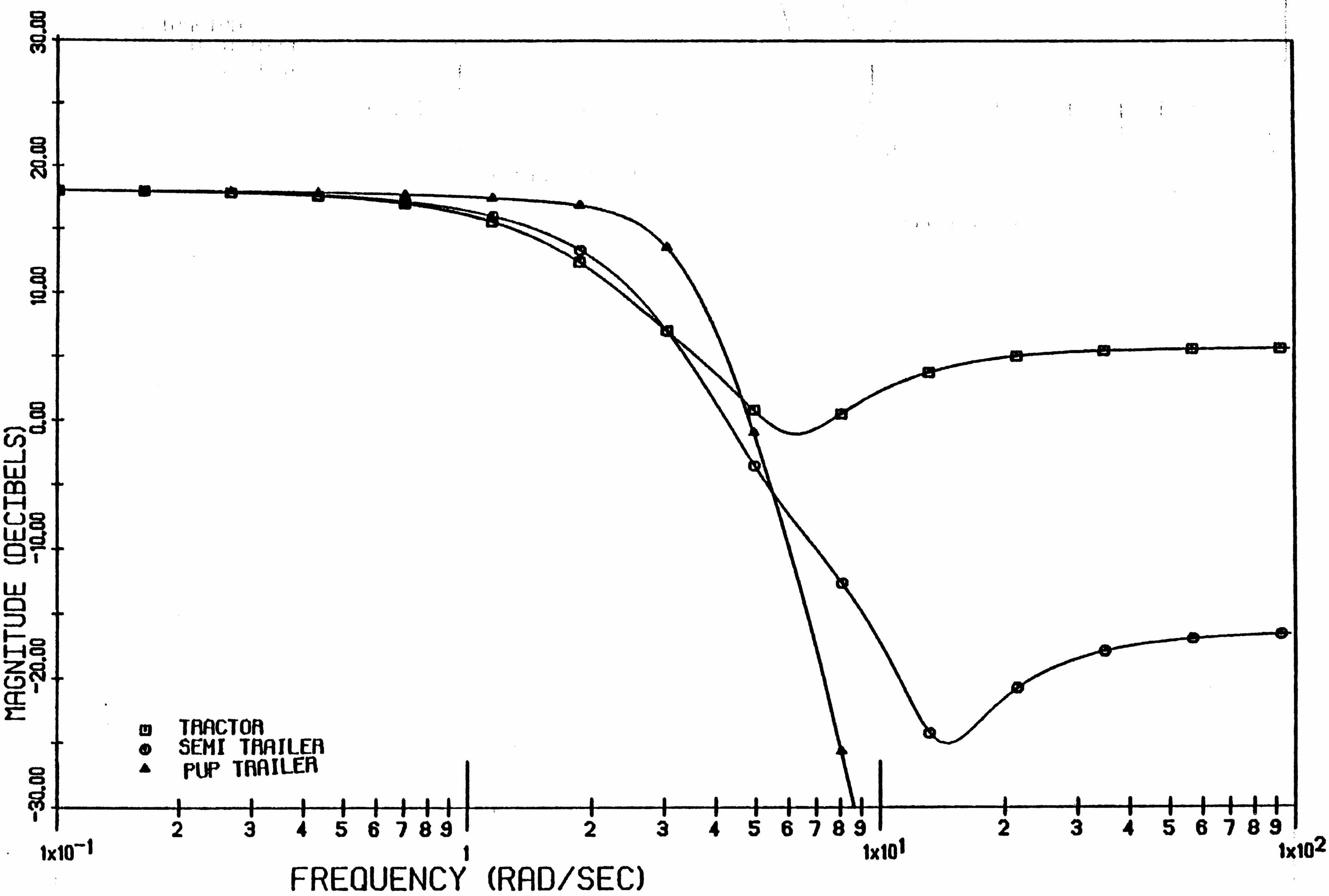

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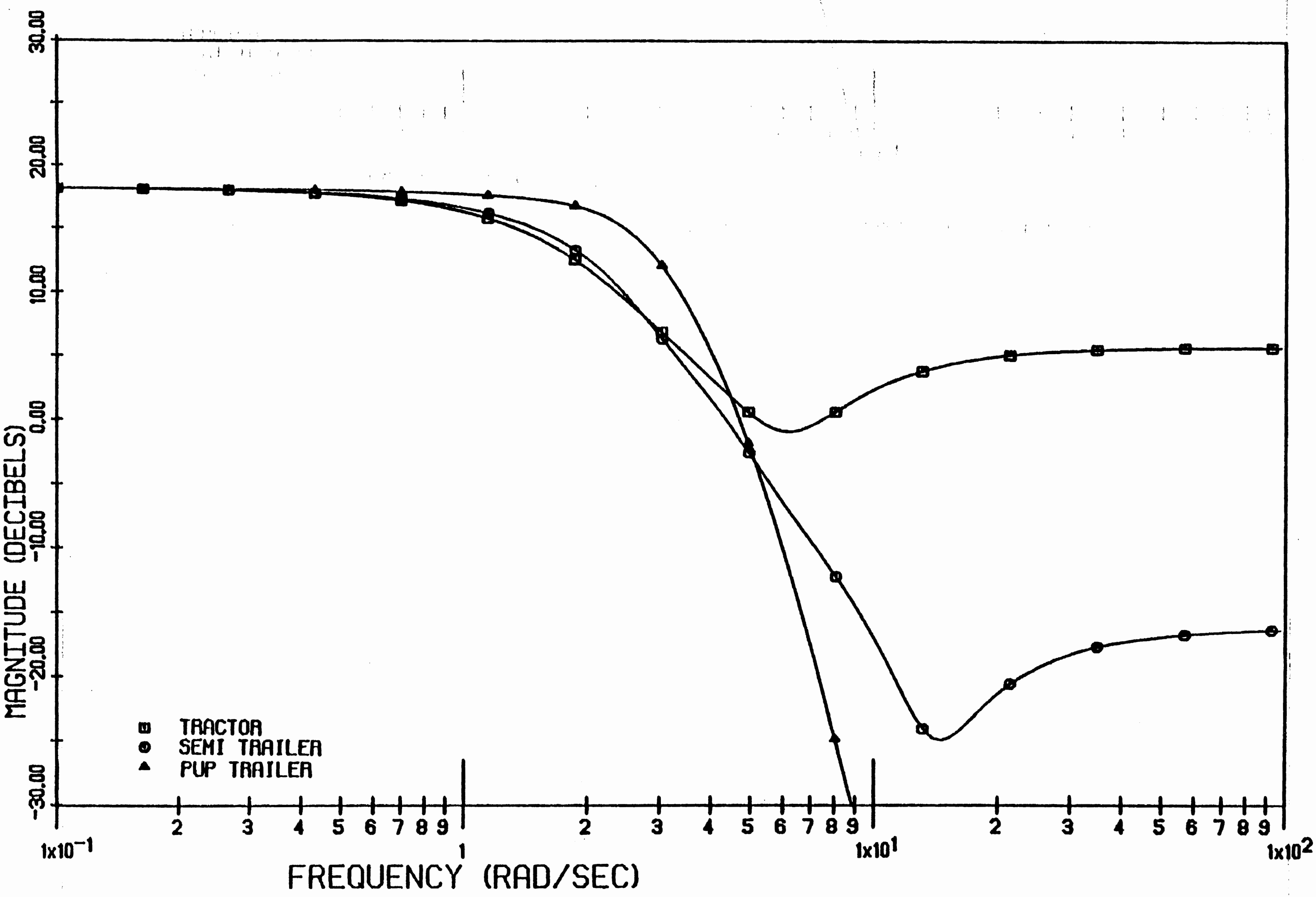
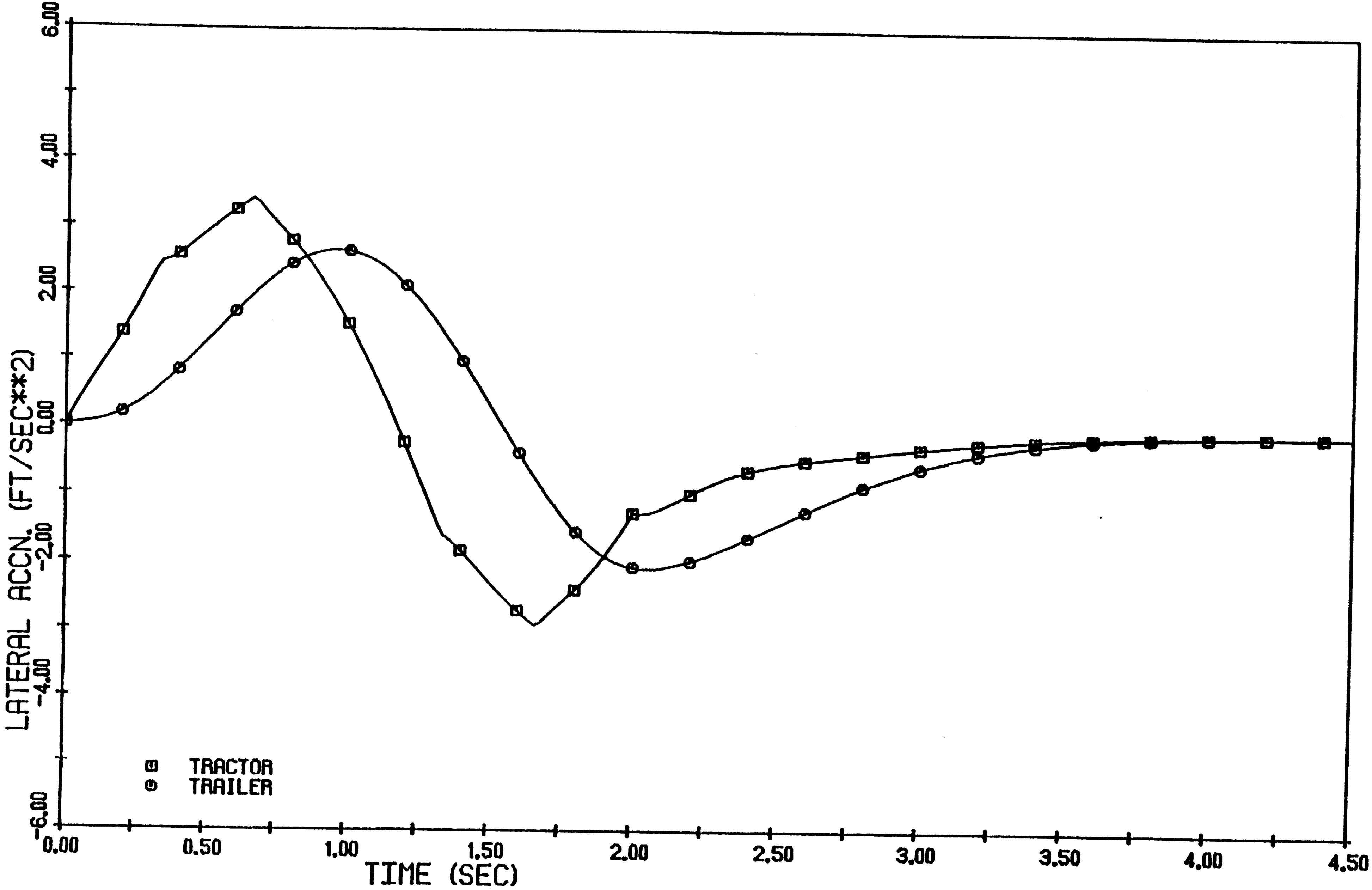


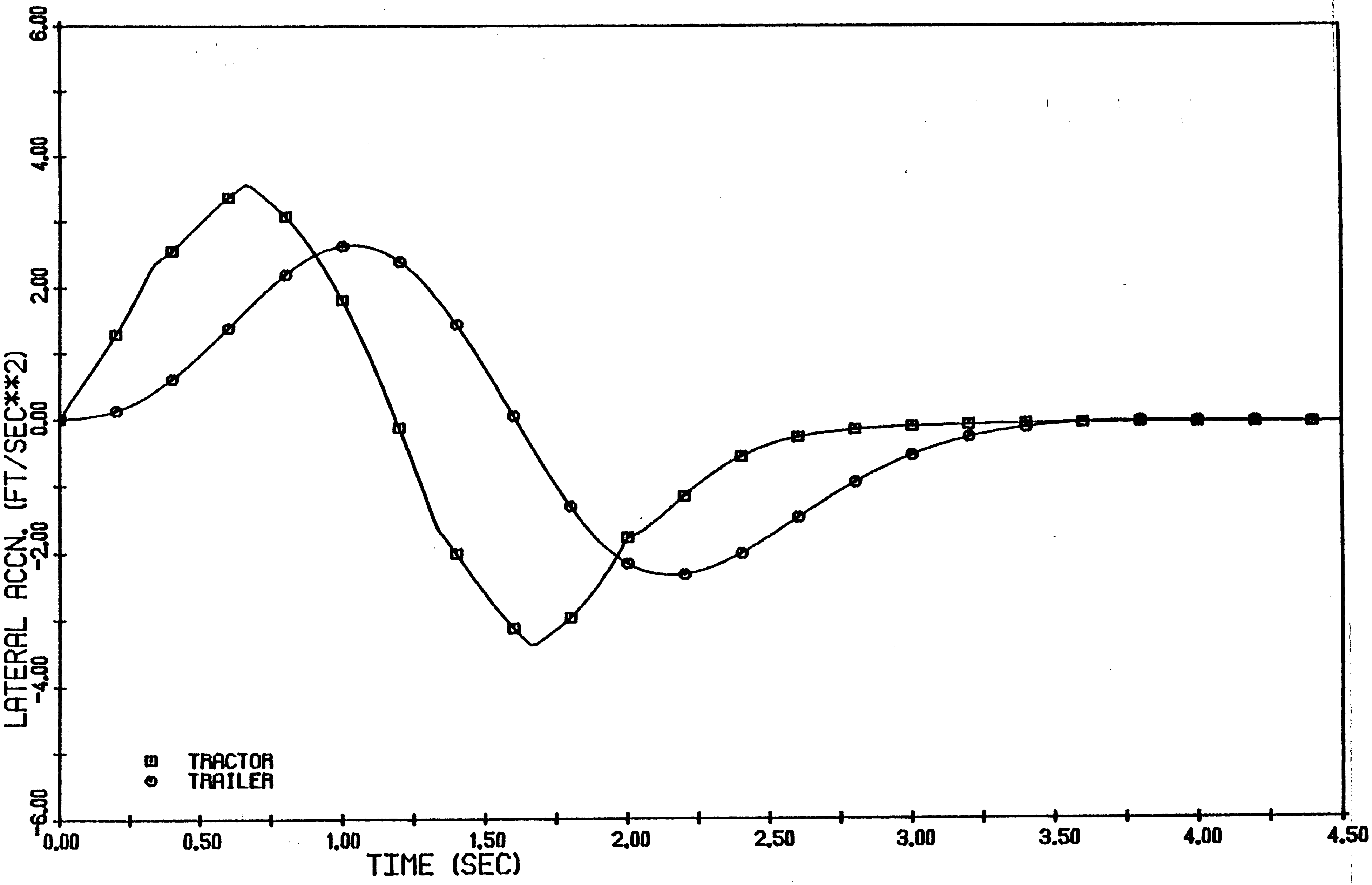
MODIFIED DOUBLE BKD-0067, SEMI FULL PUP-COMP#2&3 FULL, DATASET#38

APPENDIX D

LATERAL ACCELERATION TIME HISTORIES DURING 2-SECOND EMERGENCY LANE-CHANGE MANEUVERS AT 50 MPH



TRACTOR-SEMI BKY-8499 LOADED , DATASET#1



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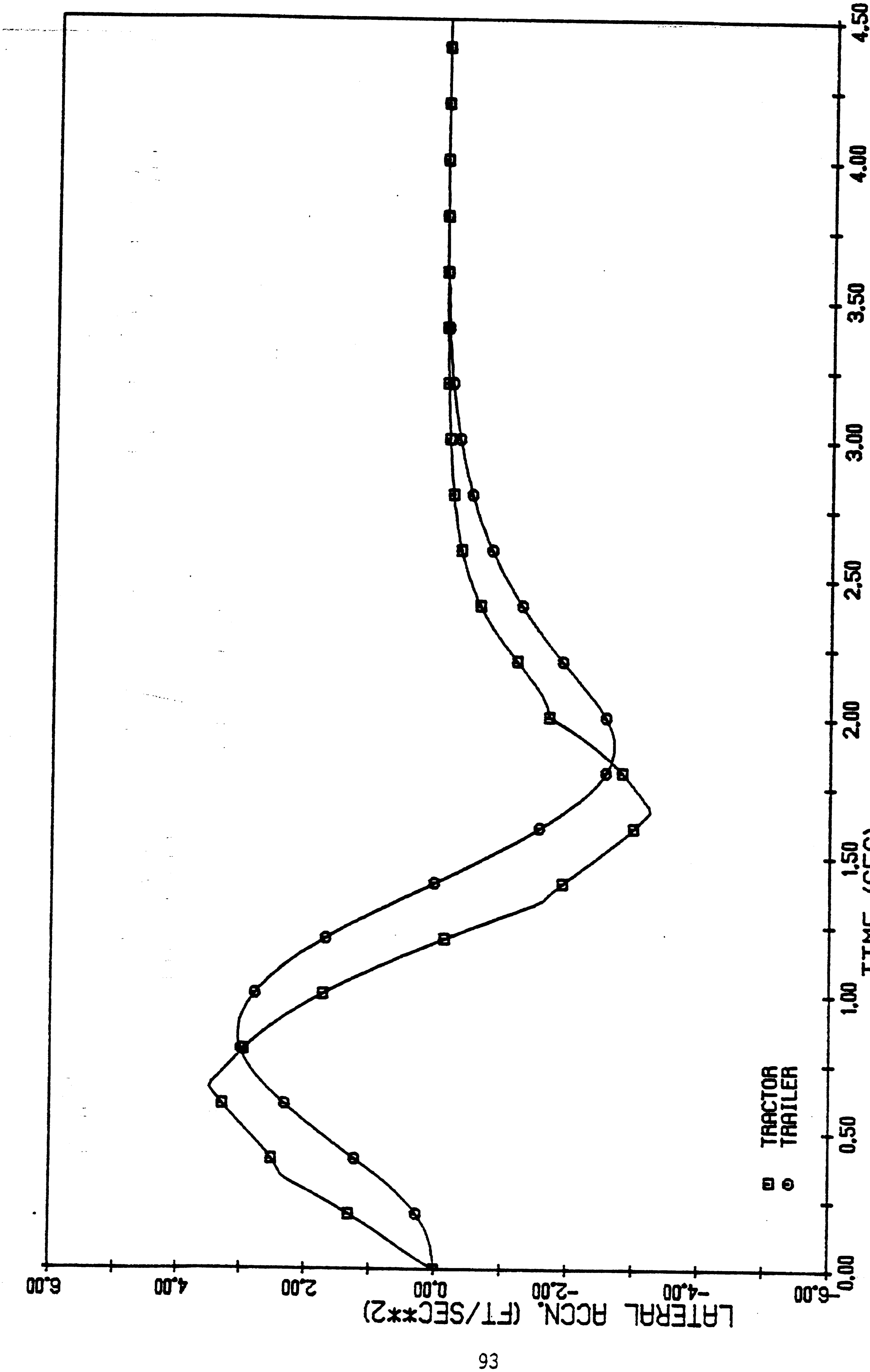
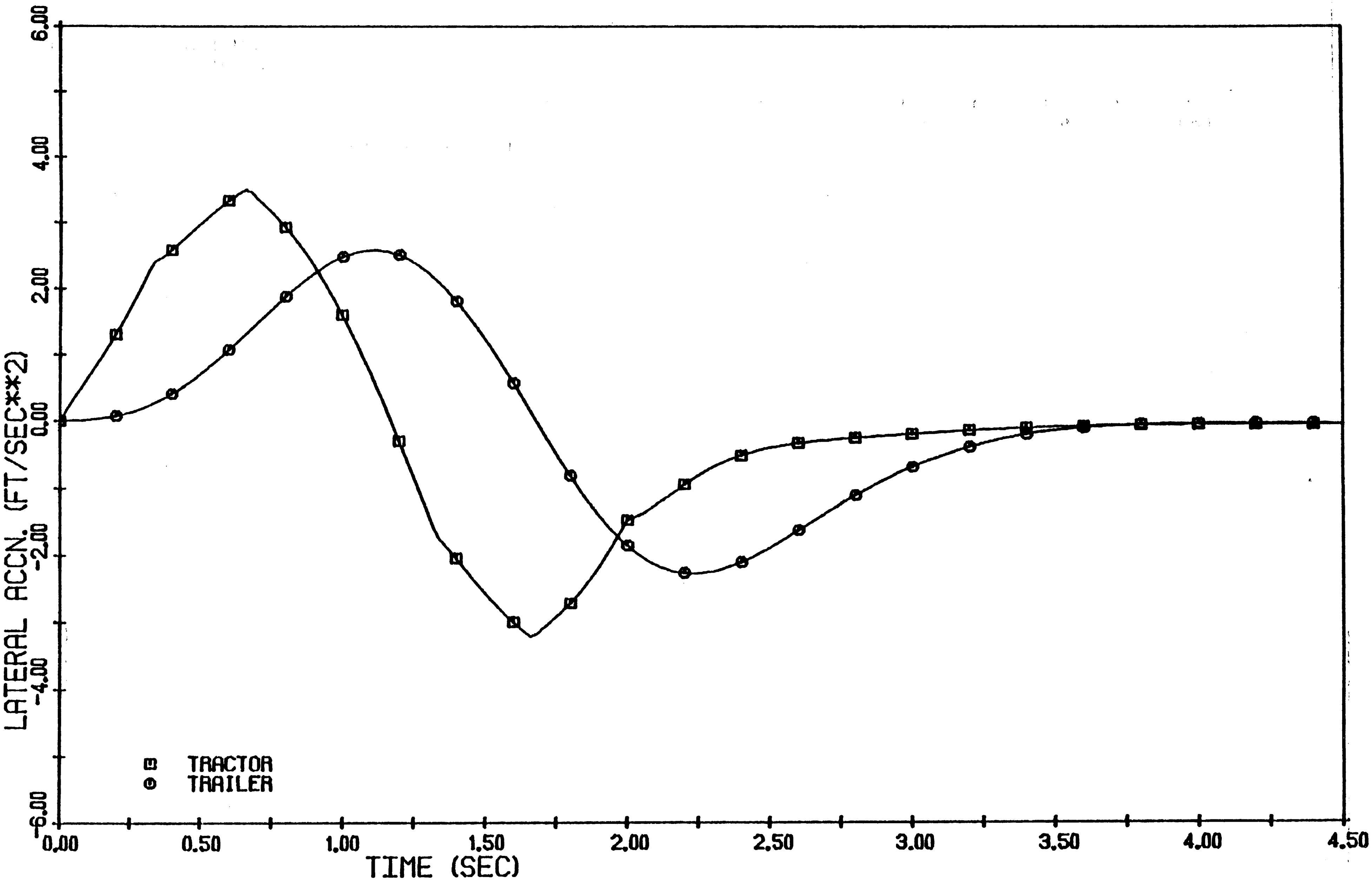
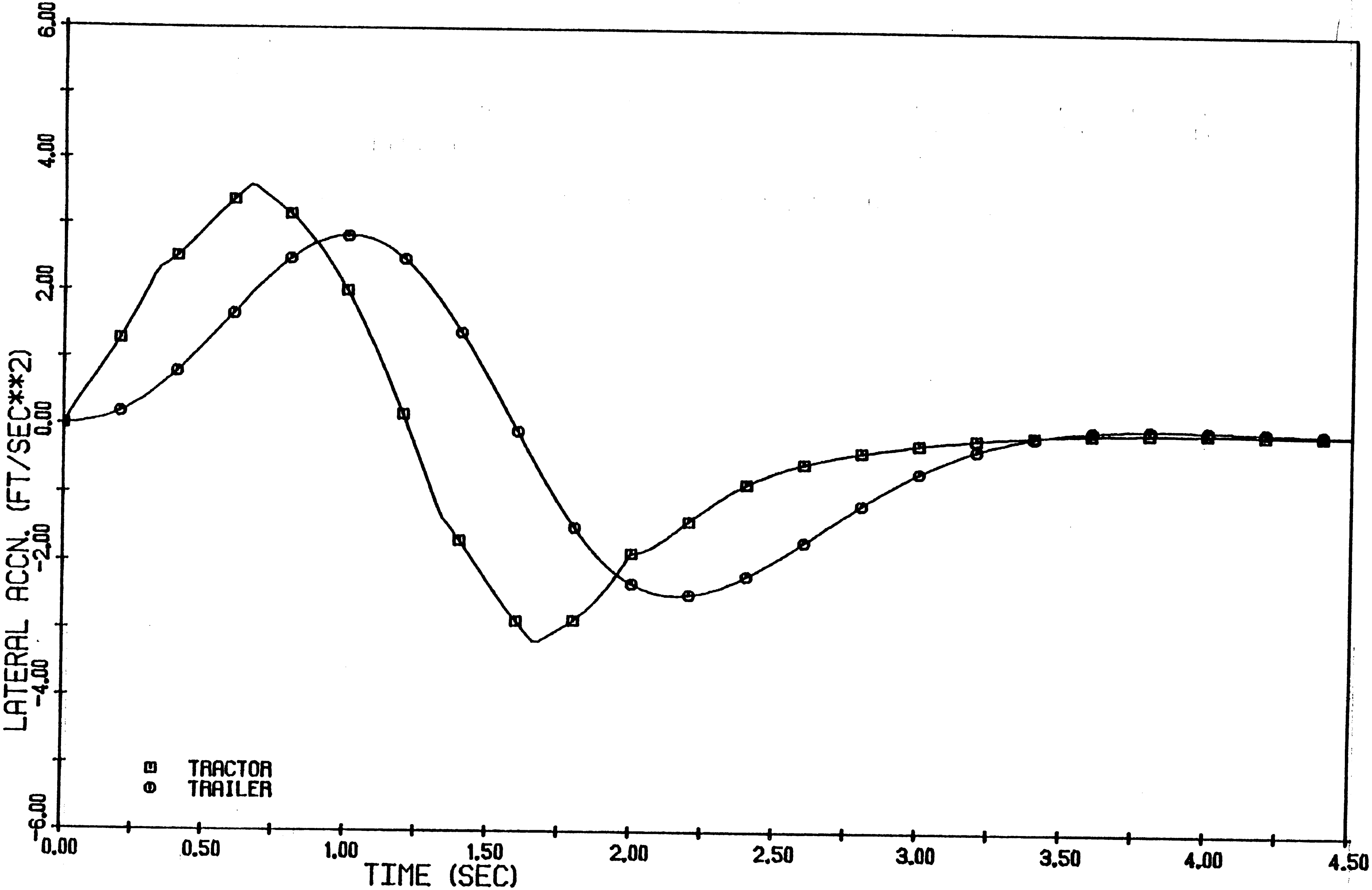


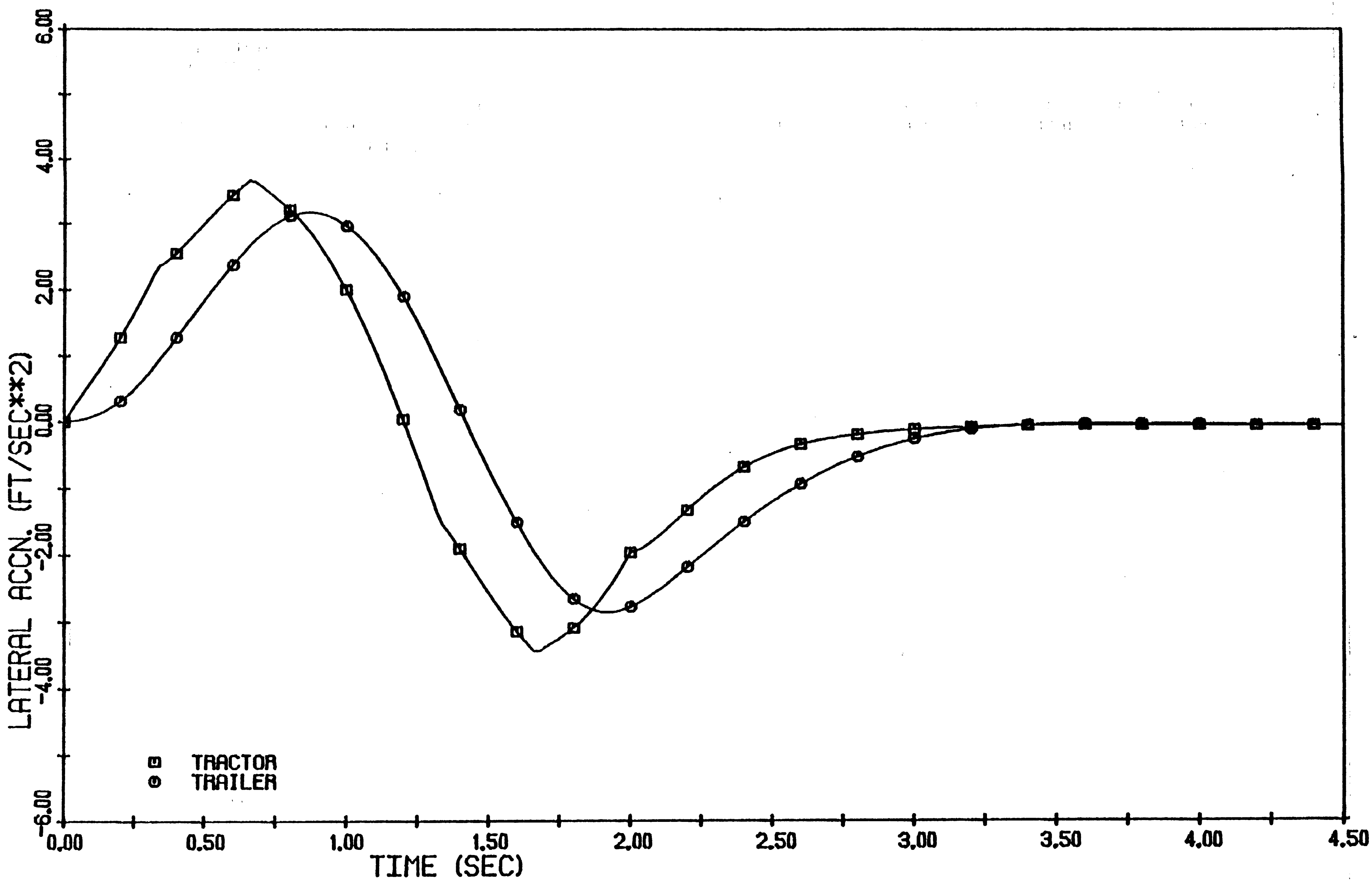
TRACTOR-SEMI BKY-8499 COMP #1 FULL , DATASET#3



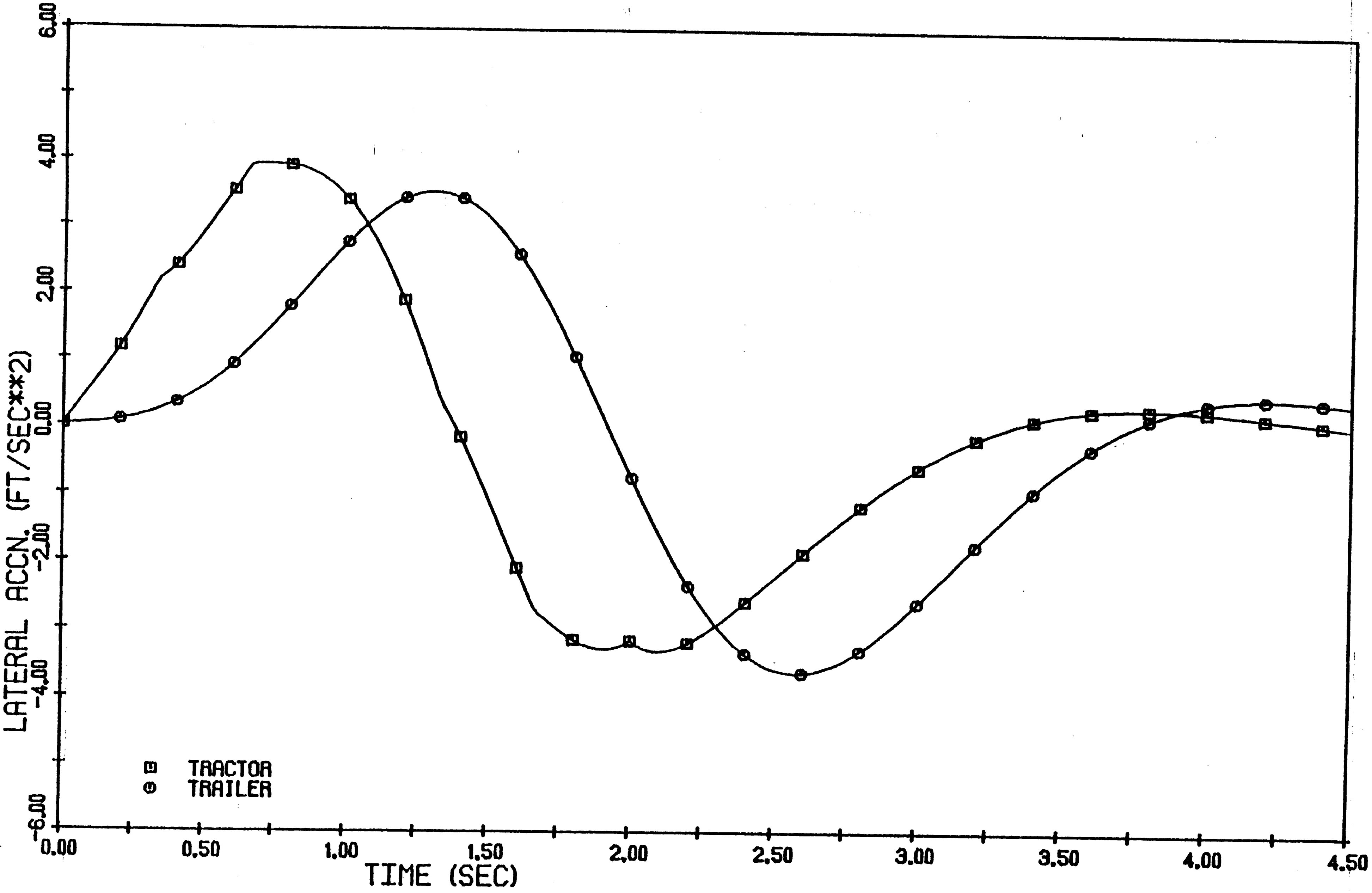
TRACTOR-SEMI BKY-8499 COMP #4 FULL , DATASET#4



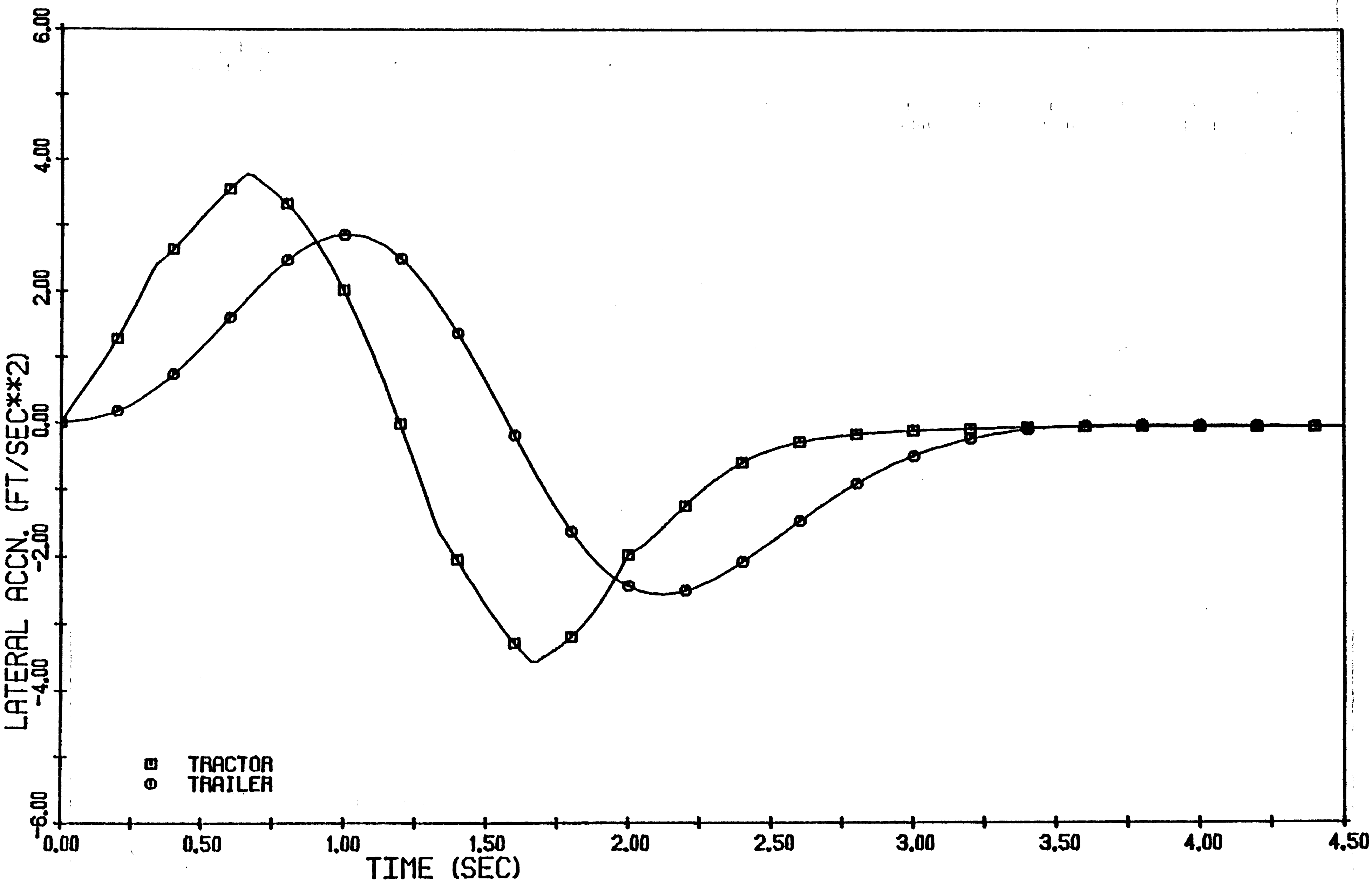
TRACTOR-SEMI BKD-0065 LOADED , DATASET#5



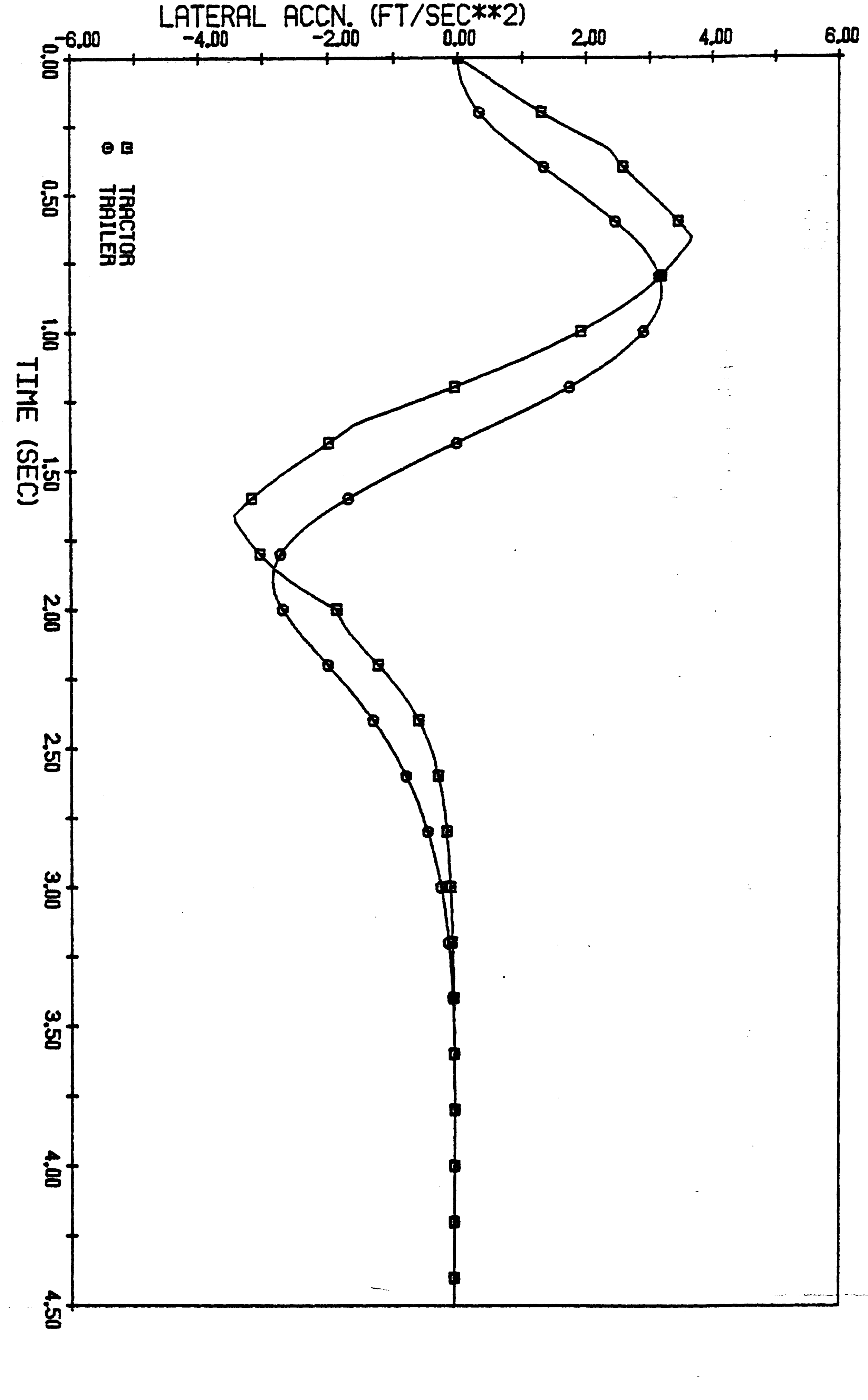
TRACTOR-SEMI BKD-0065 COMP #1 FULL , DATASET#6



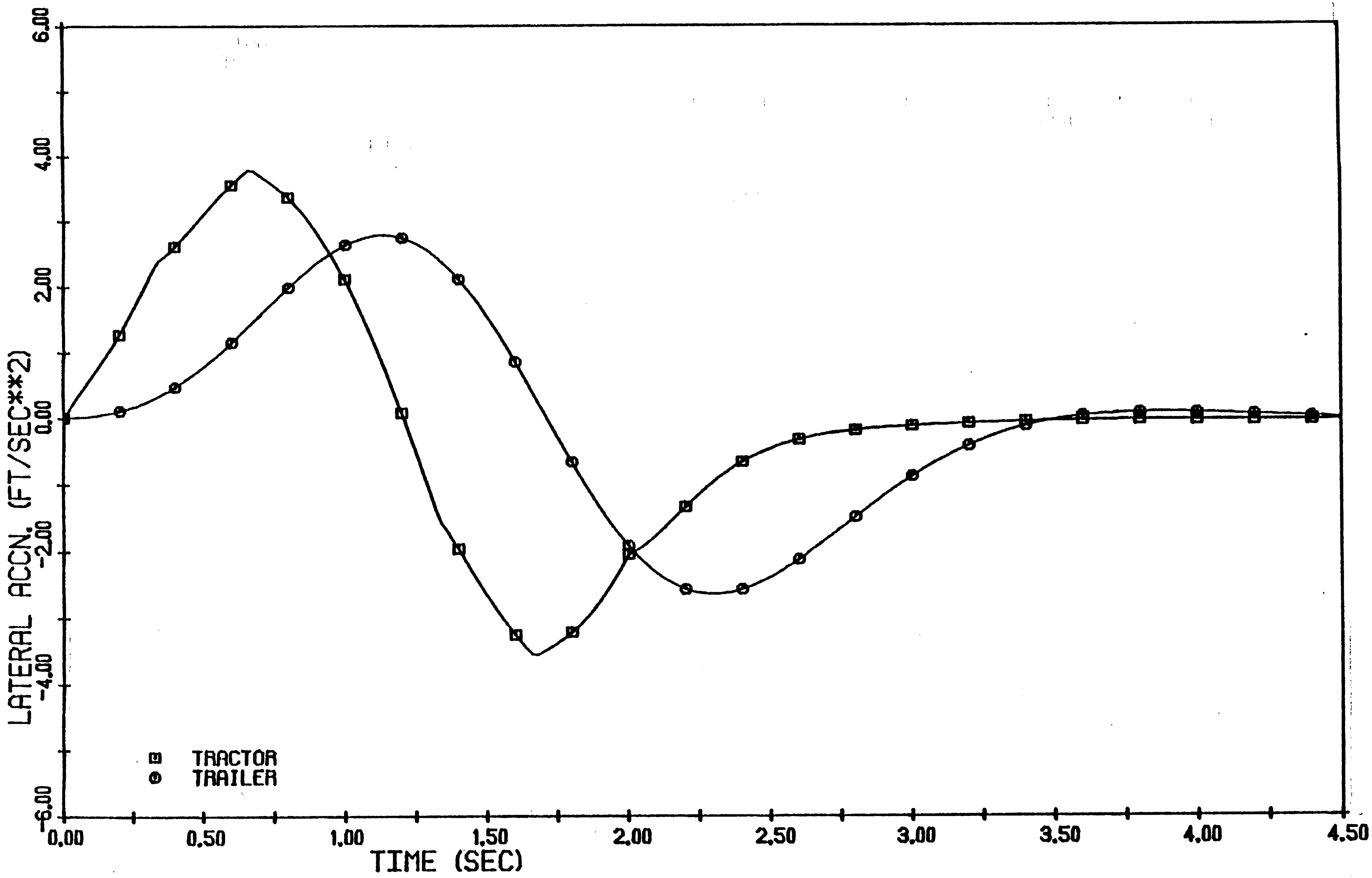
TRACTOR-SEMI BKD-0065 COMP #4 FULL , DATASET#7



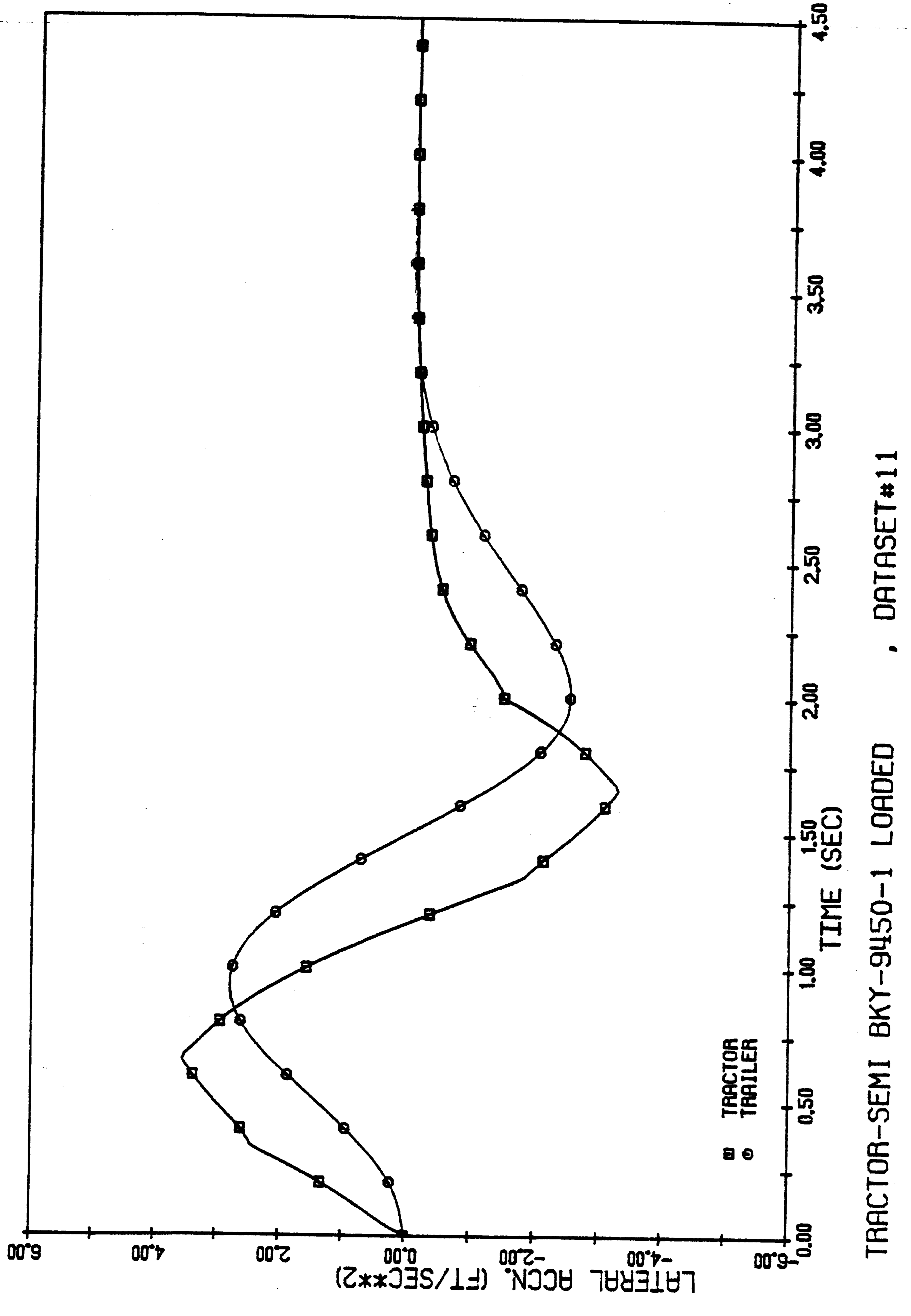
TRACTOR-SEMI BKD-0065 EMPTY , DATASET#8

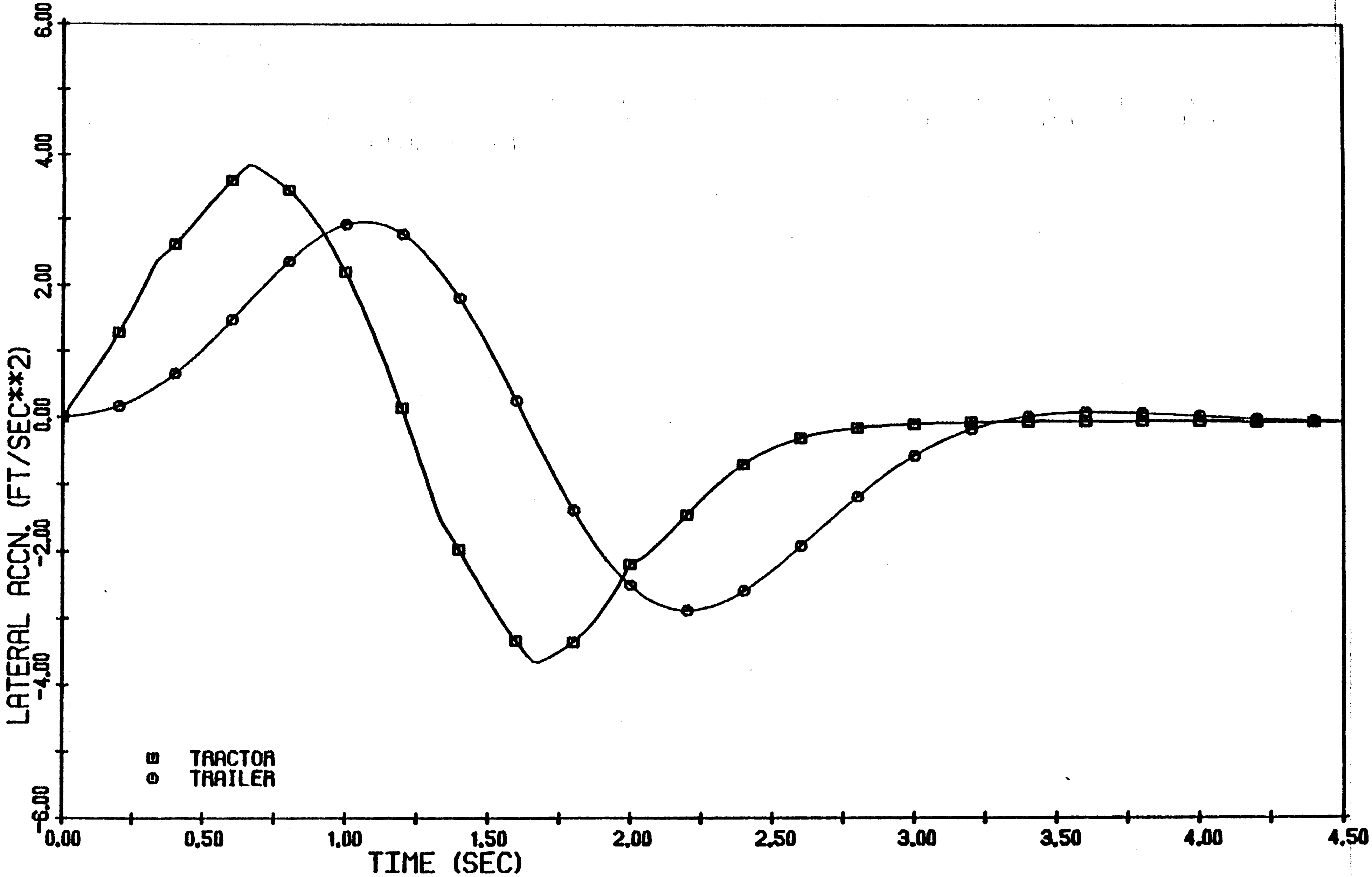


TRACTOR-SEMI BKD-0065 COMP #1 FULL , DATASET#9

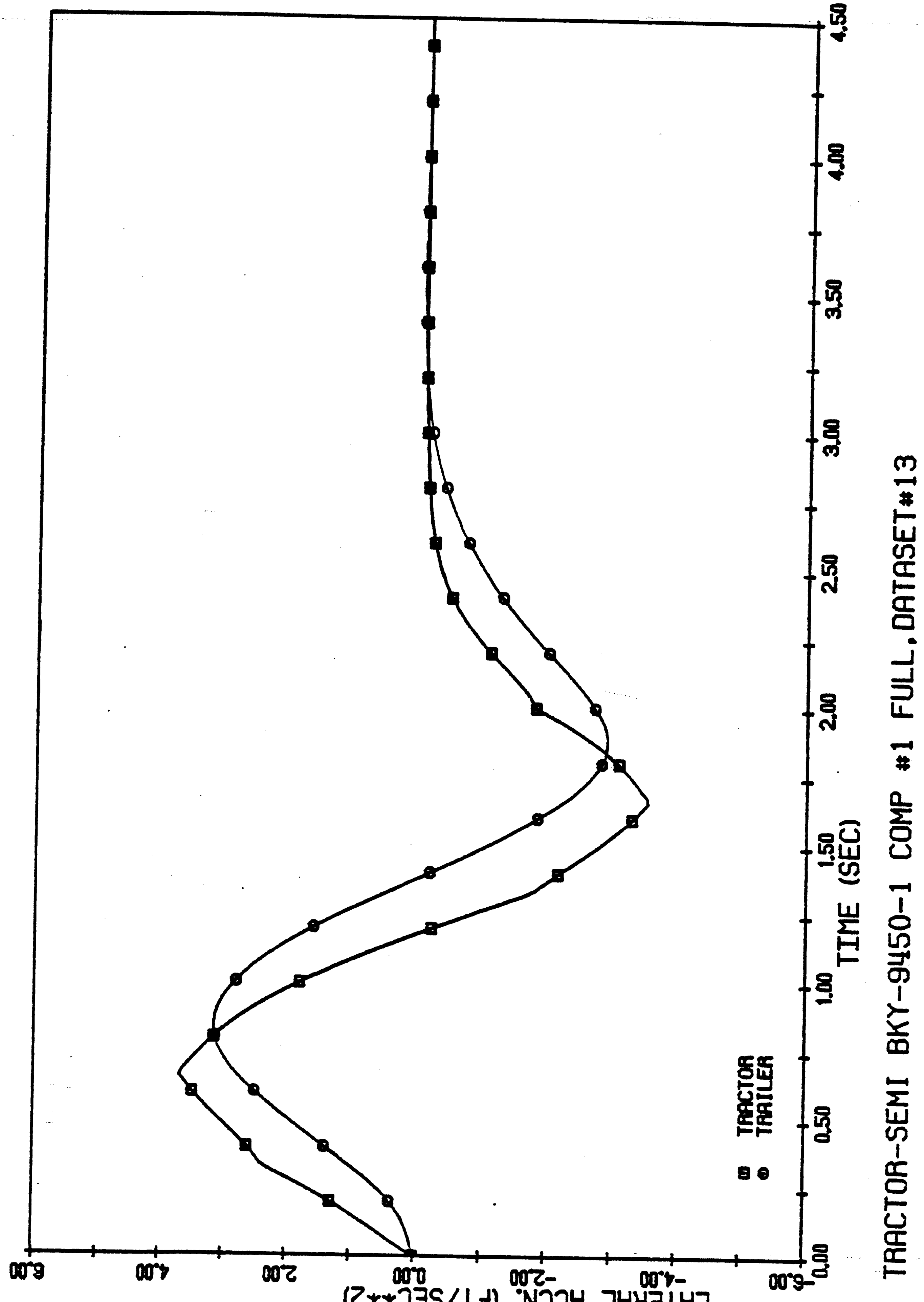


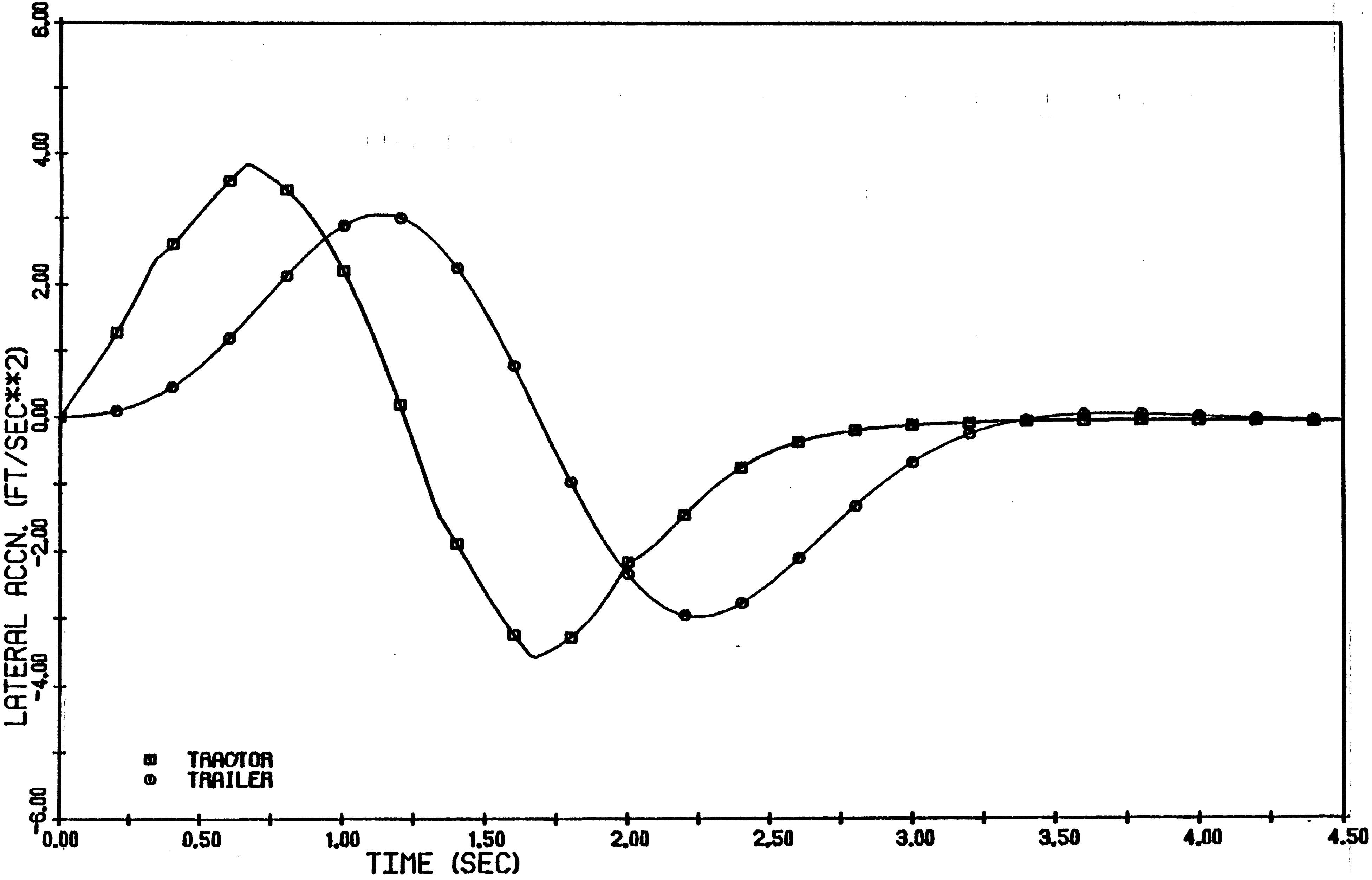
TRACTOR-SEMI BKD-0065 COMP #4 FULL , DATASET#10


TRACTOR-SEMI BKY-9450-1 LOADED , DATASET#11
TIME (SEC)
LATERAL ACCN. (FT/SEC**2)
TRACTOR
TRAILER
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
-6.00
-4.00
-2.00
0.00
2.00
4.00
6.00

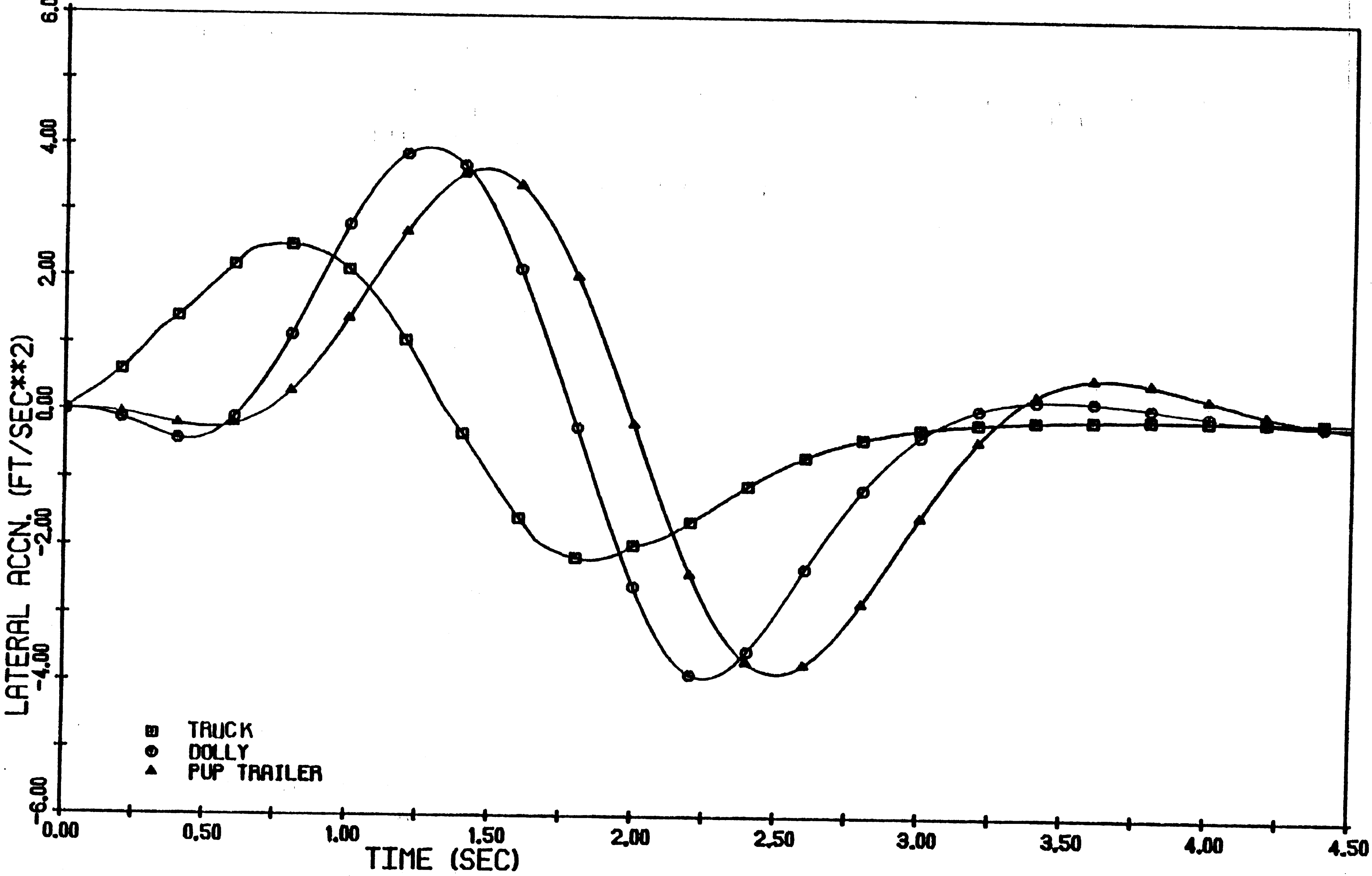


TRACTOR-SEMI BKY-9450-1 EMPTY , DATASET#12

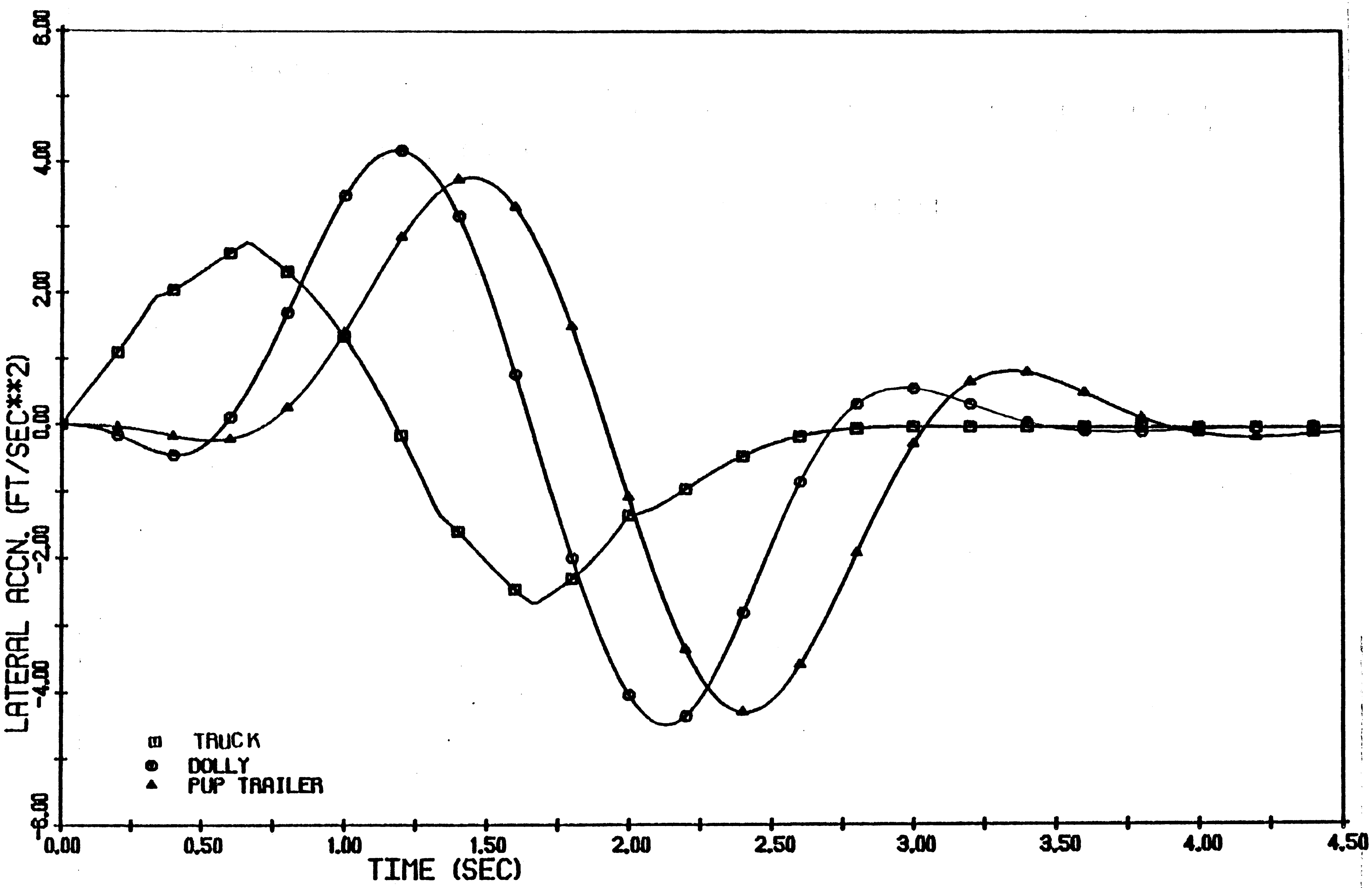

TRACTOR-SEMI BKY-9450-1 COMP #1 FULL, DATASET#13
TIME (SEC)
LATERAL ACCN. (FT/SEC**2)
TRACTOR
TRAILER
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
-6.00
-4.00
-2.00
0.00
2.00
4.00
6.00



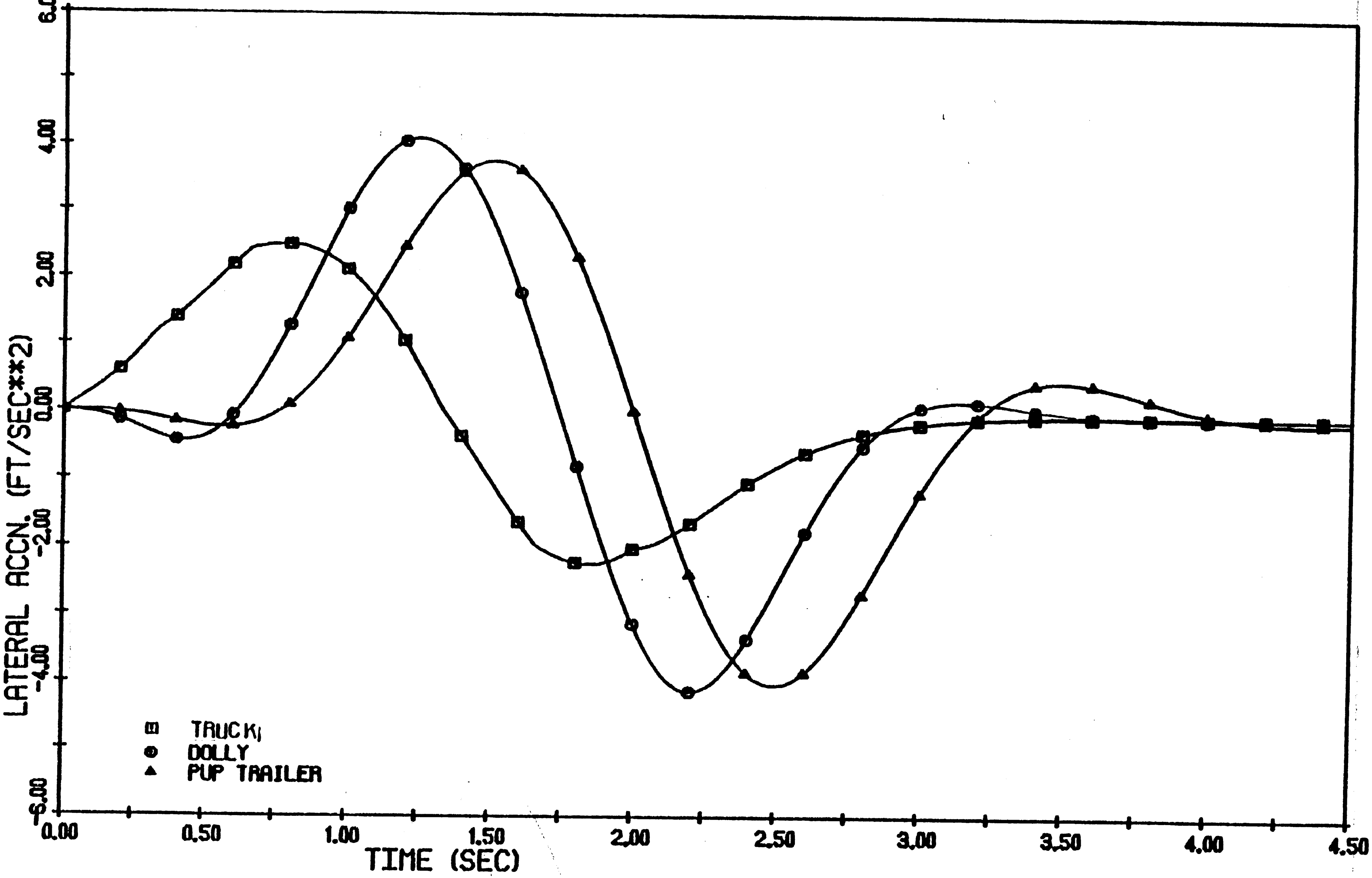
TRACTOR-SEMI BKY-9450-1 COMP #4 FULL, DATASET#14



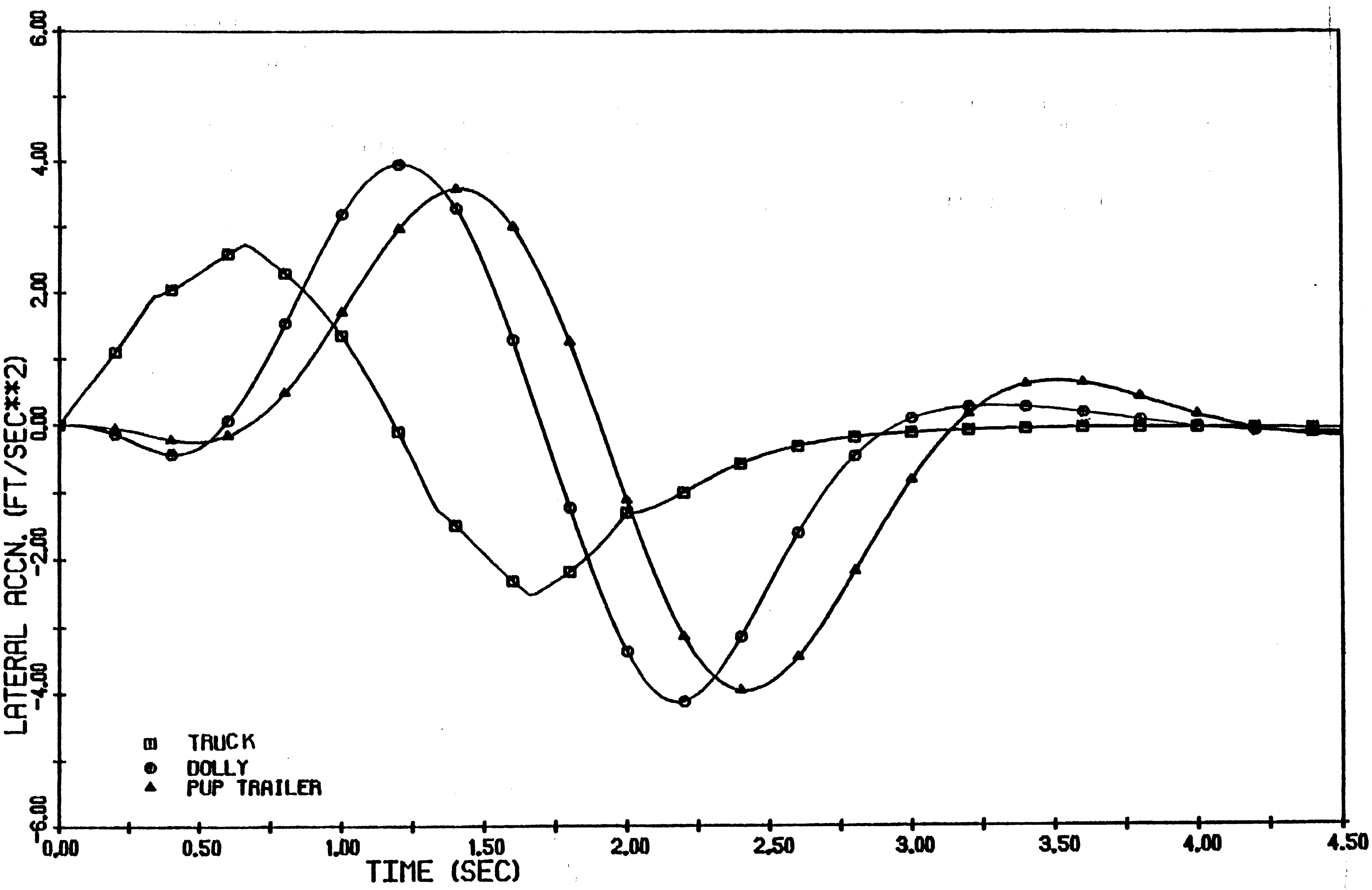
TRUCK/FULL-TRAILER BLY-2714 , LOADED , DATASET#15



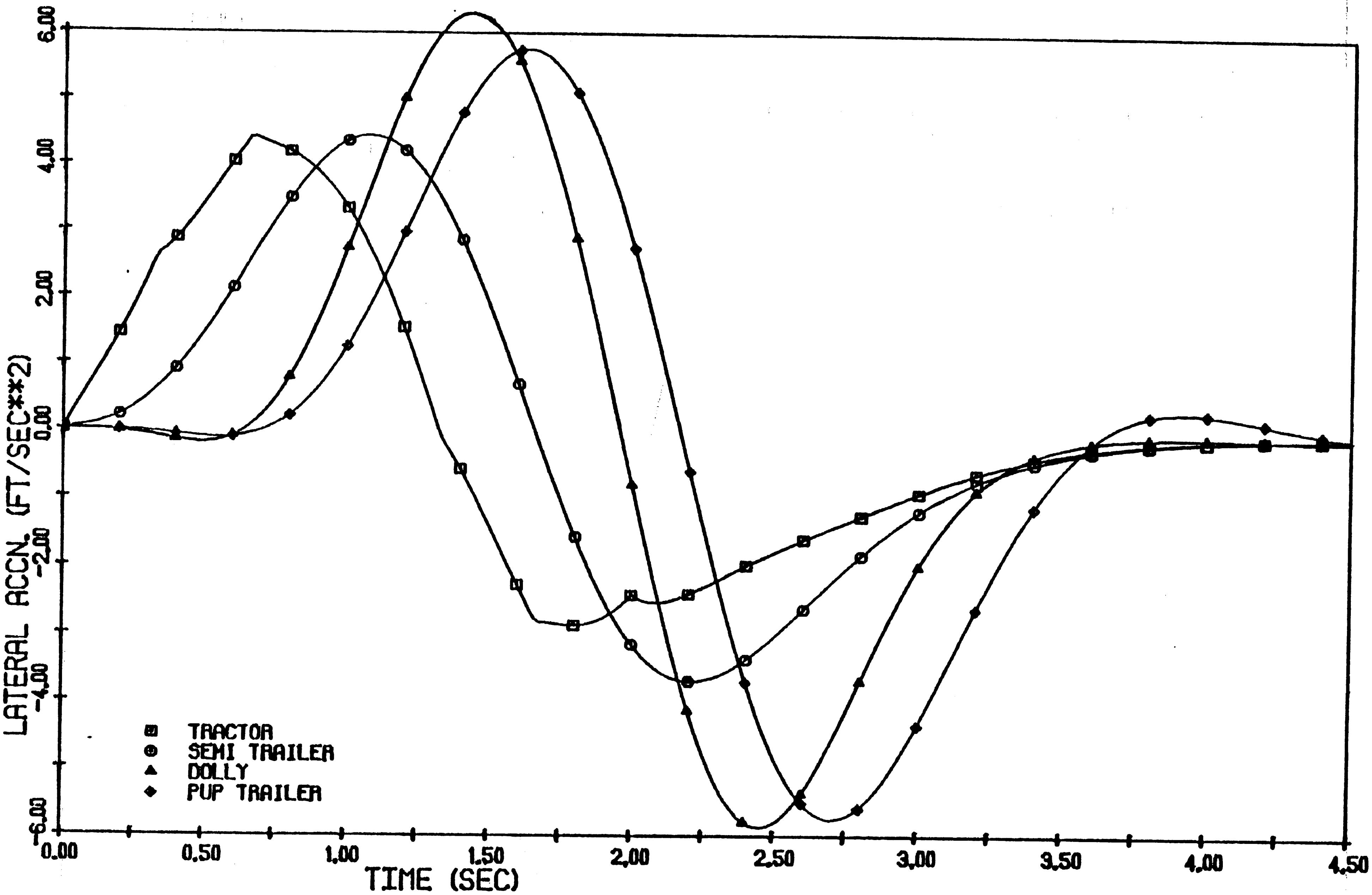
TRUCK/ FULL-TRAILER BLY-2714 , EMPTY , DATASET#16



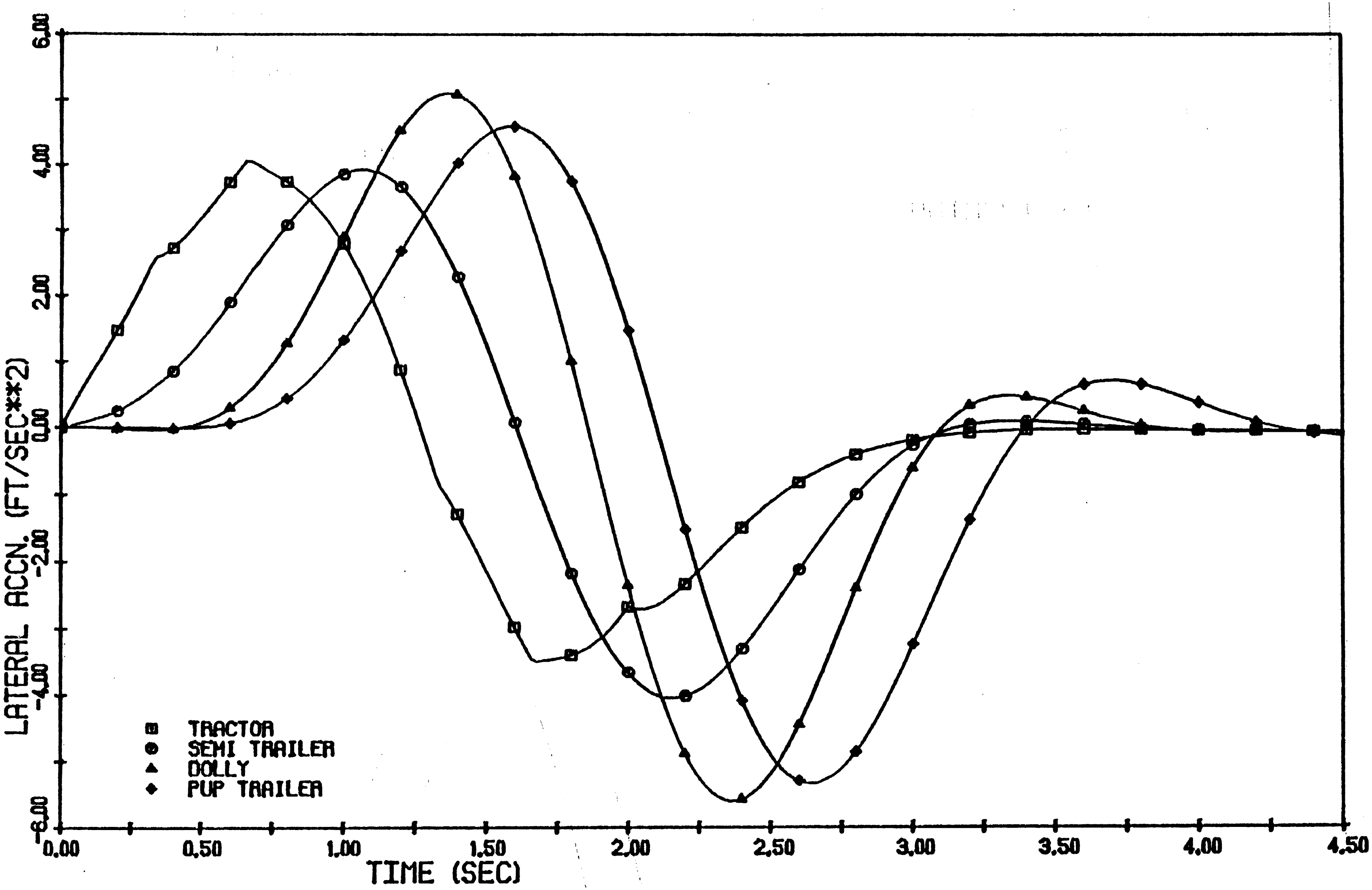
TRUCK/FULL-TRAILER BLY-2714 ,SEMI FULL-PUP EMPTY,DATASET#17



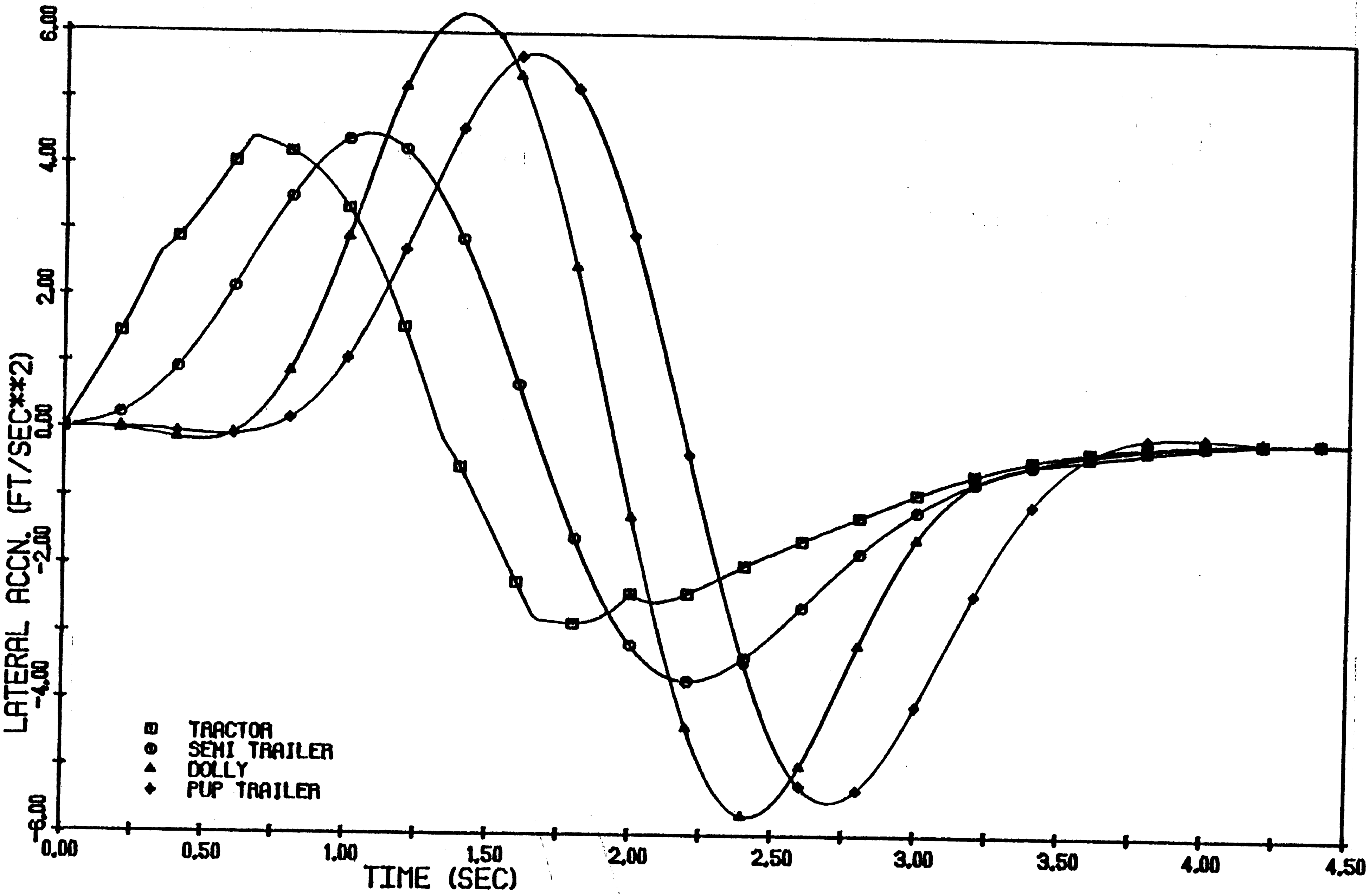
TRUCK/FULL-TRAILER BLY-2714 ,SEMI EMPTY-PUP FULL,DATASET#18



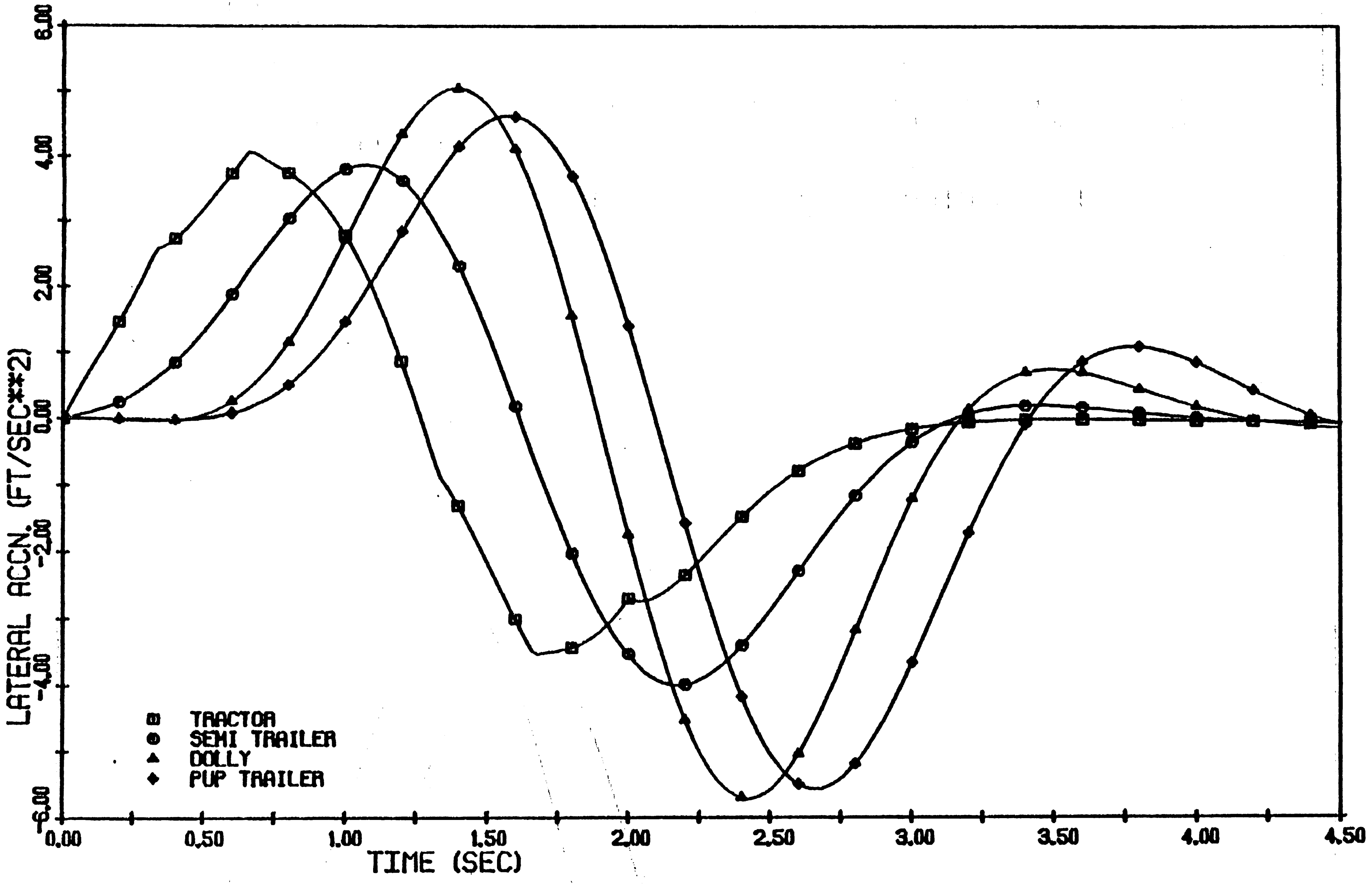
DOUBLE-TANKER-BLY-2985, FULLY LOADED DATASET#19



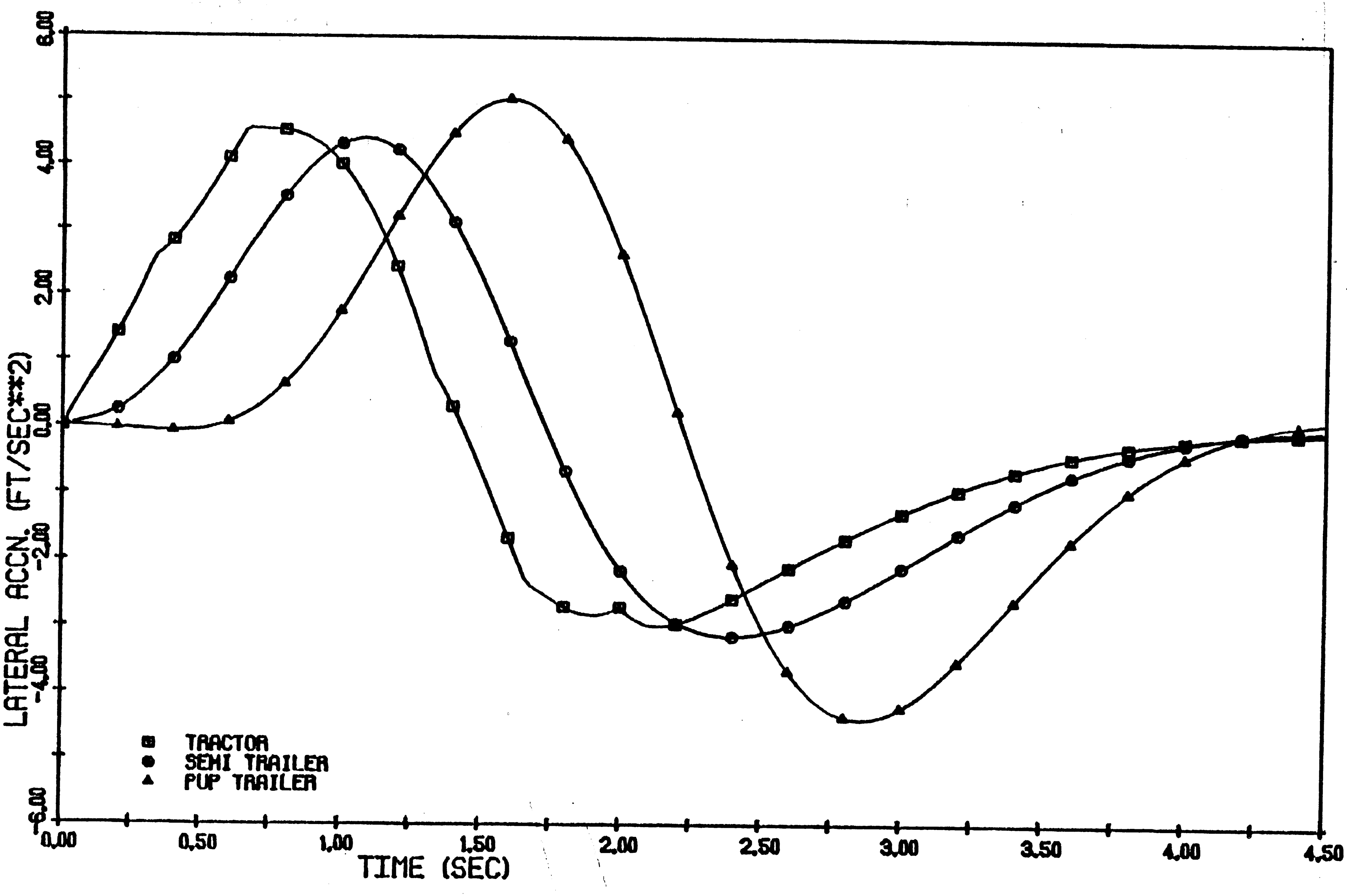
DOUBLE-TANKER-BLY-2985, SEMI TRAILER&PUP EMPTY DATASET#20



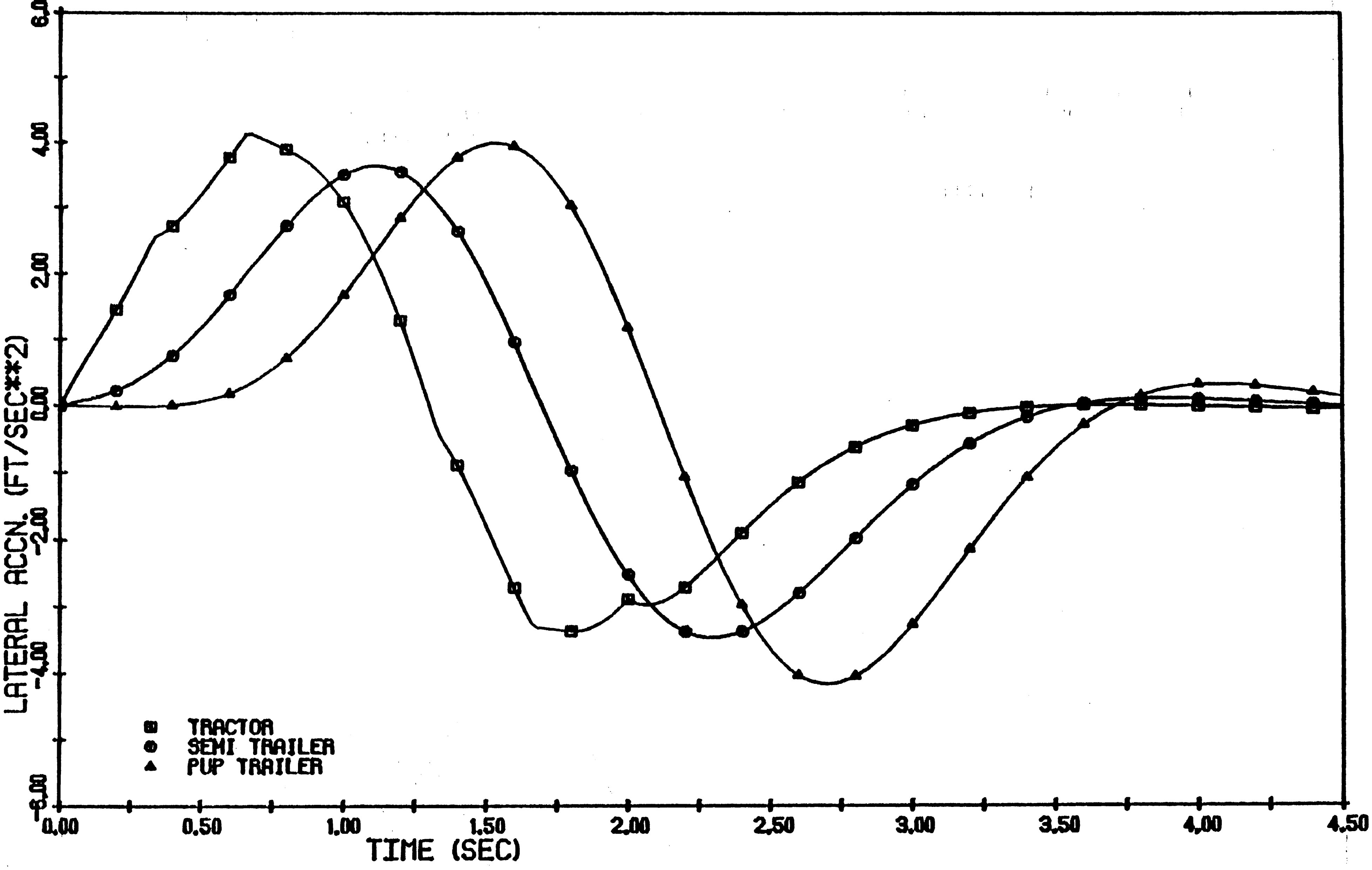
DOUBLE-TANKER-BLY-2985, SEMI LOADED, PUP EMPTY   DATASET#21



DOUBLE-TANKER-BLY-2985, SEMI EMPTY, PUP LOADED DATASET#22

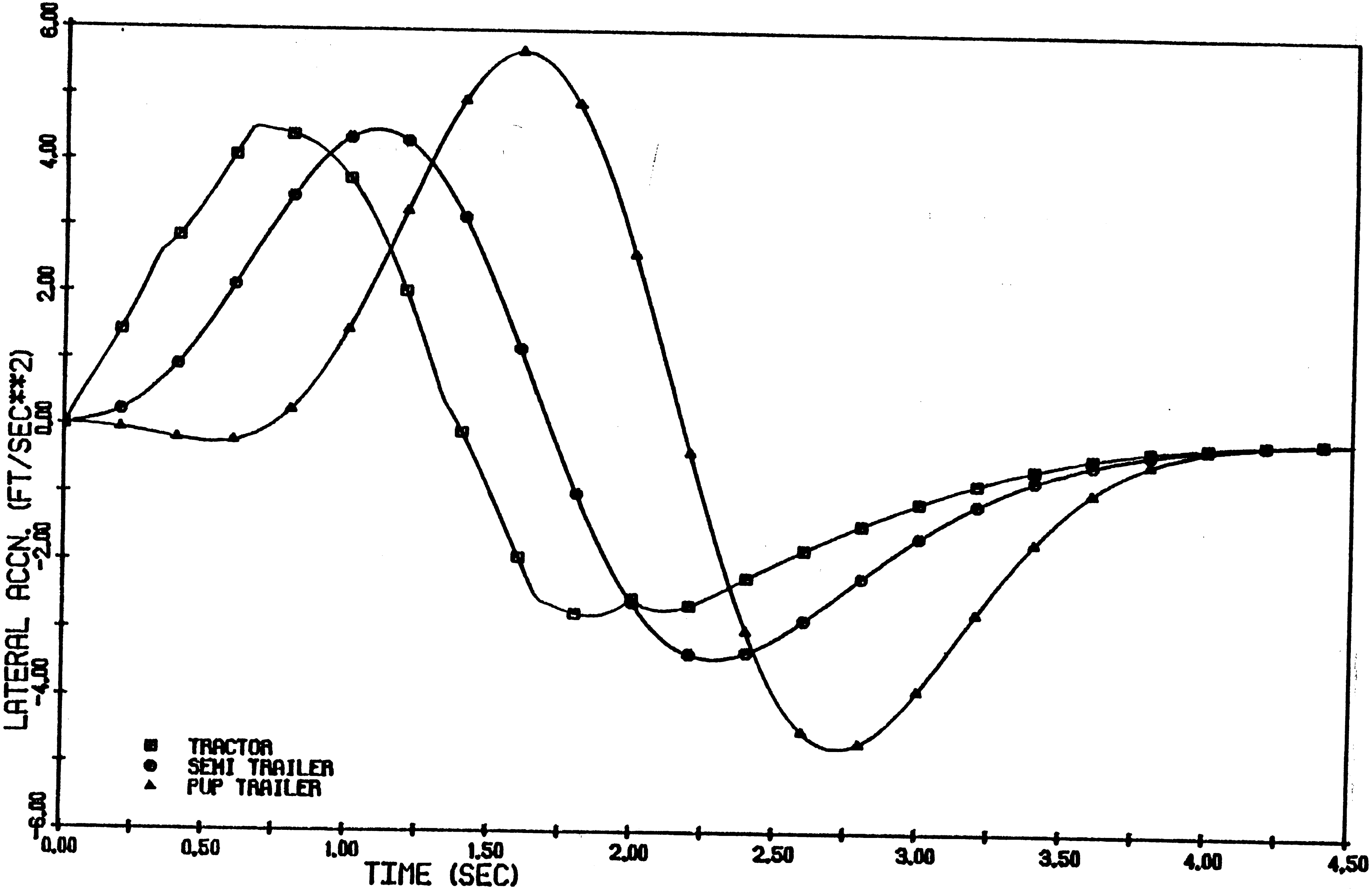


MODIFIED-DOUBLE-BLY-2985, FULLY LOADED DATASET#23

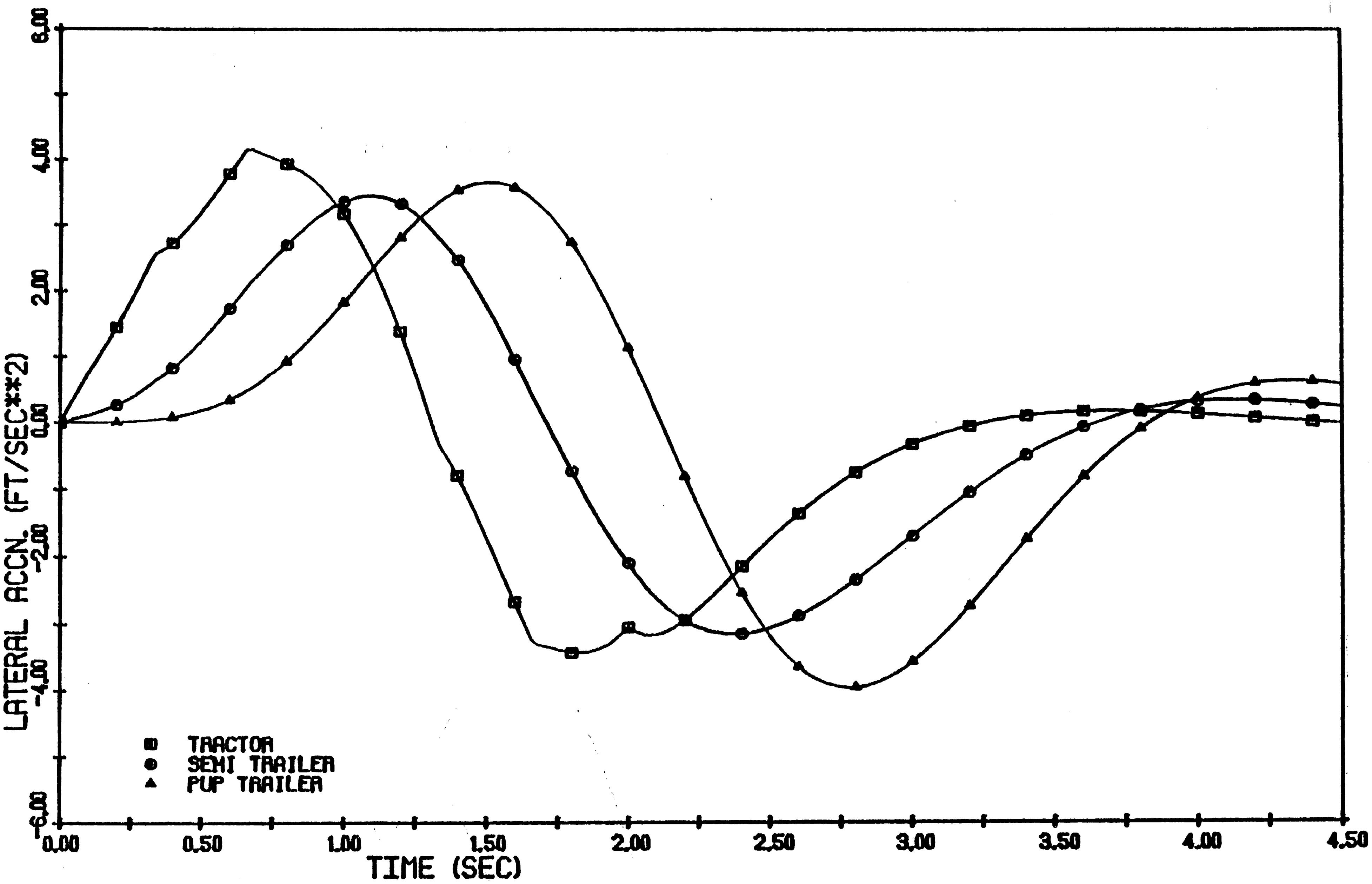


MODIFIED-DOUBLE-BLY-2985, EMPTY

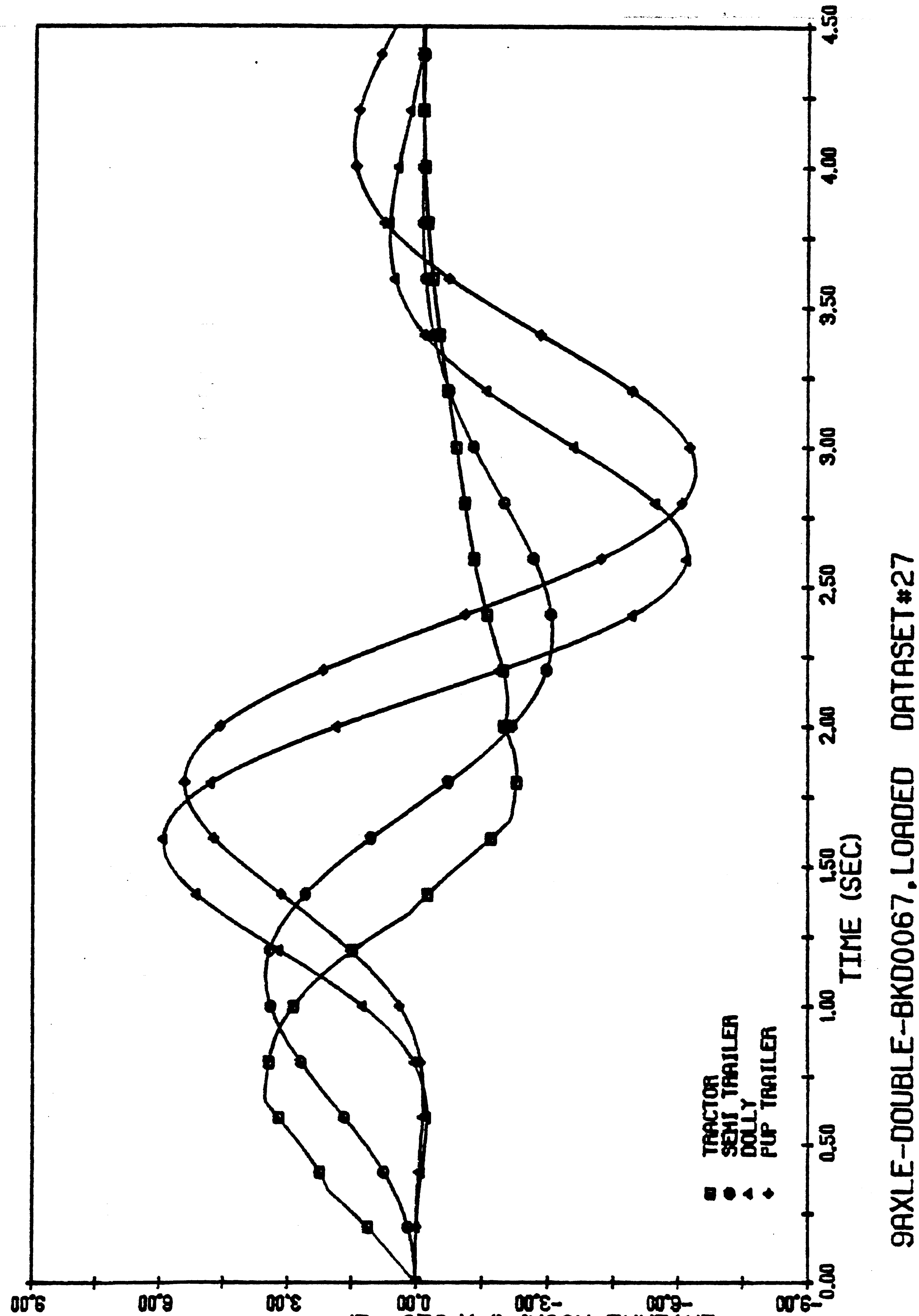
DATASET#24



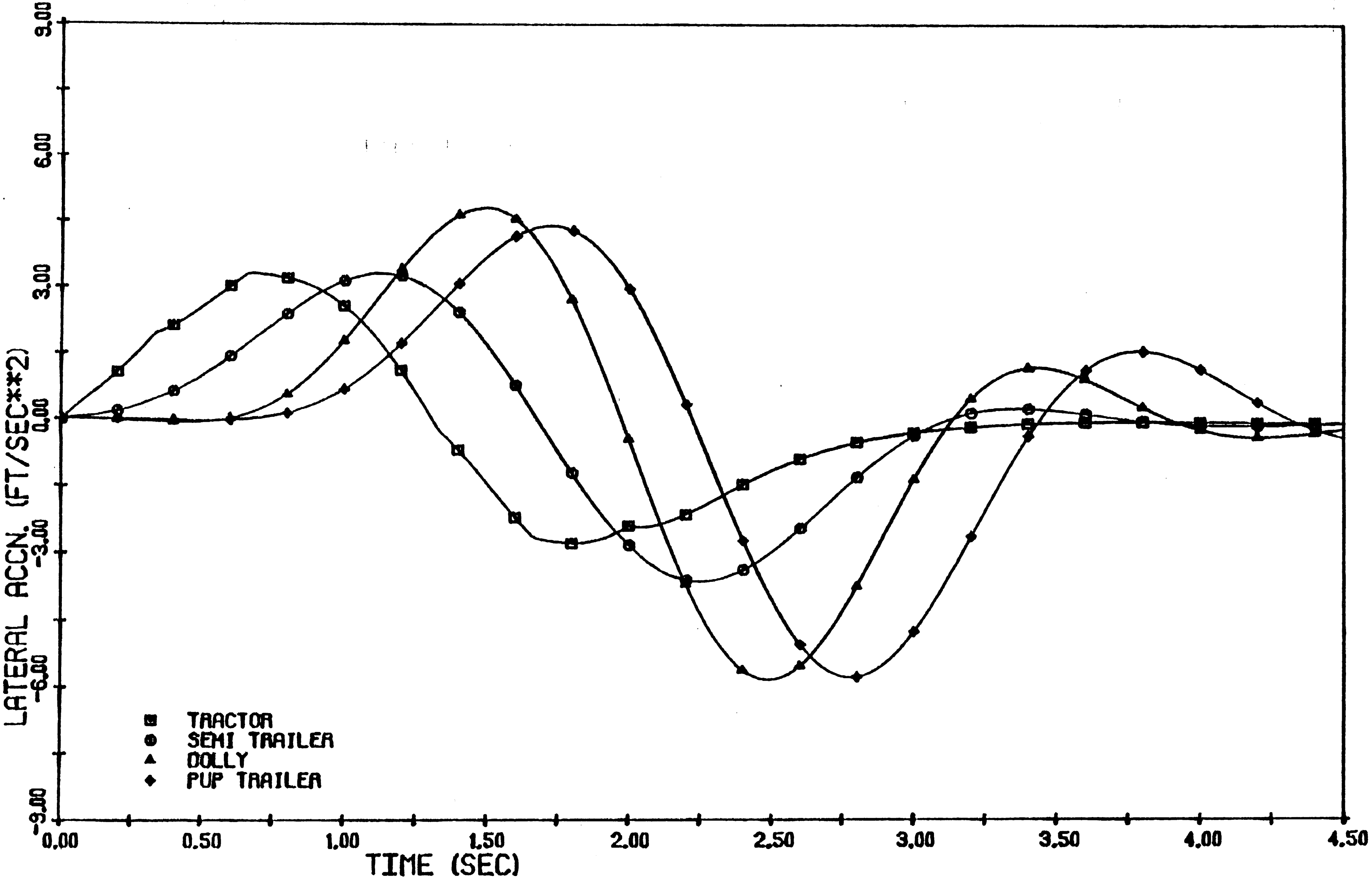
MODIFIED-DOUBLE-BLY-2985, SEMI LOADED, PUP EMPTY DATASET#25



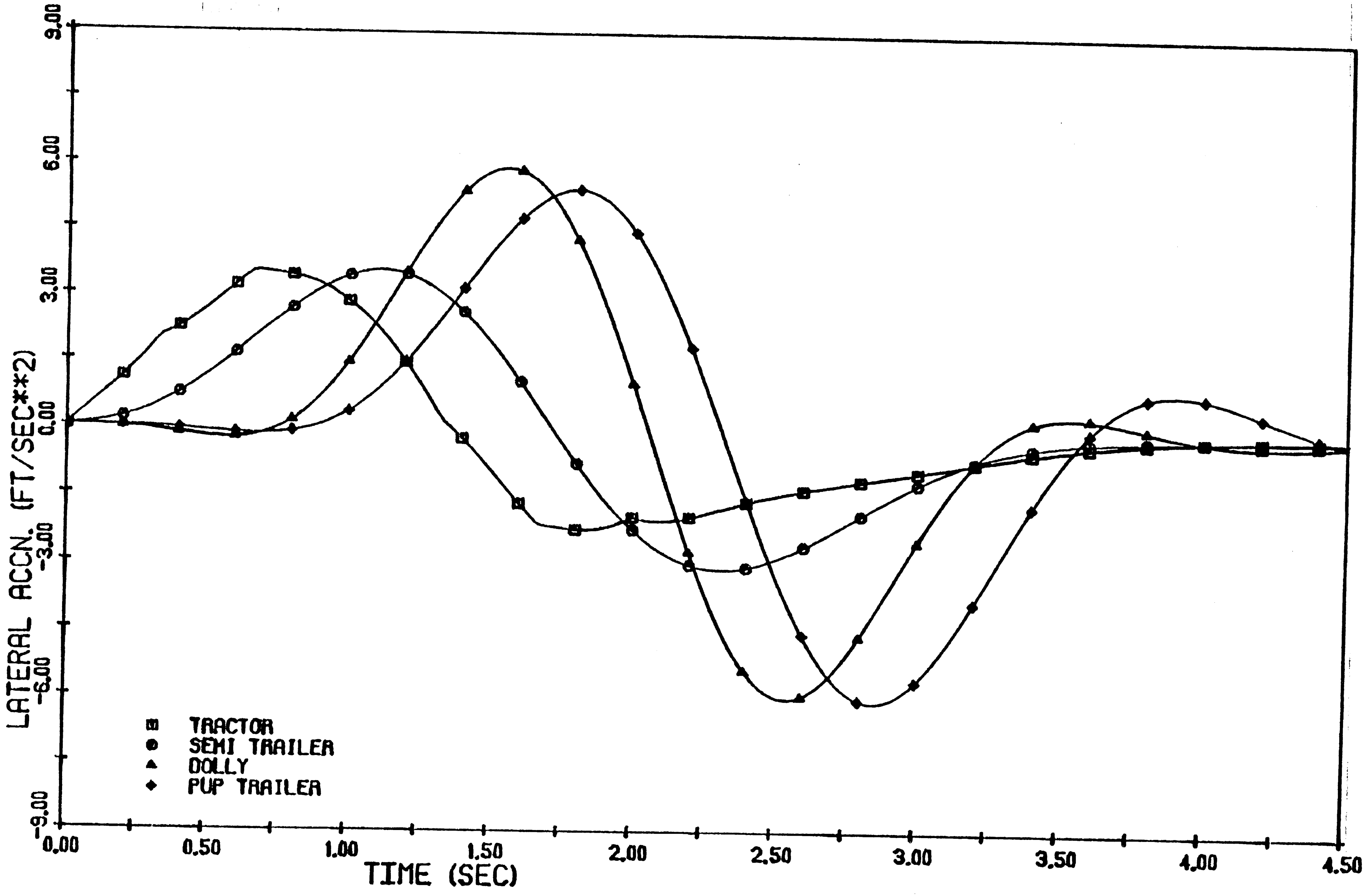
MODIFIED-DOUBLE-BLY-2985, SEMI EMPTY, PUP LOADED DATASET#26



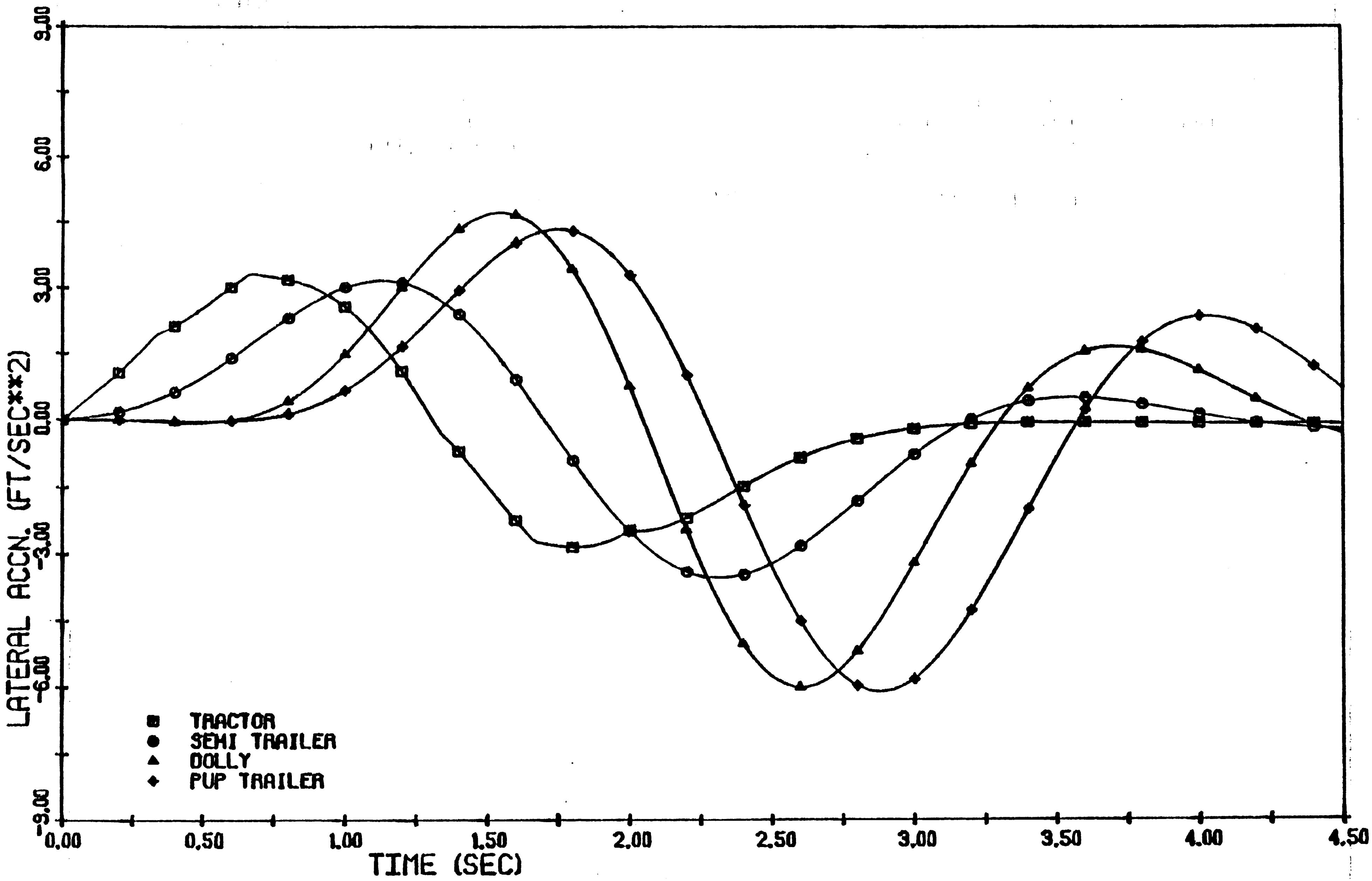
9AXLE-DOUBLE-BKD0067, LOADED DATASET #27
TIME (SEC)
LATERAL ACCN. (FT/SEC**2)
TRACTOR
SEMI TRAILER
DOLLY
PUP TRAILER
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
-9.00
-6.00
-3.00
0.00
3.00
6.00
9.00



9AXLE-DOUBLE-BKD0067.EMPTY DATASET#28



9AXLE-DOUBLE-BKD0067, SEMI LOADED PUP EMPTY DATASET#29



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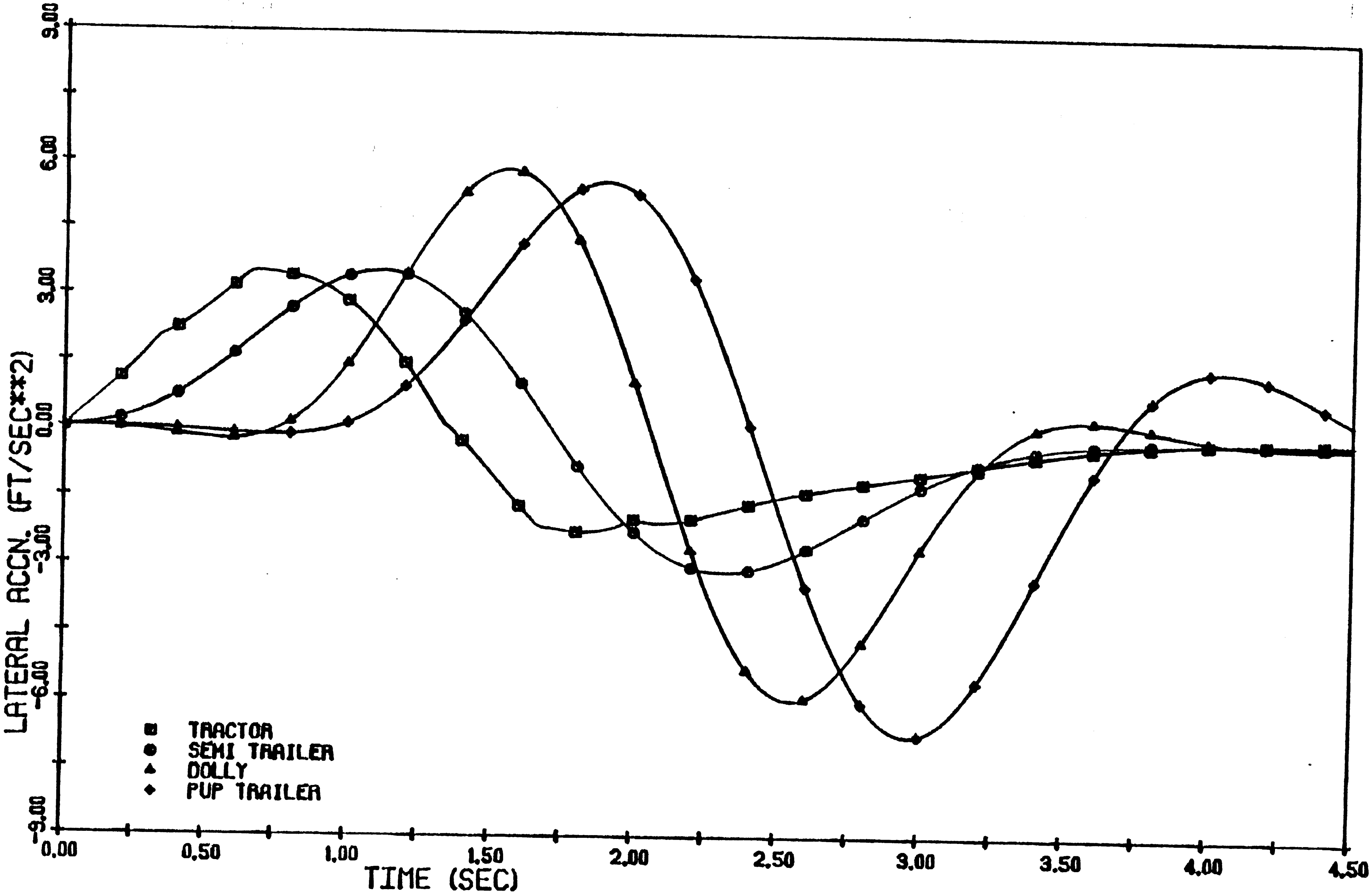
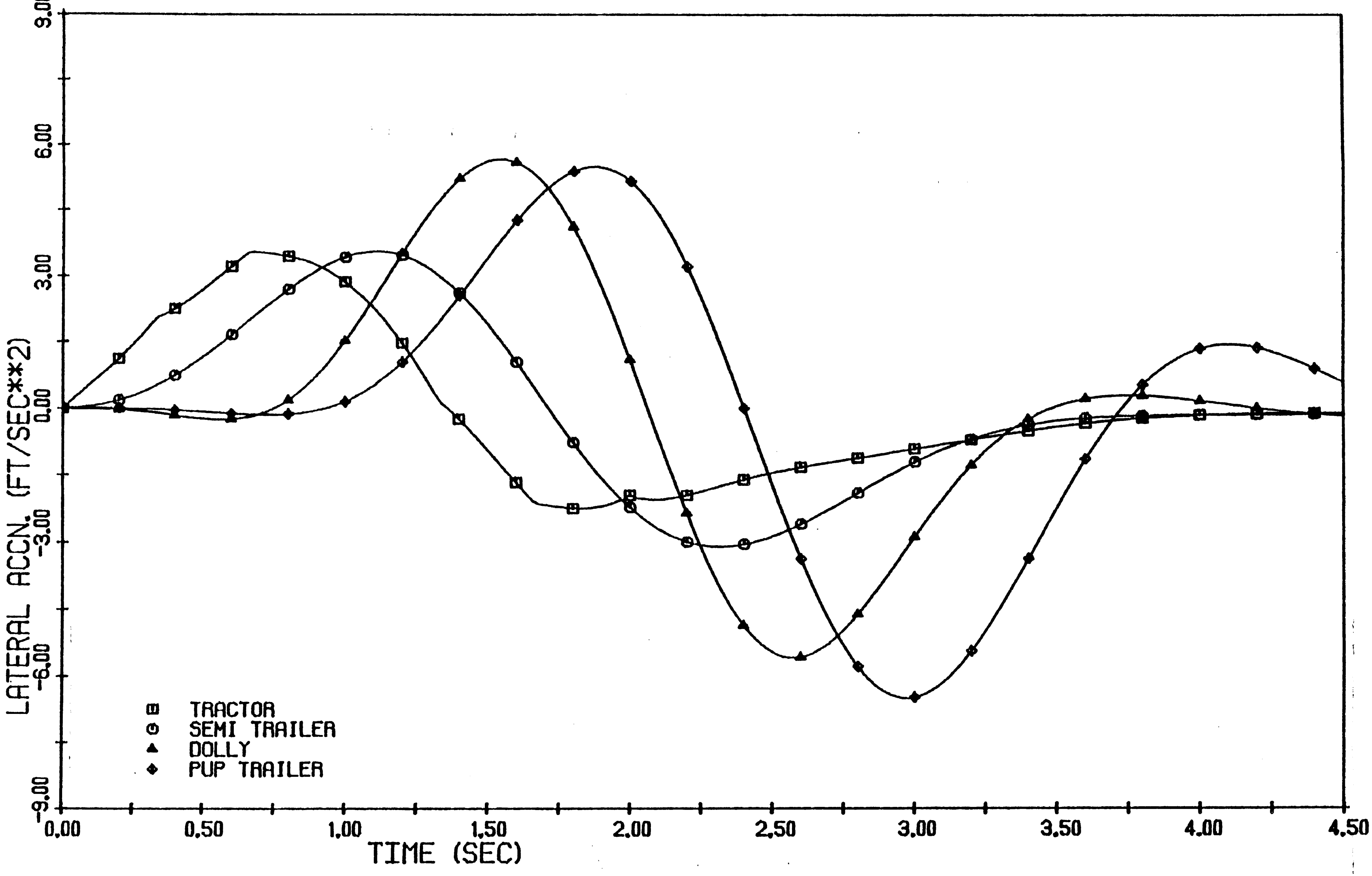
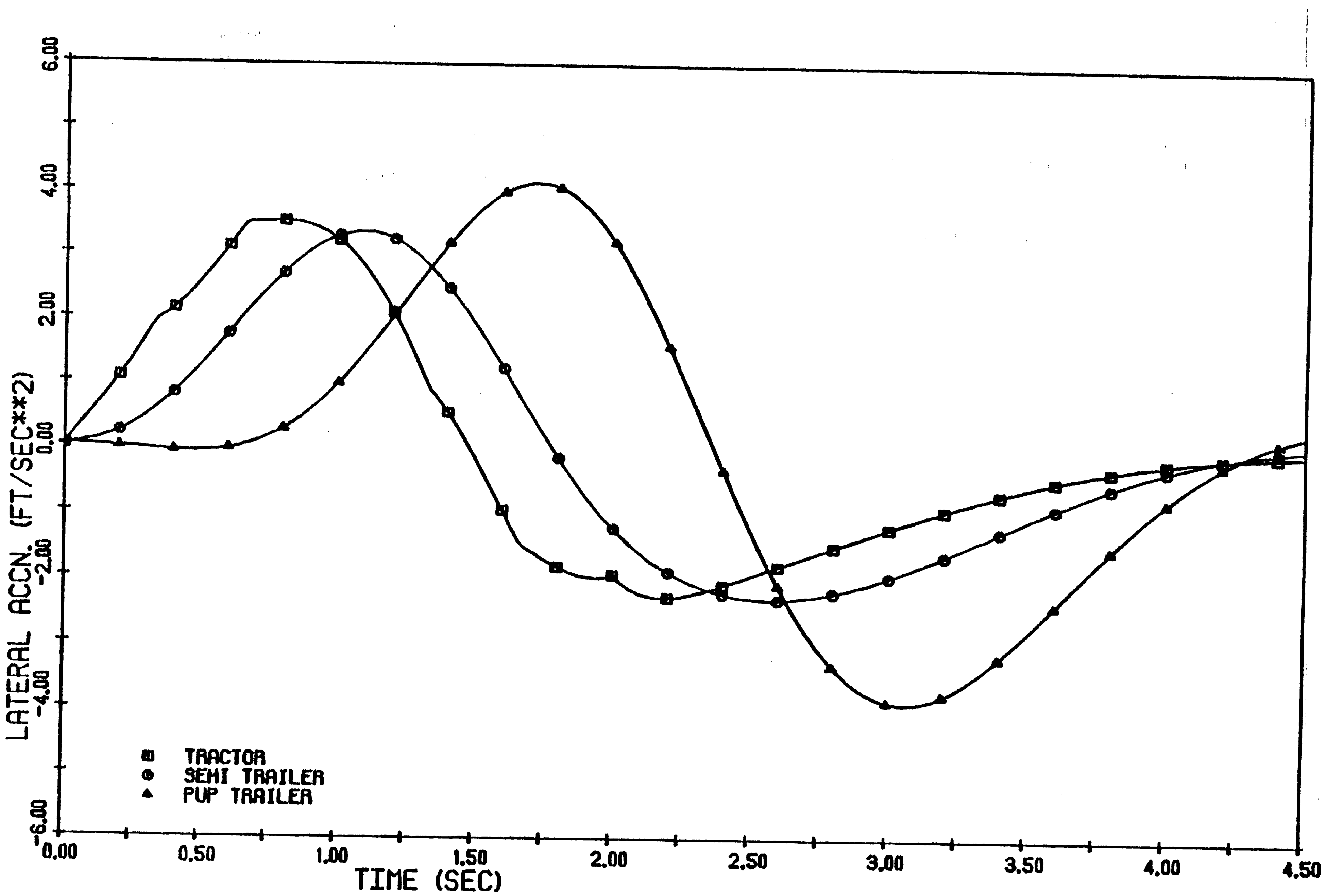


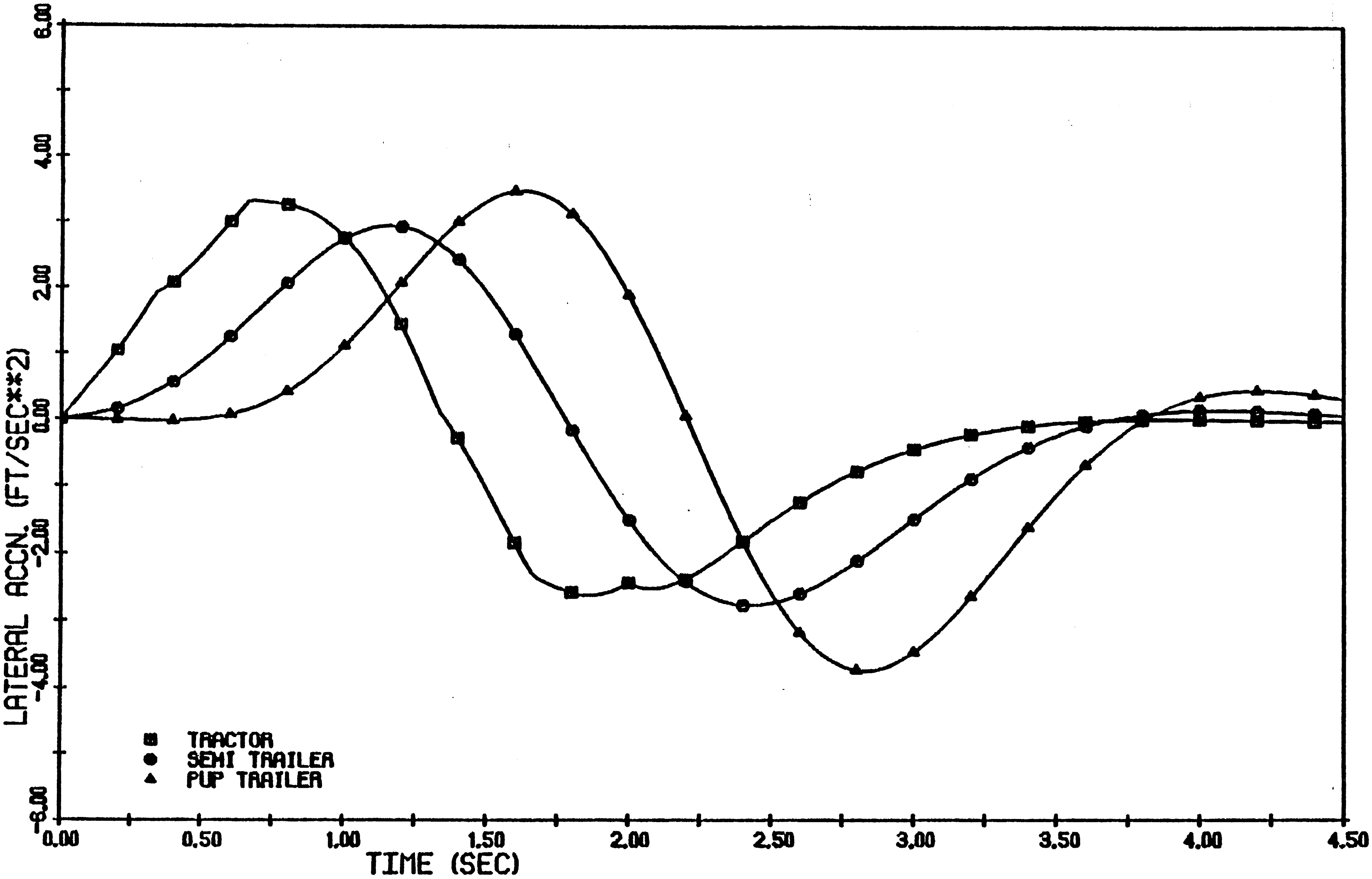
9AXLE-DOUBLE-BKD0067, SEMI FULL PUP#3 COMP FULL DATASET#31



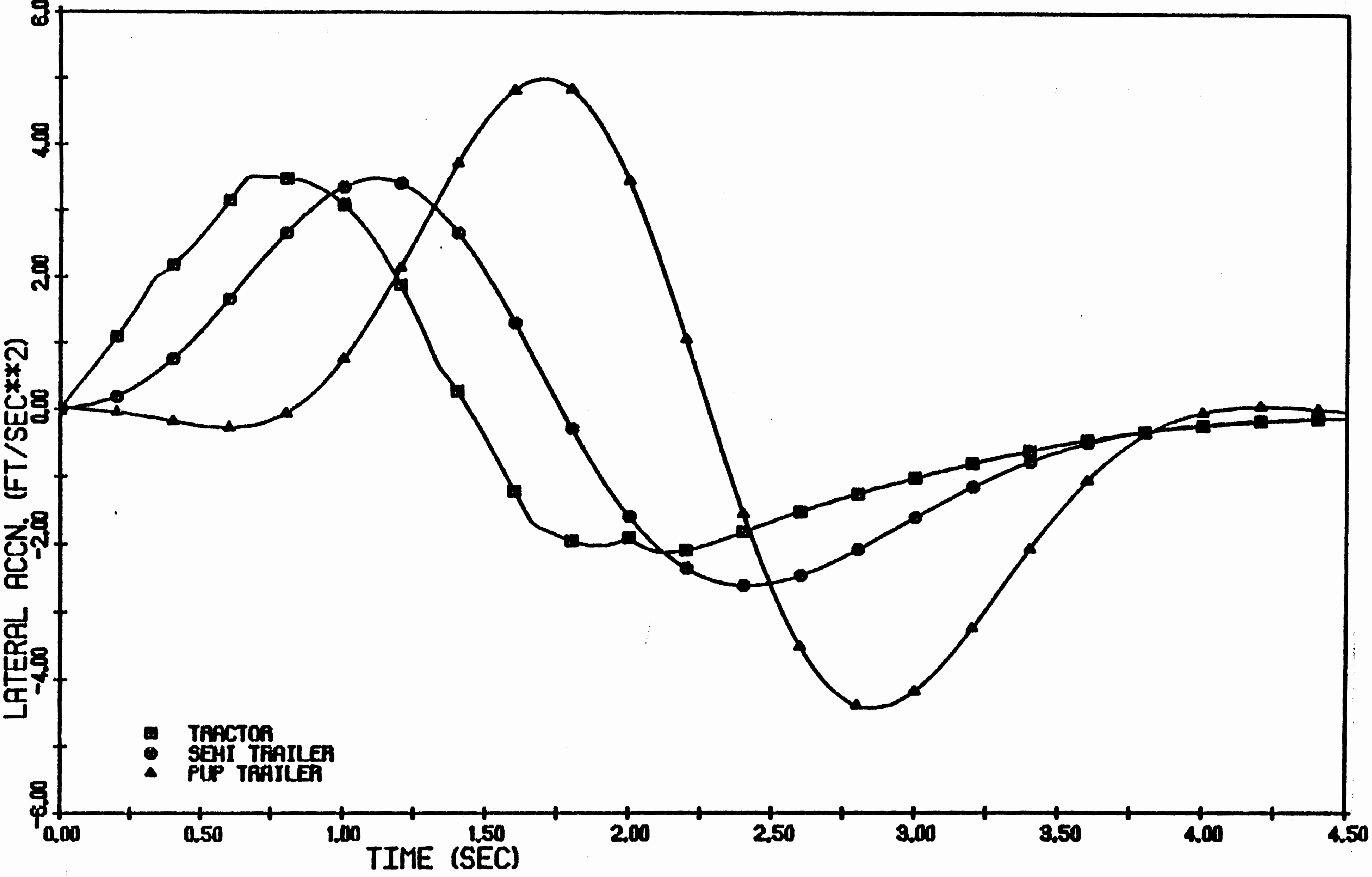
9AXLE-DOUBLE-BKD0067, SEMI FULL PUP#2&3COMP FULL DATASET#32



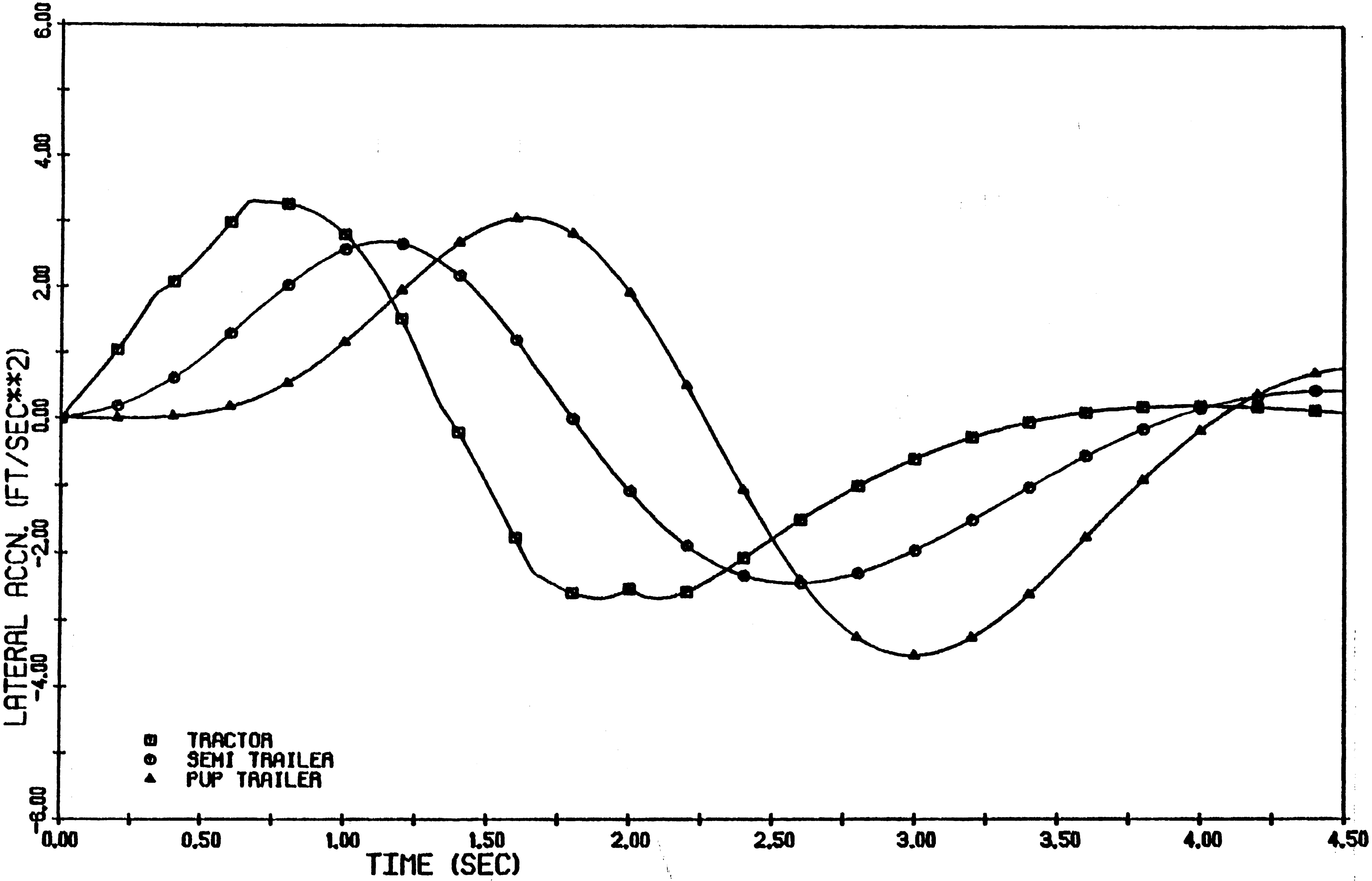
MODIFIED-DOUBLE-BKD-0067, LOADED DATASET#33



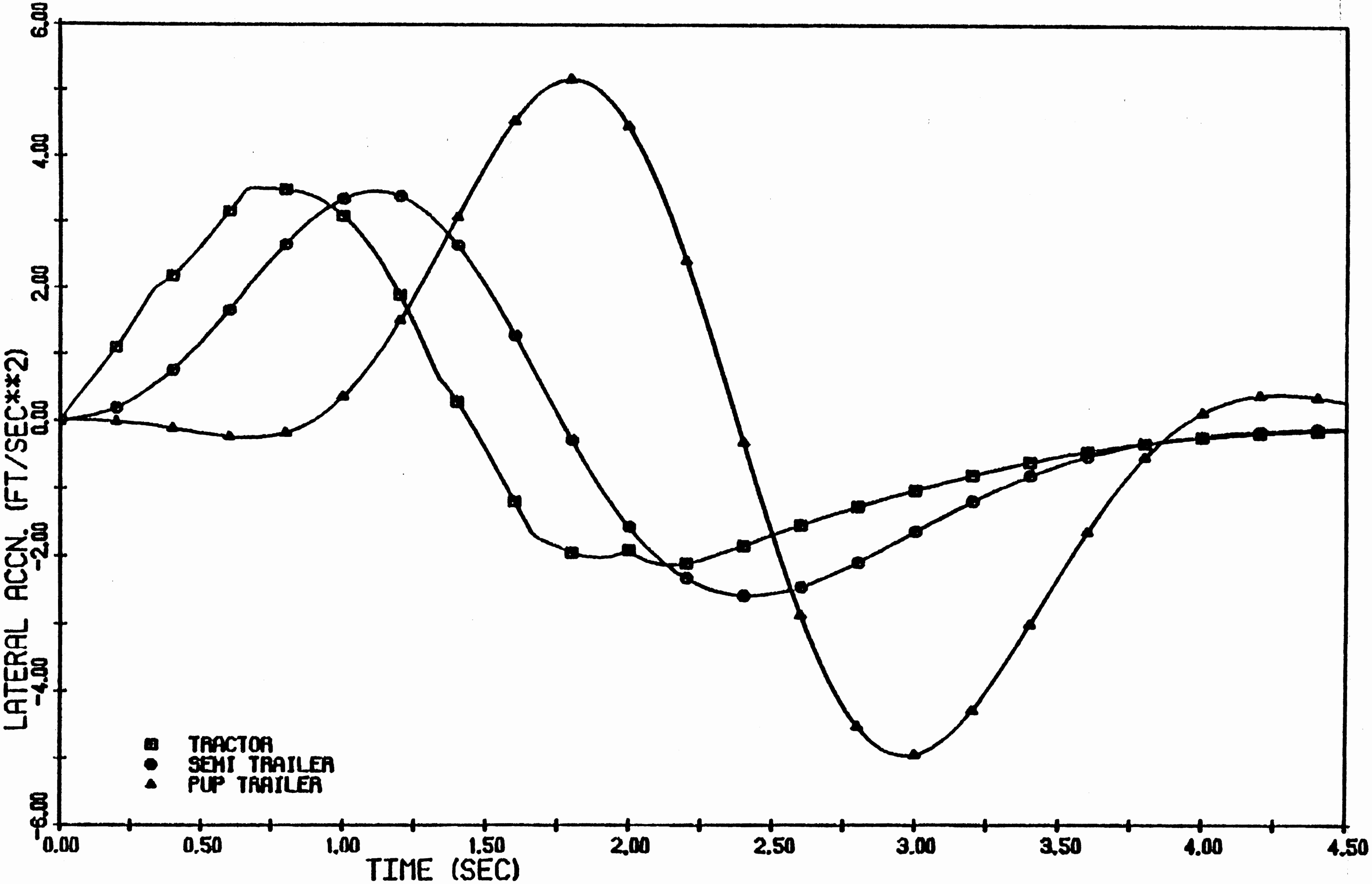
MODIFIED-DOUBLE-BKD-0067.EMPTY DATASET#34



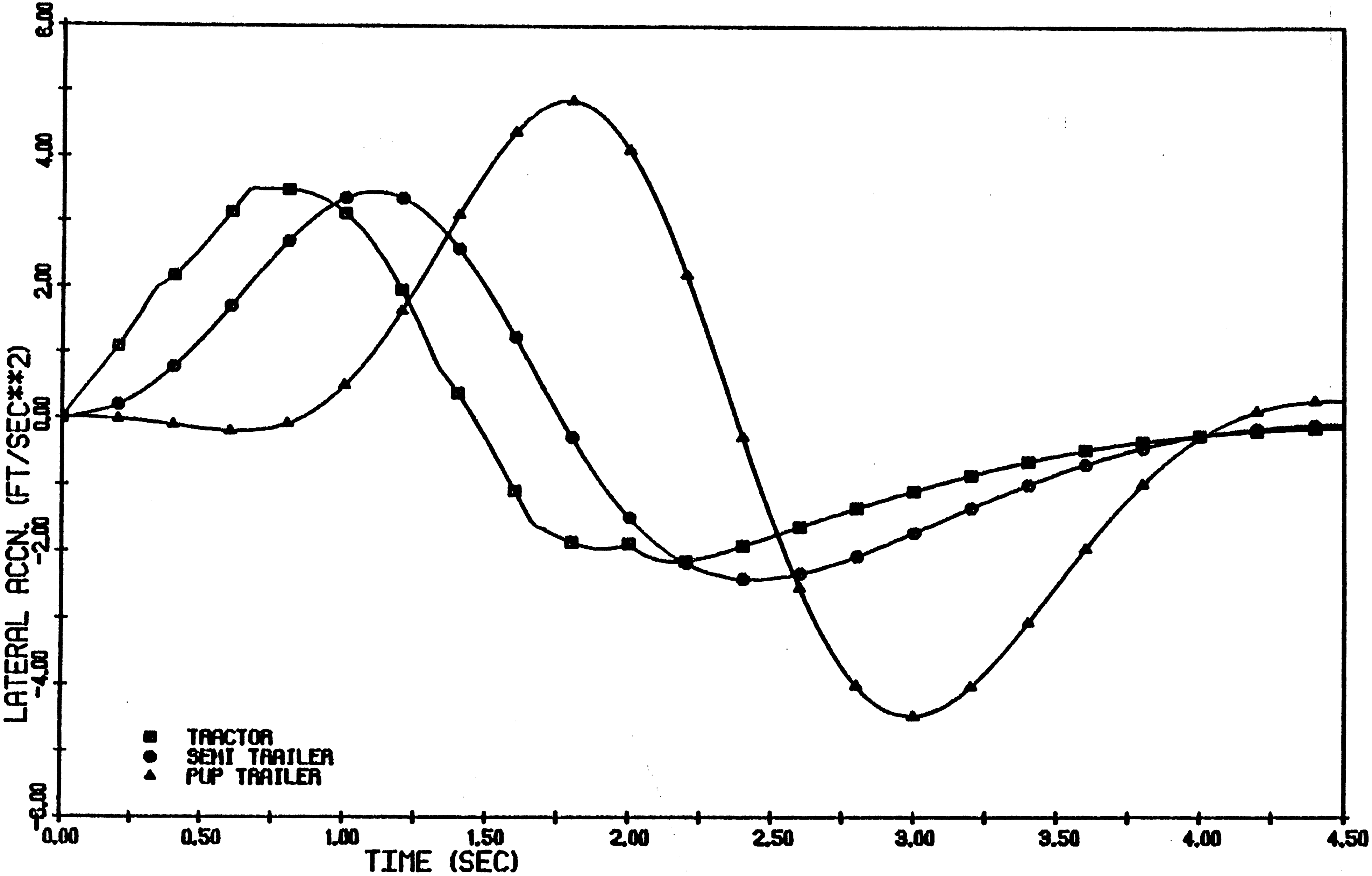
MODIFIED-DOUBLE-BKD-0067, SEMI LOADED PUP EMPTY   DATASET#35



MODIFIED-DOUBLE-BKD-0067, SEMI EMPTY PUP LOADED DATASET#36



MODIFIED-DOUBLE-BKD0067, SEMI FULL PUP#3 COMP FULL DATASET#37



MODIFIED-DOUBLE-BKD0067, SEMI FULL PUP#2&#3COMP FULL DATASET#38

APPENDIX E

SUSPENSION MODELS AND LISTING OF COMPUTER PROGRAM

This appendix describes the two suspension spring models which are available as options in the roll model. Following the discussion of the spring models, the computer program used in the roll simulation is listed at the end of this appendix.

The two suspension models which are available as options are:

1) A model which represents the suspension by linear springs with coulomb friction and dead zone:

As shown in Figure E.1, the suspension backlash is represented in the model by the dead zone "DEL." Two spring rates, "KS" and "KST," are used to represent the suspension stiffness in compression and tension, respectively.

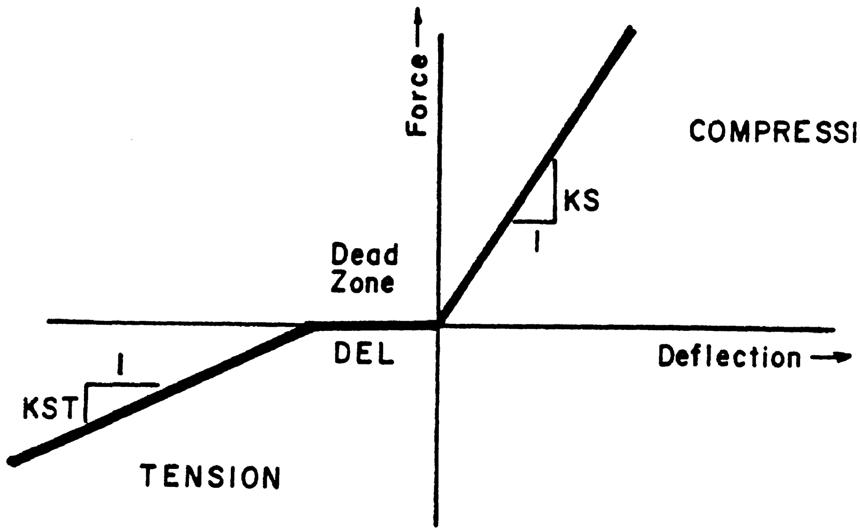
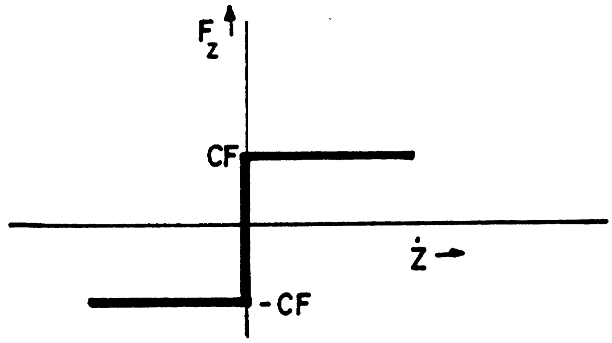


Figure E.1

Special problems are present in developing a digital simulation of a system with coulomb friction. The classical representation of coulomb friction is of the form shown in Figure E.2.



$$\dot{z} > 0 \Rightarrow F_z = +CF$$
$$\dot{z} < 0 \Rightarrow F_z = -CF$$

Figure E.2

This form of representation is unsatisfactory for digital simulation since this leads to the system chattering about any given equilibrium point. A solution to the chatter problem, which has been found to be very effective, is the representation of coulomb friction in the form shown in Figure E.3.

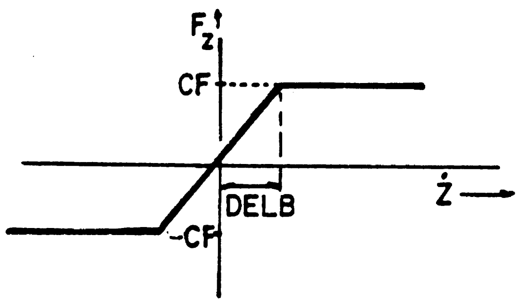


Figure E.3

A more complete discussion on suspension coulomb friction and the computation of the parameter "DELB" can be found in Reference [1]. This model is especially useful when only rough estimates of spring rates and friction levels in the suspension springs are available.

2) <u>A suspension model which is made to fit measured spring data:</u>

Measurements of suspension spring characteristics at HSRI (see Reference [2]) and at the Fruehauf Corporation revealed the relationship between vertical force and deflection to be of the form shown in Figure E.4.

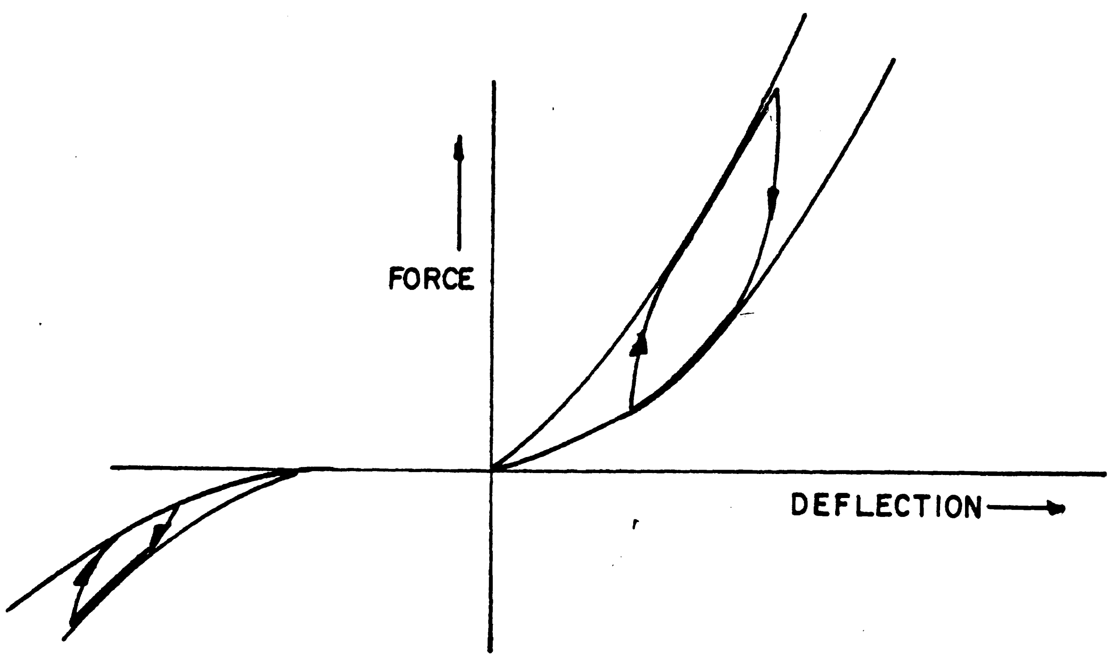


Figure E.4

This figure indicates that a model which represents the suspension by linear springs and coulomb friction cannot be made to fit the measured spring data very well. A better representation of the complex behavior of the suspension springs is made possible in this model by the use of two force versus deflection tabular functions which envelope the measured data. Typical upper and lower envelopes are shown in Figure E.5.

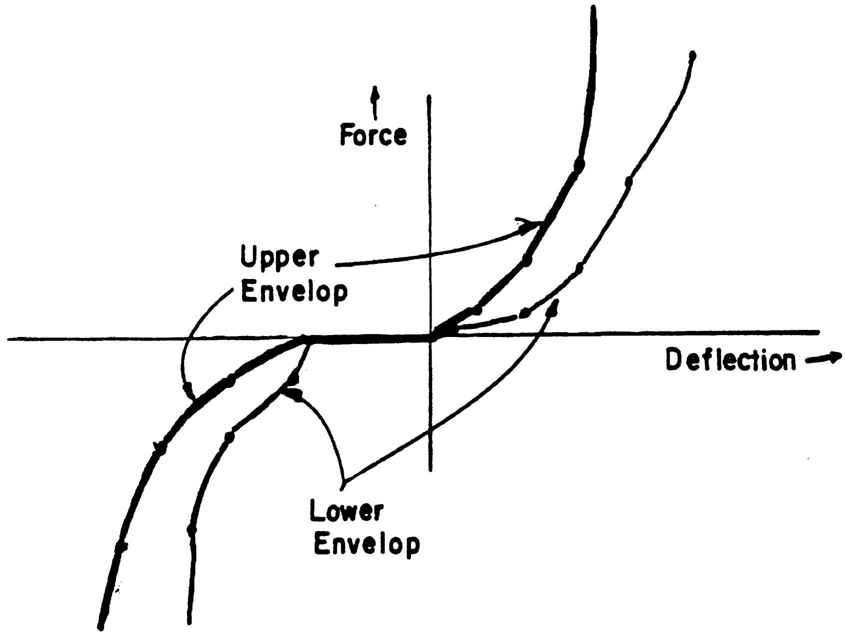


Figure E.5

In the digital simulation, the rate at which the force reaches the upper (or the lower) envelope during compression (or tension) is approximated by the following equation.

$$F_i = F_{env_i} + (F_{i-1} - F_{env_{i-1}})e^{-\beta_j|\delta_i - \delta_{i-1}|}$$

F_i = suspension force at the current simulation time

F_{i-1} = representative suspension force at the last simulation time step

δ_i = suspension deflection at the current simulation time step

δ_{i-1} = suspension deflection at the last simulation time step

F_{env_i} = force corresponding to the deflection, δ_i, of the upper envelope for compression and lower envelope for tension. This is computed from the tabular representation of the envelopes.

β_j = an input parameter used for describing the rate at which the suspension force within the envelope loop approaches the envelope. β_1 is used for the compressive portion of the loop, β_2 for the tension portion of the loop.

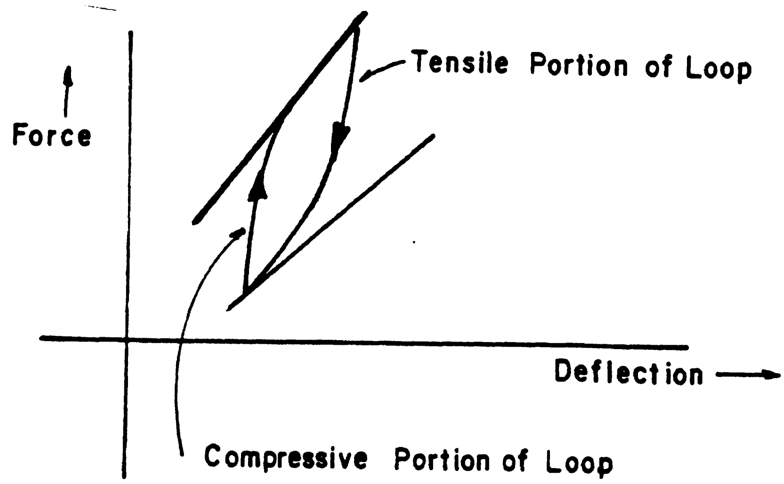


Figure E.6

The two parameters, β_1 and β_2, are chosen so as to accurately represent the hysteresis loops exhibited by the suspension springs.

REFERENCES:

1. Winkler, C.B., et al., "Predicting the Braking Performance of Trucks and Tractor-Trailers - Appendix B." Phase III Technical Report, Truck and Tractor-Trailer Braking and Handling Project, Highway Safety Research Institute, University of Michigan, Report No. UM-HSRI-76-26-2, June 1976.

2. MacAdam, C.C. "Computer Simulation and Parameter Sensitivity Study of a Commercial Vehicle During Antiskid Braking." Sixth IAVSD-IUTAM Symposium on Dynamics of Vehicles on Roads and Tracks, Berlin, September 3-7, 1979.

LISTING OF COMPUTER PROGRAM

```
C
C
C      THIS PROGRAM COMPUTES THE ROLL RESPONSE OF A VEHICLE
C           TO A LATERAL FORCE INPUT.
C      THE INPUT-OUTPUT DEVICES ARE :
C      DEVICE #
C        5  ........  FILE CONTAINING VEHICLE PARAMETERS
C        6 .......... OUTPUT DEVICE #
C        7 .......... FILE CONTAINING TIME HISTORY OF LATERAL FORCE
C
      EXTERNAL INPUT, OUTP, OUTP2, TABLE
      REAL I1, I2, KS(2), KST(2), KT1, KT2, KT3, KT4, LB, KBS
      DIMENSION XXT(25), YYT(25), XXB(25), YYB(25)
      DIMENSION Y(10), DERY(10), PRMT(5), AUX(16,10), HEAD(14)
      DATA COUL /'COUL'/
      DATA EXPL /'EXPL'/
      DATA RAMP /'RAMP'/
      DATA STEP /'STEP'/
      DATA SINE /'SINE'/
      DATA DISC /'DISC'/
      COMMON /EXPO/ NUM1, NUM2, XXT, YYT, XXB, YYB, BETA1, BETA2
      COMMON /ONE/ W1, W2, I1, I2, H1, H2, B2, A, HR
      COMMON /TWO/ KS, KST, KT1, KT2, KT3, KT4, DEL, T, S
      COMMON /THREE/ CF, CV, CVT, CFST
      COMMON /FOUR/ DEL10, DEL20, DELB
      COMMON /FIVE/ XPRINT
      COMMON /EXC/ FCT, TIME, AMP, TMAX
      COMMON /DISCR/ N, F(500), X(500)
      COMMON /SEARCH/ COAMP
      COMMON /BOOM/ HBOOM
      XNEG = -9999.00
      NUM1 = 0
      FACTOR = 0.0
      WRITE (6,410)
      READ (5,240) W1, W2, I1, I2, H1, H2, B2, A, HR
      WRITE (6,370) W1, W2, I1, I2, H1, H2, B2, A, HR
      READ (5,400) FRICT
      IF (FRICT .EQ. EXPL) GO TO 10
      READ (5,360) KS(1), KS(2), KT1, KT2, KT3, KT4, DEL, T, S
      READ (5,360) CF, CV, CVT, CFST, KST(1), KST(2), FACTOR
      WRITE (6,380) KS(1), KS(2), KST(1), KST(2), KT1, KT2, KT3, KT4,
     1DEL, T, S
      WRITE (6,390) CF, CFST, CV, CVT, FACTOR
      GO TO 50
   10 READ (5,360) KT1, KT2, KT3, KT4, T, S, CVT, CV
      READ (5,360) BETA1, BETA2
C
      DO 20 J = 1, 25
        XXT(J) = 0.0
        YYT(J) = 0.0
        XXB(J) = 0.0
   20 YYB(J) = 0.0
```

```
C
      READ (5,310) NUM1, NUM2
C
      DO 30 I = 1, NUM1
   30 READ (5,360) XXT(I), YYT(I)
C
      DO 40 I = 1, NUM2
   40 READ (5,360) XXB(I), YYB(I)
C
      WRITE (6,250) KT1, KT2, KT3, KT4, T, S, CVT
      WRITE (6,260)
      WRITE (6,270) BETA1, BETA2
      WRITE (6,280) NUM1
      WRITE (6,290) (XXT(I),YYT(I),I=1,NUM1)
      WRITE (6,300) NUM2
      WRITE (6,290) (XXB(I),YYB(I),I=1,NUM2)
   50 CONTINUE
      READ (5,360) HBOOM
   60 READ (5,400) FCT
      IF (FCT .EQ. DISC) GO TO 70
      READ (5,360) TIME, AMP, TMAX
      WRITE (6,420) FCT
      IF (FCT .EQ. SINE) WRITE (6,320) TIME, AMP
      IF (FCT .EQ. RAMP) WRITE (6,330) TIME, AMP
      IF (FCT .EQ. STEP) WRITE (6,340) AMP
      IF (FCT .EQ. STEP .OR. FCT .EQ. SINE) WRITE (6,350) TMAX
      IF (FCT .EQ. RAMP) WRITE (6,350) TMAX
      GO TO 140
   70 CONTINUE
C
      DO 80 JJ = 1, 200
   80 F(JJ) = 0.
C
C -----------------------------------------
      J = 0
      READ (7,430) HEAD
   90 J = J + 1
      READ (7,440) X(J), F(J)
      IF (X(J) .LT. 0.0) GO TO 100
      GO TO 90
  100 F(J) = 0.0
      X(J) = 0.0
      N = J - 1
      WRITE (6,460)
  140 CONTINUE
      READ (5,470) PRMT(2), PRMT(3), PRMT(4)
      READ (5,360) XPRINT
C-------------------------------------------------------
C     COMPUTE THE COULOMB FRICTION BREAK POINTS
C
      DELB = PRMT(3) * CF * ((773.0*(W1 + W2)/(W1*W2)) + (2.0*S*S*(I1 +
     1I2)/(I1*I2)))
```

```
      DELB = DELB * FACTOR
C
C---------------------------------------------
  150 CONTINUE
      IF (FRICT .EQ. EXPL) GO TO 160
      DEL10 = W1 / (KS(1) + KS(2))
      GO TO 190
C
  160 DO 170 I = 1, NUM1
        IF ((W1/2.0) .LT. YYT(I)) GO TO 180
  170 CONTINUE
C
  180 DEL10 = XXT(I - 1) + ((XXT(I) - XXT(I - 1))/(YYT(I) - YYT(I - 1)))
     1 * (W1/2.0 - YYT(I - 1))
  190 CONTINUE
      DEL20 = (W1 + W2) / (KT1 + KT2 + KT3 + KT4)
C
      DO 200 J = 1, 10
        Y(J) = 0.
        DERY(J) = 0.
  200 CONTINUE
C
      Y(9) = H1 - H2 - HR
      DERY(7) = 1. / 2.
      DERY(9) = 1. / 2.
      PRMT(1) = 0.
      READ (5,470) COAMP
      IF (COAMP .LE. 0.) GO TO 230
      WRITE (6,480) HEAD, COAMP
      CALL OUTPUT
      CALL HPCG(PRMT, Y, DERY, 10, IHLF, INPUT, OUTP2, AUX)
      IF (PRMT(5) .NE. 0.) GO TO 230
      IF (PRMT(5) .EQ. 0.) WRITE (6,500) XNEG
      IF (PRMT(5) .EQ. 0.) GO TO 150
      IF (IHLF .GE. 11) WRITE (6,510) IHLF
  230 STOP
  240 FORMAT (/9F10.3)
  250 FORMAT (1H , 'SPRING RATE OF TIRE SPRING 1', 11X, '=', F10.2,
     1       'LB/IN', /, 6X, 'SPRING RATE OF TIRE SPRING 2', 11X, '=',
     2       F10.2, 'LB/IN', /, 6X, 'SPRING RATE OF TIRE SPRING 3', 11X,
     3       '=', F10.2, 'LB/IN', /, 6X, 'SPRING RATE OF TIRE SPRING 4',
     4       11X, '=', F10.2, 'LB/IN'/1H , 5X, 'HOR DISTANCE FROM',
     5       ' UNSPRUNG MASS CG TO INNER TIRE=', F10.2, ' IN.', /, 6X,
     6       'HOR DIST FROM SPRUNG MASS CG TO SUSPENSION   =', F10.2,
     7       ' IN.', /1H , 'TIRE VISCOUS DAMPING = ', F10.2,
     8       'LB.SEC/IN')
  260 FORMAT (1H , 'SUSPENSION SPRINGS MODELLED AS A TABLE ENVELOPE'/
     1       1H , 47(1H*))
  270 FORMAT (1H , 'EXPONENT FOR UPPER ENVELOPE = ', F10.4/1H ,
     1       'EXPONENT FOR LOWER ENVELOPE = ', F10.2)
  280 FORMAT (1H0, '# OF DATA POINTS FOR UPPER ENVELOPE = ', I2)
  290 FORMAT (1H , F10.2, 2X, F10.2)
```

```
  300 FORMAT (1H0, '# OF DATA POINTS FOR LOWER·ENVELOPE = ', I2)
  310 FORMAT (2I2)
  320 FORMAT (1X, 'TIME OF ONE PERIOD =', F10.2, 'SEC.', /, 2X,
     1       'AMPLITUDE =', F10.2, 'LBS')
  330 FORMAT ('0', 1X, 'AT TIME =', F10.2, 'SEC', /, 2X, 'FORCE =',
     1       F10.2, 'LBS')
  340 FORMAT ('0', 1X, 'FORCE=', F10.2, 'LBS')
  350 FORMAT ('0', 1X, 'INPUT CONTINUES FOR', F8.2,
     1       'SEC., THEN VANISHES')
  360 FORMAT (10F10.3)
  370 FORMAT (6X, 'SPRUNG WEIGHT                           =', F10.2, ' LB.', /
     1       , 6X, 'UNSPRUNG WEIGHT                         =', F10.2, ' LB.',
     2       /, 6X, 'POLAR M.I. OF SPRUNG MASS           =', F10.2,
     3       ' LB-SEC**2-IN', /, 6X, 'POLAR M.I. OF UNSPRUNG MASS      =
     4', F10.2, ' LB-SEC**2', '-IN', /, 6X, 'STATIC HEIGHT OF SPRUNG MAS
     5S CG  =', F10.2, ' IN. ABOVE GROUND', /, 6X, 'STATIC HEIGHT OF UNS
     6PRUNG MASS CG=', F10.2, ' IN. ABOVE GROUND', /, '0', 5X,
     7       'DISTANCE FROM SPRUNG', ' MASS CG TO ITS BOTTOM =', F10.2,
     8       ' IN.', /, '0', 5X, 'SPACING ', 'BETWEEN TIRES
     9 =', F10.2, 'IN.', /, '0', 5X, 'DISTANCE FROM SPRUNG MASS CG TO CE
     *NTER OF ROTATION=', F10.2, ' IN.')
  380 FORMAT ('0', 5X, 'SPRING RATE OF RIGHT SUSPENSION SPRING IN ',
     1       'COMPRESSION  =', F10.2, ' LB/IN', /, 6X,
     2       'SPRING RATE OF LEFT SUSPENSION SPRING IN COMPRSSION',
     3       ' =', F10.2, ' LB/IN'/1H , 6X, 'SPRING RATE OF RIGHT SUSPEN
     4SION SPRING IN TENSION =', F10.2, ' LB/IN'/1H , 6X,
     5       'SPRING RATE OF LEFT SUSPENSION ', 'SPRIG IN ',
     6       ' TENSION =', F10.2, ' LB/IN', /, 6X, 'SPRING RATE OF TIRE
     7SPRING 1', 11X, '=', F10.2, 'LB/IN', /, 6X, 'SPRING RATE OF TIRE S
     8PRING 2', 11X, '=', F10.2, 'LB/IN', /, 6X, 'SPRING RATE OF TIRE SP
     9RING 3', 11X, '=', F10.2, 'LB/IN', /, 6X, 'SPRING RATE OF TIRE SPR
     *ING 4', 11X, '=', F10.2, 'LB/IN', /, '0', 5X, 'BACKLASH IN',
     1       ' SUSPENSION SPRING=', F10.2, ' IN.', /, '0', 5X,
     2       'HOR DIST. FROM', ' UNSPRUNG MASS CG TO INNER TIRE=',
     3       F10.2, ' IN.', /, 6X, 'HOR DIST FROM SPRUNG MASS CG TO SUSP
     4ENSION   =', F10.2, ' IN.')
  390 FORMAT ('0', 2X, 'COULOMB FRICTION IN EACH SPRING (COMPRESSION) ='
     1       , F10.2, ' LB'/1H , 2X, 'COULOMB FRICTION IN EACH SPRING (T
     2ENSION) =', F10.2, ' LB', /, 6X, 'COEFFICIENT OF VISCOUS DAMPING I
     3N', ' EACH SUSPENSION  =', F10.4, 'LB-SEC/IN', /, 6X,
     4       'COEFFICIENT OF TIRE VISCOUS', ' DAMPING          =',
     5       F10.4/1H , 'COULOMB FRICTION BREAK POINT FACTOR FOR SUSP. S
     6PRINGS =', F10.2)
  400 FORMAT (A4)
  410 FORMAT ('1')
  420 FORMAT ('0', 1X, 'INPUT FUNCTION IS', 2X, A4)
  430 FORMAT (14A4)
  440 FORMAT (2E11.4)
  450 FORMAT (2F15.5)
  460 FORMAT ('0', 5X, 'DISCRETE INPUT')
  470 FORMAT (3F15.9)
  480 FORMAT (T1, 14A4, 4X, 'AMPLIFIACATION=', F6.2)
```

```
      490 FORMAT (T1, 'DATA FROM:', A4, ' INPUT', 5X, 'AMPLIFICATION =',
         1        F10.2)
      500 FORMAT (T1, E11.4)
      510 FORMAT (2X, 'IHLF=', I3)
      520 FORMAT ('0', 'INPUT RAMP RISES FOR', F8.2, ' SEC., THEN',
         1        ' REMAINS CONSTANT')
          END
          SUBROUTINE INPUT(X, Y, DERY)
          DIMENSION XXT(25), YYT(25), XXB(25), YYB(25)
          DIMENSION Y(10), AA(5,5), AT(5), F(5), DERY(10), FLAST(2),
         1           DLAST(2)
          DIMENSION SV1(15), DL(2), DDEL(2), FORC(2), FORC1(2)
          COMMON /EXPO/ NUM1, NUM2, XXT, YYT, XXB, YYB, BETA1, BETA2
          COMMON /ONE/ W1, W2, I1, I2, H1, H2, B2, A, HR
          COMMON /TWO/ KS, KST, KT1, KT2, KT3, KT4, DEL, T, S
          COMMON /THREE/ CF, CV, CVT, CFST
          COMMON /FOUR/ DEL10, DEL20, DELB
          COMMON /SIX/ F11, F22, F33, F44, F55, F66, FY, DL
          REAL I1, I2, KS(2), KST(2), KT1, KT2, KT3, KT4, LB, KBS
          REAL M1, M2
          M1 = W1 / 386.
          M2 = W2 / 386.
          FY = FEXT(X)
          B = B2
          F1 = 0.
          F2 = 0.
          F31 = 0.
          F32 = 0.
          F41 = 0.
          F42 = 0.
          FD1 = 0.
          FD2 = 0.
C-------------------------------------------
          SIN8 = SIN(Y(8))
          SIN10 = SIN(Y(10))
          SIN108 = SIN(Y(10) - Y(8))
          COS8 = COS(Y(8))
          COS10 = COS(Y(10))
          COS108 = COS(Y(10) - Y(8))
C-------------------------------------
          DO 10 I = 1, 5
C
            DO 10 J = 1, 5
       10 AA(I,J) = 0.
C
          HX = H1 - H2 - HR
C
C---------------------------------------------
C
       20 DL(1) = H1 - B - H2 + DEL10 - (Y(9) + (HR - B)*COS108 - S*SIN108)
          DL(2) = H1 - B - H2 + DEL10 - (Y(9) + (HR - B)*COS108 + S*SIN108)
          DEL31 = -(T + A) * SIN8 - Y(7) + DEL20
```

```
      DEL32 = -T * SIN8 - Y(7) + DEL20
      DEL41 = T * SIN8 - Y(7) + DEL20
      DEL42 = (T + A) * SIN8 - Y(7) + DEL20
      DDEL(1) = -Y(4) + (HR - B) * (Y(5) - Y(3)) * SIN108 + S * (Y(5) -
     1Y(3)) * COS108
      DDEL(2) = -Y(4) + (HR - B) * (Y(5) - Y(3)) * SIN108 - S * (Y(5) -
     1Y(3)) * COS108
      IF (NUM1 .NE. 0) GO TO 100
C-----------------------------------
C   SPRING FRICTION -- COULOMB
C-------------------------------------
      DO 90 I = 1, 2
        IF (DL(I) .GT. 0.0) GO TO 30
        IF (DL(I) .LT. (-DEL)) GO TO 60
        FORC(I) = 0.0
        GO TO 90
   30   IF (ABS(DDEL(I)) .GT. DELB) GO TO 40
        FORC(I) = DDEL(I) * CV + (DDEL(I)*CF/DELB) + DL(I) * KS(I)
        GO TO 90
   40   IF (DDEL(I) .GT. 0.0) GO TO 50
        FORC(I) = DDEL(I) * CV - CF + DL(I) * KS(I)
        GO TO 90
   50   FORC(I) = DDEL(I) * CV + CF + DL(I) * KS(I)
        GO TO 90
   60   IF (ABS(DDEL(I)) .GT. DELB) GO TO 70
        FORC(I) = DDEL(I) * CV + (DDEL(I)*CFST/DELB) + KST(I) * (DL(I) +
     1   DEL)
        GO TO 90
   70   IF (DDEL(I) .GT. 0.0) GO TO 80
        FORC(I) = DDEL(I) * CV - CF + (DL(I) + DEL) * KST(I)
        GO TO 90
   80   FORC(I) = DDEL(I) * CV + CF + (DL(I) + DEL) * KST(I)
   90 CONTINUE
C
      GO TO 140
C-----------------------------------
C SPRING FRICTION EXPONENTIAL -- CURVE FIT
C-----------------------------------
  100 CONTINUE
C
      DO 130 J = 1, 2
        IF (X .EQ. 0.0) DLAST(J) = DL(J)
        IF (X .EQ. 0.0) FLAST(J) = W1 / 2.0
*       IF (DDEL(J) .GT. 0.0) GO TO 110
        ZZ = DL(J)
        ZZL = DLAST(J)
        CALL TABLE(1, NUM2, XXB, YYB, ZZ, FSENV)
        CALL TABLE(1, NUM2, XXB, YYB, ZZL, FSENVL)
        BETA = BETA2
        GO TO 120
  110   ZZ = DL(J)
        ZZL = DLAST(J)
```

```
          CALL TABLE(1, NUM1, XXT, YYT, ZZL, FSENVL)
          CALL TABLE(1, NUM1, XXT, YYT, ZZ, FSENV)
          BETA = BETA1
  120     DELL = ABS(ZZ - DLAST(J))
          FORC1(J) = (FLAST(J) - FSENVL) * EXP(-DELL/BETA) + FSENV
          FLAST(J) = FORC1(J)
          FORC(J)=FORC1(J)+CV*DDEL(J)
  130 DLAST(J) = ZZ
C
  140 CONTINUE
C
C----------------------------------------------
C
      DDEL31 = -(T + A) * Y(3) * COS8 - Y(2)
      DDEL32 = -T * Y(3) * COS8 - Y(2)
      DDEL41 = T * Y(3) * COS8 - Y(2)
      DDEL42 = (T + A) * Y(3) * COS8 - Y(2)
      FD31 = 0.
      FD32 = 0.
      FD41 = 0.
      FD42 = 0.
      IF (DEL31 .GT. 0.) FD31 = CVT * DDEL31
      IF (DEL32 .GT. 0.) FD32 = CVT * DDEL32
      IF (DEL41 .GT. 0.) FD41 = CVT * DDEL41
      IF (DEL42 .GT. 0.) FD42 = CVT * DDEL42
      IF (DEL31 .GT. 0.) F31 = DEL31 * KT1
      IF (DEL32 .GT. 0.) F32 = KT2 * DEL32
      IF (DEL41 .GT. 0.) F41 = KT3 * DEL41
      IF (DEL42 .GT. 0.) F42 = KT4 * DEL42
      AA(1,1) = M2 + M1
      AA(2,2) = (M1 + M2)
      AA(1,3) = -M1 * Y(9) * COS8
      AA(2,3) = -M1 * Y(9) * SIN8
      AA(3,3) = I2 + M1 * Y(9) ** 2
      AA(1,4) = -M1 * SIN8
      AA(2,4) = M1 * COS8
      AA(4,4) = M1
      AA(1,5) = -M1 * HR * COS10
      AA(2,5) = -M1 * HR * SIN10
      AA(3,5) = M1 * HR * Y(9) * COS108
      AA(4,5) = M1 * HR * SIN(Y(8) - Y(10))
      AA(5,5) = I1 + M1 * HR ** 2
      F11 = FORC(1)
      F22 = FORC(2)
      F33 = F31 + FD31
      F44 = F32 + FD32
      F55 = F41 + FD41
      F66 = F42 + FD42
      F(1) = -M1 * HR * Y(5) ** 2 * SIN10 + 2. * Y(4) * Y(3) * M1 *
     1COS8 - M1 * Y(9) * Y(3) ** 2 * SIN8 + FY
      F(2) = 2. * M1 * Y(4) * Y(3) * SIN8 + M1 * Y(9) * Y(3) ** 2 *
     1COS8 + M1 * HR * Y(5) ** 2 * COS10 - W1 - W2 + F33 + F44 + F55 +
```

```
     2F66
      F(3) = -2. * M1 * Y(9) * Y(3) * Y(4) + M1 * HR * Y(9) * Y(5) ** 2
     1* SIN108 + W1 * Y(9) * SIN8 + FY * (H2 + Y(7)) + (F11 - F22) * S +
     2 (F33*(T + A) + F44*T - F55*T - F66*(T + A)) * COS8
      F(4) = M1 * HR * Y(5) ** 2 * COS108 - W1 * COS8 + F11 + F22 + M1 *
     1 Y(3) ** 2 * Y(9)
      F(5) = -2. * M1 * HR * Y(4) * Y(3) * COS(Y(8) - Y(10)) - HR * Y(9)
     1 * M1 * Y(3) ** 2 * SIN108 + W1 * HR * SIN10 - (F11 + F22) * (HR -
     2 B) * SIN108 - (F11 - F22) * S * COS108
C
      DO 150 I = 1, 5
C
        DO 150 J = 1, I
  150 AA(I,J) = AA(J,I)
C
  160 CALL SIMQ(AA, F, 5, IER)
      IF (IER .NE. 0) GO TO 190
C
      DO 170 I = 1, 5
  170 DERY(I) = F(I)
C
      DERY(6) = Y(1)
      DERY(7) = Y(2)
  180 DERY(8) = Y(3)
      DERY(9) = Y(4)
      DERY(10) = Y(5)
      GO TO 200
  190 WRITE (6,210)
  200 RETURN
  210 FORMAT (5X, '***** MATRIX IS NOT POSITIVE DEFINITE *****')
      END
      SUBROUTINE OUTPUT
      COMMON /ONE/ W1, W2, I1, I2, H1, H2, B2, A, HR
      COMMON /TWO/ KS, KST, KT1, KT2, KT3, KT4, DEL, T, S
      COMMON /FOUR/ DEL10, DEL20, DELB
      COMMON /SIX/ F11, F22, F33, F44, F55, F66, FY, DL
      DIMENSION Y(10), DERY(10), AUX(16,10), PRMT(5), DL(2)
      COMMON /FIVE/ XPRINT
      COMMON /SEARCH/ COAMP
      COMMON /BOOM/ HBOOM
      REAL I1, I2, LB, KBS
      REAL KS(2), KST(2), KT1, KT2, KT3, KT4
      I = 0
C
C    SET ROLL LIMIT = OUTRIGGER TOUCHING GROUND
C
      OUTL = SQRT((118.5)**2 + (H1 - HBOOM)**2)
      THET = ATAN(118.5/(H1 - HBOOM))
      RETURN
      ENTRY OUTP(X,Y,DERY,IHLF,NDIM,PRMT)
      XP = I * XPRINT
      X2 = X / 2.
```

```
   10 IF (ABS(XP - X) .LE. PRMT(3)) GO TO 20
      RETURN
   20 CONTINUE
      WRITE (6,80) X
C
      DO 30 J = 1, 10
   30 WRITE (6,70) J, Y(J)
C
      I = I + 1
      RETURN
      ENTRY OUTP2(X,Y,DERY,IHLF,NDIM,PRMT)
      XP = I * XPRINT
      HX = H1 - H2 - HR
C
C     LATERAL ACCN OF SPRUNG MASS
C
      Y12DD = DERY(1) - Y(9) * DERY(3) * COS(Y(8)) - 2. * Y(4) * Y(3) *
     1COS(Y(8)) + Y(9) * Y(3) ** 2 * SIN(Y(8)) - DERY(4) * SIN(Y(8)) -
     2HR * DERY(5) * COS(Y(10)) + HR * Y(5) ** 2 * SIN(Y(10))
C
C    ROLL ANGLE OF SPRUNG MASS
C
      PHI12 = Y(10) * 180. / 3.14115927
      HY7 = H2 + Y(7)
      HY9 = H2 + Y(7) + Y(9) * COS(Y(8)) + HR * COS(Y(10))
      PHI2 = Y(8) * 180. / 3.1415927
C
C    CALCULATE THE HEIGHT OF OUTRIGGER TIRE
C
      HGHT = HY9 - OUTL * COS(THET - Y(10))
      HGHT1 = HY9 - OUTL * COS(THET + Y(10))
      IF (HGHT .GT. 0. .AND. HGHT1 .GT. 0.) GO TO 40
      IF (HGHT .LE. 0. .OR. HGHT1 .LE. 0.) PRMT(5) = 1.
      XNEG = -9999.0
      WRITE (6,100) XNEG
      WRITE (6,110) COAMP, FY, PHI12, HGHT, HGHT1, HY9, THET, OUTL
   40 CONTINUE
      IF (ABS(XP - X) .LE. PRMT(3)) GO TO 50
      RETURN
   50 CONTINUE
      I = I + 1
      WRITE (6,120) X, Y12DD, DERY(1), PHI12, HY7, HY9, PHI2, F11, F22,
     1F33, F44, F55, F66, FY, DL(1), DL(2)
   60 RETURN
   70 FORMAT (2X, 'Y(', I2, ') = ', E20.10)
   80 FORMAT (2X, 'TIME =', F15.5)
   90 FORMAT (2E20.10)
  100 FORMAT (T1, E11.4)
  110 FORMAT ('0', 5X, 'CO-EFF. OF AMPLITUDE =', F15.5, /, 6X, 'FY =',
     1       F15.5, /, 6X, 'SPRUNG MASS ROLL ANGLE=', F15.5, ' DEG.', /,
     2       6X, 'HEIGHT OF OUTRIGGER TIRES AT THIS INSTANT=', F10.5,
     3       ' ,', F10.5, ' INCHES ABOVE GROUND', /, 6X,
```

```
     4         'HEIGHT OF SPRUNG MASS CG', F15.5, ' INCHES ABOVE GROUND',
     5         /, 6X, 'OUTRIGGER LOCATION', /, 15X, 'ANGLE FROM SPRUNG MAS
     6S AXIS( VERTICAL)=', F10.5, ' DEG', /, 15X, 'TOTAL LENGTH=',
     7         F10.5, ' INCHES')
  120 FORMAT (T1, 16E11.4)
      END
      FUNCTION FEXT(T)
      COMMON /EXC/ FCT, TIME, AMP, TMAX
      COMMON /DISCR/ N, F(500), X(500)
      COMMON /SEARCH/ COAMP
      DATA RAMP /'RAMP'/
      DATA STEP /'STEP'/
      DATA SINE /'SINE'/
      DATA DISC /'DISC'/
      IF (FCT .EQ. DISC) GO TO 10
      FEXT = 0.
      IF (FCT .EQ. RAMP .AND. T .LE. TIME) FEXT = AMP / TIME * T
      IF (FCT .EQ. RAMP .AND. T .GT. TIME) FEXT = AMP
      IF (FCT .EQ. SINE .AND. T .LE. TMAX) FEXT = AMP * SIN(2.*3.
     11415927*T/TIME)
      IF (FCT .EQ. STEP .AND. T .LT. TMAX) FEXT = AMP
      FEXT = FEXT * COAMP
      RETURN
   10 CONTINUE
C
      DO 20 J = 1, N
        IF (T .LE. X(J)) GO TO 30
   20 CONTINUE
C
   30 IF (J .EQ. 1) GO TO 40
      FEXT = F(J - 1) + (F(J) - F(J - 1)) / (X(J) - X(J - 1)) * (T - X(
     1J - 1))
      GO TO 50
   40 FEXT = F(1)
   50 CONTINUE
      FEXT = COAMP * FEXT
      RETURN
      END
      SUBROUTINE TABLE(M, N, X, Y, Z, Q)
      DIMENSION X(1), Y(1)
C
      DO 10 I = M, N
        IF (Z .LE. X(I)) GO TO 20
   10 CONTINUE
C
   20 IF (Z .NE. X(I)) GO TO 30
      Q = Y(I)
      RETURN
   30 IF (I .EQ. M) I = M + 1
      Q = (Y(I)*(Z - X(I - 1)) - Y(I - 1)*(Z - X(I))) / (X(I) - X(I - 1)
     1)
      RETURN
      END
```

APPENDIX F

ROLL PARAMETERS

Listed in this appendix are vehicle parameters which were used in the rollover threshold calculations. These parameters describe the roll properties of each of the thirteen vehicle configurations which were analyzed. The thirteen configurations are defined in Table 1.

The mass, roll moment of inertia and dimensional properties of each vehicle configuration in the fully loaded condition are given in Table F.1. The symbols used in the table are defined in Table F.2. The parameters for the tractor-semitrailers (configurations Ia through III) and the modified double tankers—which are equipped with rigidized pintle hooks (configurations Vb and VIc) were computed by assuming the vehicles to be completely rigid in roll. The entire vehicle was, therefore, represented in the model by a single sprung mass and a single unsprung mass. Parameters which correspond to such a composite vehicle representation are listed in Table F.1 for these nine configurations.

In the case of the truck-full trailer (configuration IV) and the double tankers equipped with a conventional pintle hook (Va, VIa, and VIb) the full trailer is not coupled in roll to the rest of the vehicle. Moreover, the full trailer is the one that is most susceptible to a rollover. Hence, calculations of rollover threshold were made for these vehicles using parameters which describe the full trailer alone.

The measured force deflection characteristics of the three, multileaf suspension springs, UCD-9637, UCD-0511 and UXB0201, are portrayed in Figures F.1, F.2, and F.3, respectively. The coordinates chosen to define the upper and lower envelopes of the force-deflection characteristics are also tabulated in these figures. (The representation of the springs in the roll model is discussed in detail in Appendix E.)

Roll properties of the T-type air suspension used in calculations made for the tractor-semitrailers, BKY8499 and BKD0065, were also measured by the Fruehauf Corporation. From the measurements, it was found that, due to the active nature of the pneumatic system, this suspension did not

Table F.1. Roll Parameters.

PARAMETER	Ia	Ib	IIa	IIb	IIc	IId	III	IV	Va	Vb	VIa	VIb	VIc
W_s	69800	69800	73550	73550	71300	71300	71390	35000	32625	71960	42700	42700	93200
W_u	8700	8700	10200	10200	8700	8700	10200	3000	3000	8040	4800	4800	12300
h_s	79.33	78.25	78.25	78.25	76.78	76.78	80.73	78.65	78.65	76.92	85.34	85.34	81.43
h_u	20.0	20.0	20.0	20.0	20.0	20.0	20	20	20	20	22	22	22
I_s	99034	99034	101546	101546	109450	109450	103370	20760	24290	90206	30641	30641	117194
I_u	20500	20500	24600	24600	20500	20500	24600	8200	8200	20500	14000	14000	32120
h_r	52.33	52.33	51.25	51.25	49.78	49.78	53.73	51.65	52.43	49.92	58.34	58.34	54.43
b	51.33	51.33	50.25	50.25	48.78	48.78	52.73	50.65	51.43	48.92	57.34	57.34	53.43
a	13.0	13.0	13.0	13.0	13.0	13.0	13	13	13	13	0.0	0.0	0.0
s	19	19	19	19	19	19	19	19	19	19	22.0	19.0	19.0
t	29	29	29	29	29	29	29	29	29	29	38.75	35.75	35.75
C_v	0.0	160	80	240	160	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
K_t	22500	22500	27500	27500	22500	22500	27500	10000	10000	22500	10000	10000	22500
β_1	.07	.07	.07	.07	.07	.07	0.05	0.07	0.07	0.07	0.07	0.07	0.07
β_2	.05	.05	.05	.05	.05	.05	0.05	0.05	0.05	0.05	0.07	0.07	0.07
C_{VT}	22.5	22.5	27.5	27.5	22.5	22.5	27.5	10.0	10.0	22.5	10.0	10.0	22.5

Table F.2

W_s	weight of sprung mass (lb)
W_u	weight of unsprung mass (lb)
h_s	height of sprung mass c.g. above ground (in)
h_u	height of unsprung mass c.g. above ground (in)
I_s	roll moment of inertia of sprung mass about its c.g. (in·lb·sec^2)
I_u	roll moment of inertia of unsprung mass about its c.g. (in·lb·sec^2)
h_r	height of sprung mass c.g. above the roll axis (lb·in·sec^2)
b	vertical distance between sprung mass c.g. and the spring hanger (in)
a	dual tire spacings (in)
s	suspension spring half spacings (in)
t	lateral distance between the inner tire and the center line of the vehicle (in)
C_V	viscous damping in the suspension spring—used only for air springs (lb·sec/in)
K_t	vertical stiffness of the tires (lb/in)
β_1	a parameter which describes the rate at which the suspension force approaches the upper envelope (see Appendix E)
β_2	a parameter which defines the rate at which the suspension force approaches the lower envelope (see Appendix E)
C_{VT}	viscous damping in the tires (lb·sec/in)

UPPER ENVELOPE		LOWER ENVELOPE	
DEFN.	FORCE	DEFN.	FORCE
-1·25	-11177	-1·25	-13039
-0·175	-392	-0·12	-980
0·0	0·0	0·0	0·0
1·55	0·0	1·55	0·0
2·30	2621	2·35	1748
3·91	20000	2·80	4466
		4·05	17330

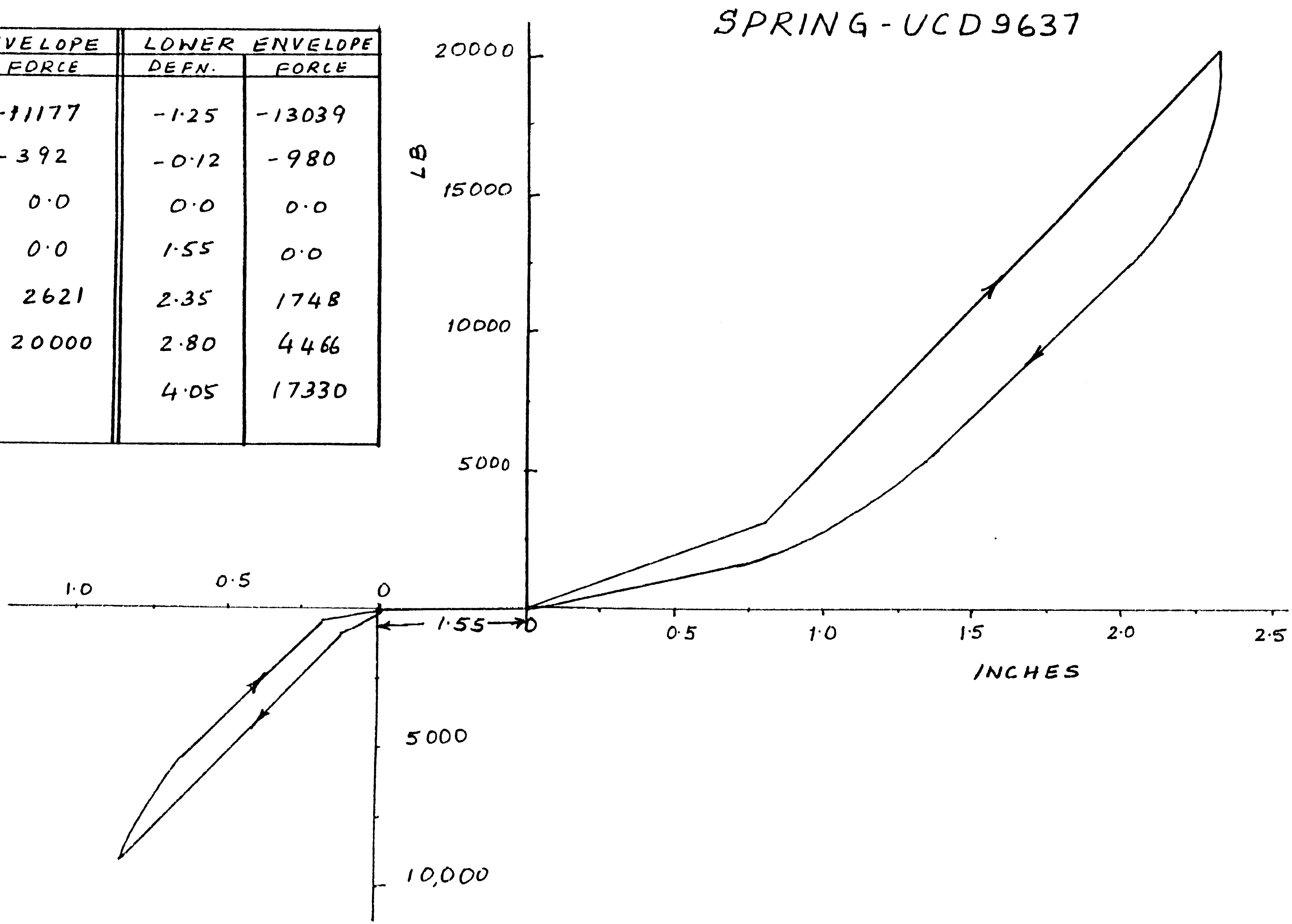


Figure F.1

SPRING UCD 0511

UPPER ENVELOPE		LOWER ENVELOPE	
DEFN.	FORCE	DEFN.	FORCE
-2.5	-8700	-2.11	-10000
-1.325	-3650	-1.19	-7200
-0.09	0.0	-0.14	-400
2.25	0.0	0.00	0.0
2.47	1600	2.25	0.0
2.87	5000	2.42	400
3.33	9600	2.72	1550
3.725	14400	2.83	3100
4.11	20000	3.44	8900
		3.78	12800
		4.37	20000

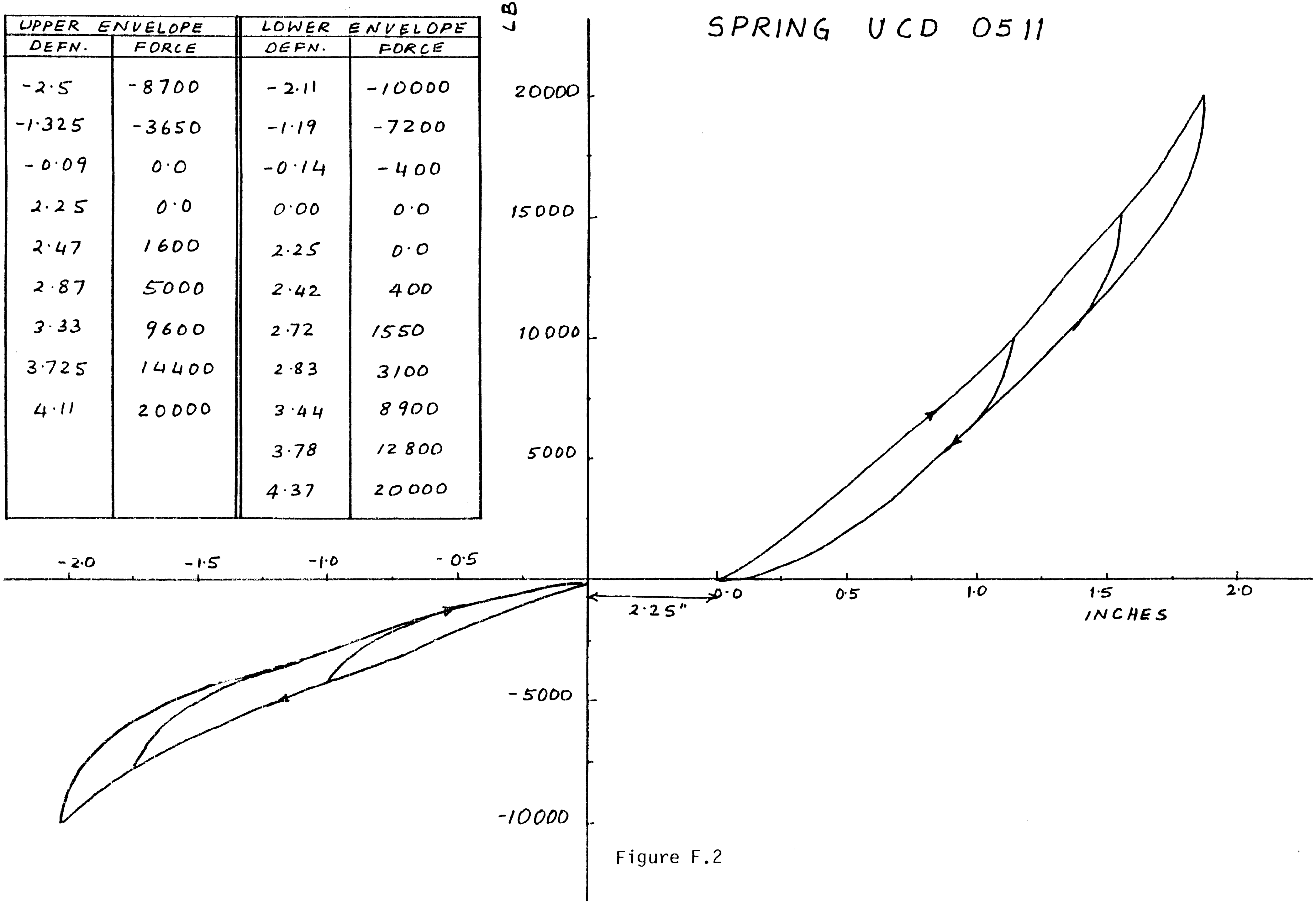


Figure F.2

SPRING - UXB 0201

UPPER ENVELOPE		LOWER ENVELOPE	
DEFN.	FORCE	DEFN.	FORCE
-2.5	-9400	-1.92	-10000
-1.13	-3300	-0.92	-4250
-0.35	-700	-0.41	-1550
0.0	0.0	0.0	0.0
1.5	0.0	1.5	0.0
1.68	950	1.7	350
1.94	3450	1.83	1000
3.14	20000	2.01	2400
		2.28	5200
		2.5	8000
		3.41	20000

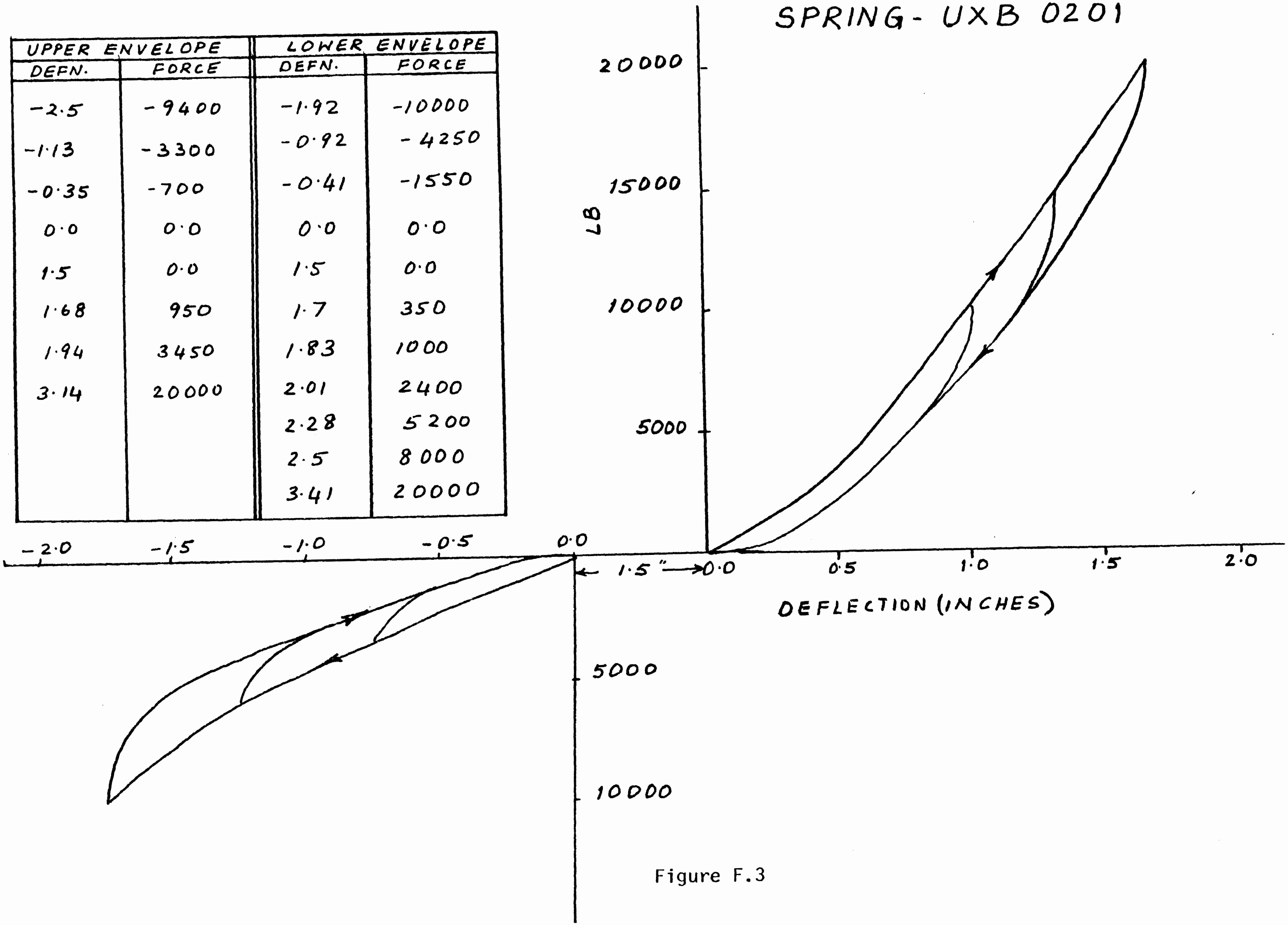


Figure F.3

possess a hysteresis loop similar to the ones shown in Figures F.1 through F.3. The roll stiffness was also found to be sensitive to the vertical load carried by the suspension. Hence, a set of four measurements were made with vertical loads of 0, 10000, 15000 and 20000 lbs. An average linear roll stiffness rate of 241005 in•lbs/deg was obtained from the measurements. The air suspension was therefore represented in the model by linear springs of stiffness 9563 lb/in, spaced 38-in. apart.

Since shock absorbers were used on the T-type air suspensions, it was decided to represent them in the roll model by a linear viscous damper. An estimate of 80 lb•sec/in, for the equivalent viscous damping of the shock absorbers was obtained from ride measurements made at HSRI (see Reference [1]) on a tractor-semitrailer equipped with an air suspension.

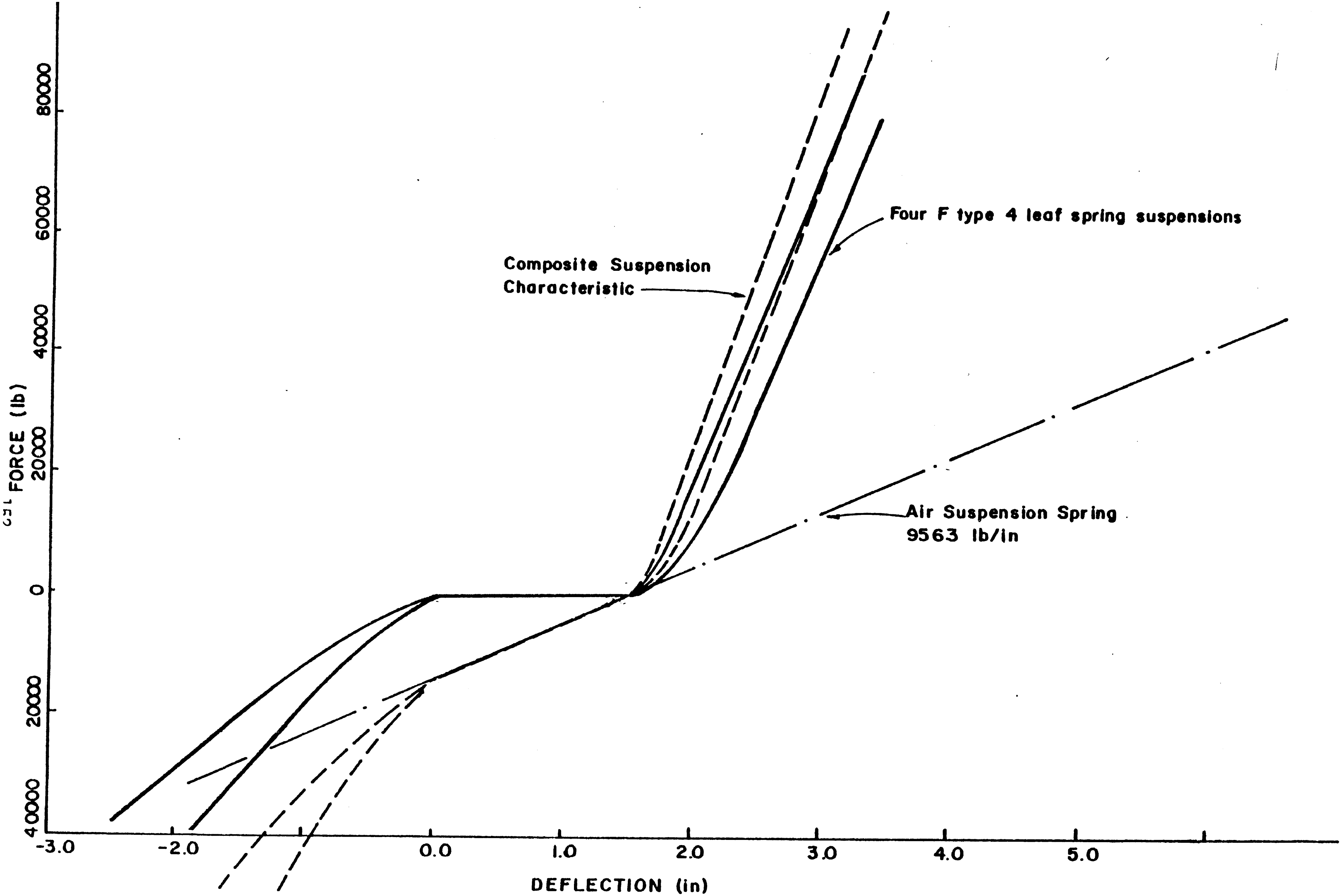
Since no data was available for the tractor suspensions, the following assumptions were made:

1) The tractor rear suspension was assumed to be a multileaf suspension, similar to the ones used on the trailers. In the case of tractor-semitrailers BKY 8499 and BKD 0065, the tractor rear suspension was assumed to be an F2 with four-leaf springs, UXB0201, for all configurations (Ia through IId) including the ones with air suspensions on the semitrailer.

2) Since the tractor front suspension is usually very compliant, it was assumed that the roll stiffness contributed by the tractor front suspension was negligible.

3) For configurations where a mixture of air and leaf spring type suspensions are used on the vehicle, a composite force-deflection envelope was constructed. Figure F.4 shows the spring characteristics used for configuration IIa.

4) A roll center height of 27 in. was assumed for all suspensions.



80000
60000
40000
20000
0
20000
40000
FORCE (lb)
Composite Suspension
Characteristic
Four F type 4 leaf spring suspensions
Air Suspension Spring
9563 lb/in
-3.0
-2.0
0.0
1.0
2.0
3.0
4.0
5.0
DEFLECTION (in)

Figure F.4

REFERENCE

1. Nisonger, R.L. and Ervin, R.D. "Measurement of Ride Vibrations on Semitrailers Incorporating Different Suspensions," Technical Memorandum, Highway Safety Research Institute, University of Michigan, September 5, 1979.