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ANALYSIS OF THE ROLL STABILITY OF CRYOGENIC TANKERS

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Final Report

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16. Abstract

The roll stability of an existing fleet of tractor-semitrailers used for hauling cryogenic liquids was evaluated. The evaluation involved the conduct of computerized simulations, together with laboratory suspension measurements which provided a portion of the simulation input data. Vehicles comprising the existing fleet were found to exhibit a wide range of roll stability levels—partly as a result of differences in the geometric layout of the respective cryogenic tanks and partly due to differences in the various purchased suspensions.

Candidate changes in vehicle design were examined as potential means of improving roll stability. The fleet accident record is reviewed and projections are made as to the reductions in rollover rate likely to accrue from changes in suspension selection and the layout of basic vehicle dimensions.

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APPENDICES

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This project was conceived by Mr. C.R. Lowry and managed by Mr. T. Gallagher, both of Linde's Safety and Training Department. The Linde accident reports appearing in Appendix E were also compiled by Mr. Gallagher.

The computer simulation runs were conducted at HSRI by Mr. Gary Hu, following initial development of the mathematical model by Dr. C. Mallikarjunarao. Laboratory measurement of suspension properties employed a machine which had been built by HSRI under sponsorship of the Motor Vehicle Manufacturers Association.

The report was typed by Ms. Jeannette Nafe.

EXECUTIVE SUMMARY

This report presents results of a study of cryogenic tanker roll stability conducted by the Highway Safety Research Institute (HSRI) of The University of Michigan. The study sought to evaluate the roll stability of the current fleet of tankers operated by the Linde Division of the Union Carbide Corporation and to determine the safety payoff deriving from various design changes.

Methods

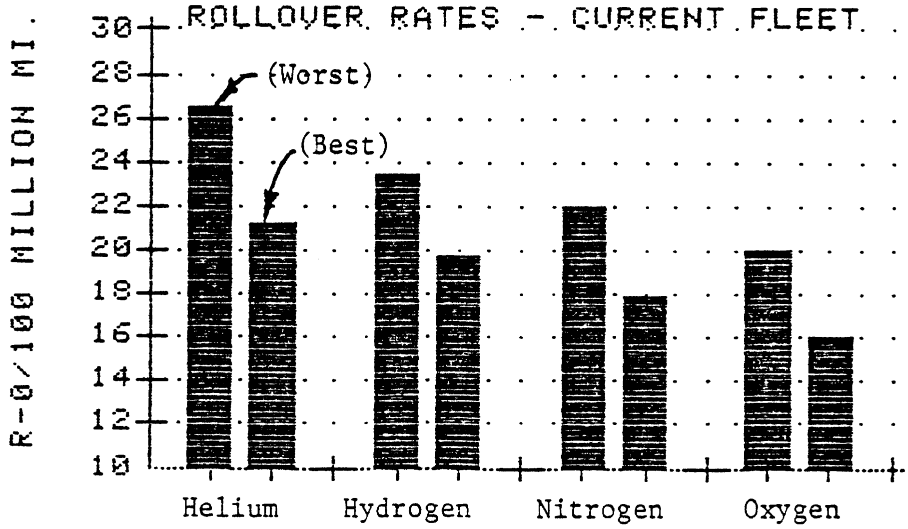
The primary investigative tool used for evaluating the roll stability of differing vehicle types was a computerized simulation. This simulation model has been previously shown to accurately predict the rollover limits of tractor-semitrailers in full-scale tests. The simulation requires that input data be provided describing the geometric layout of the vehicle, the mass of various elements, and the mechanical properties of the tires, suspensions, and coupling mechanisms. These data were obtained in this study directly from engineering drawings, by use of existing "comparable" data available at HSRI, and through laboratory measurement.

All suspension data were measured directly on four of Linde's tractor suspensions and three trailer suspensions using a special laboratory machine. Additionally, a set of tractor-semitrailer combinations was employed in measuring the looseness existing in fifth wheel couplings. The computer program employed here represents all of the major mechanisms which HSRI research has shown to influence the roll stability of tractor-semitrailers. This simulation was developed with the aid of extensive laboratory measurements on commercial vehicle suspensions, tires, frame, and coupling elements in order to determine the proper behavior of the respective components. The simulation's ability to predict the absolute level of the so-called "rollover threshold" rendered it especially useful for this study. The "rollover threshold" is expressed in units of "g" describing the maximum tolerable level of lateral acceleration beyond which the vehicle rolls over. Computer simulations were run first to evaluate the range of rollover thresholds resulting from all the possible combinations of Linde tractors and trailer types. The computed results serve to describe the stability level of the existing fleet. Subsequently, various candidate design changes were input to the simulation, so that prospective future improvements in stability could be evaluated.

An accident rate prediction method was used to relate the inherent roll stability of individual vehicle types to their likely rate of rollover accident involvement in service. This basic scheme was "calibrated" to reflect the actual rollover record of the Linde fleet over the last five years. Having been calibrated, the method is able to predict the nominal rate of rollovers occurring per 100 million miles of service for each type of vehicle.

<u>Results</u>

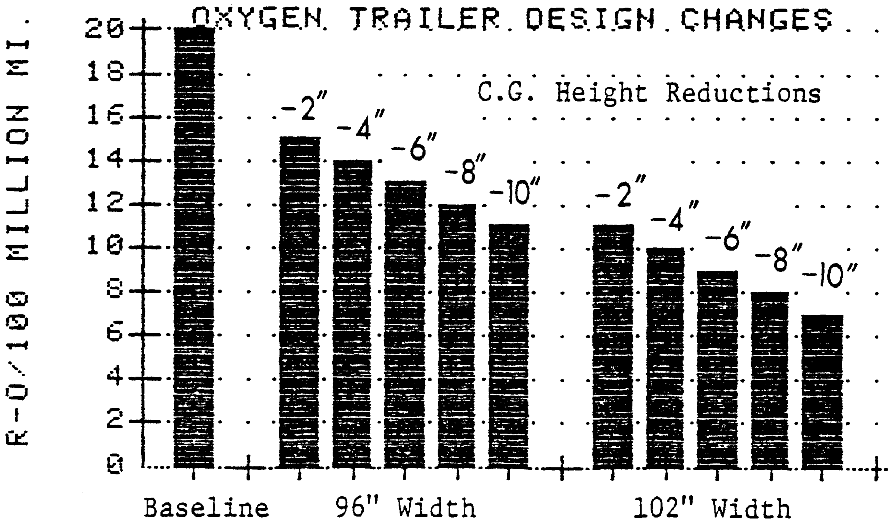
Shown below is a chart of the projected rate of rollovers per 100 million miles of travel for each of four basic types of cryogenic tankers in the fleet. The chart shows, for each type of tank vehicle, values



Range of predicted rollover rates resulting from range of current suspension designs.

representing the worst and best combinations of tractor and trailer suspensions currently in use. Thus, for example, Linde's Helium tankers are predicted to experience from 21 to 26.5 rollovers per 100 million miles of travel, depending upon the suspensions installed on each tractor and semitrailer.

Certain design changes in the vehicle were also considered as possible means of improving roll stability. Three items were identified as offering minimal (one percent or less) improvement in stability, namely (a) reduced level of looseness in fifth wheel coupling, (b) reduced height of fifth wheel mounting on tractor, (c) variation in tire carcass construction. The two parameters which are known to have the greatest influence on roll stability are the height of the center of gravity and the outside width across the tires. The figure below presents rollover rate projections resulting from simulations of c.g. height and width variations on an Oxygen tanker. Each of the variation conditions represented at the right of the baseline case also incorporates the "best" of the suspension installations for this tanker.



Reductions in rollover rate achievable by means of design changes.

As shown in the figure, c.g. height reductions were considered in two-inch increments. It was found that for each two-inch reduction, the projected rollover rate declined by approximately five percent of the baseline rate. When the track width measured across the tandem suspensions of both tractor and semitrailer is widened from the standard 96 inches to 102 inches, the rollover rate reduces by an additional 20 percent of the baseline rate.

In summary, the study has revealed the following:

a) The current Linde fleet is low in roll stability compared to tractor-semitrailers in common freight service in the U.S. (Rollover thresholds for the current Linde fleet are seen to range from .26 to .36 g's. By way of contrast, MC 306 gasoline tankers in the U.S. show rollover thresholds around .32 g's and tractor-semitrailers in general freight service are estimated to register "typical" values around .37 g.)

b) The Linde fleet is currently suffering a high incidence of rollover (on the order of 20 rollovers per 100 million vehicle miles compared to a U.S. average (for tractor-semitrailers hauling general freight) which is approximately six).

c) The rollover rate can be reduced by 20 percent simply by using the most favorable of the currently-available suspensions.

d) Another 25-percent reduction in the rollover rate can be obtained by lowering the tank center of gravity by 10 inches.

e) An additional 20-percent reduction is achievable, if and when new legislation permits, by widening the vehicle track from the currently-legal width of 96 inches to the expected future allowance of 102 inches.

Recommendations

On the basis of this study, and upon HSRI's understanding of the Linde transportation operation, it is recommended that Linde take the following action:

1) Adopt a practice of procuring only those suspensions which maximize vehicle roll stability. (The text of the report presents a specific performance criterion to be applied.)

2) Assure that the height of the fifth wheel plate on Linde tractors is not above a value of 49 inches, when a loaded trailer is attached.

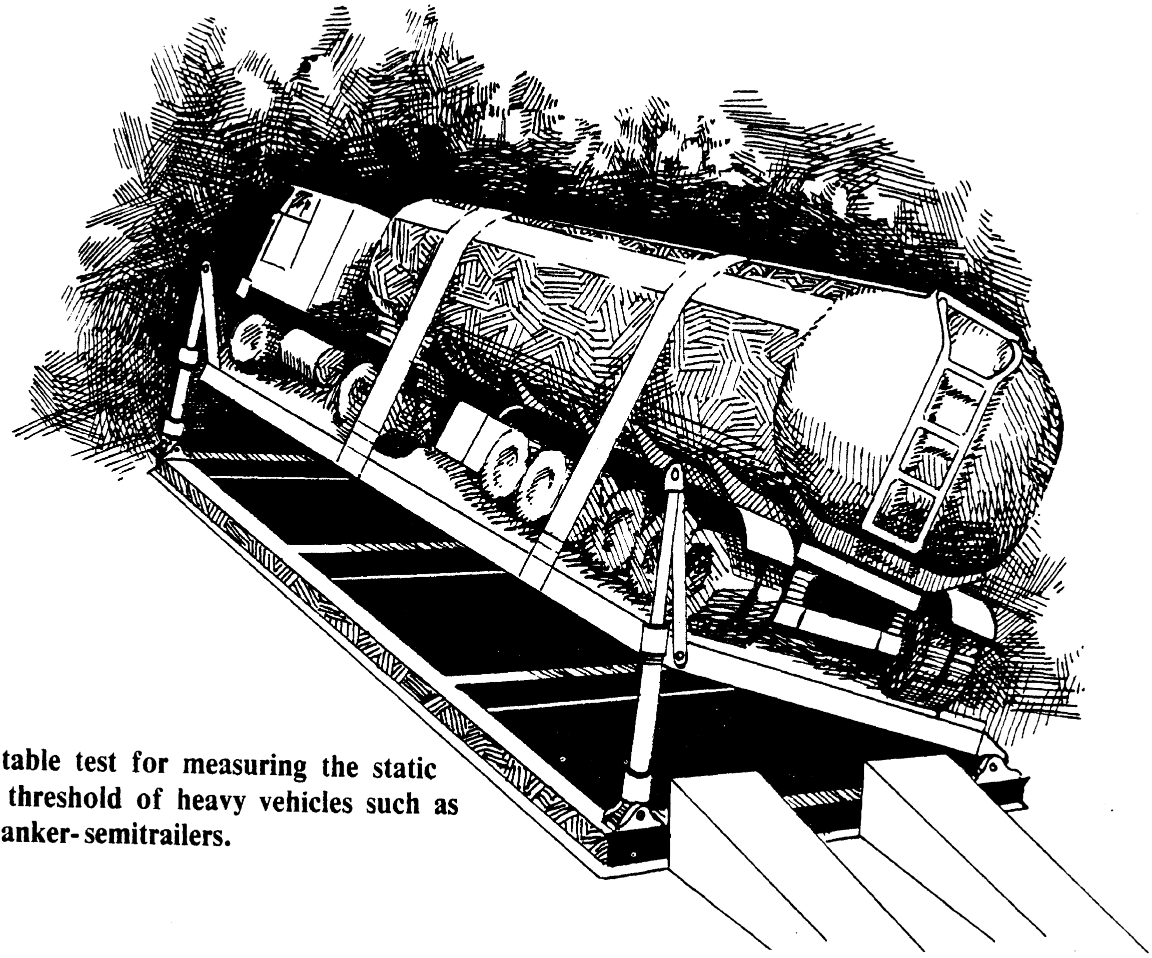
3) Explore the design flexibility of Linde tank trailers to determine whether the conventionally-shaped tank vessels can be cradled lower in the sub-frame/suspension assembly. (Each two-inch reduction lowers rollover incidence by five percent.)

4) Determine whether dramatic reductions in tank c.g. height (i.e., on the order of 10 inches or greater) can be practicably achieved through wholesale redesign of the tank layout.

5) Provide encouragement for Congressional approval of an increase in the allowable truck width from 96 inches to 102 inches—at least for the sake of carriers hauling hazardous commodities, if not for general trucking. If a 102-inch allowance is granted, Linde should hasten to apply it on the tandem suspensions of both tractors and semitrailers.

6) For the long term, support the development of a tilt table device, such as sketched on the following page, for directly measuring the overall roll stability of

assembled vehicle combinations. Such a device would be the best means for Linde to screen newly-developed tractors and trailers for roll stability. Such screening, over time, will motivate the heavy vehicle industry to develop more roll-stable products.



The tilt-table test for measuring the static rollover threshold of heavy vehicles such as loaded tanker-semitrailers.

1.0 INTRODUCTION

This document is the final report of the Highway Safety Research Institute (HSRI) of The University of Michigan on a research study procured by the Union Carbide Corporation under P.O. #131-423003-4 CN#1. The project has involved a study of the roll stability of cryogenic tankers such as are operated by the Linde Division of Union Carbide.

The project grows out of Union Carbide's desire to improve the safety of its tanker operations, especially in regard to minimizing the occurrence of rollover. With an average of seven to eight tanker rollovers in the Linde fleet each year, there has arisen an interest in examining the basic stability of these vehicles to determine whether safety improvements can be made. To this end, the study has pursued three objectives, namely,

1) To obtain, through computerized simulation, values of rollover threshold characterizing all of the basic tractor-semitrailer types operated by the Linde Division in transporting cryogenic liquids.

2) To employ the rollover threshold information, together with accident data, in estimating the current rollover involvement rate, per vehicle mile, of each of the vehicle types in the fleet.

3) To illustrate the approximate level of reduction in the rollover rates which might be achieved in the future through changes in vehicle design.

The research effort has involved direct laboratory measurements on Linde tractors and semitrailers, and computerized simulation of the actual rollover-resistance qualities of the various vehicle combinations. The study has considered not only the various tanker configurations which carry alternative cryogenic products, but also the variations in selection of trailer and tractor suspensions. Further, future changes in vehicle design properties were considered as means to improve the roll stability of vehicle combinations.

This line of research represents an application of certain methodologies which have been developed at HSRI in recent years. While the main engineering tools used here constitute the measurement and simulation items cited above, the key item enabling a projection of rollover involvement derives from a study of a sample of national accident data. Using data gathered from regulated carriers by the Federal Bureau of Motor Carrier Safety (BMCS), it has been possible to relate the inherent roll stability of a given tractor-semitrailer to the likely involvement of that vehicle in rollover accidents. Thus, with the evaluation of the nominal roll stability level of Linde's vehicles, the rollover involvement rates could be projected.

This report provides, firstly, an overview of the technical aspects of the investigation, in Section 2.0. The results of the computer-aided analysis of vehicle roll stability level are presented in Section 3.0. The results are categorized as follows:

-the roll stability levels exhibited by the existing fleet (Section 3.1)

-the improvements in roll stability level achievable through changes in vehicle design (Section 3.2)

-a projection of the rollover involvement rates pertaining to both the existing and possible future vehicle configurations (Section 3.3)

Conclusions and recommendations are presented in Section 4.0.

2.0 TECHNICAL DISCUSSION OF METHODS

In this section, the investigative methods will be described and the results of direct vehicle measurements will be presented. Vehicle measurements included the use of a laboratory facility for characterizing suspension parameters as needed for computer simulation. Also, a sample of tractors and cryogenic tankers was examined for measurement of the lash space existing between the tractor fifth wheel and the trailer coupling plate.

Measurements of suspension properties and fifth-wheel lash were combined with other vehicle parameters which were either measured, estimated, or obtained from engineering drawings. Parameter sets were thus assembled for use in simulating each tractor-semitrailer combination. The parameter sets are discussed below and the simulation model is described.

2.1 Suspension Measurements

To obtain the parameters necessary for accurate representation of the vehicle suspension system in a mathematical model, four tractor and three trailer suspensions were tested on the HSRI tandem suspension parameter measurement facility. This facility fastens the tractor or trailer-bogie frame to an overhead structure while the suspension is exercised by the movable table. Figure 2.1 shows a trailer bogie equipped with a Chalmers rubber spring walking-beam suspension installed on the facility. The suspension is exercised by moving the table vertically and tilting it relative to the fixed frame. Forces and moments at the tire contact patch are measured with instrumented pads constituting the tire-table interface. These data, along with measurement of axle vertical and roll deflection, are used to arrive at the respective stiffness properties of the suspension.

Measurements were performed on the following tractor suspension systems:

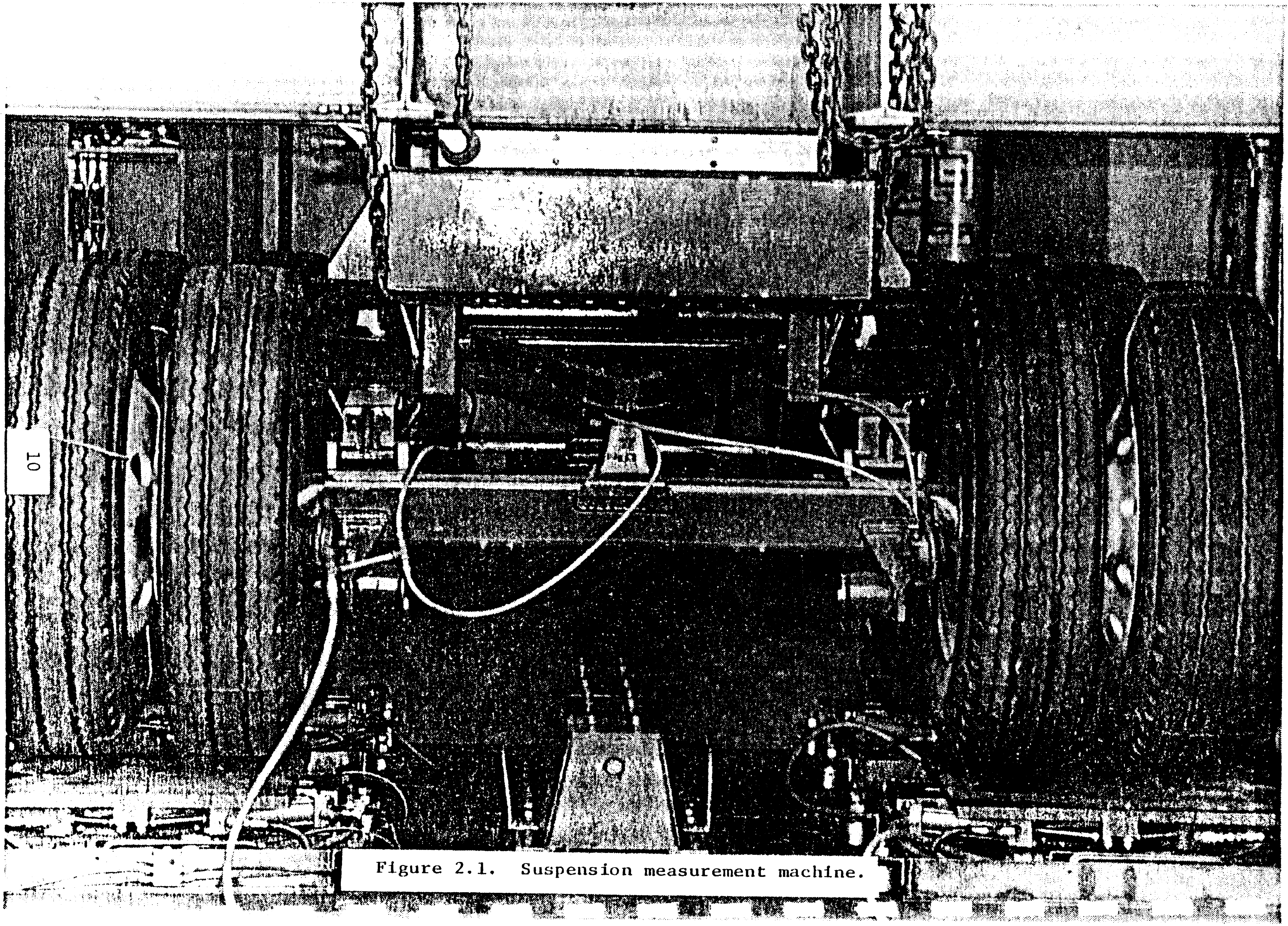


Figure 2.1. Suspension measurement machine.

- Freightliner four-spring
- Peterbilt four-spring
- Mack (Reyco-manufactured) four-spring
- Kenworth torsion bar

The trailer suspensions tested were:

- Hutchens taper leaf four-spring
- Chalmers rubber spring walking-beam
- Neway air suspension

Each suspension was tested to determine those parameters relevant to the rollover process, specifically, vertical spring rate, roll stiffness, and roll center height. In addition to these parameters, the amount of lash present between spring connection elements was measured directly. Shown in Figure 2.2 is a photo of the spring lash space existing at the aft spring slipper of the Freightliner four-spring suspension. Note that the spring lash constitutes the free space through which the main spring leaf must pass when the vehicle is approaching rollover, and is thus completely unloading the springs on one side. The presence of a non-zero lash space has been shown [1] to reduce the effective stiffness level of the suspension spring, resulting in a reduced resistance to rollover.

A simplified condensation of the results of the suspension measurement activity are summarized in Table 2.1. We see in the table that large differences exist in the nominal spring rates and lash space dimensions distinguishing the various suspensions currently used in the Linde fleet. Also, it is significant that certain suspensions (most notably, the Kenworth torsion bar suspension) exhibit very different properties on the leading versus trailing tandem axles. The study results will show that roll stability is compromised when the suspension roll rate is low and, also, when the lash space is relatively large.

The detailed suspension data are presented in Appendix A.

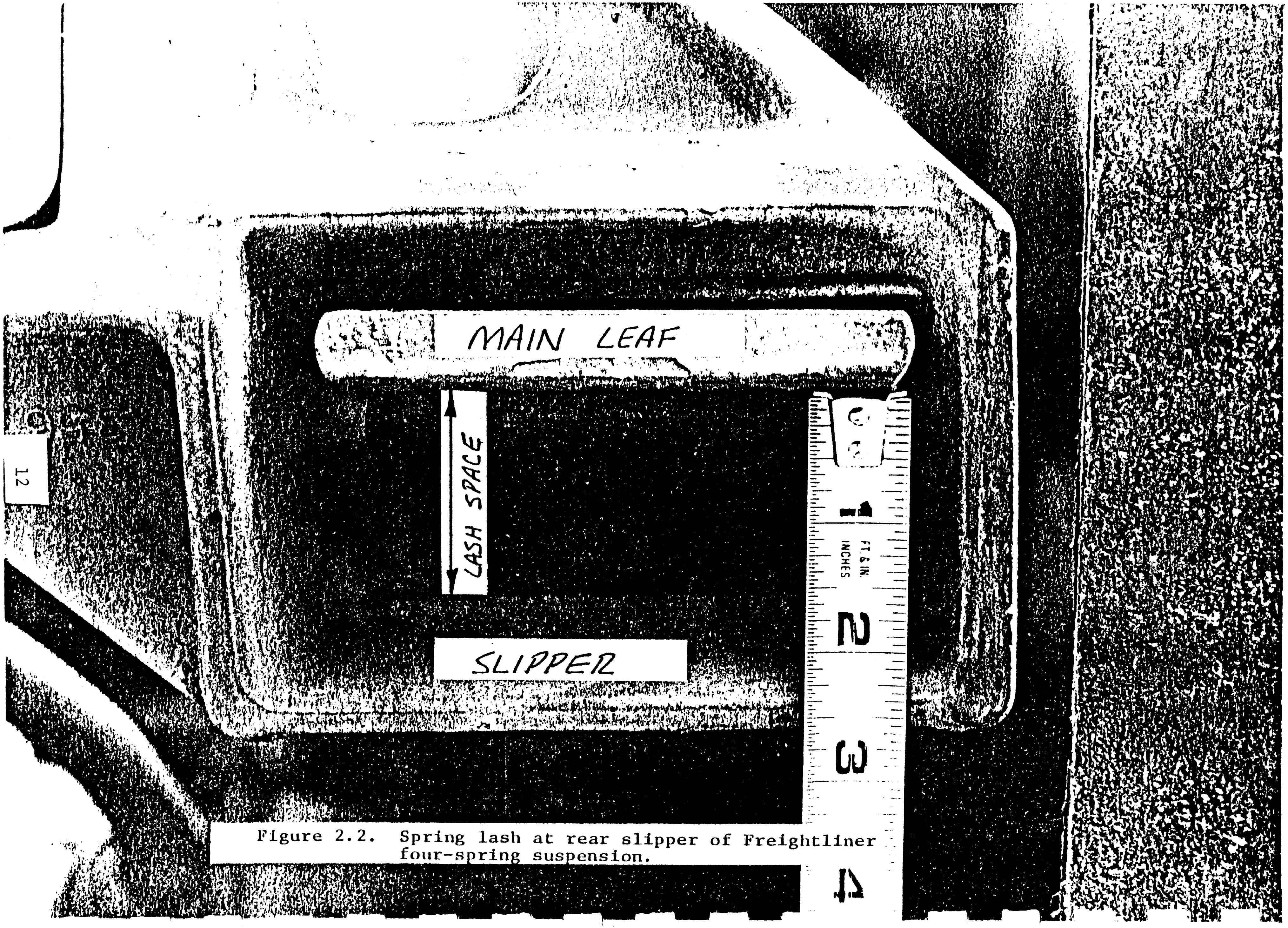


Figure 2.2. Spring lash at rear slipper of Freightliner four-spring suspension.

Table 2.1

Vehicle	Suspension Type	Vertical Rate (lb/in)	Vertical Lash (in) Slipper/Equalizer	Roll Rate (K in•lb/deg) Leading/Trailing
Freightliner	Four Spring	5450	.75/.75	90/90
Peterbilt	Four Spring	7740	.75/.75	95/95
Mack	Reyco	8420	1.5/2.0	125/150
Kenworth	Torsion Bar	5160	nil	80/40
Trailer	Four Spring	6670	1.75/2.5	110/120
Trailer	Chalmers	4920	.75/.75*	85/85
Trailer	Neway Air	1890	nil	80/200**

*Lash between walking beam and axle/lash between spring and frame.

**This suspension becomes dramatically stiffer beyond a 2-3° roll angle, exhibiting nominal roll rates of approximately 250,000 in-lb/deg.

2.2 Fifth Wheel Lash Measurements

The fifth wheel lash dimension of interest is that angle included between the fifth wheel plate, on the tractor, and the upper coupler plate on the trailer which becomes "opened up" when a large roll moment is transmitted from the trailer to the tractor, such as during an impending rollover condition. Thus, the lash is defined in terms of an angle which is subtended between tractor and semitrailer. The desire to obtain measurements of fifth wheel lash did not stem from an hypothesis that this parameter would be of high importance to roll stability, but rather was undertaken because very few example data were available. Also, the measurement became especially desirable since it was observed that the fifth wheel lash space would definitely be traversed prior to the rollover of Linde's Hydrogen and Helium trailers, given their high center of gravity locations.

A simple physical experiment was undertaken, as photographed in Figure 2.3, to provide the pertinent measurement of fifth wheel lash.

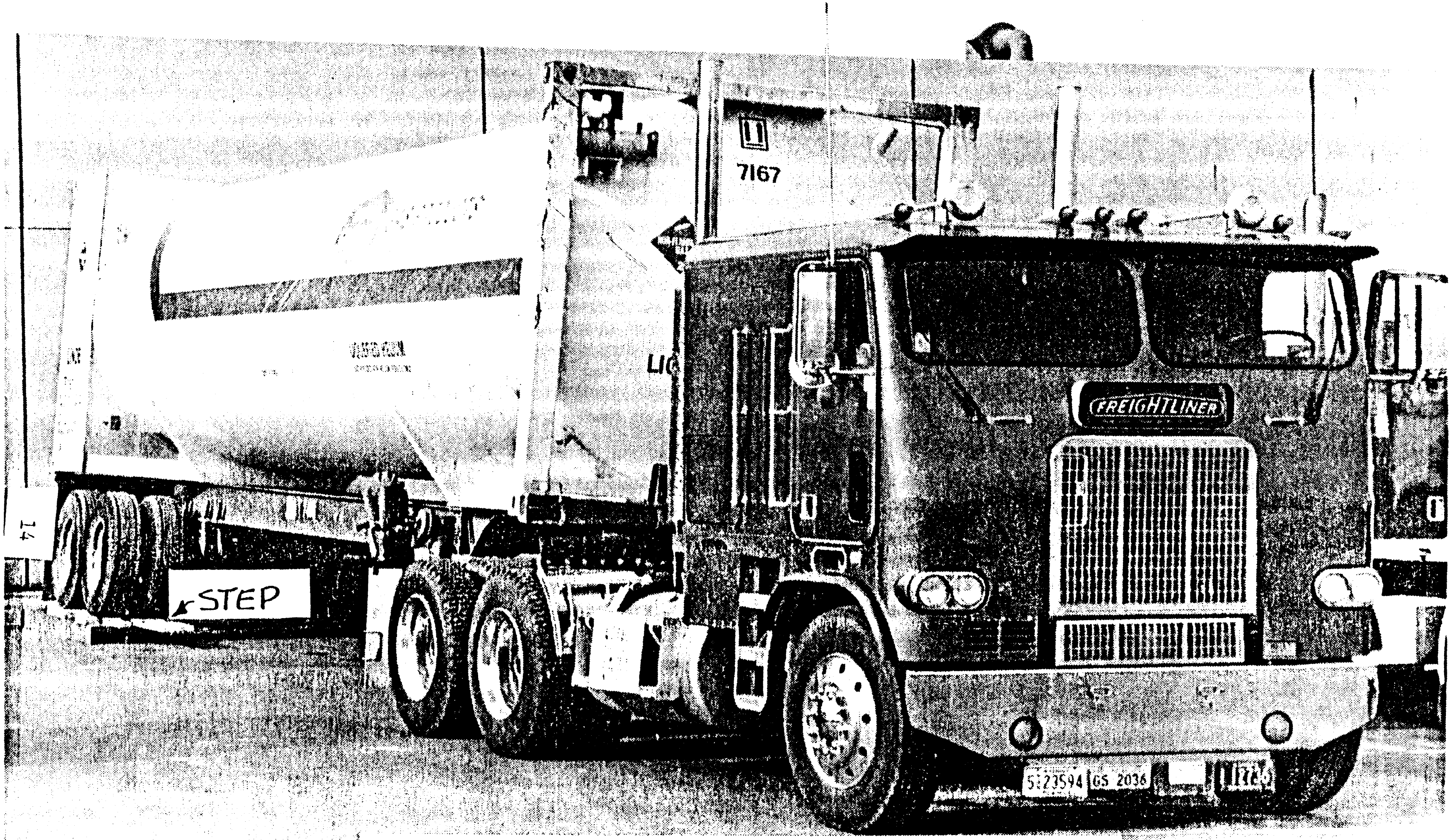


Figure 2.3. Setup for measuring fifth wheel lash angle.

Namely, with the tractor and semitrailer coupled together, the right-side trailer wheels were brought up a ramp onto an eight-inch step such that the desired roll moment was transmitted to the tractor. The step height was chosen such that the available lash space was completely opened up.

Shown in Table 2.2 are the measurements of fifth wheel lash angle as measured on various combinations. Fifteen separate measurements were performed using four cryogenic trailers and five tractors. It should be noted that a variety of vehicles were employed in these measurements simply to provide multiple samples for characterizing a property which varies more or less randomly as a function of wear and manufacturing tolerances in the fifth wheel and trailer kingpin assemblies.

The data show fifth wheel lash values ranging from approximately two to over four degrees. While the measurements showed some inconsistencies with regard to the relative ranking of the various tractors over the set of trailers, it was noted that an older Mack tractor (No. 306114) produced uniformly high amounts of lash while a six-month-old Freightliner tractor was consistently near the bottom of the scale.

The primary purpose in conducting these measurements was not to discriminate among specific vehicles which exhibited small or large amounts of fifth wheel lash, but rather to simply define a reasonably typical value of lash for use in simulating all of Linde's vehicles. It was concluded that a value of fifth wheel lash equal to 3-1/4 degrees would suitably represent vehicles in the Linde fleet.

2.3 Simulation Model Employed

Vehicle roll stability level was evaluated in this study using a static model of the roll response of tractor-semitrailers. This model was developed previously and is documented in Reference [2]. Basically, the model orients the sprung mass of the vehicle (in this case, the tank body) at each of an increasing sequence of roll angle values, and computes the level of lateral acceleration needed to sustain each roll attitude. Eventually, the vehicle arrives at a roll angle beyond which only reduced levels of lateral acceleration are needed to continue the roll motion. This point defines the "rollover threshold" in g's of lateral acceleration

Table 2.2. Fifth Wheel Lash Measurement.

Trailer	Tractor	Lash (degrees)
Liquified Helium	Freightliner	2.53
	Peterbilt	3.53
	Mack 306114	4.41
	Mack 5588	3.61
	Mack COE 5550	3.75
Liquified Nitrogen (Russel)	Mack COE 5550	2.83
	Mack 5588	3.36
	Mack 306114	3.90
	Peterbilt	3.40
	Peterbilt (repeat)	3.62
	Freightliner	3.10
Liquified Oxygen	Mack COE 5550	3.20
Liquified Hydrogen	Mack 306114	3.10
	Freightliner	2.37
	Mack 5588	2.15
	Average	3.26

and provides the basic measure of the inherent roll stability of the vehicle. In real practice, a vehicle would roll over as soon as the imposed lateral acceleration condition exceeded the rollover threshold.

Features of the model and the assumptions made in the process of deriving the underlying equations are listed below.

1. The vehicle is assumed to be effectively rigid in torsion. The structural compliance of the tractor and trailer sprung masses are therefore neglected and the sprung masses are lumped together and represented by a single sprung mass in the roll plane.

2. In order to simplify the calculations, axles with similar suspension properties are grouped together such that a tractor-semitrailer is represented by a set of three composite axles. Figure 2.4 shows the side view of an example tractor-semitrailer, as represented in the roll model. The composite axles are:

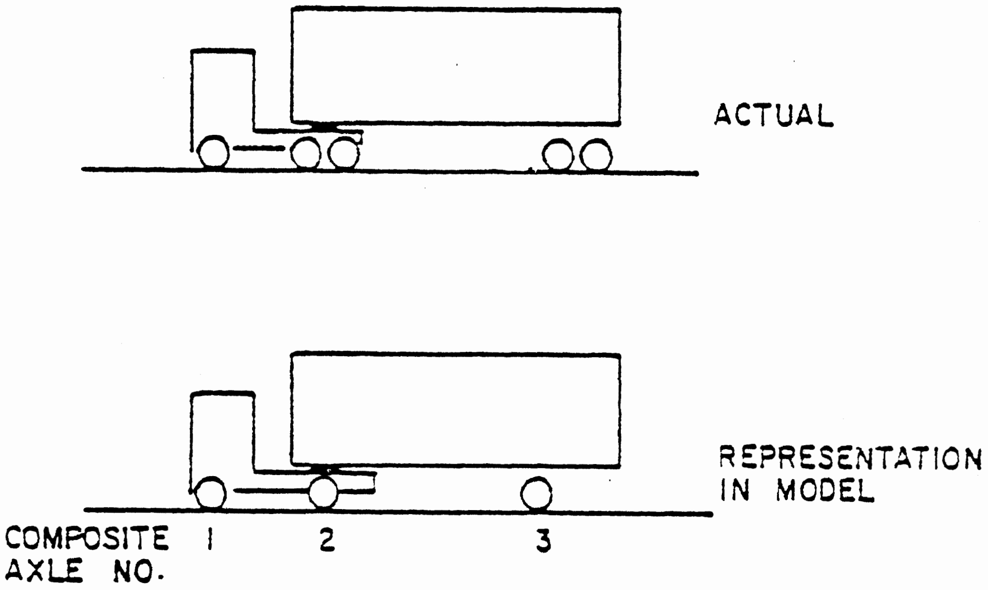


Figure 2.4. Representation of the axles of a tractor-semitrailer in the static roll plane model.

a) tractor front axle,

b) tractor rear axles (either a single axle or a tandem) combined and represented by one axle, and

c) all trailer axles, combined and represented as one axle.

3. The articulation angles are small so that the effect of articulation angle on the rollover threshold can be neglected.

4. Figure 2.5 shows the representation of axles and suspensions in the roll plane model. The relative roll motion between the sprung mass and the axles is assumed to take place about roll centers which are at fixed distances beneath the sprung mass. The suspension springs are assumed to remain parallel to the $\vec{k}_{ui}$ axes of the axles and transmit only compressive or tensile forces.

The roll centers are permitted to slide freely (with respect to the axles) along the $\vec{k}_{ui}$ axes. All axle forces which act in a direction parallel to the $\vec{k}_{ui}$ are taken up by the suspension springs, while all axle forces along the $\vec{j}_{ui}$ axes are assumed to act through the roll center, R_i.

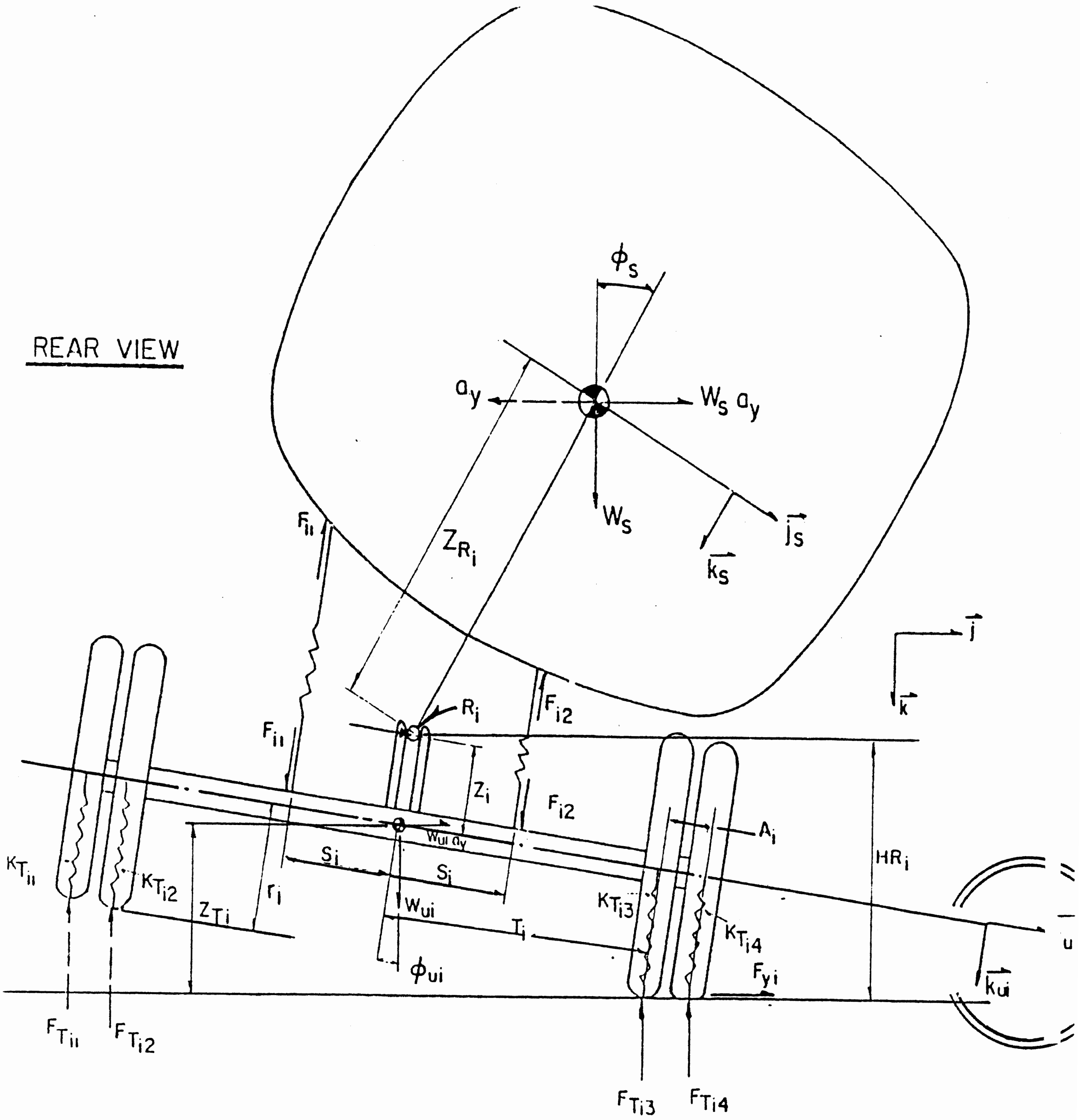


Figure 2.5. Representation of the axles and suspensions in the static roll plane model.

5. Suspension nonlinearities such as backlash and progressively hardening suspension springs are represented by a tabular load-deflection input format. The suspension forces and the spring rates at any given deflection are then compared by linear interpolation. Figure 2.6 shows the representation of a suspension spring in the roll model.

6. The total vertical load carried by each composite axle is assumed to remain constant during the rollover process. In order to accommodate any pitching motion that might take place during rollover, the sprung mass is permitted to take up different vertical deflections at each of the three axle locations.

7. The vertical load carried by the tires is assumed to act through the midpoint of the tread width. As shown in Figure 2.7, the effect of camber angle and the effect of the lateral compliance of the tire tend to have opposing effects on the lateral translation of the centroid of the normal pressure distribution at the tire-road interface. Both of these effects are small and tend to cancel out. In order to keep the analysis simple, the lateral translation of the normal load is neglected.

8. The roll angles of the sprung mass and the axles are small, such that the small angle assumptions $\sin(\phi) = \phi$ and $\cos(\phi) = 1$ hold.

Each vehicle combination is represented in the model by a set of parameter values covering the following items:

- -weights of the axle assemblies and "sprung" masses for tractor and semitrailer
- -lateral spacing of tires and spring centers at each axle
- -height of sprung mass centers
- -undeflected radius of the tires
- -tire vertical stiffness
- -tire lateral and overturning moment stiffnesses
- -torsional stiffness of tractor frame
- -fifth wheel lash
- -roll moment needed to separate the fifth wheel plate from the trailer's upper coupler plate, thus leading to traversal of the lash in the tank roll motion

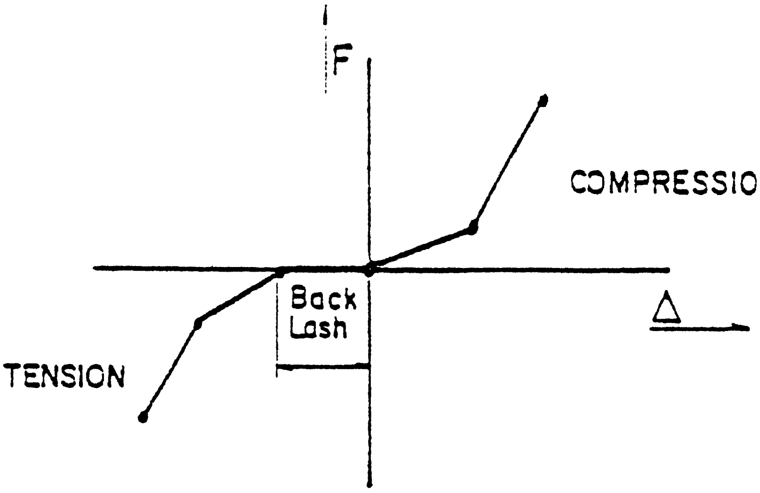


Figure 2.6. Representation of suspension spring characteristics in the roll plane model.

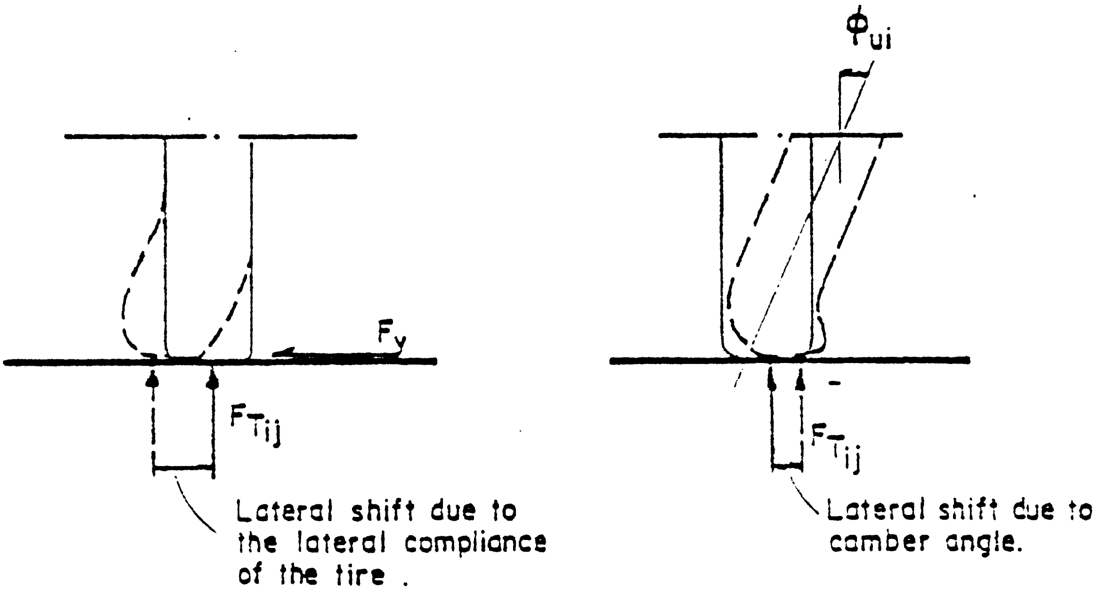


Figure 2.7. The effect of lateral compliance and camber angle on the centroid of the normal pressure distribution at the tire/road interface.

- force/deflection tables for each suspension set
- auxiliary roll stiffness attributed to each suspension set

In Appendix B are presented parameter listings for the baseline cases of vehicles studied here.

3.0 SIMULATION RESULTS

In this section, the study results will be presented. The simulation was run for cases covering both the existing configuration of vehicles in the Linde fleet and for cases representing certain changes in vehicle design which might be made. Following presentation, in Sections 3.1 and 3.2, of the rollover threshold levels computed for both existing and future configurations, the net rollover accident involvement rate is predicted for the various cases examined.

3.1 Rollover Thresholds, Existing Fleet

The existing Linde fleet was represented in the analysis of rollover threshold by the following specific vehicle and suspension selections:

Semitrailers

- 11,000-gallon Helium trailer configured as an intermodal shipping container on a sub-frame trailer having a four-spring Hutchens suspension (see Fig. 3.1).
- 13,250-gallon Hydrogen trailer having a Neway Airide tandem suspension (see Fig. 3.2).
- 8,300-gallon Nitrogen trailer (Fig. 3.3) considered to be equipped with each of the three alternative suspensions described below:
    1) Chalmers rubber
    2) Hutchens four-spring
    3) Neway Airide
- 6,000-gallon Oxygen trailer also considered with each of the above three suspensions (see Fig. 3.4).

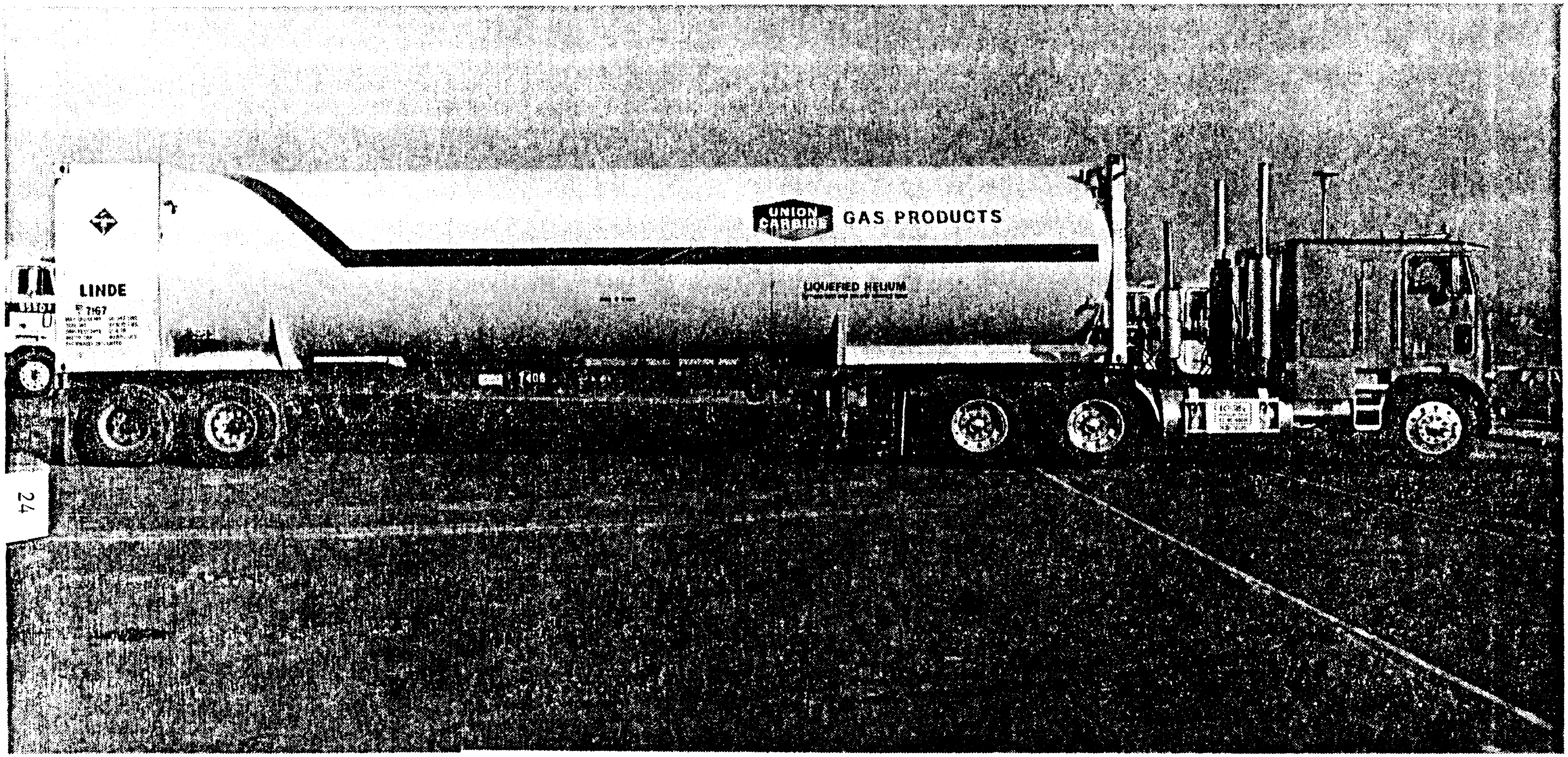


Figure 3.1. Helium trailer combination.

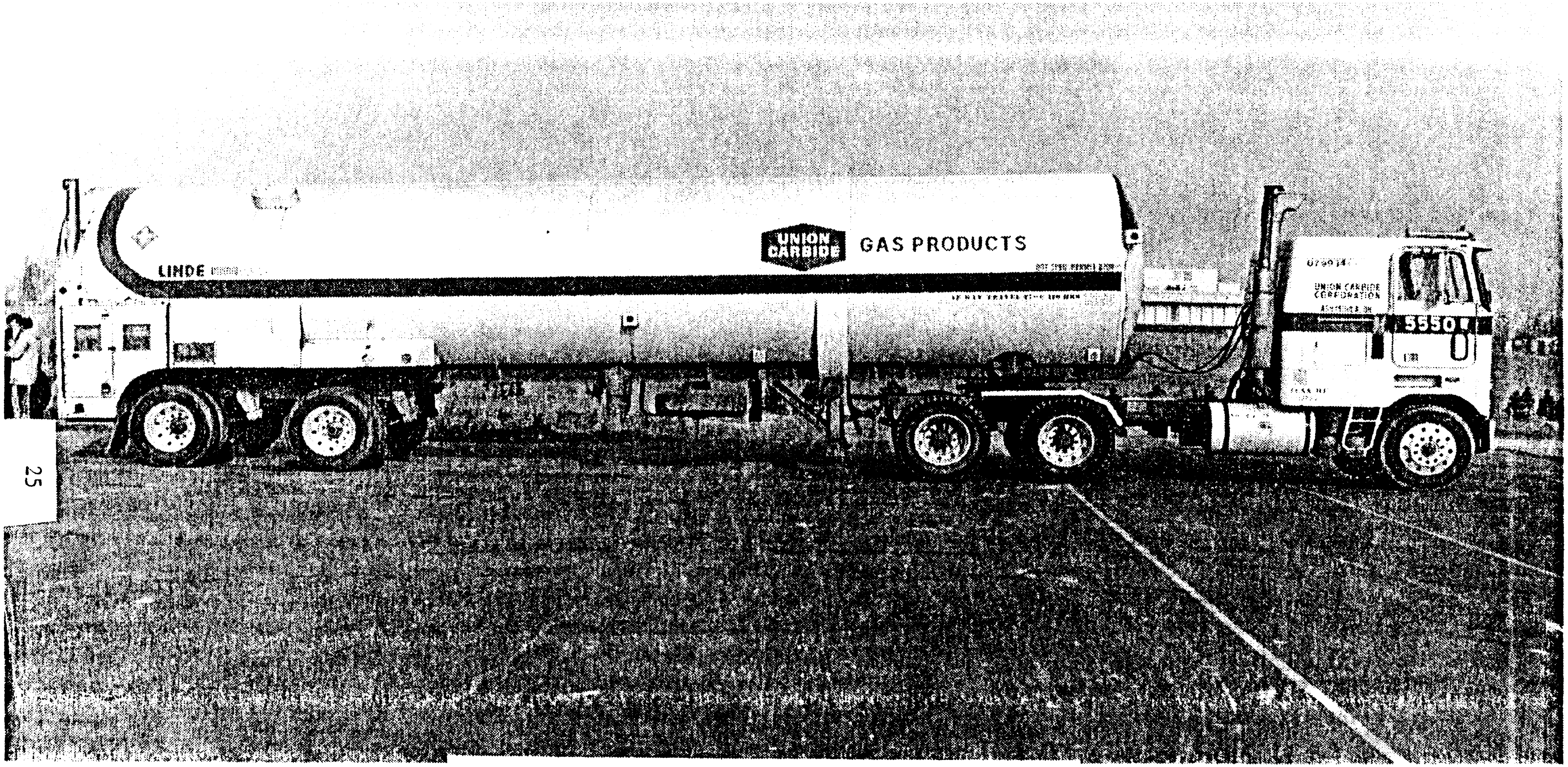


Figure 3.2. Hydrogen trailer combination.

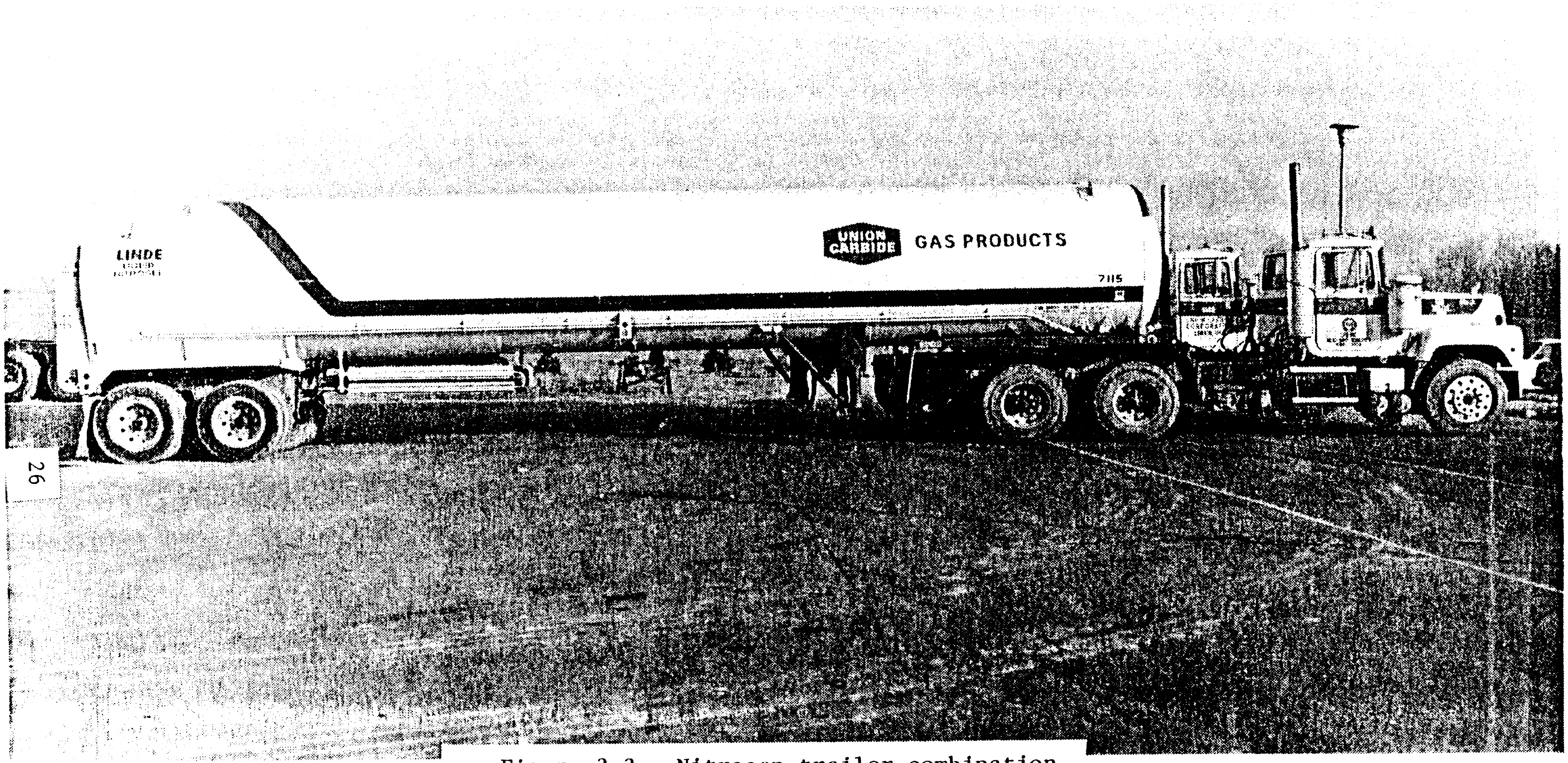


Figure 3.3. Nitrogen trailer combination.

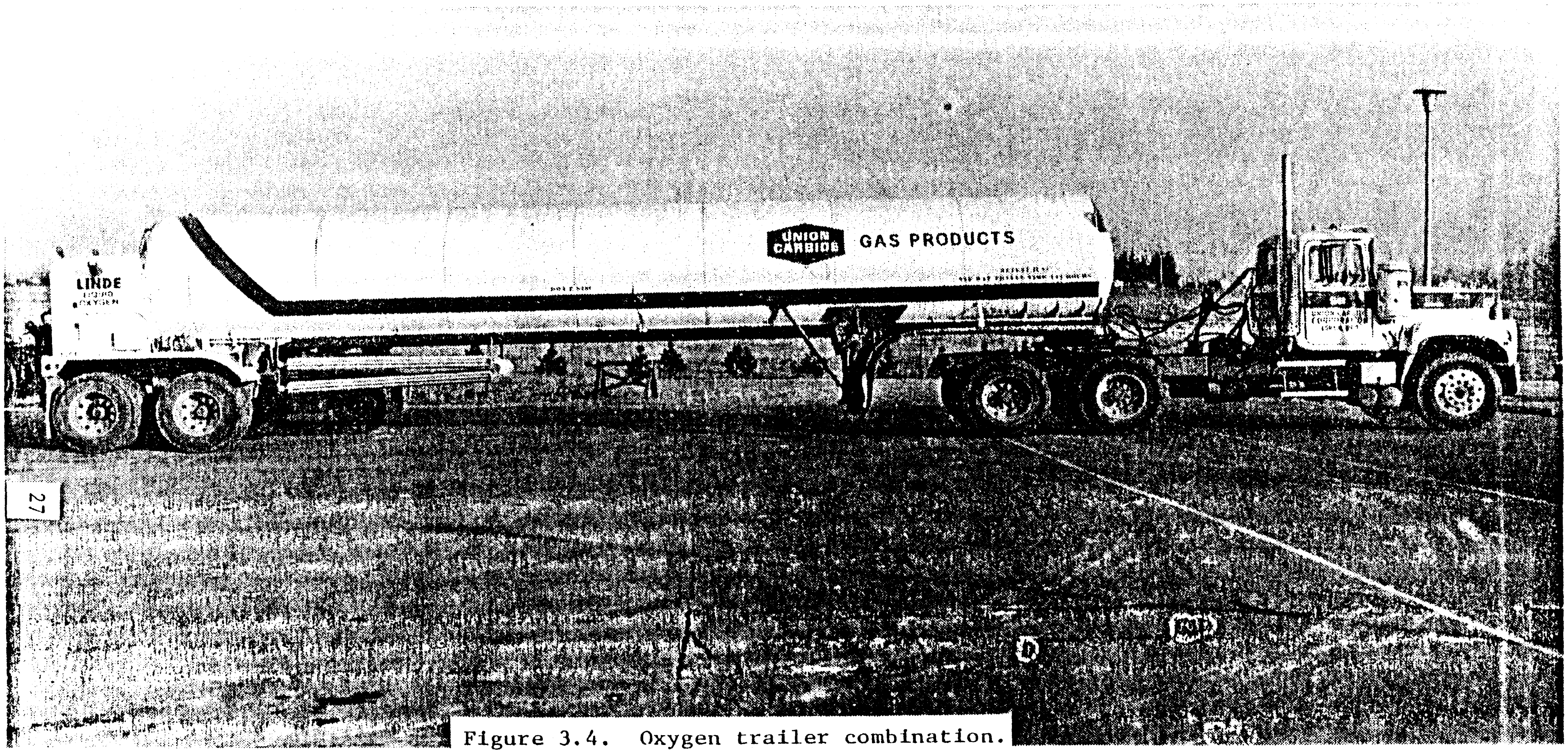


Figure 3.4. Oxygen trailer combination.

Tractors (distinguished from one another only by the following tandem suspension varieties)

- -Kenworth torsion bar
- -Peterbilt four-spring
- -Freightliner four-spring
- -Mack (Reyco-manufactured) four-spring

Thus the Helium and Hydrogen tankers were considered with the single trailer suspension types which are commonly employed, while the Nitrogen and Oxygen tankers were examined for the cases incorporating alternative trailer suspensions. Of the three alternative trailer suspensions, the Hutchens and Neway variety are in common service in the Linde fleet, while the Chalmers suspension was included only as a possible candidate for future use.

Simulations were run with all combinations of tractors and semitrailers identified above. Thus, four cases of the Helium and Hydrogen vehicles were covered in addition to twelve cases (four tractors × three trailers) representing the Nitrogen and Oxygen vehicles.

For each vehicle combination, the simulation initially produces a tabular display of the lateral acceleration and roll angle data leading up to the rollover condition. Examples of such data are shown for the Helium-Kenworth and Hydrogen-Kenworth combinations in Tables 3.1 and 3.2. The tables list the lateral acceleration level needed to achieve each of the roll angle conditions shown at the right. The respective roll angle values, PHI (S1 through S3), represent the roll attitudes of the tractor cab, the tractor fifth wheel, and the trailer tank, respectively.

Descending the list of acceleration values, the "rollover threshold" measure (representing the vehicle's ultimate roll stability level) is the peak value listed. In the case of the Helium-Kenworth combination, Table 3.1, a peak value of .260 g's is achieved at the very bottom of the table. Details of the simulated vehicle response revealed that the rollover threshold of this vehicle is defined by the point at which wheels have lifted off the ground at each axle except the steering axle. (Prior research has shown that liftoff of the tractor steering axle is of no

Table 3.1

```
>\
#EMPTY -1
#DONE.
#EMPTY -2
#DONE.
#R HU.ROLL.O 4=*SINK* 5=HELIUM.D(150) 6=-1 7=-2
#EXECUTION BEGINS
             13250 GALLON HELIUM TANKER (W/CHASSIS), KENWORTH TRACTOR


     LAT.ACC    PHI(S1)    PHI(S2)    PHI(S3)
     -------    -------    -------    -------
       0.0        0.0        0.0        0.0
       0.042      0.483      0.477      0.520
       0.068      0.971      0.964      1.040
       0.092      1.464      1.456      1.560
       0.117      1.958      1.948      2.080
       0.141      2.451      2.441      2.600
       0.164      2.946      2.932      3.120
       0.185      3.450      3.421      3.640
       0.203      3.918      3.908      4.160
       0.220      4.404      4.394      4.680
       0.237      4.889      4.880      5.200
       0.235      5.389      5.386      5.720
       0.240      5.861      5.861      6.240
       0.245      6.332      6.336      6.760
       0.245      6.632      6.639      7.280
       0.236      6.546      6.554      7.800
       0.237      6.556      6.564      8.320
       0.244      6.618      6.625      8.840
       0.250      6.680      6.686      9.360
       0.254      6.714      6.719      9.640
       0.251      6.683      6.689      9.880
       0.244      6.657      6.664     10.400
       0.248      7.128      7.138     10.920
       0.251      7.428      7.614     11.439
       0.254      7.698      8.092     11.959
       0.256      7.967      8.571     12.479
       0.259      8.235      9.050     12.999
       0.260      8.411      9.364     13.339
#EXECUTION TERMINATED
#C -1+*SOURCE*+-2 HEDOUT(LAST+1)
>1
>\
```

Table 3.2

```
/*
>\
#EMPTY -1
#DONE.
#EMPTY--2
#DONE.
#R HU.ROLL.O 4=*SINK* 5=HYDROGEN.D(150) 6=-1 7=-2
#EXECUTION BEGINS
            13250 GALLON GARDNER HYDROGEN TANKER , KENWORTH TRACTOR


    LAT.ACC    PHI(S1)    PHI(S2)    PHI(S3)
    -------    -------    -------    -------
      0.0        0.0        0.0        0.0
      0.030      0.468      0.467      0.520
      0.055      0.955      0.954      1.040
      0.078      1.447      1.446      1.560
      0.102      1.939      1.938      2.080
      0.125      2.431      2.430      2.600
      0.149      2.923      2.922      3.120
      0.172      3.414      3.414      3.640
      0.196      3.906      3.906      4.160
      0.219      4.398      4.398      4.680
      0.242      4.889      4.890      5.200
      0.254      5.405      5.409      5.720
      0.270      5.780      5.785      6.120
      0.270      5.889      5.895      6.240
      0.274      6.359      6.369      6.760
      0.277      6.675      6.844      7.280
      0.280      6.936      7.319      7.800
      0.282      7.192      7.797      8.320
      0.276      7.094      7.740      8.840
      0.268      6.983      7.662      9.360
      0.261      6.872      7.584      9.880
      0.254      6.762      7.507     10.400
      0.247      6.652      7.430     10.920
      0.245      6.724      7.631     11.439
      0.247      6.977      8.111     11.959
      0.249      7.231      8.590     12.479
      0.251      7.484      9.069     12.999
      0.253      7.698      9.475     13.439
#EXECUTION TERMINATED
#C -1+*SOURCE*+-2 HOUT(LAST+1)
>1
>\
#
```

consequence to the determination of the roll stability limit.) Thus, for the Helium-Kenworth combination, the rollover threshold is reached with the liftoff of the Kenworth's tandem axle. In Table 3.2, however, we see that the Hydrogen-Kenworth combination reaches a peak value of .282 g's well before the end of the run—at a time at which the simulation shows only the trailer tandem axle to have lifted off the ground. (For a treatise on the mechanics of rollover and the sequential development of wheel liftoff on tractor-semitrailers, the reader is referred to Reference [3].)

The lateral acceleration condition is plotted against the trailer roll angle for the above two example vehicles in Figure 3.5. Here we see that the Hydrogen vehicle reaches its .282-g peak at a considerably smaller roll angle than that at which the Helium vehicle achieves its peak value of .260 g. In general, the subtle differences distinguishing the roll behavior of these two vehicles derive primarily from distinctions in trailer suspension properties. The Hydrogen trailer's Neway suspension provides a stiffer and more continuous roll reaction moment such that the rollover threshold is reached at a lower value of roll angle, yielding a higher net roll stability level.

Perhaps a more dramatic illustration of the influence of suspension properties on the lateral acceleration versus roll angle behavior is shown in Figure 3.6. This figure shows a plot of the lateral acceleration/roll angle relationship for the Nitrogen/Freightliner combination for each of the three alternative trailer suspensions. We see that the "early" peaking of the vehicle response with the Neway suspension produces the highest rollover threshold value, while the "delayed" peaking behavior of the Hutchens suspension yields a slightly reduced stability level. The Chalmers suspension is found to be so soft that it achieves its rollover threshold only at a high value of roll angle, at which the outboard rolling of the mass center has caused a deteriorated stability level. Accordingly, in data summarizing the overall vehicle set, we find that the Chalmers suspension cases rate the lowest, and the Neway cases the highest. Plots of the format seen in Figures 3.5 and 3.6 are shown for all of the examined vehicle combinations in Appendix C.

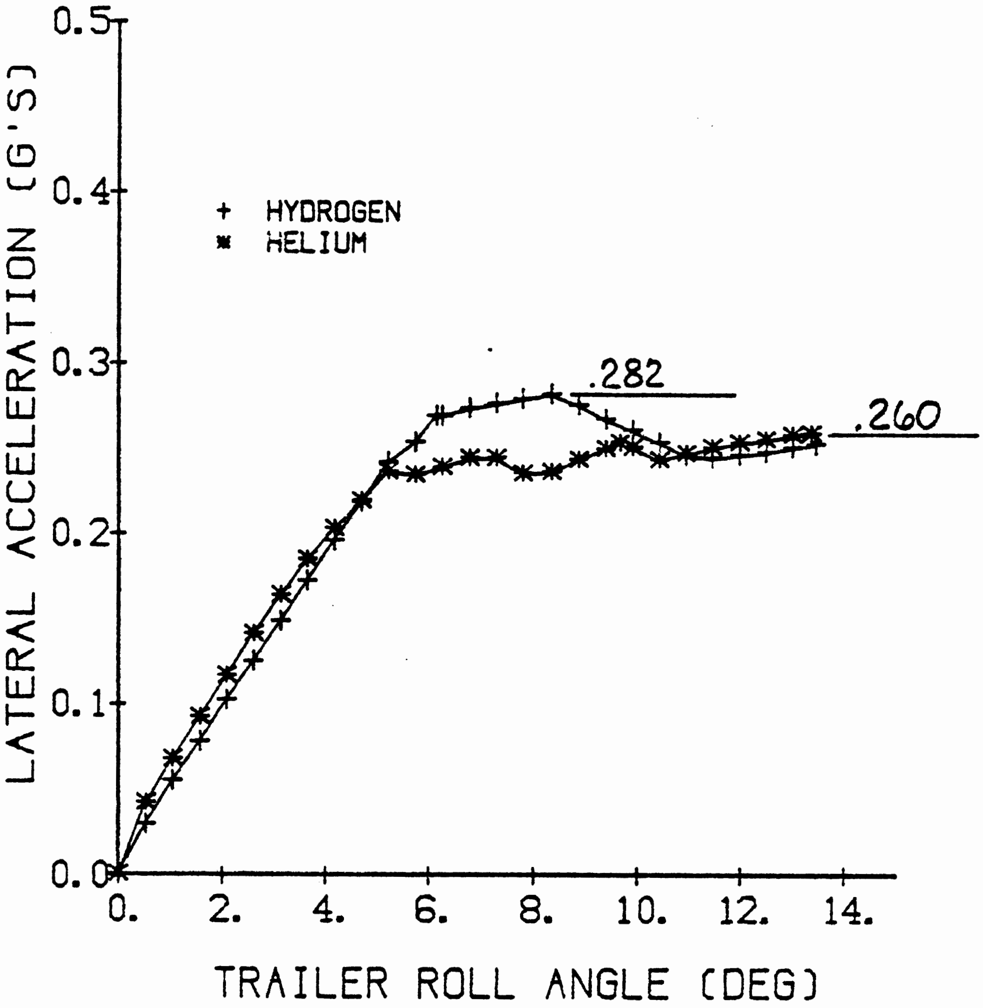


Figure 3.5. Simulation results for Hydrogen and Helium trailers coupled to Kenworth (torsion bar) tractor.

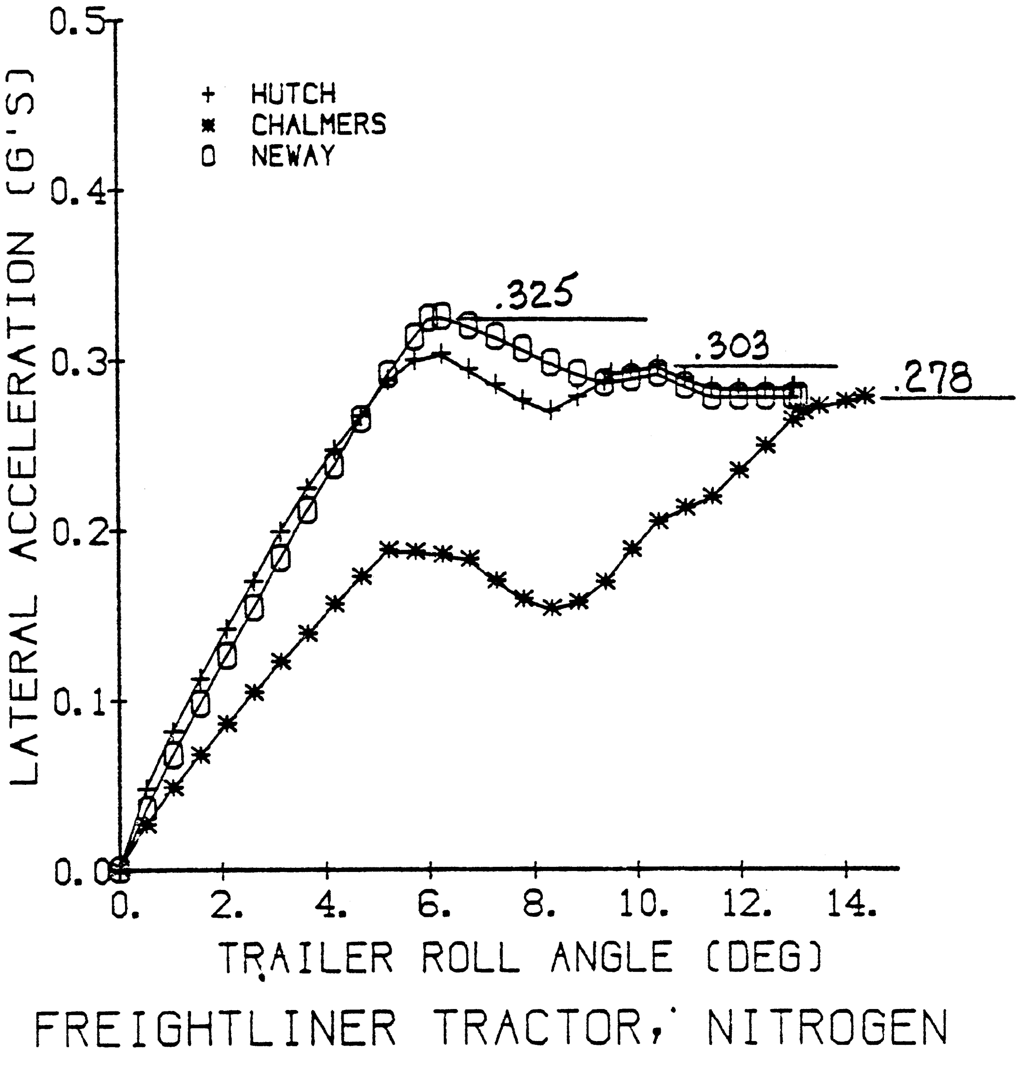


Figure 3.6. Simulation results distinguishing three different trailer suspensions.

Values of rollover threshold covering the overall set of "current" Linde vehicles are shown in Figure 3.7. The bar-charted values are grouped by trailer type and are distinguished along the horizontal axis by tractor suspension type and trailer suspension type. For example, results for the Nitrogen trailer are shown in the third group from the left. The first (left-most) bar in the Nitrogen group pertains to the vehicle combination having a Chalmers trailer suspension and a Kenworth (KW) tractor suspension.

Overall, we see that the Linde fleet exhibits rollover threshold values which range from .260 g to .358 g. We also find that the differences in tractor suspension properties introduce substantial changes in rollover threshold except for the cases involving the Chalmers rubber suspension on the trailer. In these latter cases, the extremely soft nature of the Chalmers trailer suspension tends to dominate the result, thus rendering the differences from one tractor suspension to another inconsequential.

Although the differences observed in rollover threshold from one combination to the next may seem to be rather small, the discussion in Section 3.3 will reveal that the actual influence of the vehicle's rollover threshold on rollover accident involvement is surprisingly high. Thus, the influence of tractor and trailer suspension properties on the rollover threshold of the combination vehicle will be seen to be quite substantial.

3.2 Improvements in Rollover Threshold Achieved by Changing Vehicle Design

An array of candidate design changes was evaluated for the cases of the Oxygen and Helium trailers. These two trailers were chosen to span the range of center of gravity heights represented within the Linde fleet. Application of results obtained with these two example vehicles to the other Linde vehicles simply requires interpolation of the data.

Shown in Figure 3.8 are the values of rollover threshold computed for the Oxygen trailer, given a set of 16 parameter changes. The changes are numbered along the horizontal axis corresponding to the following scheme of conditions:

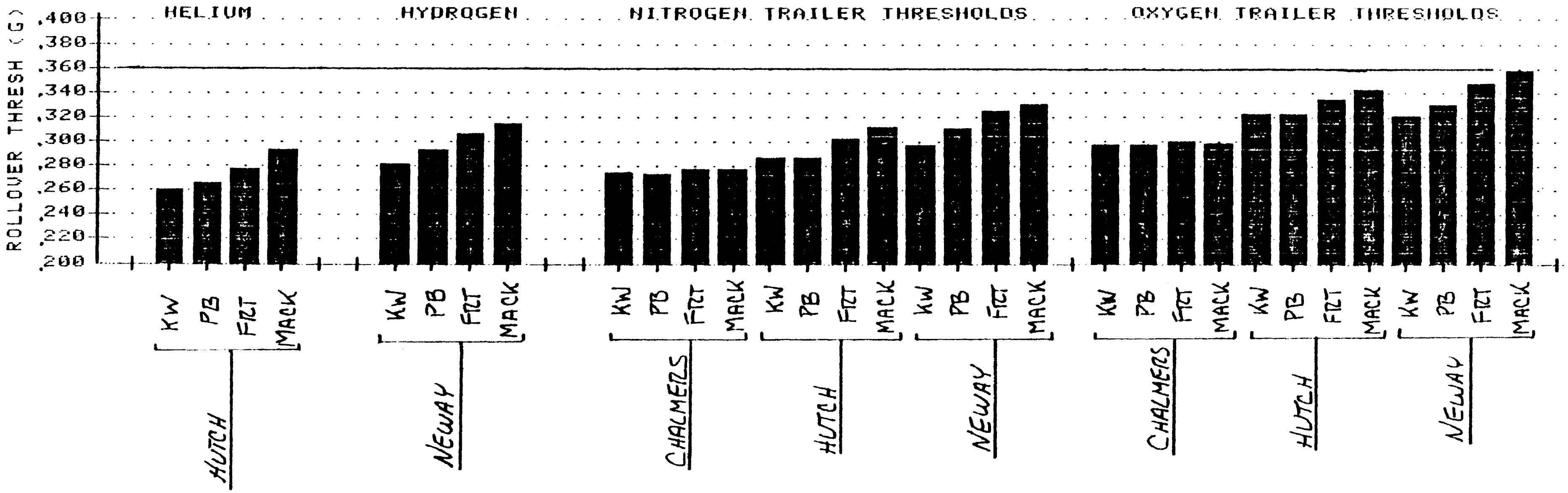


Figure 3.7. Rollover threshold values describing the current Linde fleet (except that the Chalmers suspension is not currently in use).

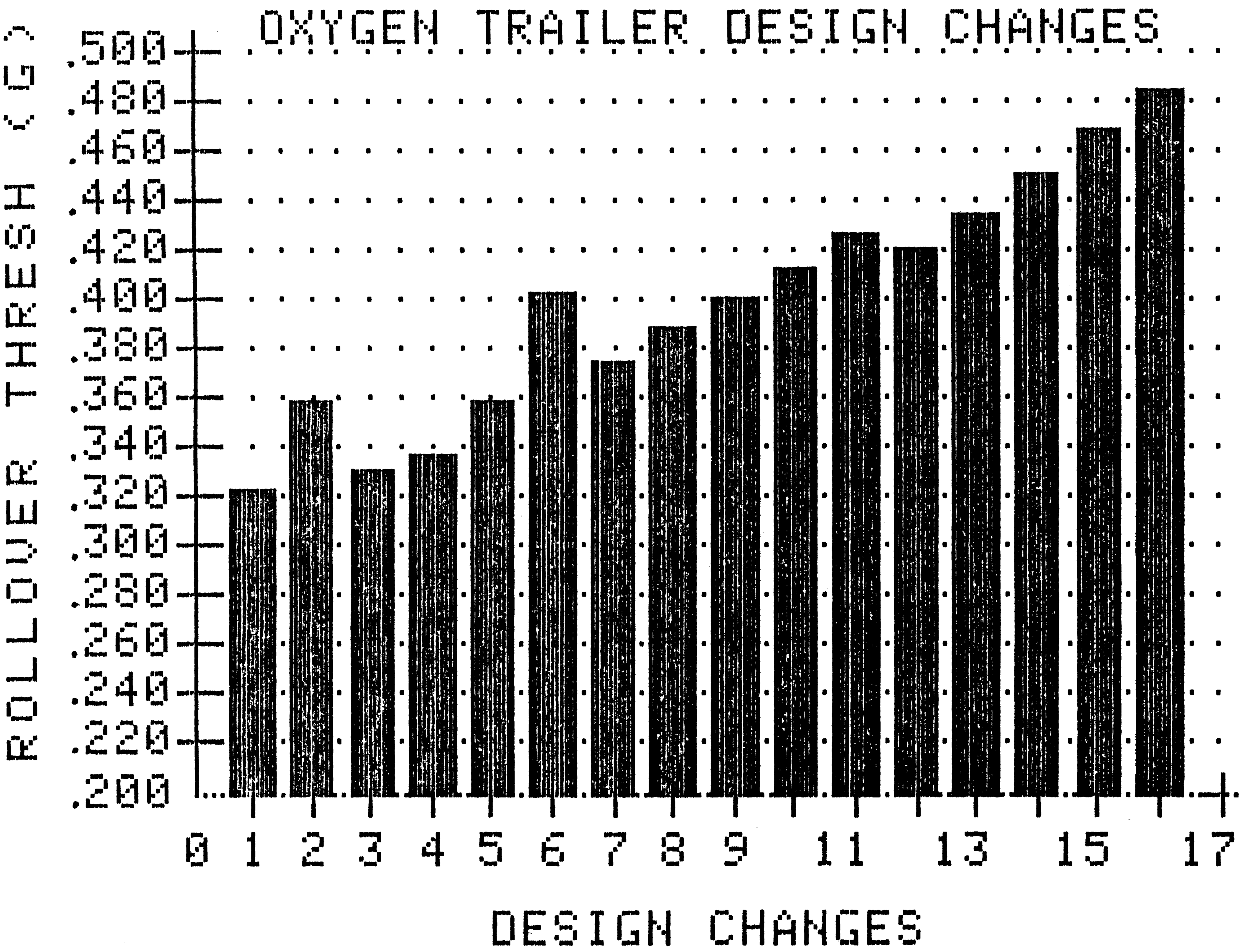

OXYGEN TRAILER DESIGN CHANGES
ROLLOVER THRESH (G)
.500
.480
.460
.440
.420
.400
.380
.360
.340
.320
.300
.280
.260
.240
.220
.200
0
1
2
3
4
5
6
7
8
9
11
13
15
17
DESIGN CHANGES

Figure 3.8

1) "Worst case" suspension combination found in the existing fleet—Kenworth tractor and Hutchens trailer suspension. (Note that the Chalmers trailer suspension, which looks poorer than the Hutchens suspension, is not considered as an item existing in the current Linde fleet.)

2) Most favorable suspension selections—Neway Airide suspensions on both the tractor and trailer tandems.

3) Peterbilt tractor (a more-or-less average choice, from a suspension point of view), represented with fifth wheel lash reduced from 3.5 degrees to 2 degrees, and with Neway suspension on trailer. (The indicated improvement over Case 1 is due almost entirely to the trailer suspension change.)

4) Peterbilt tractor, but with Neway suspension on trailer and fifth wheel height reduced from 48 inches to 46 inches, thus lowering trailer mass center by one inch.

5) Improvements 2, 3, and 4, above, all incorporated together. (Result is similar to Case 2.)

6) Case 5, above, is represented together with a change to 102-inch width at the tractor and trailer tandem axles. The tank also nestles one inch lower into the sub-frame as enabled by the wider suspension layout.

7 through 11) Case 5 is represented with sequential two-inch reductions in height of trailer mass center. Thus, Cases 7 through 11 simply involved variations on Case 5 as follows:

Case 7 = Case 5 - two inches in trailer c.g. height

Case 8 = Case 5 - four inches

Case 9 = Case 5 - six inches

Case 10 = Case 5 - eight inches

Case 11 = Case 5 - ten inches

12 through 16) Case 6 (with the 102-inch track widths) is represented with sequential two-inch reductions in height of trailer mass center. Accordingly:

Case 12 = Case 6 - two inches in trailer c.g. height

Case 13 = Case 6 - four inches

Case 14 = Case 6 - six inches

Case 15 = Case 6 - eight inches

Case 16 = Case 6 - ten inches

Figure 3.8 shows that the rollover threshold of the Oxygen trailer combination can be improved from .322 g to .483 g over the range of considered improvements. Of course, it should be recognized that substantial reductions in the height of the trailer c.g. will be very difficult to obtain. Further, the extension to 102-inch width must await enabling legislation (which has been sought for each of the last few years in Washington). Nevertheless, even the improvement from .322 to .358 which is achievable simply by specifying the most favorable tractor and trailer suspensions, constitutes a very significant upgrading of roll stability level.

Shown in Figure 3.9 are the corresponding data representing improvements in the stability of the Helium trailer combinations resulting from vehicle design changes. The cases numbered 1 through 16 along the horizontal axis correspond, identically, to the cases itemized above for the Oxygen trailer. Again we see that a very substantial improvement, from .260 g to .301 g, can be attained simply by specifying favorable tractor and trailer suspensions. Combinations of tank height reduction and track width expansion provide means of increasing the rollover threshold up to .410 g.

Plots showing the lateral acceleration versus roll angle behavior for each of the design-varied cases are presented in Appendix D.

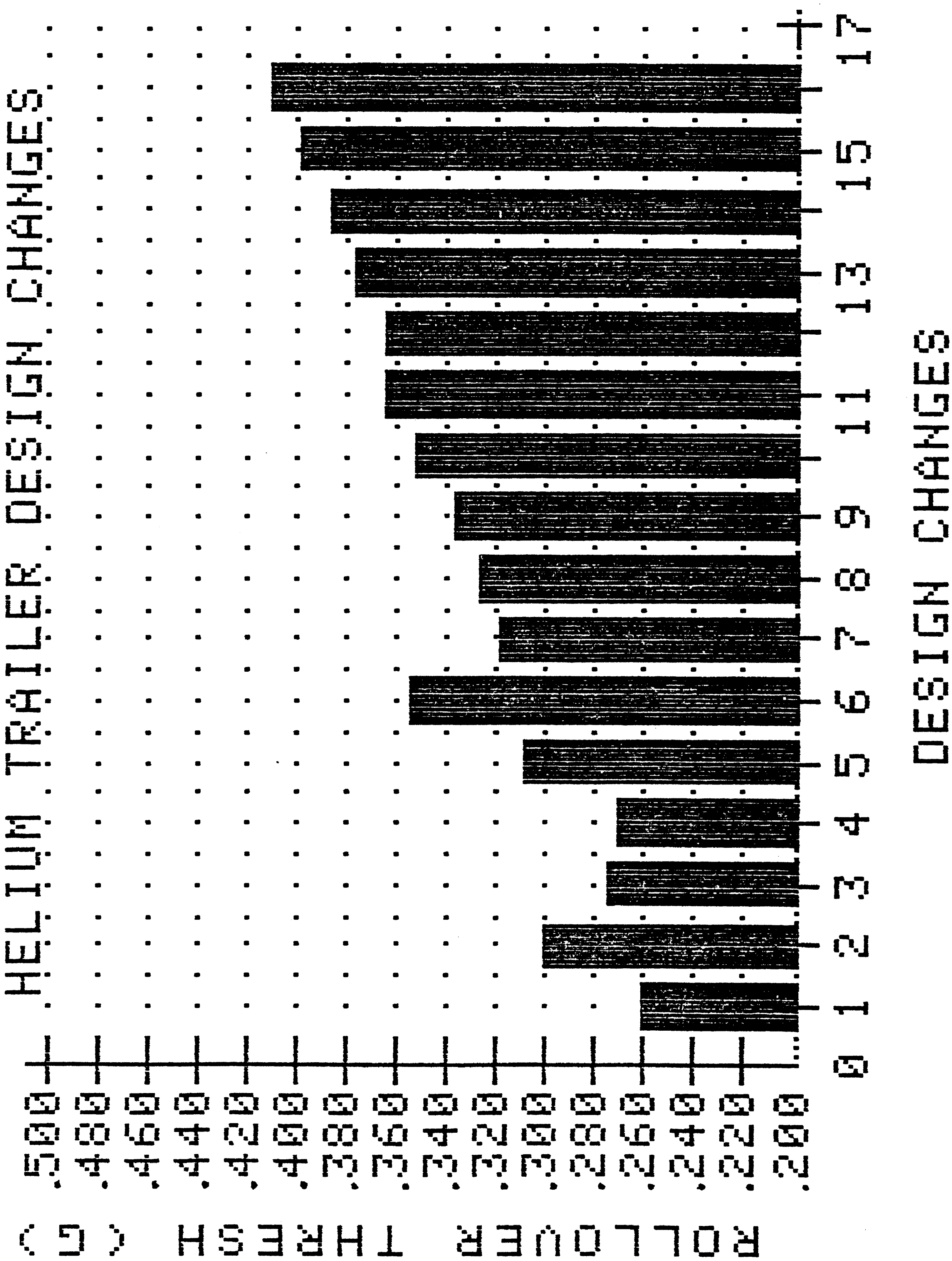

HELIUM TRAILER DESIGN CHANGES
ROLLOVER THRESH (G)
.500
.480
.460
.440
.420
.400
.380
.360
.340
.320
.300
.280
.260
.240
.220
.200
0
1
2
3
4
5
6
7
8
9
11
13
15
17
DESIGN CHANGES

Figure 3.9

3.3 Projections of Safety Benefits

The above results indicate that rollover thresholds for Linde vehicles are:

a) rather widely varying due to differences in tractor and trailer suspensions currently being procured, and are

b) far below what could be achieved by means of design changes

In this section, the net influence of the rollover threshold values on actual rollover accident involvement will be predicted. The Linde rollover accident record will be briefly reviewed, and this record will be placed in the context of the national rollover experience with tractor-semitrailers. A scheme will be presented for relating rollover threshold directly to the likely frequency of rollover incidents in service. The calculated rollover thresholds will then be converted, together with data on the annual mileage in the Linde fleet, into projected rollover rates as a "bottom-line" assessment of the safety benefits which should follow from design changes.

Linde's Rollover Accident Record. Shown in Appendix E is a listing and brief description of each of 36 rollover accidents which have occurred in the Linde fleet between April 1976 and August 1981. This record shows the following number of rollovers for each of the nominal trailer types:

Vehicle	No. Rollovers
Nitrogen (or Argon)	21
Oxygen	9
Hydrogen	1
Helium	5
Total	36

Of these 36 events, 34 involved single-vehicle accidents in which no other vehicle was struck. In the other two accidents, contact with another vehicle preceded the rollover. This experience establishes that the rollover of these vehicles involves primarily single-vehicle accidents (SVA)—a result which parallels national experience (the national distribution of accidents involving tractor-semitrailers is approximately 80 percent SVA rollovers and 20 percent rollovers involving another vehicle impact). It is also interesting that five of the rollovers with Linde vehicles involved virtually zero speed with the vehicle on soft ground—a classic case in which a heavy load and a low rollover threshold combine to produce an anomalous incident.

Mileage Exposure of the Linde Fleet. In order to provide a measure of the rollover rate, in terms of rollovers per 100 million miles, Linde vehicle mileage data were obtained for projection of the annual mileage exposure. The average annual mileages accumulated on each of the four nominal vehicle types cited above were multiplied by the number of each vehicle type in service to obtain annual mileage by vehicle type. These figures are shown below.

Vehicle	Annual Miles/Vehicle	Number of Vehicles	Total Annual Miles
Nitrogen/Argon	84,600	222	18,781,200
Oxygen	90,300	172	15,531,600
Hydrogen	138,000	32	4,320,000
Helium	278,208	21	5,842,368

We see that the more roll-stable Nitrogen and Oxygen vehicles are much more numerous and accumulate considerably greater total annual fleet miles; the less stable Hydrogen and Helium vehicles are considerably more exposed, on a mileage-per-vehicle basis.

Rollover Rates for the Existing Fleet. Although it is recognized that the above vehicle numbers constitute the current Linde fleet size and do not account for changes in the fleet which have occurred over the five years covered by the fleet accident data, we will use these numbers to obtain a crude measure of the nominal current rollover rate. Additionally, in the case of the Helium trailer, it was observed that four out of the five reported rollovers occurred during the last two years of the accident sample and that these four all involved the 11,000-gallon vehicle size of which 12 out of the 14 in the fleet were just brought into service during this later period. Thus it was apparent that some insight could be gained by calculating another rollover rate covering the last two years of usage for this particular subset of the Helium trailers.

Dividing the total number of rollovers for each vehicle type by the annual mileage for that type, we obtain the following rollover rates:

Vehicle Type	Rollovers/ 100 Million Miles
Nitrogen/Argon	22
Oxygen	12
Hydrogen	5
Helium (all)	17
11,000-gal. Helium ('80 & '81)	102

In order to assure a properly balanced view toward these computed rates, certain precautionary remarks are in order. It must be recognized, firstly, that the set of 36 Linde rollover accidents is simply too small a sample to permit any rigorous statistical inferences to be made. The contrast between the involvement rate of Hydrogen and Helium trailers, for example, is quite likely the result of an insufficient sampling of the phenomena—these rates are expected to be nearly equal over the long run. Indeed, the "102" value of rollover rate for the two-year operation of 11,000-gallon Helium trailers may be as statistically improbable as is the "5" value for the Hydrogen trailers. Further, it is certain that substantial variations in both vehicle numbers and average annual mileage exposures have occurred over the six years of accident reporting.

For the sake of contrasting the Linde fleet rollover rates with national experience, accident data from the Bureau of Motor Carrier Safety (BMCS) have been combined with mileage data from the Truck Inventory and Use Survey [4] produced by the Bureau of Census. Some adjustments have been made to normalize these two data sets so as to represent only three-axle tractors coupled to two-axle van-type semitrailers in for-hire interstate service (which constitute the largest single category that can be identified with some confidence in both data sources). These data show that the nominal rollover rate involving five-axle tractor/van-semitrailers across the U.S. for the years 1977 through 1980 is six rollovers per 100 million vehicle-miles.

Accordingly, although there is a substantial level of crudity in the various figures available, it would appear that Linde vehicles are generally experiencing a considerably higher incidence of rollover than are tractor-semitrailers, nationally. Of course, there may be a number of operational differences contributing to the overinvolvement of Linde vehicles, such as the class of roads traveled, the topographical and climate situations in the primary operating locations, traffic density conditions encountered, etc. Nevertheless, a substantial difference appears to be simply in the inherent roll stability of the vehicles involved. That is, the Linde vehicles are clearly low in rollover threshold with respect to tractor-semitrailers in general freight service. For example, HSRI believes that the typical tractor and van semitrailer has a rollover threshold around 0.37 g's. Linde vehicles were shown earlier to have rollover thresholds in the range from 0.26 g to 0.36 g. Also, the cryogenic tanks are so high in tare weight that Linde vehicles experience higher likelihood of rollover on both the loaded and empty legs of their trips.

A Scheme for Relating Rollover Threshold to the Likely Frequency of Rollover. In recent HSRI research, a data set based on four years of BMCS accident data was augmented with the results of the computer simulation of rollover response to produce the plot shown in Figure 3.10. The figure shows that a remarkable correlation exists between the percent of rollovers occurring among single-vehicle accidents with tractor-semitrailers and the static rollover threshold of each vehicle. The plot represents 21,000 cases of single-vehicle accidents involving three-axle tractors coupled to two-axle, van-type semitrailers. The plot was produced beginning with data from the BMCS accident report forms establishing the gross weight of each accident-involved vehicle. In a computerized determination of the

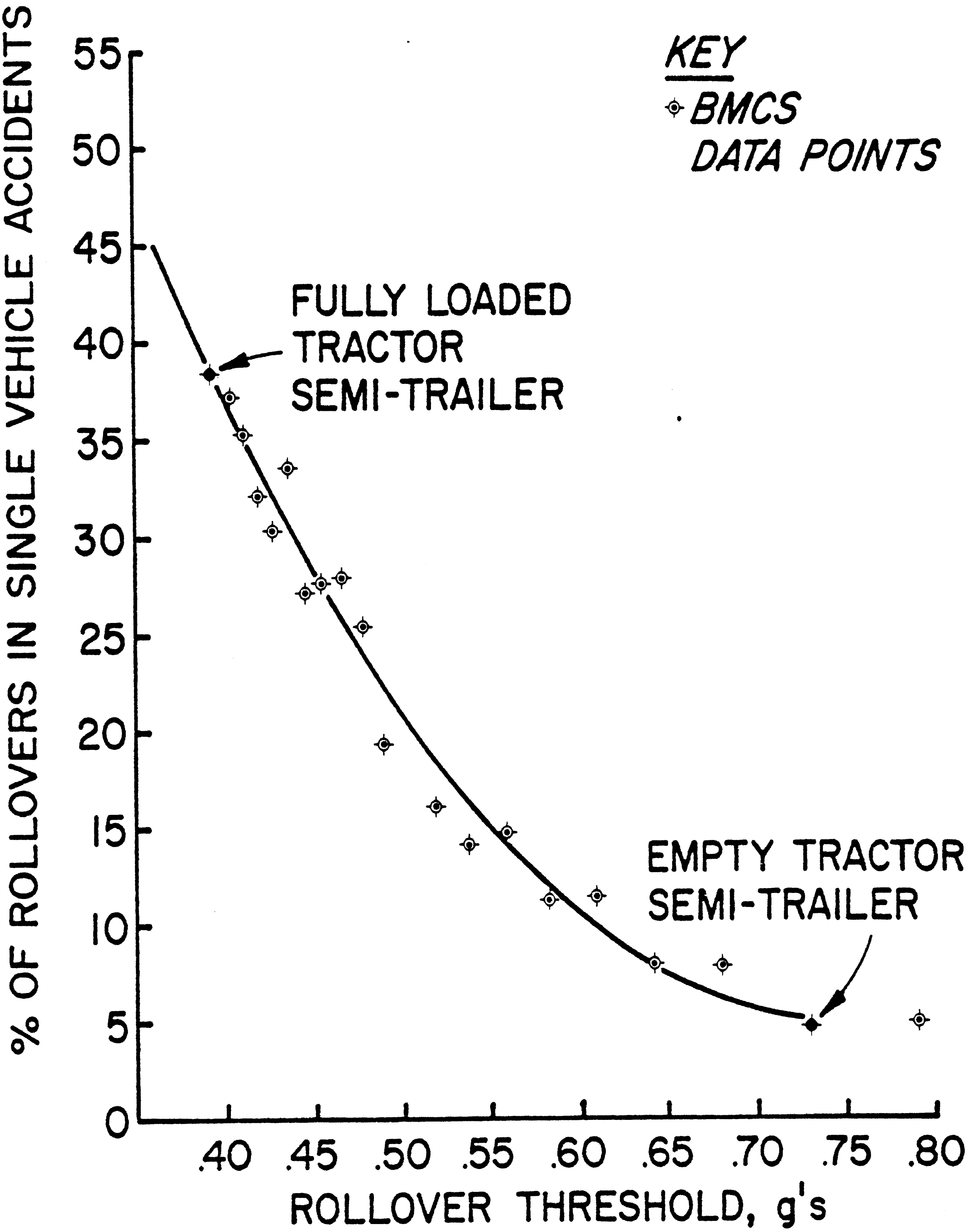


Figure 3.10. Percent of single-vehicle accidents in which rollover occurs as a function of the vehicle's inherent rollover threshold, in g's.

vehicle's roll stability, then, payload was placed to represent reasonable distributions of medium-density freight. Typical values for tires, springs, and geometric properties were then employed to calculate rollover thresholds for each increment in gross weight in the accident file. From the figure, we see that typical empty tractor-semitrailers experience rollover in approximately five percent of their single-vehicle accidents. When such vehicles are fully loaded, on the other hand, the reduction in roll stability due to the higher c.g. location causes an eight- to ninefold increase in the incidence of rollover.

The figure clearly establishes that the rollover of tractor-semitrailers is highly sensitive to the vehicle's inherent roll stability threshold in the lower end of the rollover threshold range. Since it is in this range that the Linde vehicles are found, we see immediately that the Linde fleet may be, indeed, paying a high price in rollovers for the lower rollover thresholds which are present.

The Influence of Design Changes on the Likely Frequency of Rollover. Using the rollover threshold data shown earlier in Figures 3.8 and 3.9, the influence of design changes on the likely frequency of rollovers can now be illustrated. Shown in Figure 3.11 is a plot of the percent rollovers per SVA which are likely given the values of rollover threshold computed for the various design changes on the Oxygen trailer. We see that the lowest value of rollover threshold, pertaining to the baseline case, yields a rollover frequency of approximately 51 percent rollovers/SVA. Design improvements are seen to sequentially reduce the rollover frequency according to the prediction curve developed earlier from the BMCS accident file. Over the range of design improvements considered, the rollover frequency percentage reduces from 51 percent to 18 percent. Thus, even the rather small increases in rollover threshold which result from certain improvements result in very sizable reductions in accident frequency.

Similarly, Figure 3.12 shows the influence of design changes on the rollover frequency of the Helium trailer. We see that the baseline cases, producing 70 percent rollovers/SVA, reduces as far as 30 percent.

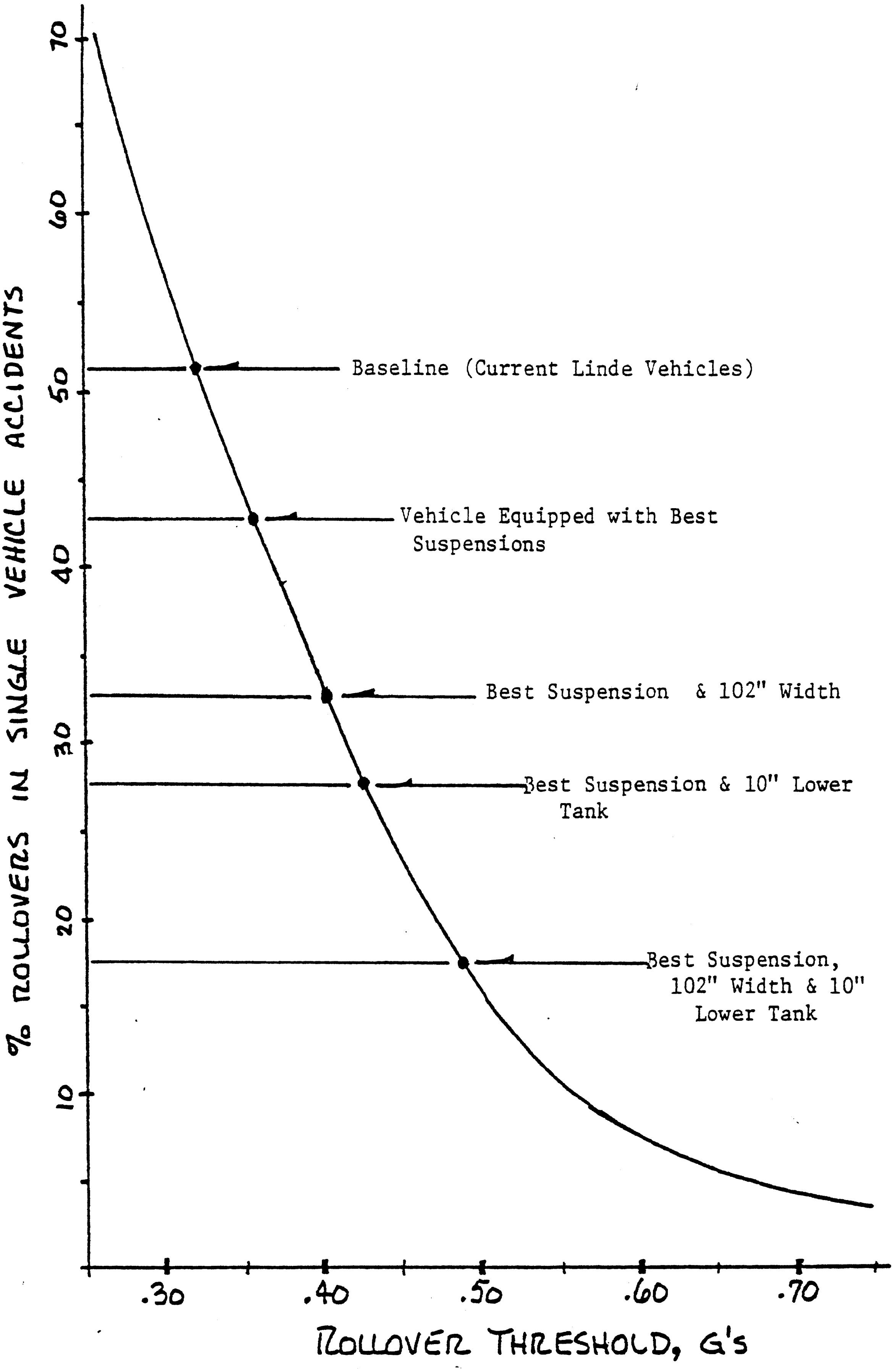


Figure 3.11. Oxygen trailer (Kenworth baseline tractor).

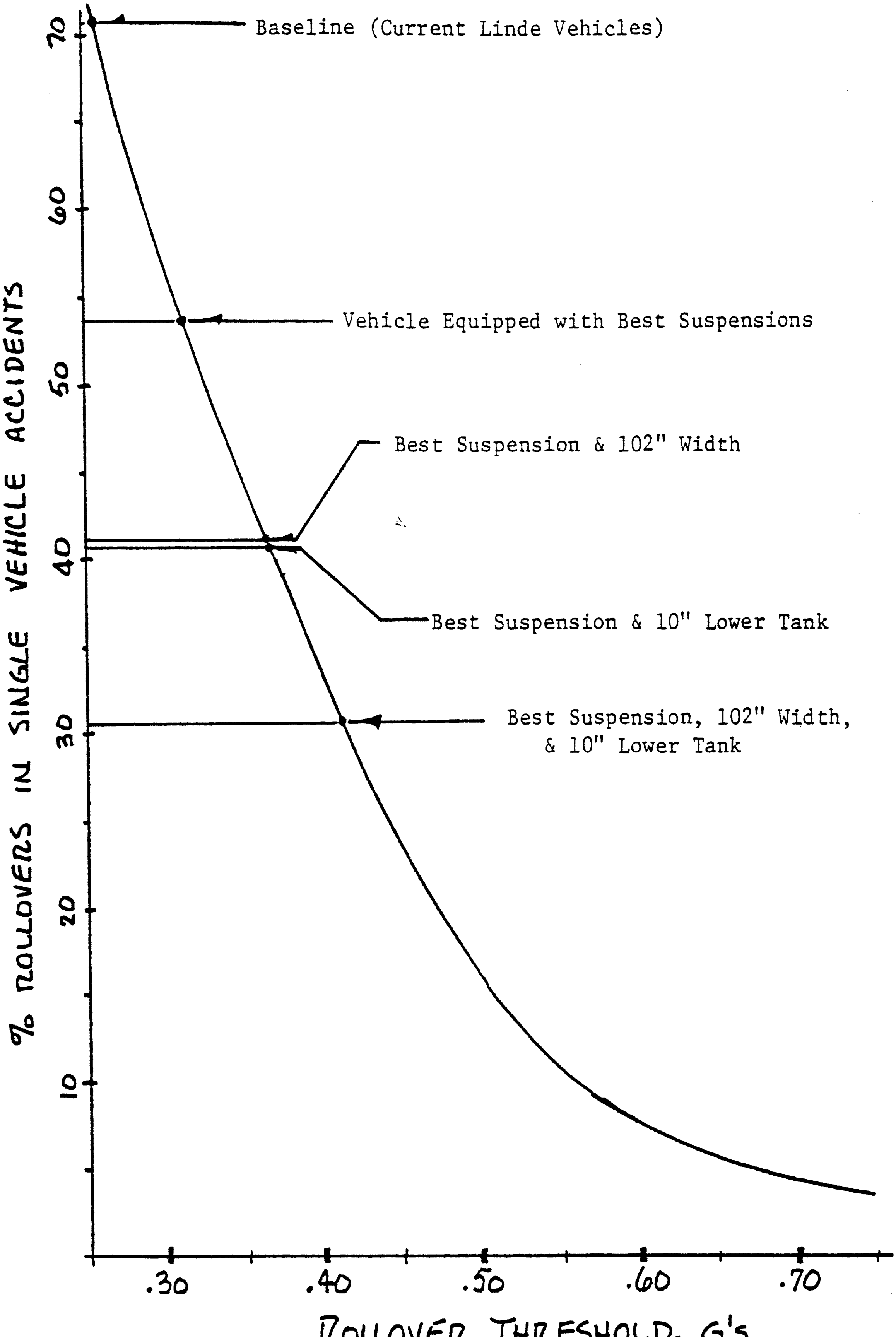


Figure 3.12. Helium trailer (Kenworth baseline tractor).

While the above two plots serve to provide continuity in piecing together the sequence by which computer simulation results were eventually converted into a prediction of rollover accidents, the following section provides the final and most easily understood illustration of the net safety benefits.

Prediction of the Rollovers per 100 Million Miles of Travel for Linde Vehicles with Design Changes. Using the relationship illustrated in Figures 3.11 and 3.12, the reductions in rollover rate achievable through design changes in Linde vehicles can be predicted. So as to obtain some reasonable estimate of the absolute rollover rates which might apply, we have chosen to normalize the overall Linde fleet to the actual rollover rate experienced by the Nitrogen/Argon vehicles during the 1976 through 1981 time period. This vehicle type was chosen since it is the most numerous and thus provides the most statistically satisfying sample of accident data. Further, choosing to reference the projection of rollover rate to the actual rate of the most-populous Linde vehicle serves to scale the results to account for whatever special factors actually determine Linde's overall exposure (such as road classes, topography, etc., as mentioned above).

The previously presented rollover rate of 22 per 100 million miles was taken as the baseline rate for the Nitrogen trailer. From the original BMCS data curve, illustrated earlier in Figure 3.10, a value of 59 percent was identified as the percent rollover/SVA applying to the Nitrogen trailer's .287-g rollover threshold (assuming a Kenworth/Hutchens combination of suspensions).

Rollover rates $(\text{R-0/100 M-miles})_x$ were then computed for the other vehicle types, x, using the relationship:

$$\left(\frac{\text{R-0}}{\text{100 M-miles}}\right)_x = \frac{(\text{R-0/SVA})_x}{(\text{R-0/SVA})_{N2}} \cdot \left(\frac{\text{R-0}}{\text{100 M-miles}}\right)_{N2} = \frac{(\text{R-0/SVA})_x}{(.59)} \quad (22)$$

where $(\text{R-0/SVA})_x$ = Rollovers per SVA for individual vehicle, x

$(\text{R-0/SVA})_{N2}$ = Rollovers per SVA for basic Nitrogen trailer

By this approach, we obtain rollover rate projections which are "calibrated" to the absolute rate of Linde vehicle rollovers, while also factoring in the sensitivity of rollover frequency to the rollover threshold value for individual vehicle types.

Shown in Figure 3.13 are the rollover rates predicted for the various configurations of Oxygen trailer considered. Again, note that design changes are coded 1 through 16 as defined earlier in Section 3.2. We see that rollover involvement is reduced by 20 percent from 20 to 16 rollovers per 100 million miles by optimal selection of suspensions. A total of 35 percent improvement is made (to a value of 13 rollovers/100 million miles) if the vehicle incorporates 102-inch track width, as well. In general, we see that for each two-inch reduction in tank c.g. height, the rollover rate reduces by one rollover/100 million miles, or approximately five percent of the baseline rate. This result is observed whether 96-inch or 102-inch track widths are being considered. Note that the complete set of design improvements on the Oxygen trailer yields a total rollover involvement which is very near to the six rollover/100 million miles value that occurs in general freight trucking in the U.S.

Shown in Figure 3.14 are the corresponding data for the various configurations of Helium trailer which were considered. We see that the Helium trailer has a projected baseline rollover rate of 27 rollovers/100 million miles. A 22-percent reduction in rollovers is predicted to accrue from optimal selection of suspensions, and an additional 15 percent (to a total value of 17 rollovers/100 million miles) from extension of track width to 102 inches. Again, each two-inch reduction in tank c.g. height yields a nominal reduction of one rollover/100 million miles.

Moreover, the design changes which were considered are seen to offer as much as a 50-percent reduction in rollover rate, although regulatory allowance of the 102-inch track width would be required, and substantial changes in tank geometric layout would have to be developed. More modest, yet still very significant, improvements can be made through suspension selection and, perhaps, less dramatic reductions in tank c.g. height.

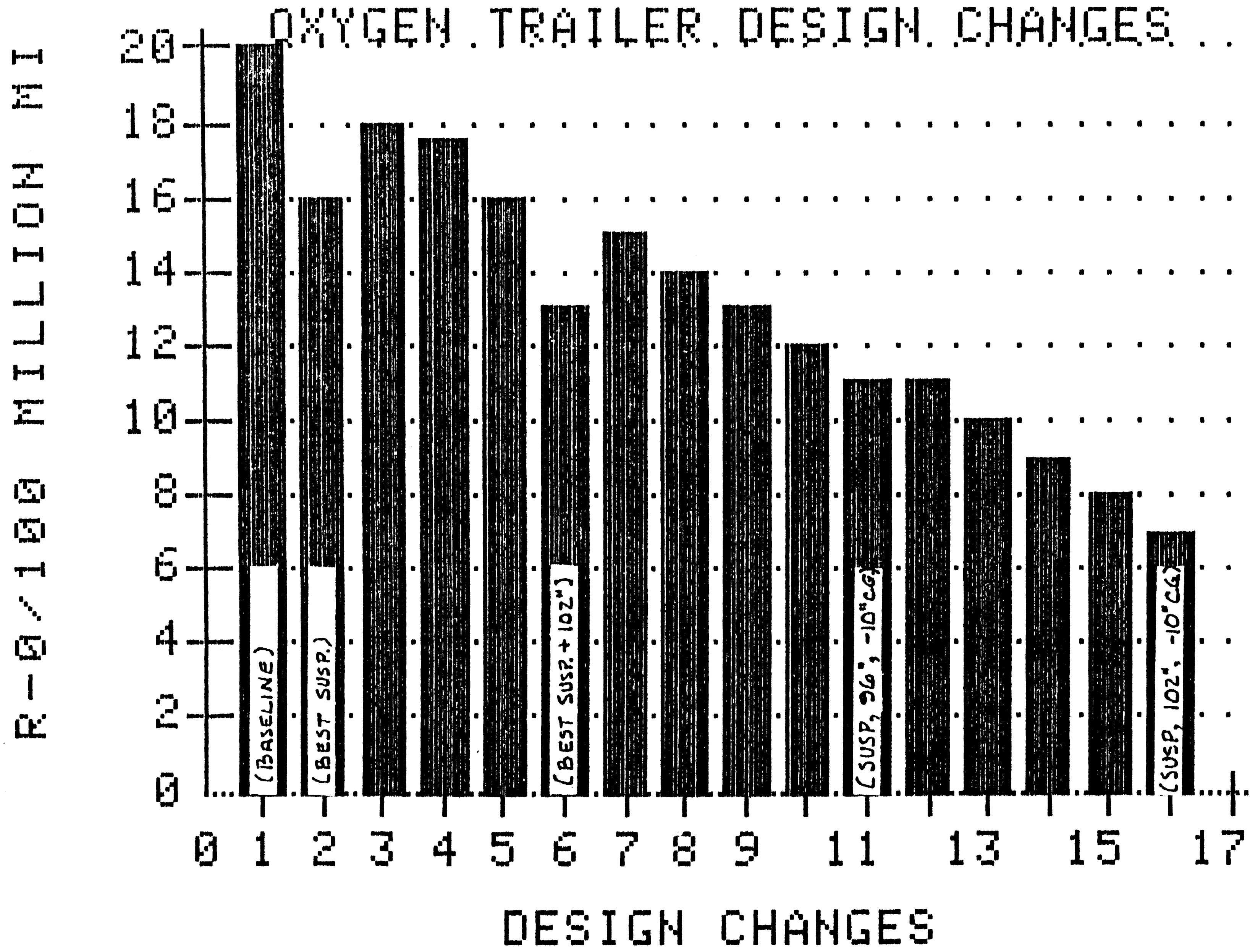


Figure 3.13. Reductions in rollover rate achievable in Oxygen trailer combinations by means of design changes.

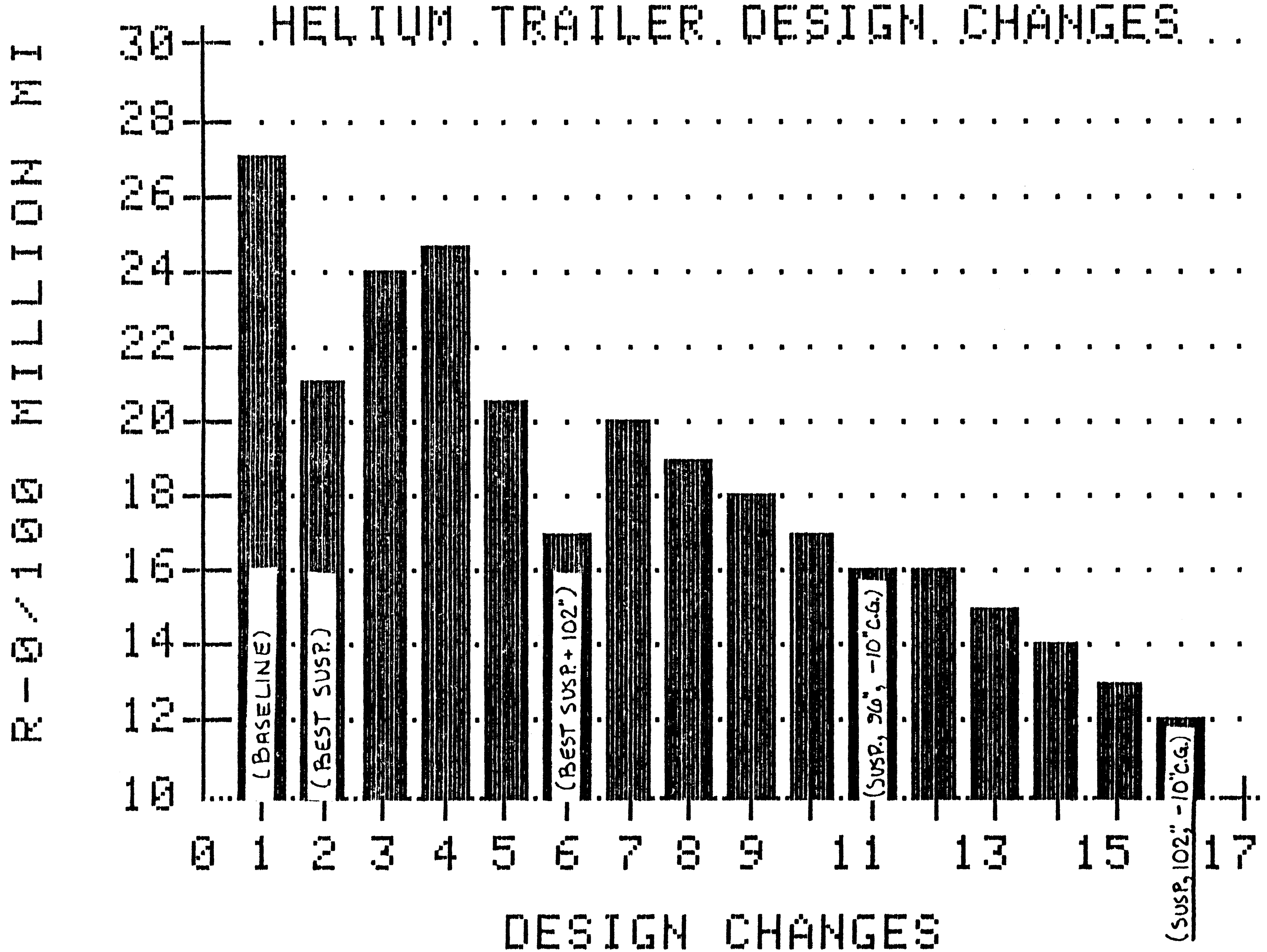


Figure 3.14. Reductions in rollover rates -- Helium trailer combinations with design changes.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The executive summary presented brief statements of the conclusions which were documented in the Results section, above. Essentially, these results establish a generally low level of roll stability in Union Carbide vehicles and illustrate that these stability characteristics can be directly interpreted as having strong influence on the rollover accident rate.

Insofar as Linde may conclude that reductions in its current roll-over rate warrant efforts toward improvement in vehicle stability, certain candidate improvements are suggested. Of most immediate utility as an area of possible improvement is the selection of suspensions assuring higher levels of roll stability. It is recommended that Linde adopt a practice of "qualifying" suspensions on the basis of a suitable set of roll moment versus roll angle properties. The suggested concept for implementing this approach is illustrated in Figure 4.1. The figure shows a plot of the roll moment reaction at each axle of a tandem pair versus the roll angle subtended between the sprung mass and the axle. The plot illustrates, by cross-hatched areas, the range of measurements which were made in this study on tractor and trailer suspensions, respectively. It is recommended that suspensions be carefully selected in the future so that only the stiffer ends of each indicated performance range be employed.

In particular, it is recommended that Linde cite the point labeled "A" as the "target value" establishing a criterion for tractor suspensions, and the point labeled "C" as the "target value" establishing a trailer suspension criterion. The criterion for tractor suspensions would be stated as follows:

> "Each axle of the tractor tandem suspension must produce a roll moment exceeding 500,000 in-lbs when a roll angle of six degrees is subtended between the sprung mass and the axle, for both polarities of roll angle."

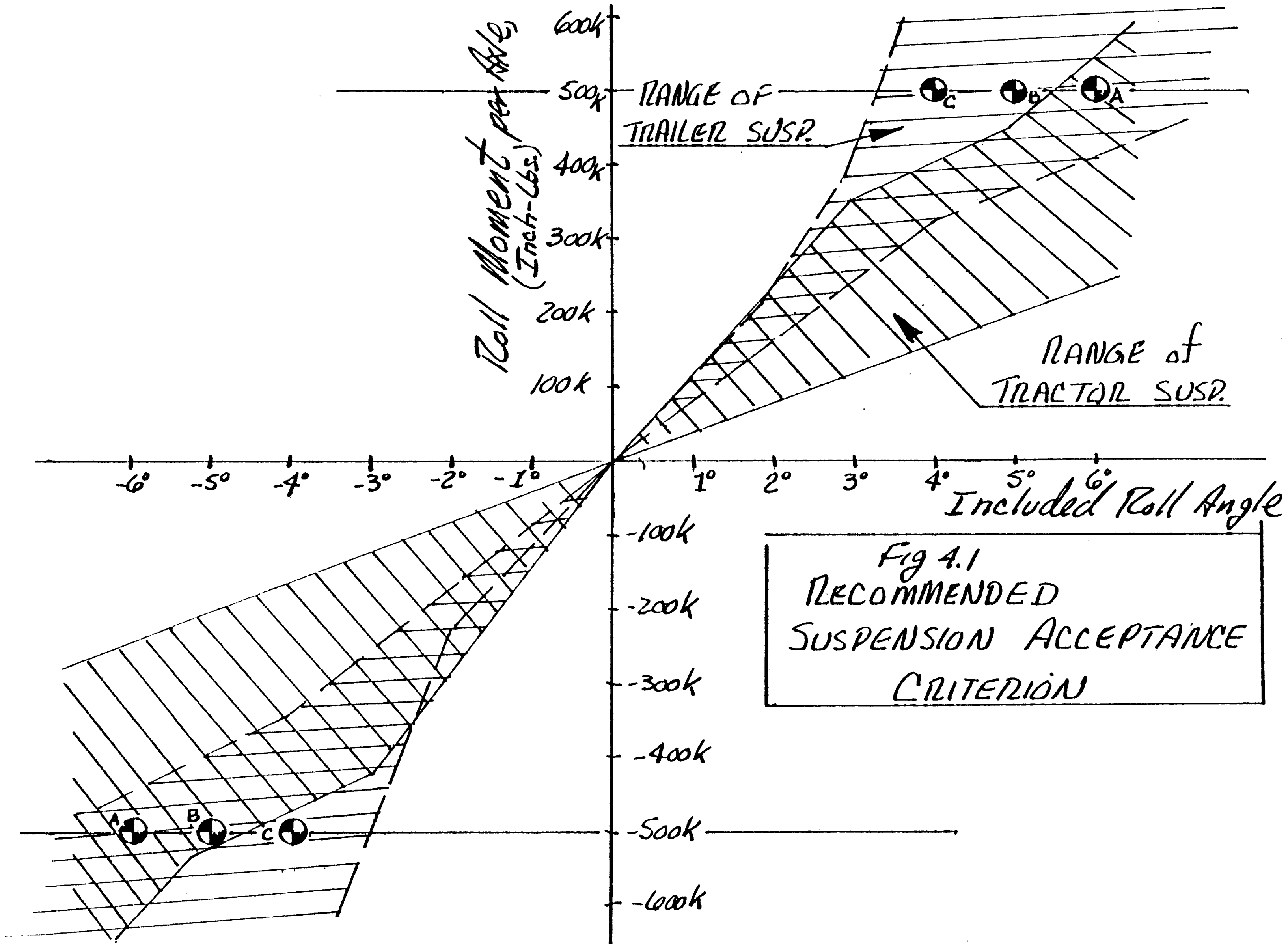


Fig 4.1
RECOMMENDED
SUSPENSION ACCEPTANCE
CRITERION

Likewise, the trailer suspension would be qualified by reference to point "C" with the following criterion:

> "Each axle of the trailer tandem suspension must produce a roll moment exceeding 500,000 in-lbs when a roll angle of four degrees is subtended between the sprung mass and the axle, for both polarities of roll angle."

One additional proviso seems to be needed if certain of the available suspensions which are nominally suitable are to satisfy the criterion. Namely, there must be an allowance that the roll moment reacted at each of the two tandem axles can be averaged together in arriving at the requirement (since it was noted that considerable differences are often seen between the leading and trailing axles in a tandem pair). If such a "relaxed" interpretation is allowed, Linde should stipulate that at no value of roll angle below the four-degree or six-degree criterion conditions can the roll moment produced at one axle differ by more than 150,000 in-lbs from the moment produced at the other axle. This stipulation would guard against potentially deficient arrangements in which all of the roll moment is lumped on one axle.

Figure 4.1 also shows a point labeled "B" which is seen as the future target condition to be satisfied by tractor tandem suspensions. This point defines a 500,000 in-lb and five degree condition as a preferable performance level for a tractor tandem. This performance level is attainable, even in the relatively near term, by suspensions such as the Mack-Reyco four-spring tested in this study simply by means of reducing the unnecessary level of spring lash.

It is recognized that if Linde choses to pursue this recommendation with vigor, they will encounter opposition and dismay on the part of vehicle and suspension suppliers. This resistance will stem primarily from an unfamiliarity with the suggested types of suspension specification, and partly because a large number of currently available products will not satisfy the criterion.

In addition to the initiative on specifying roll-stability-enhancing suspensions, it is recommended that Linde review tank trailer design practices and determine the maximum practicable reduction in trailer c.g. height which can be implemented—either as a modification during the normal rehabilitation of existing equipment, or as a design approach in purchasing new vehicles. It is suggested that the results of this study should serve to scale the very high importance which otherwise "minor" adjustments in c.g. height have upon the ultimate rollover involvement rate. Thus, future efforts toward lowering trailer c.g. height should be focused upon even the small height reductions which might be feasible with otherwise conventional tank constructions, as well as the "dramatic" reductions in height achievable only by means of wholesale redesign of cryogenic tanks.

Finally, the savings in rollover involvement implied by widening track width have been shown to be, indeed, large. Thus it is recommended that Linde adopt a policy favoring national adoption of a 102-inch width allowance. It is HSRI's conviction, all things considered, that such a step would constitute the single most significant adjustment in truck size and weight constraints which is feasible to make in behalf of trucking safety. If such an allowance were adopted, nationwide, it is recommended that the 102-inch dimension be implemented as the width across the outside of the tires on both the tractor and trailer tandems.

5.0 REFERENCES

1. Ervin, R.D., et al. "Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers." Final Report to Michigan State Office of Highway Safety Planning, Contract No. MPA-78-002A, Highway Safety Research Institute, Univ. of Michigan, Rept. No. UM-HSRI-78-18, May 7, 1978.

2. Mallikarjunarao, C., Ervin, R.D., and Segel, L. "Roll Response of Articulated Motor Trucks During Steady Turning Maneuvers." Presented at Winter Annual Meeting of ASME, Phoenix, Ariz., November 1982.

3. Segel, L., et al. "Mechanics of Heavy-Duty Trucks and Truck Combinations." Engineering Summer Conferences, The Univ. of Michigan, June 22-26, 1981.

4. U.S. Dept. of Commerce, Bureau of Census. "Truck Inventory and Use Survey - The 1977 Census of Transportation." May 1980.

5. Ervin, R.D., Mallikarjunarao, C., and Gillespie, T.D. "Future Configuration of Tank Vehicles Hauling Flammable Liquids in Michigan." Final Report to Michigan Dept. of State Highways, Contract No. 78-2230, Highway Safety Research Institute, Univ. of Michigan, Rept. No. UM-HSRI-80-73, December 1980.

6. Winkler, C.B. and Hagan, M. "A Test Facility for the Measurement of Heavy Vehicle Suspension Parameters." SAE Paper No. 800906, 1980.

APPENDICES

APPENDIX A

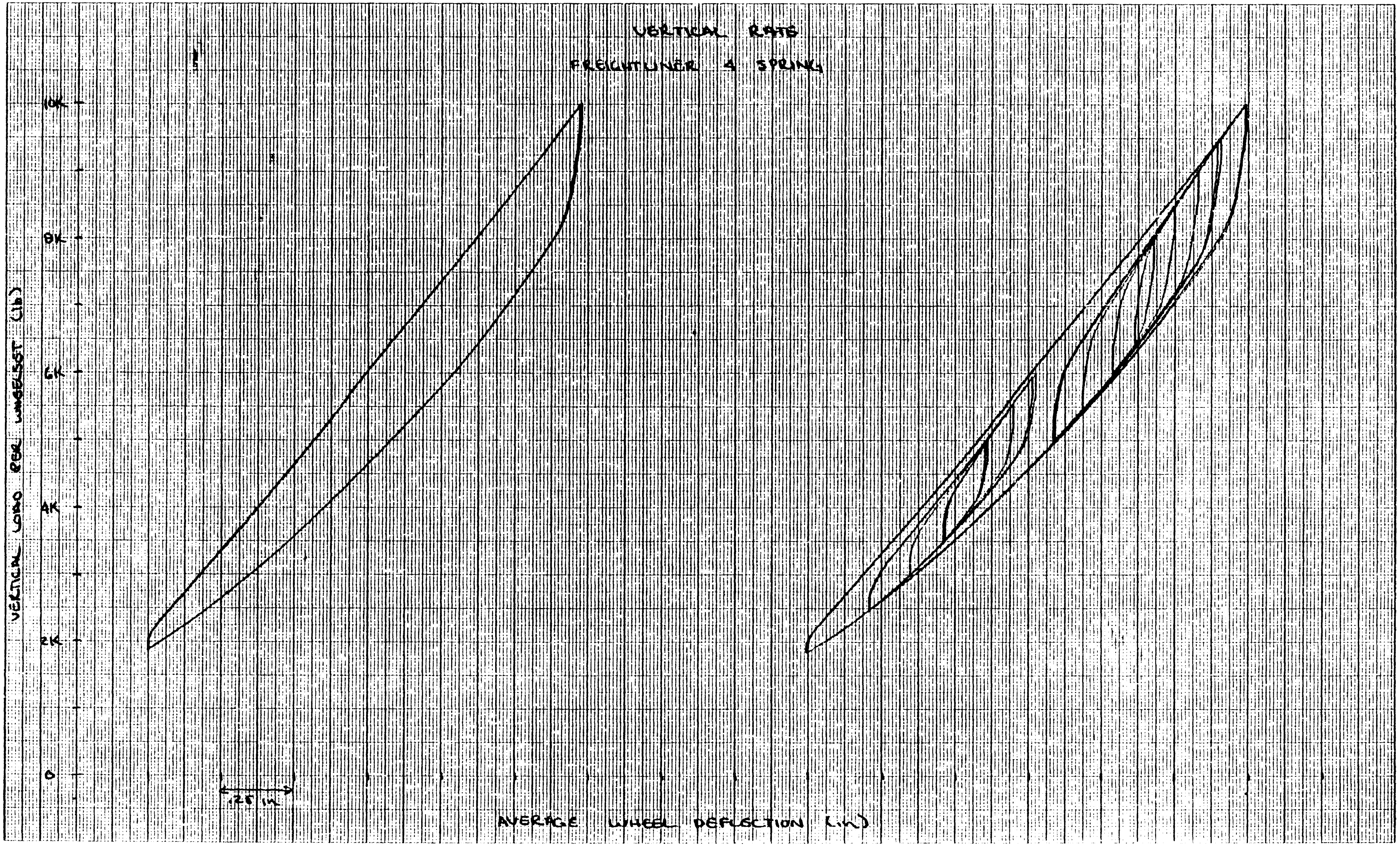
DETAILED SUSPENSION DATA

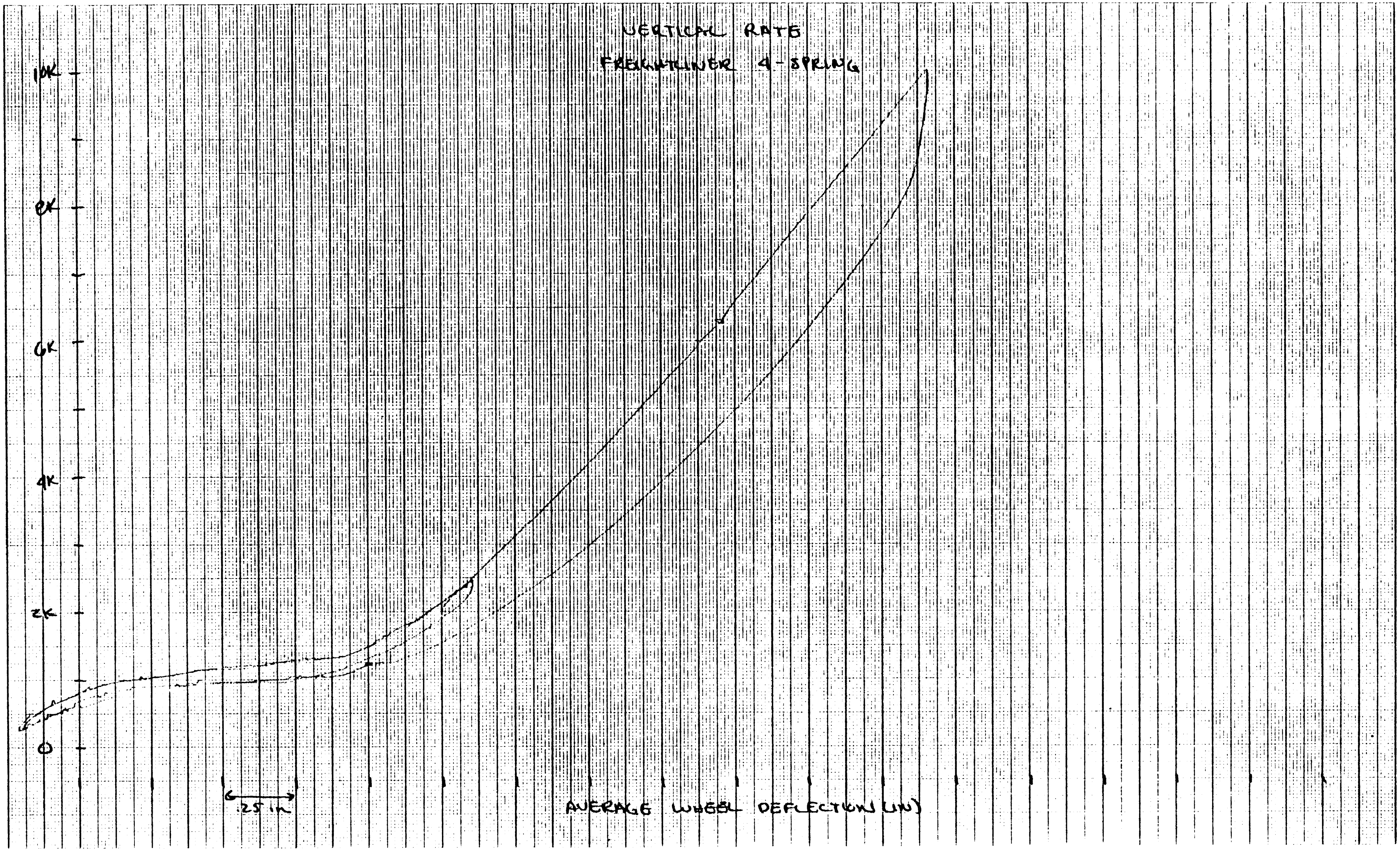
This appendix contains suspension data collected on the HSRI tandem suspension parameter measurement facility. The data describe vertical and roll stiffness properties of the following suspensions:

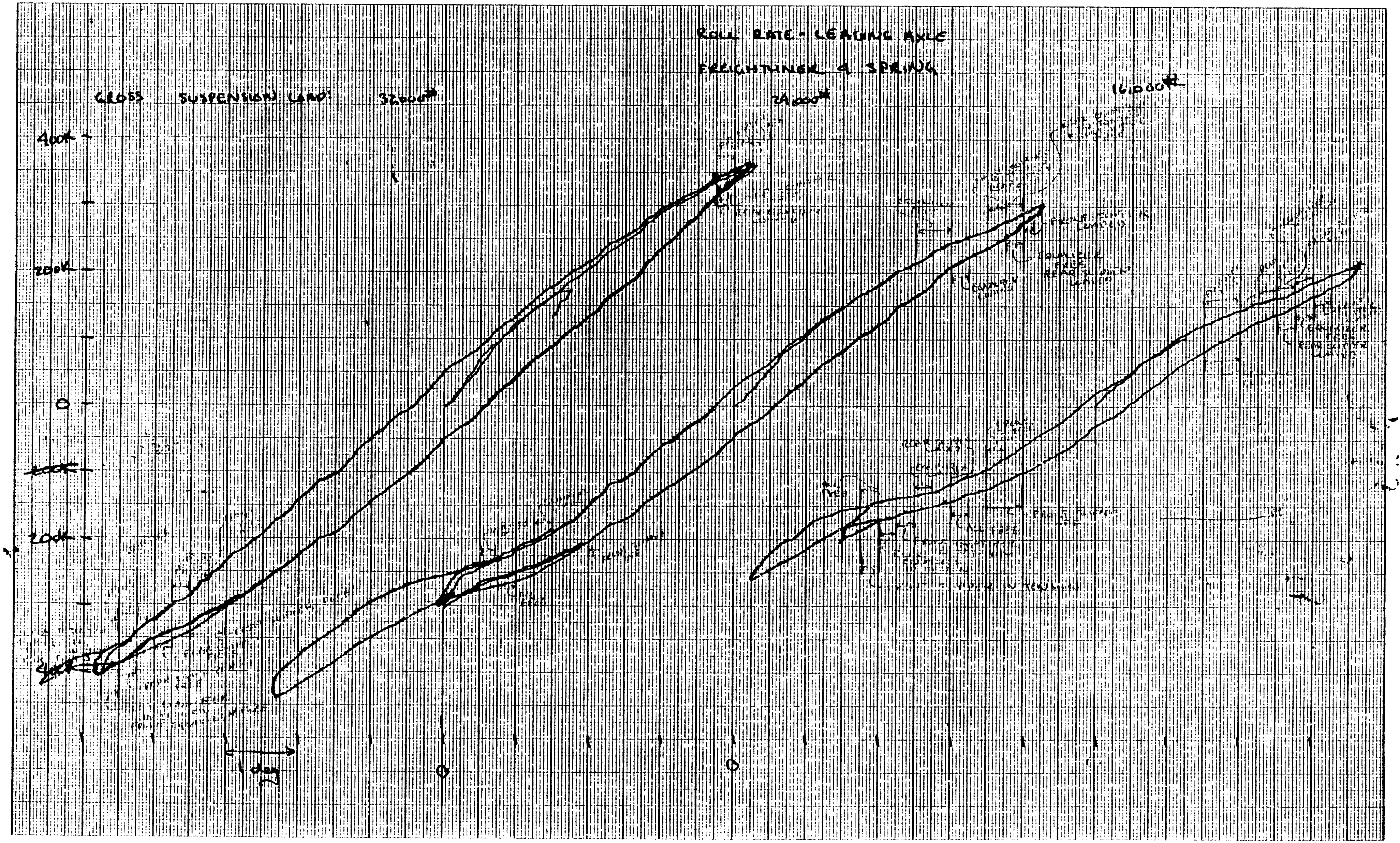
1) Freightliner four-spring
2) Peterbilt four-spring
3) Mack (Reyco-manufactured) four-spring
4) Kenworth torsion bar
5) Hutchens taper leaf four-spring
6) Chalmers rubber spring walking-beam
7) Neway air suspension

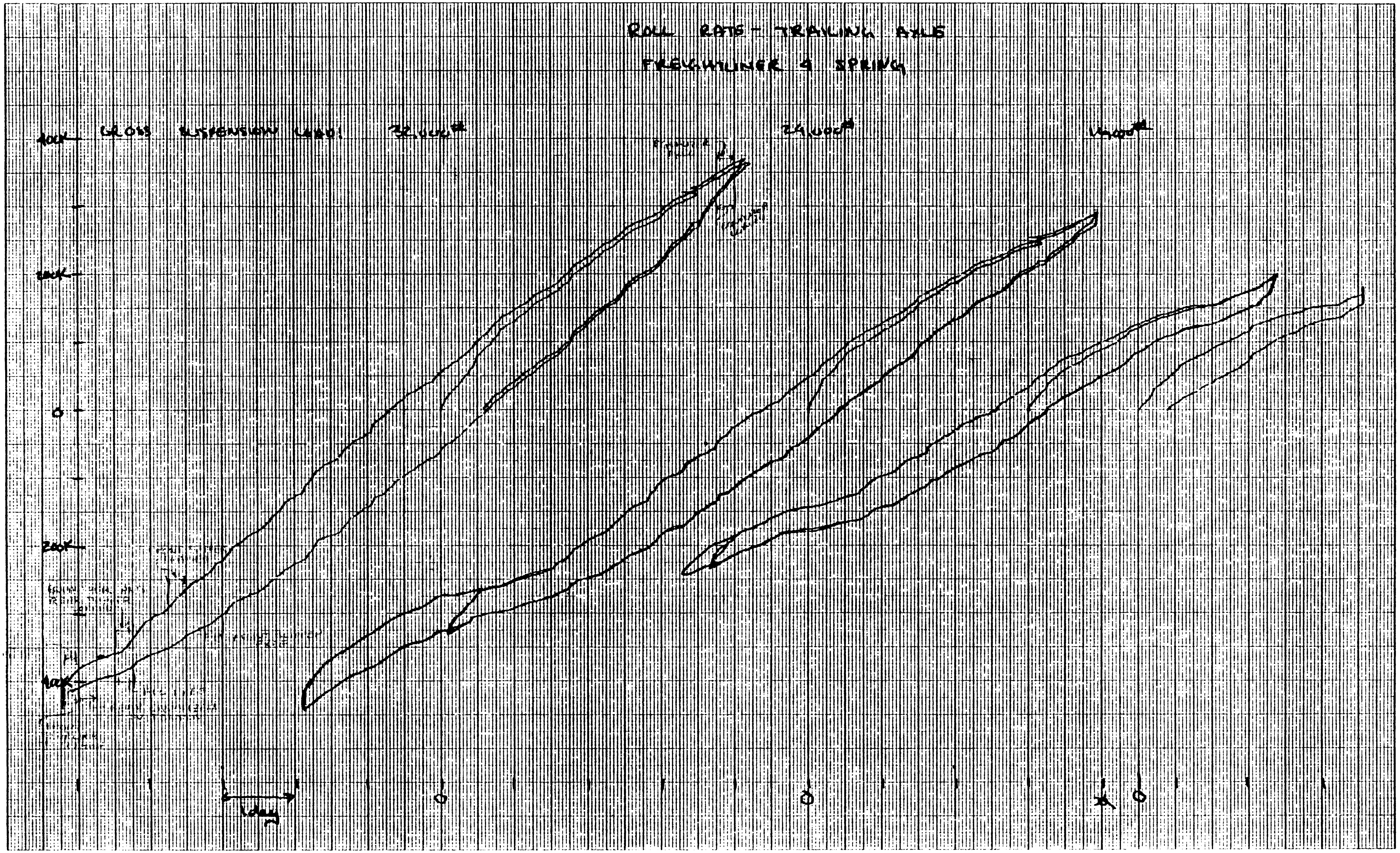
For detailed discussion of the measurement methodology and interpretation of these data, the reader should consult the SAE paper cited in Reference [6].

A.1 Freightliner Four-Spring

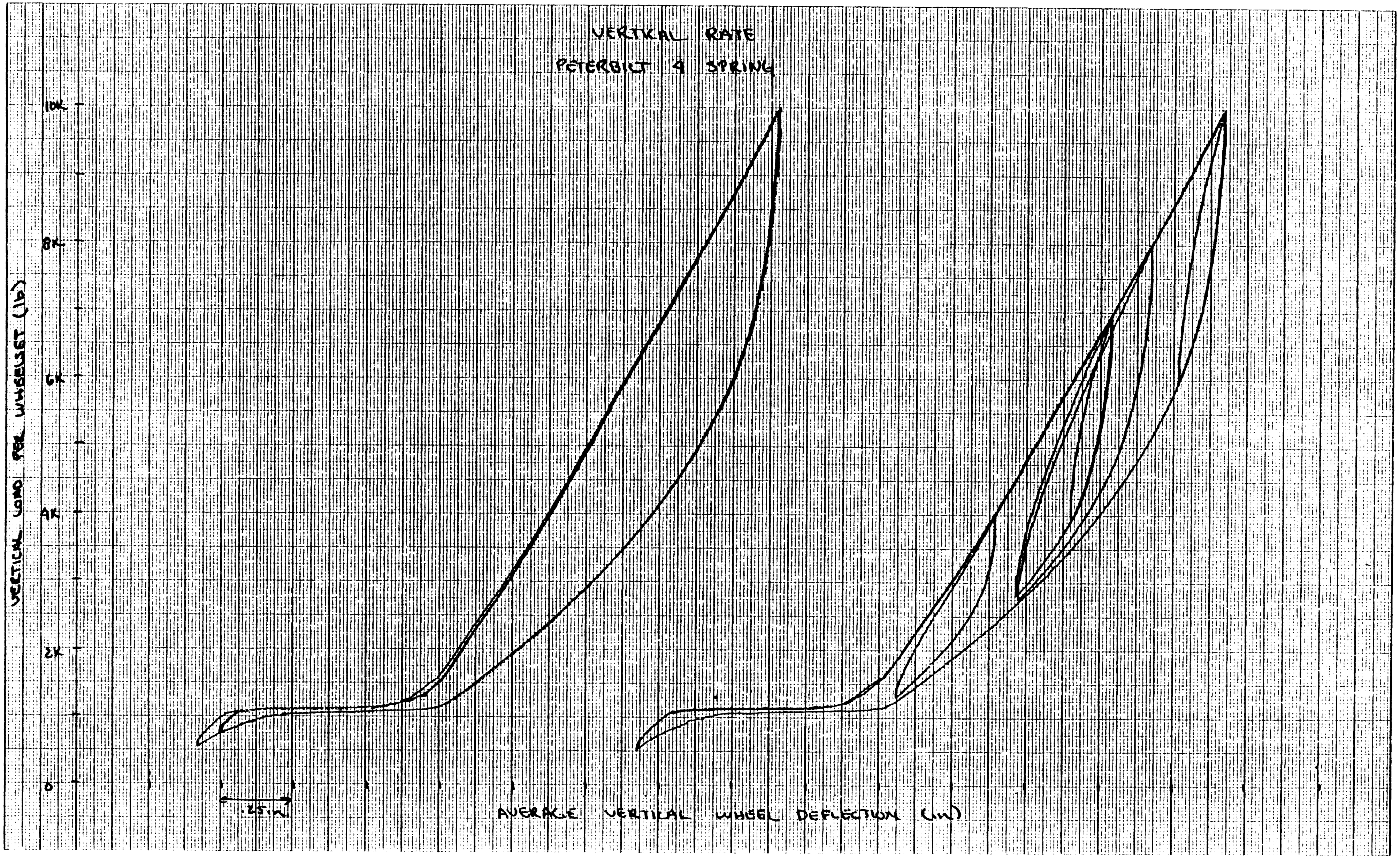

VERTICAL RATE
FREIGHTLINER 4 SPRING
VERTICAL LOAD PER WHEELSET (lb)
10K
8K
6K
4K
2K
0
.25 in
AVERAGE WHEEL DEFLECTION (in)

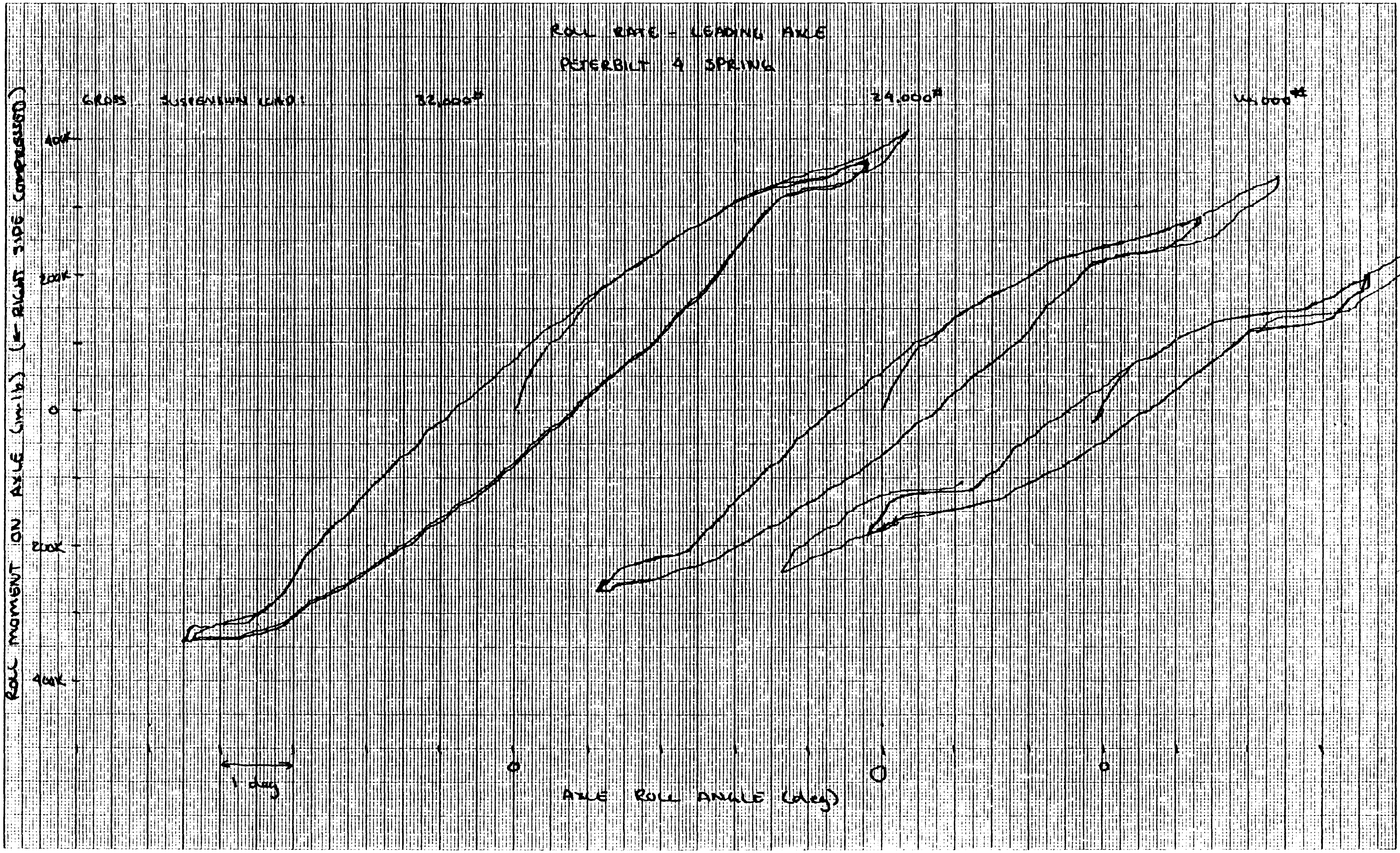

VERTICAL RATE
FREIGHTLINER 4-SPRING

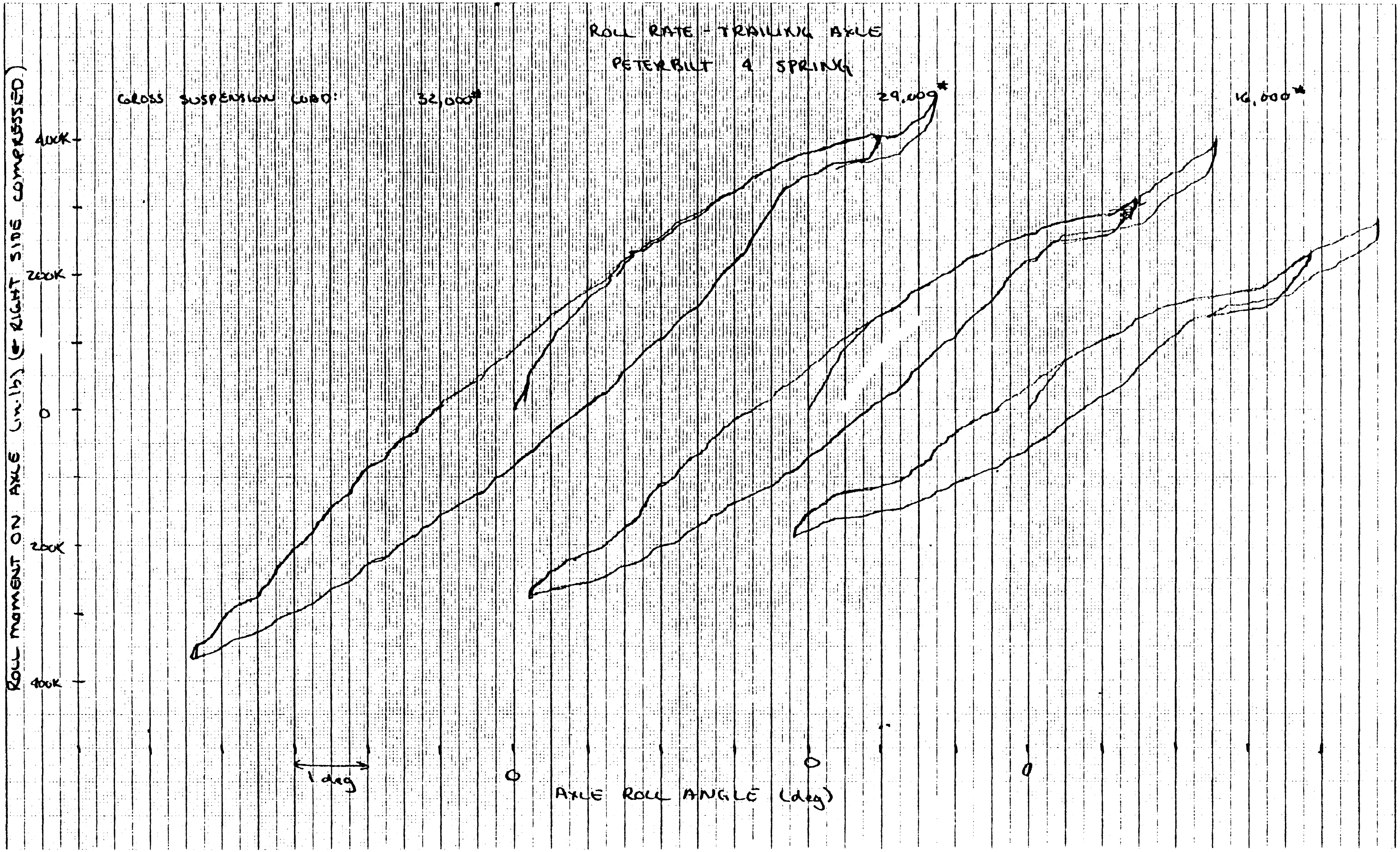

ROLL RATE - LEADING AXLE
FREIGHTLINER 4 SPRING
GROSS SUSPENSION LOAD: 32,000#
24,000#
16,000#
400K
200K
0
~~100K~~
200K
400K
0
0
1 deg


ROLL RATE - TRAILING AXLE
FREIGHTLINER 4 SPRING
GROSS SUSPENSION LOAD: 32,000#
24,000#
16,000#
400K
200K
0
200K
400K
0
0
0
1 deg

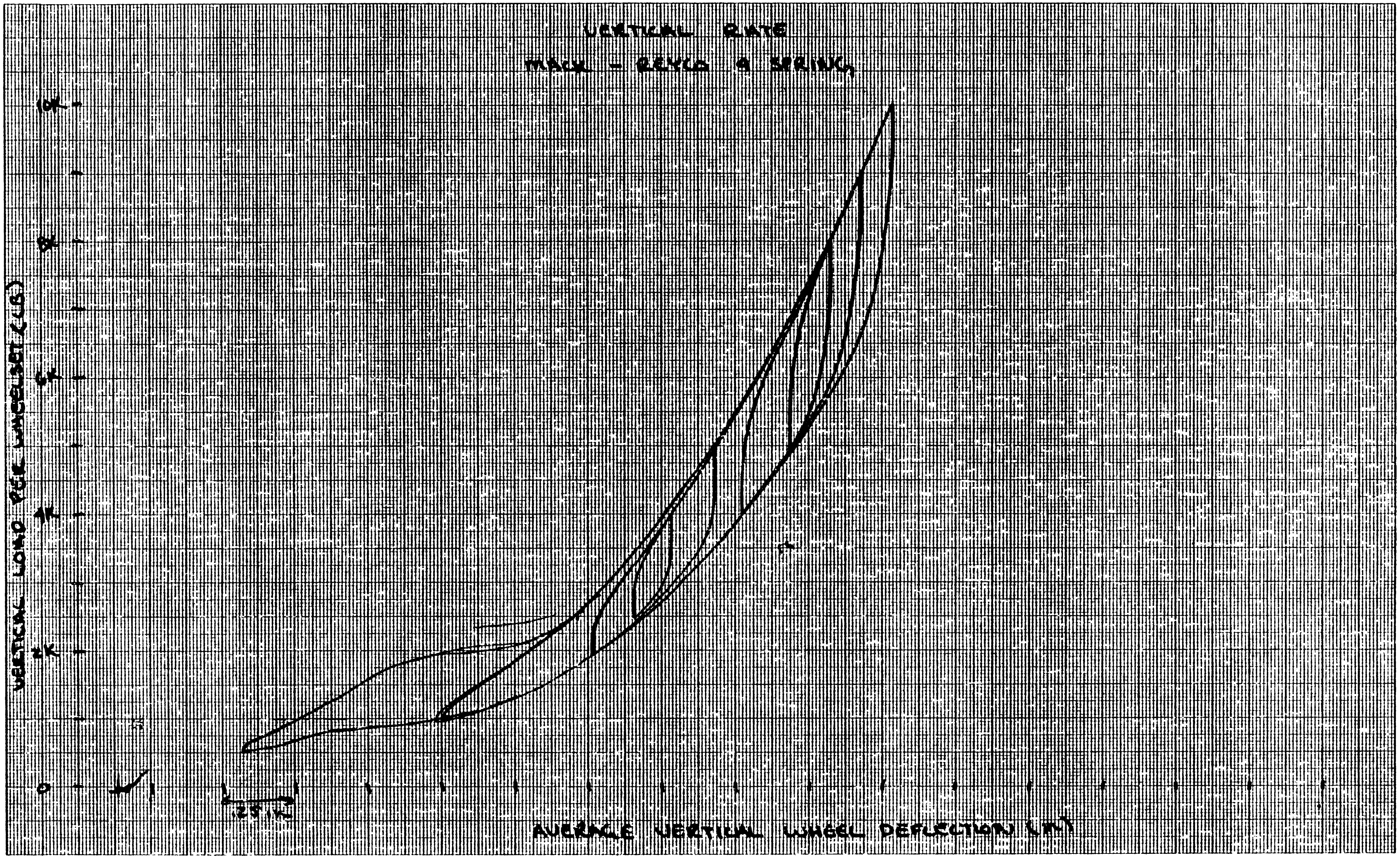
A.2 Peterbilt Four-Spring


VERTICAL RATE
PETERBILT 4 SPRING
VERTICAL LOAD PER WHEELSET (lb)
10K
8K
6K
4K
2K
0
.25 in
AVERAGE VERTICAL WHEEL DEFLECTION (in)


ROLL RATE - LEADING AXLE
PETERBILT 4 SPRING
GROSS SUSPENSION LOAD:
32,000#
24,000#
16,000#
400K
200K
0
200K
400K
ROLL MOMENT ON AXLE (in-lb) (← RIGHT SIDE COMPRESSED)
0
0
0
1 deg
AXLE ROLL ANGLE (deg)


ROLL RATE - TRAILING AXLE
PETERBILT 4 SPRING
GROSS SUSPENSION LOAD:
32,000#
29,000*
16,000*
ROLL MOMENT ON AXLE (in.lb) (← RIGHT SIDE COMPRESSED)
400K
200K
0
200K
400K
1 deg
0
0
0
AXLE ROLL ANGLE (deg)

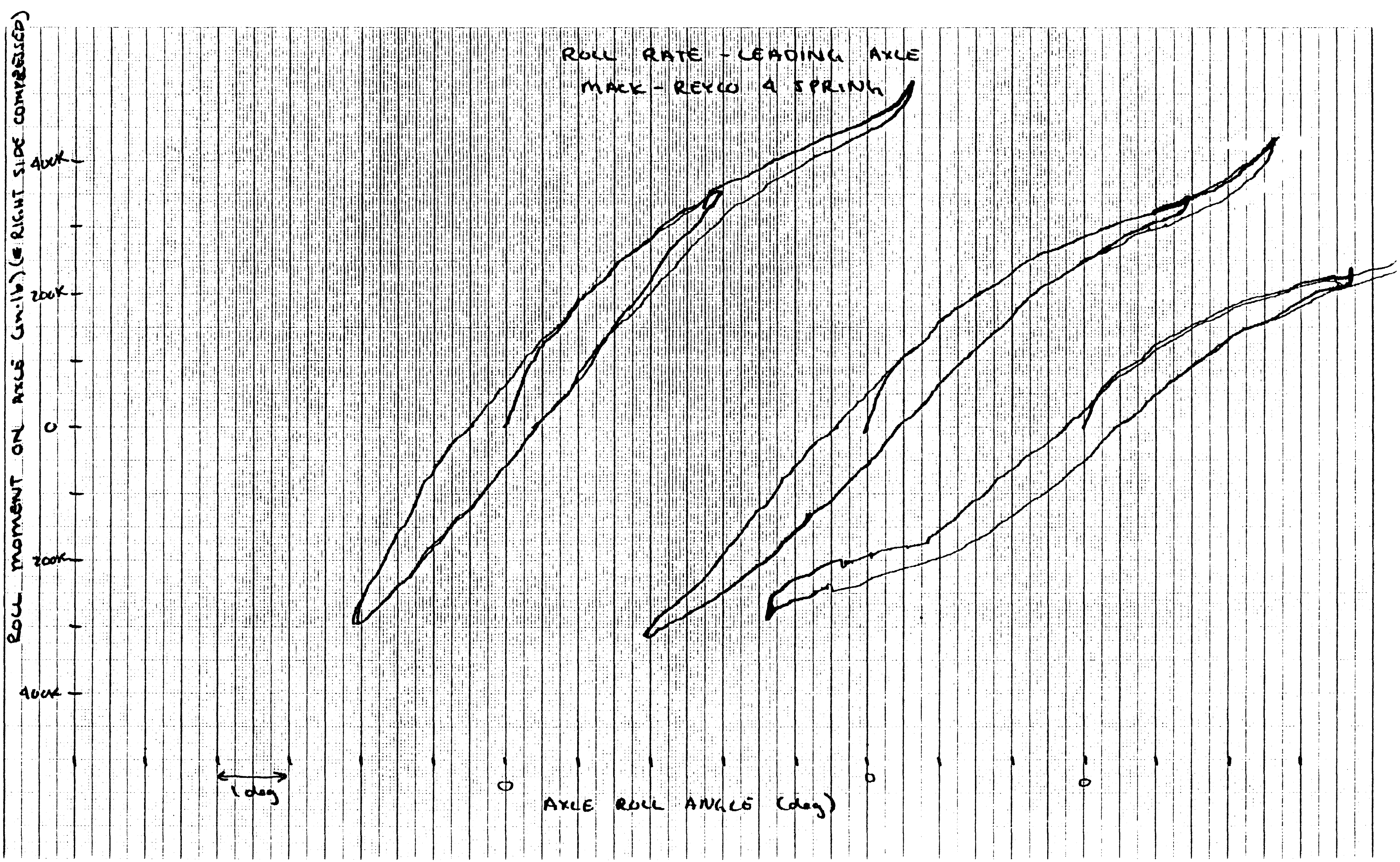
A.3 Mack (Reyco-Manufactured) Four-Spring

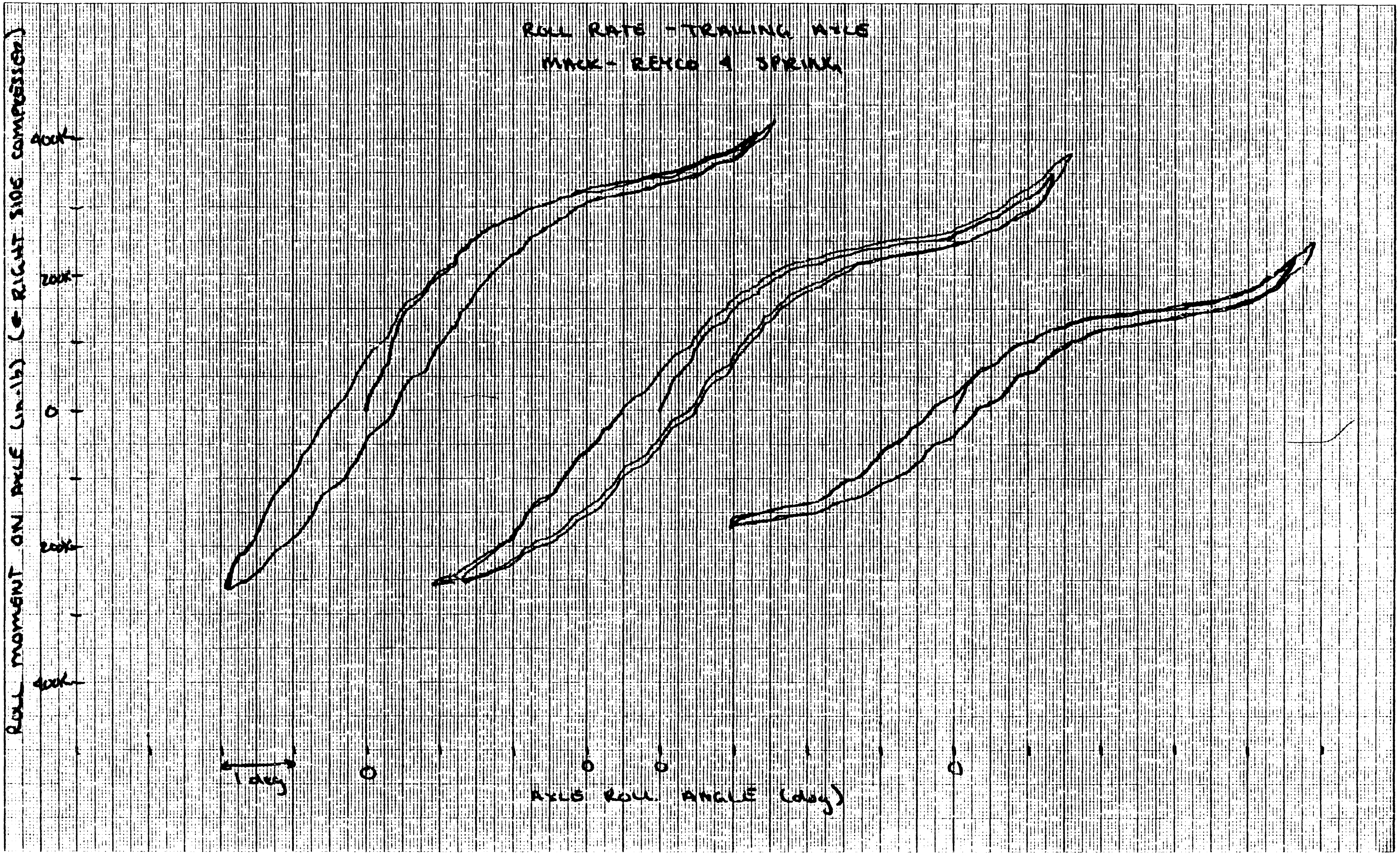


VERTICAL RATE

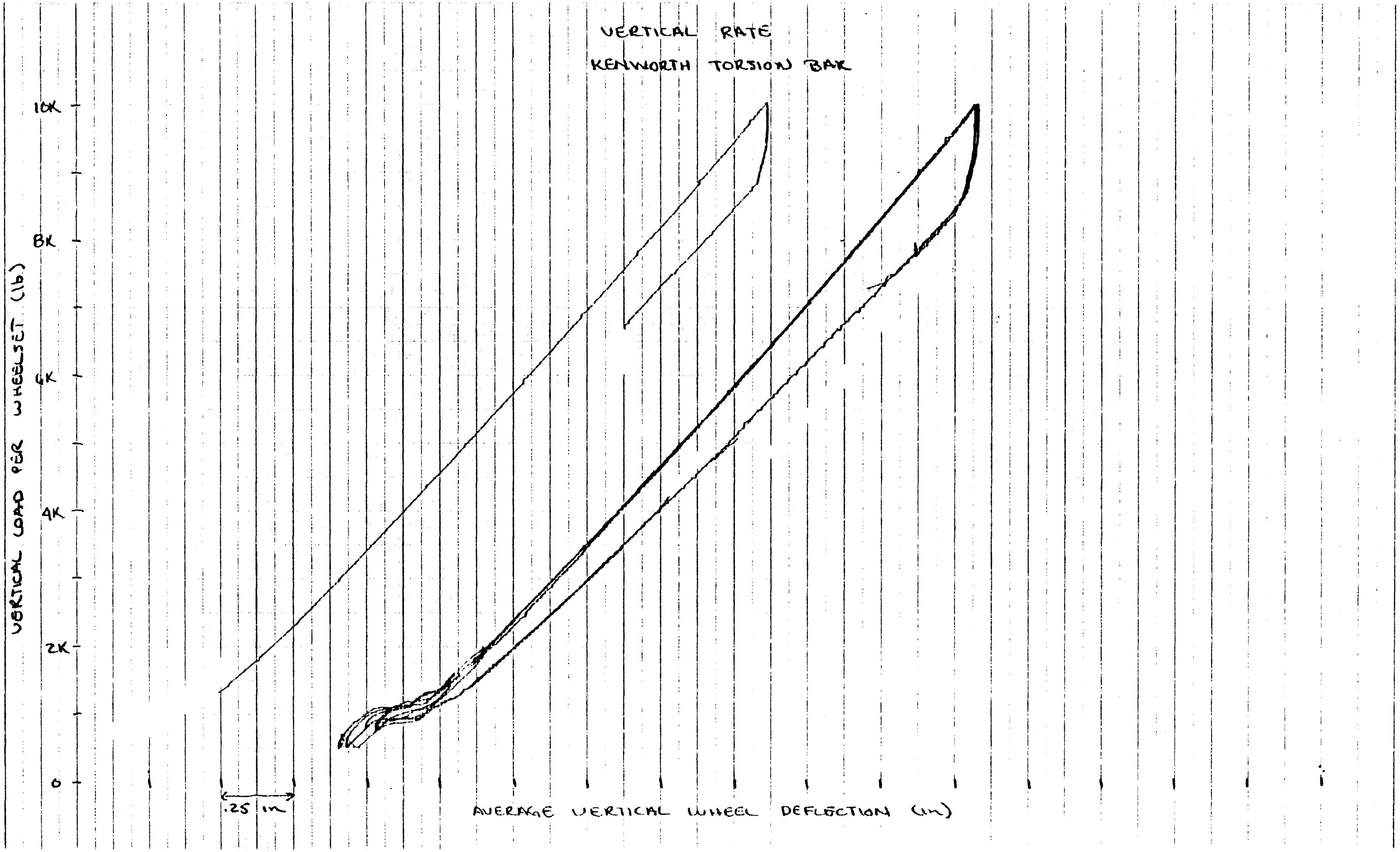
MACK - REYCO 4 SPRING

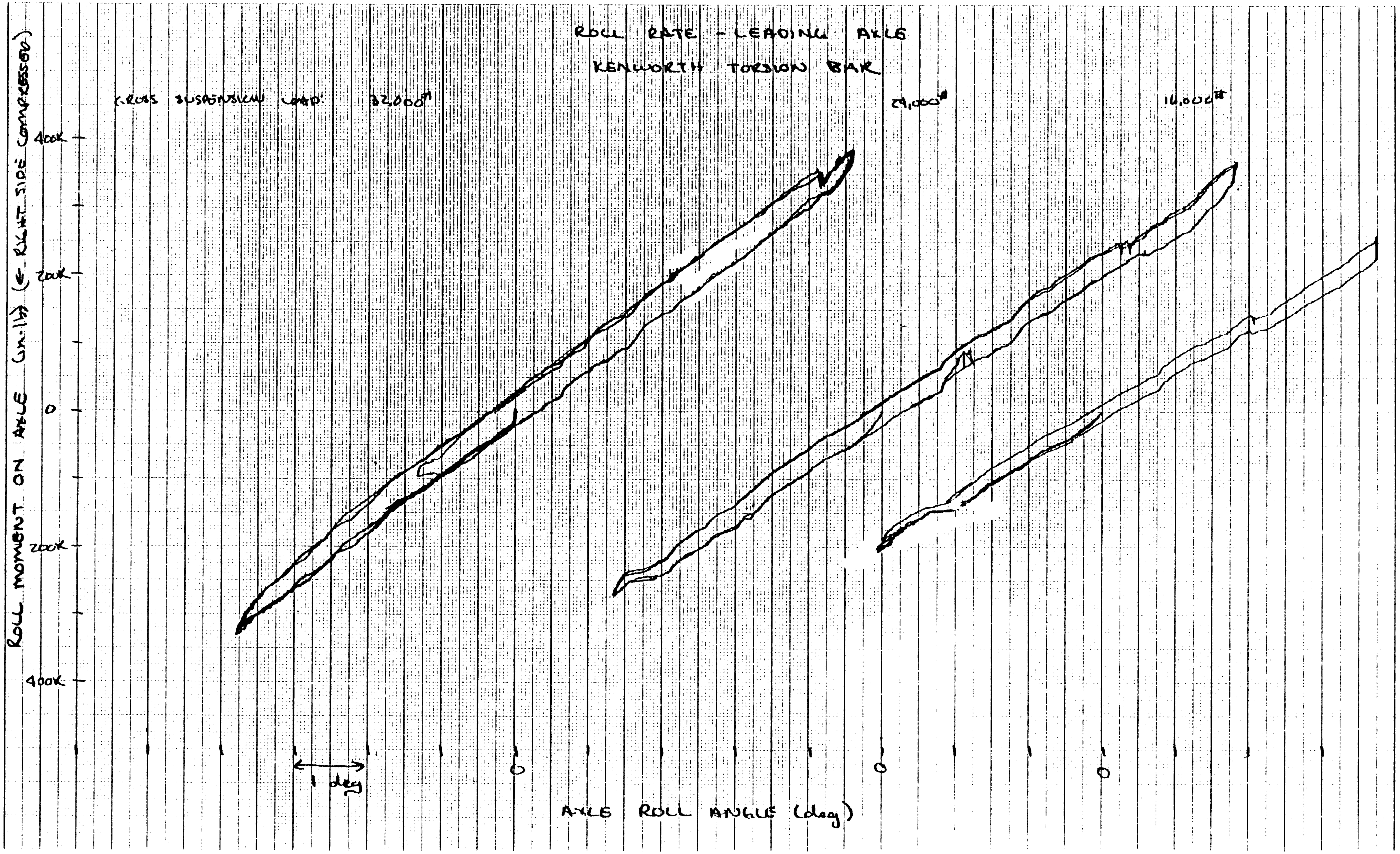
ROLL RATE - LEADING AXLE
MACK - REYCO 4 SPRING

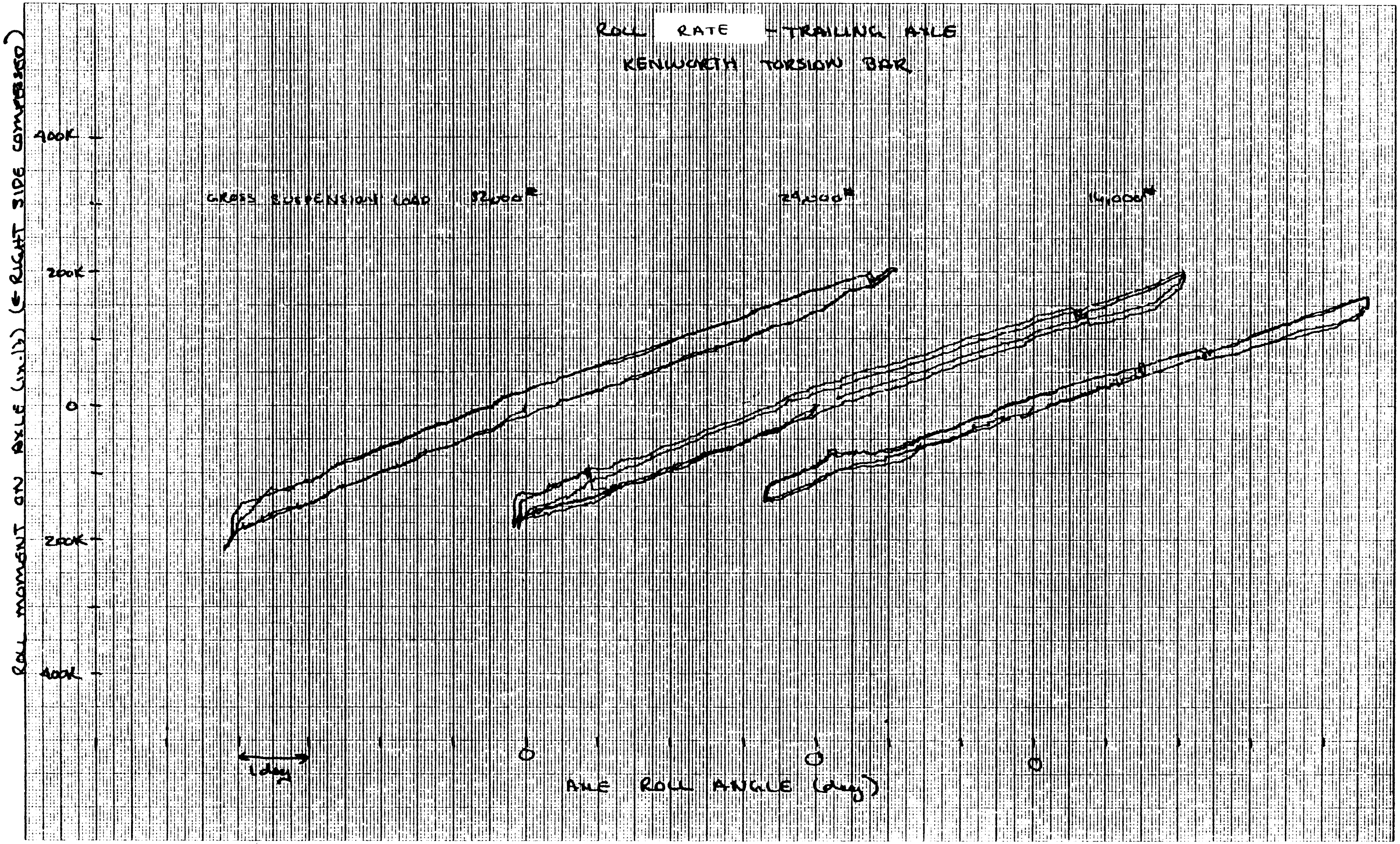


ROLL RATE - TRAILING AXLE
MACK - REYCO 4 SPRING
ROLL MOMENT ON AXLE (in-lb) (← RIGHT SIDE COMPRESSED)
400K
200K
0
200K
400K
1 deg
0
0
0
0
AXLE ROLL ANGLE (deg)

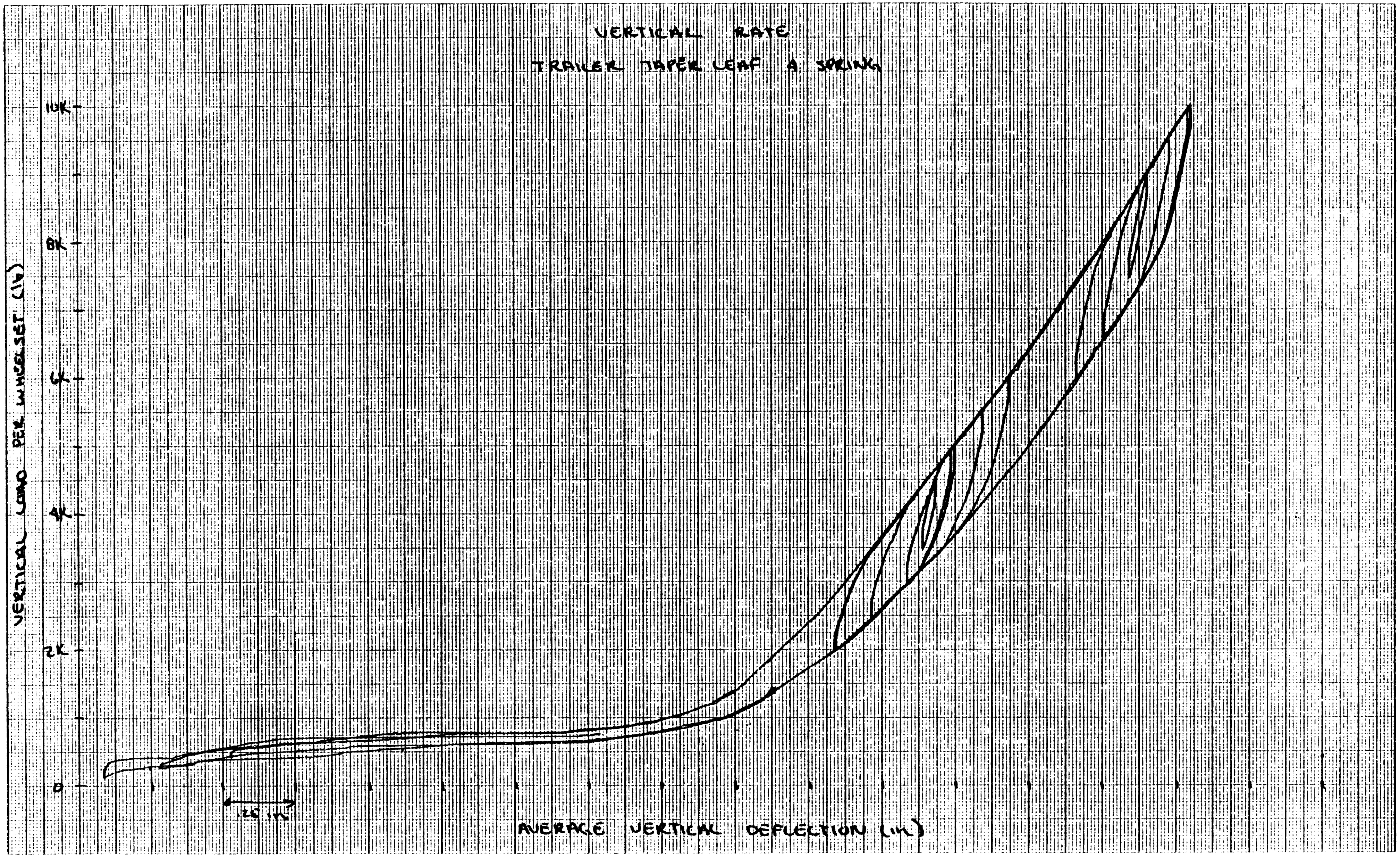
A.4 Kenworth Torsion Bar

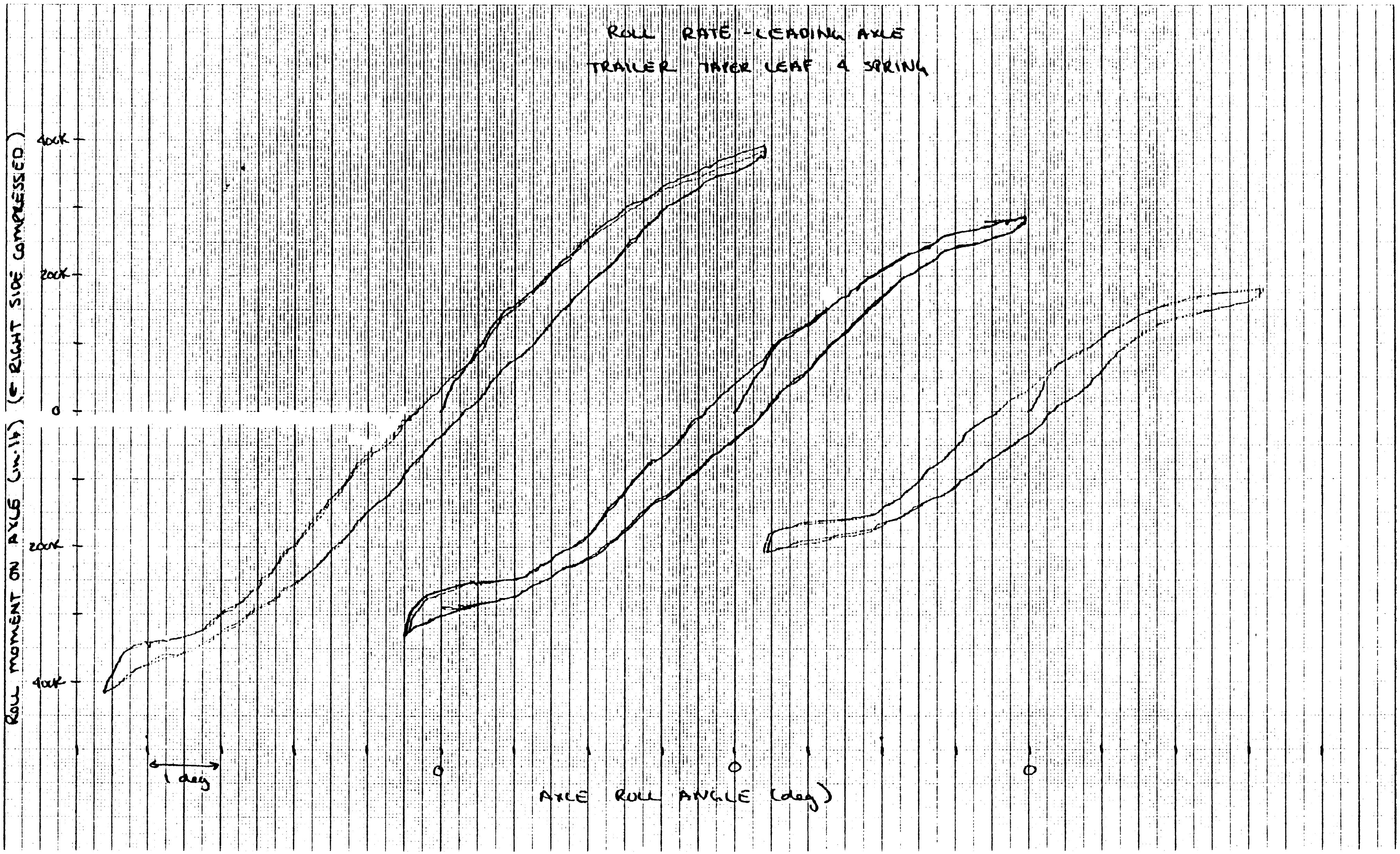

VERTICAL RATE
KENWORTH TORSION BAR
10K
8K
6K
4K
2K
0
VERTICAL LOAD PER WHEELSET (lb)
.25 in
AVERAGE VERTICAL WHEEL DEFLECTION (in)

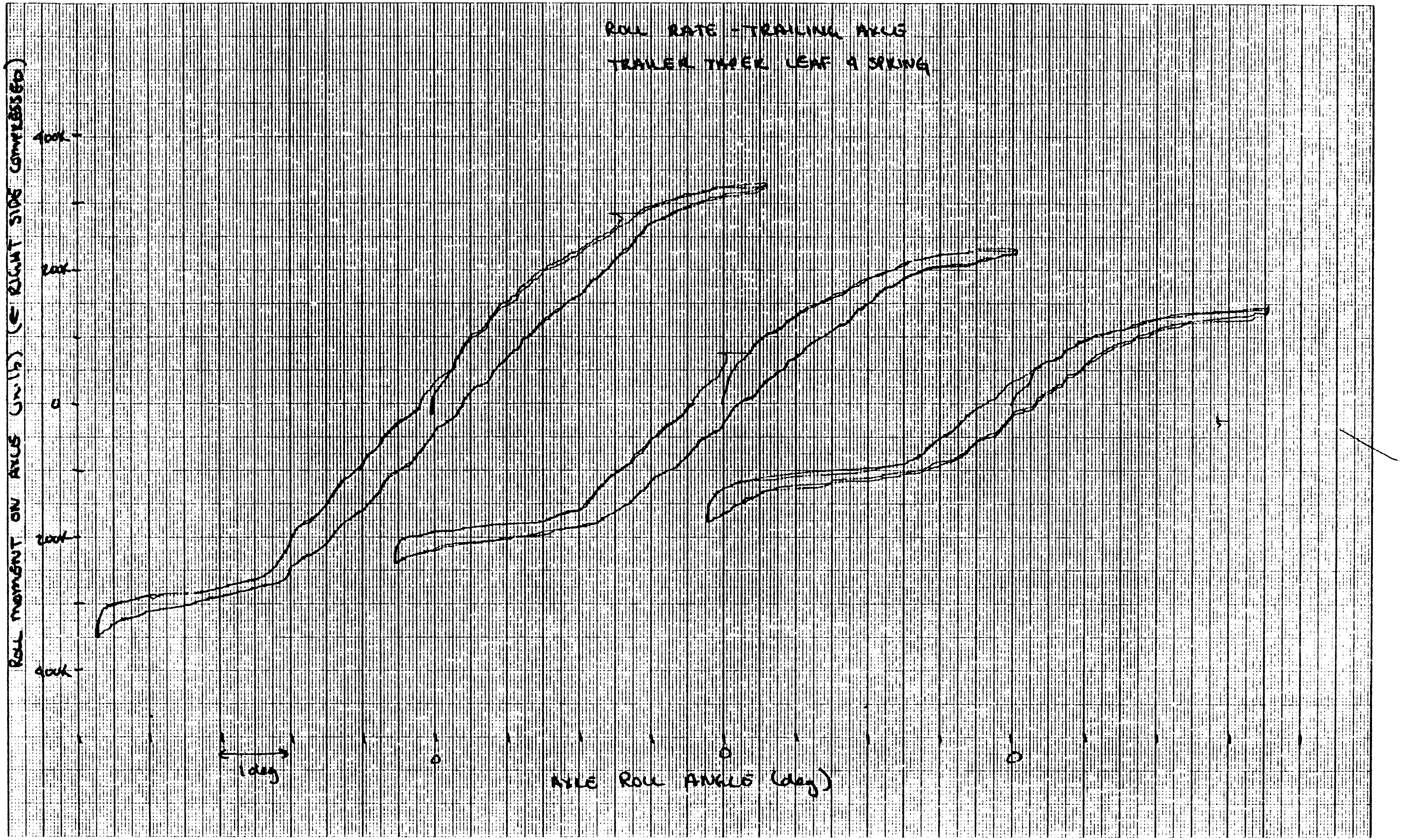

ROLL RATE - LEADING AXLE
KENWORTH TORSION BAR
CROSS SUSPENSION LOAD: 32,000#
29,000#
16,000#
ROLL MOMENT ON AXLE (in-lb) (← RIGHT SIDE COMPRESSED)
400K
200K
0
200K
400K
1 deg
0
0
0
AXLE ROLL ANGLE (deg)


ROLL RATE - TRAILING AXLE
KENWORTH TORSION BAR
GROSS SUSPENSION LOAD 32,000#
24,000#
14,000#
400K
200K
0
200K
400K
ROLL MOMENT ON AXLE (in-lb) (← RIGHT SIDE COMPRESSED)
0
0
0
1 deg
AXLE ROLL ANGLE (deg)

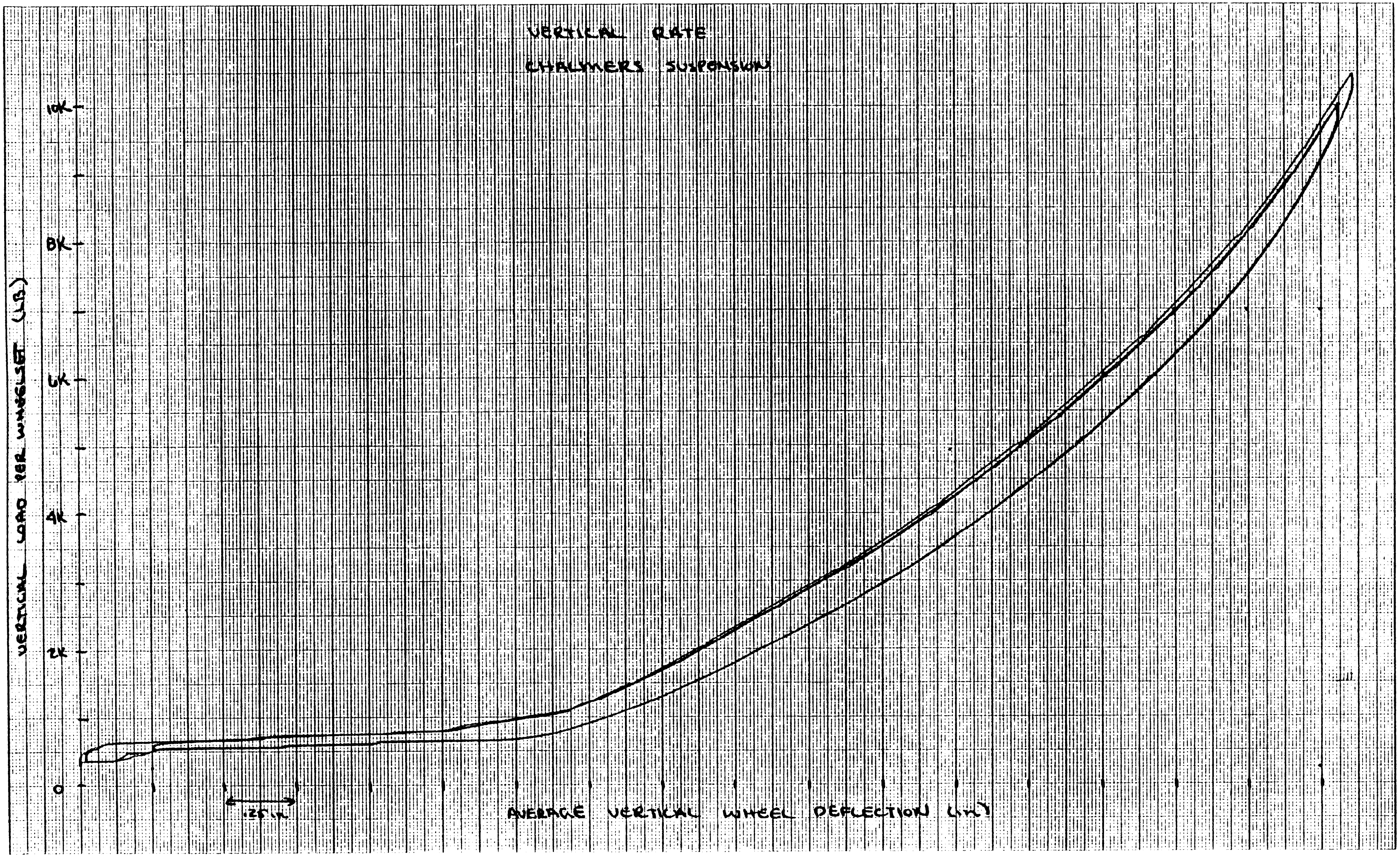
A.5 Hutchens Taper Leaf Four-Spring

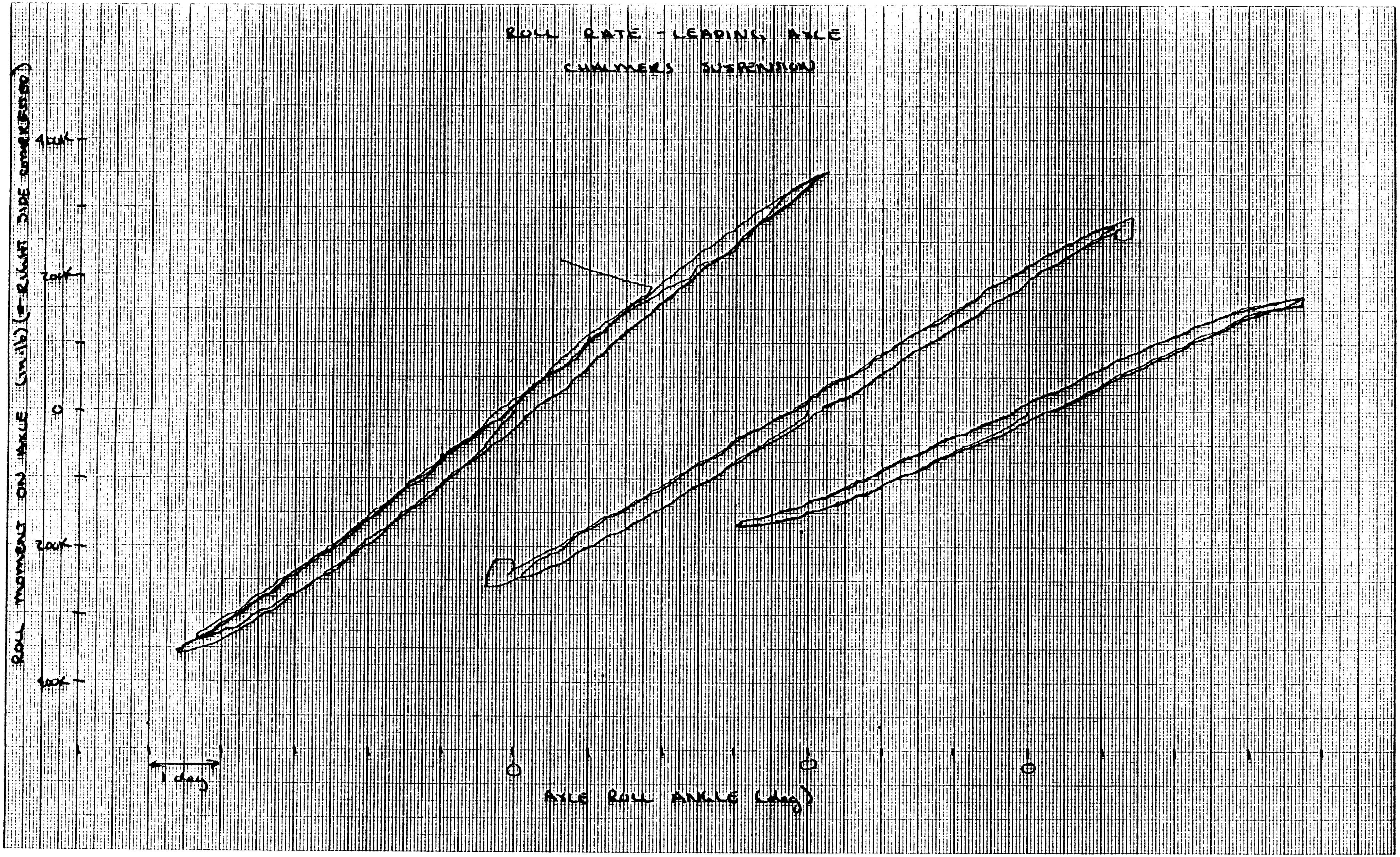

VERTICAL RATE
TRAILER TAPER LEAF A SPRING
10K
8K
6K
4K
2K
0
VERTICAL LOAD PER WHEELSET (lb)
.25 in
AVERAGE VERTICAL DEFLECTION (in)


ROLL RATE - LEADING AXLE
TRAILER TAPER LEAF 4 SPRING
ROLL MOMENT ON AXLE (in.lb) (← RIGHT SIDE COMPRESSED)
400K
200K
0
200K
400K
1 deg
0
0
0
AXLE ROLL ANGLE (deg)


ROLL RATE - TRAILING AXLE
TRAILER TAPER LEAF 9 SPRING
ROLL MOMENT ON AXLE (in-lb) (← RIGHT SIDE COMPRESSED)
400k
200k
0
200k
400k
0
0
0
1deg
AXLE ROLL ANGLE (deg)

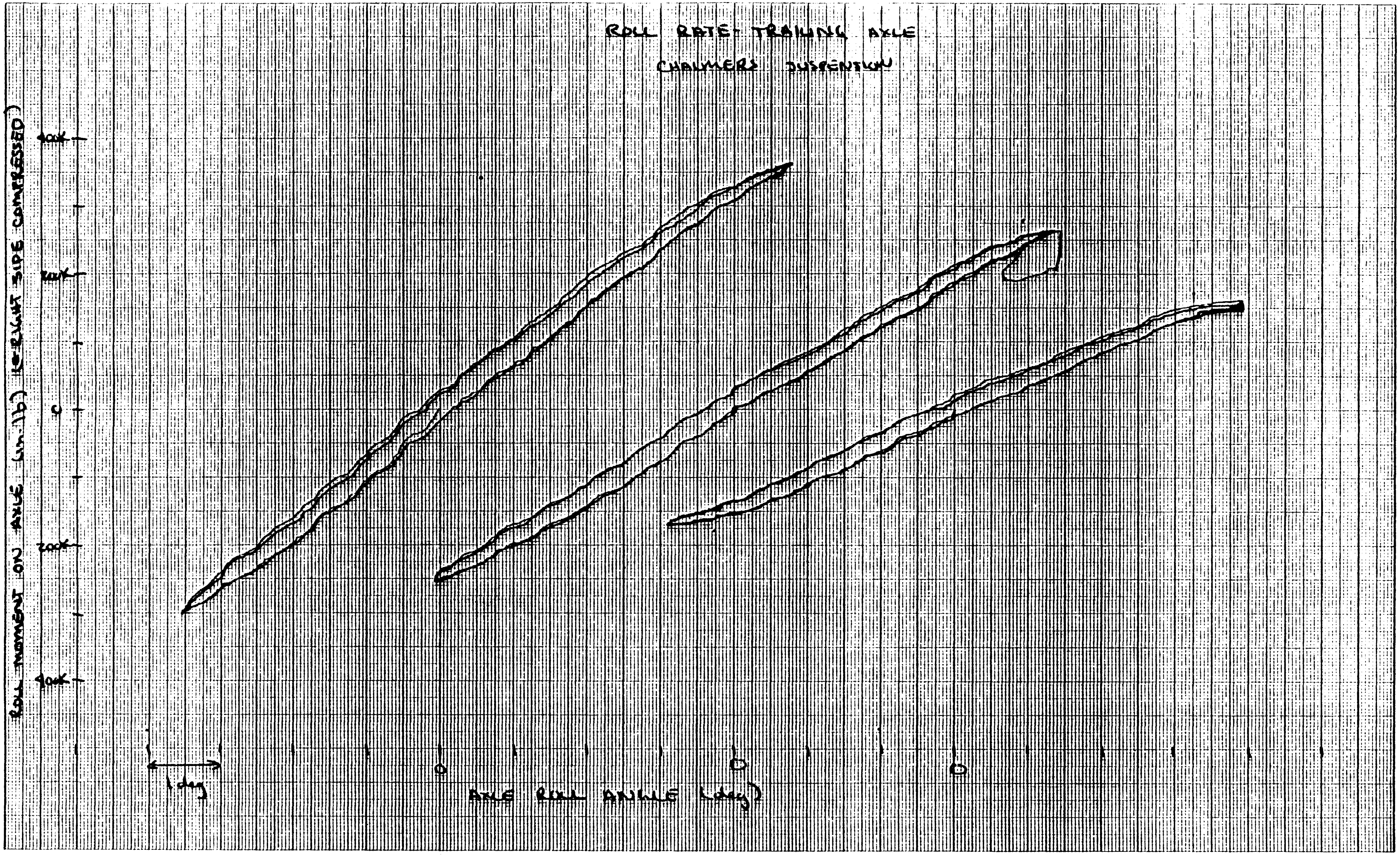
A.6 Chalmers Rubber Spring Walking-Beam


VERTICAL RATE
CHALMERS SUSPENSION

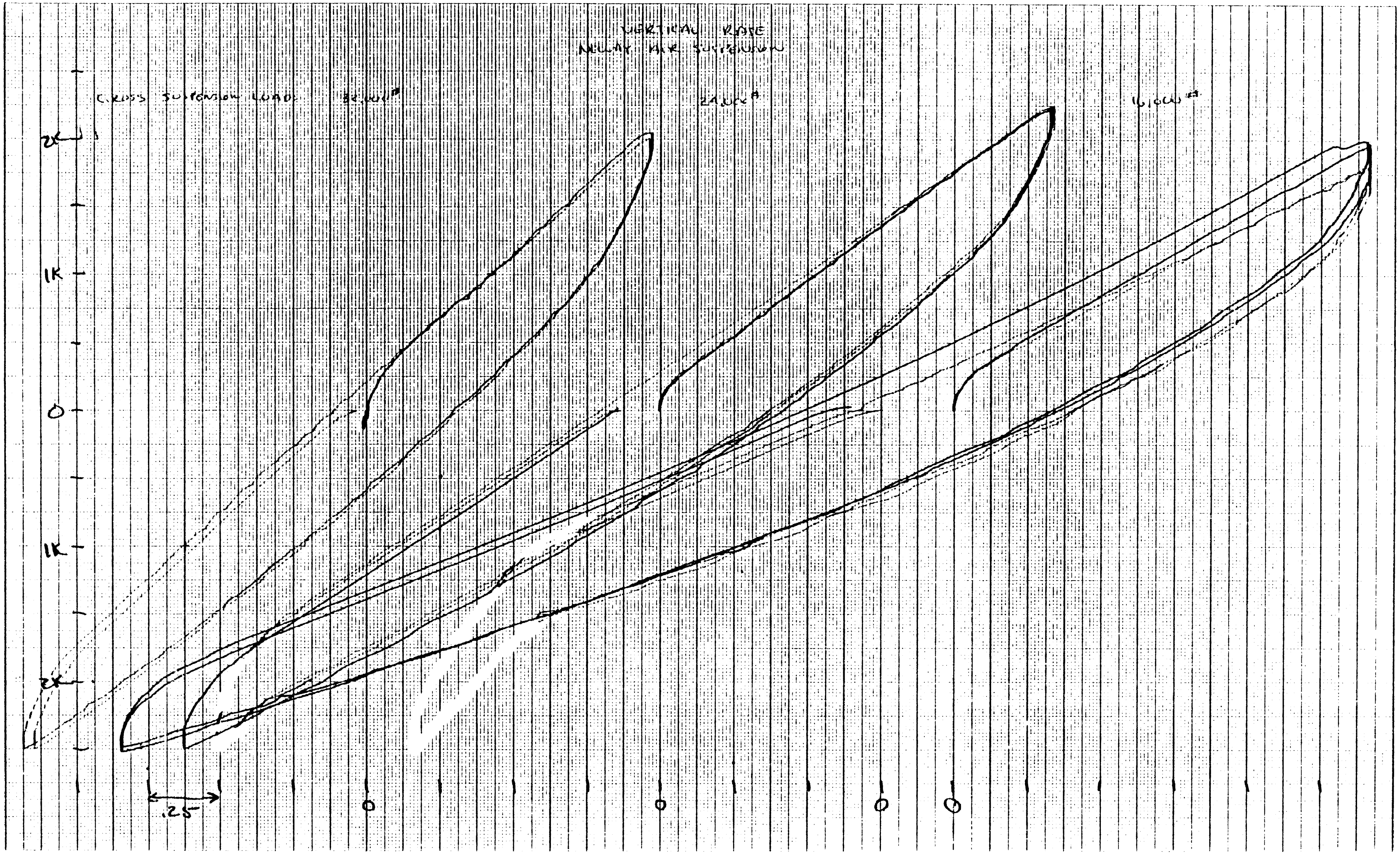


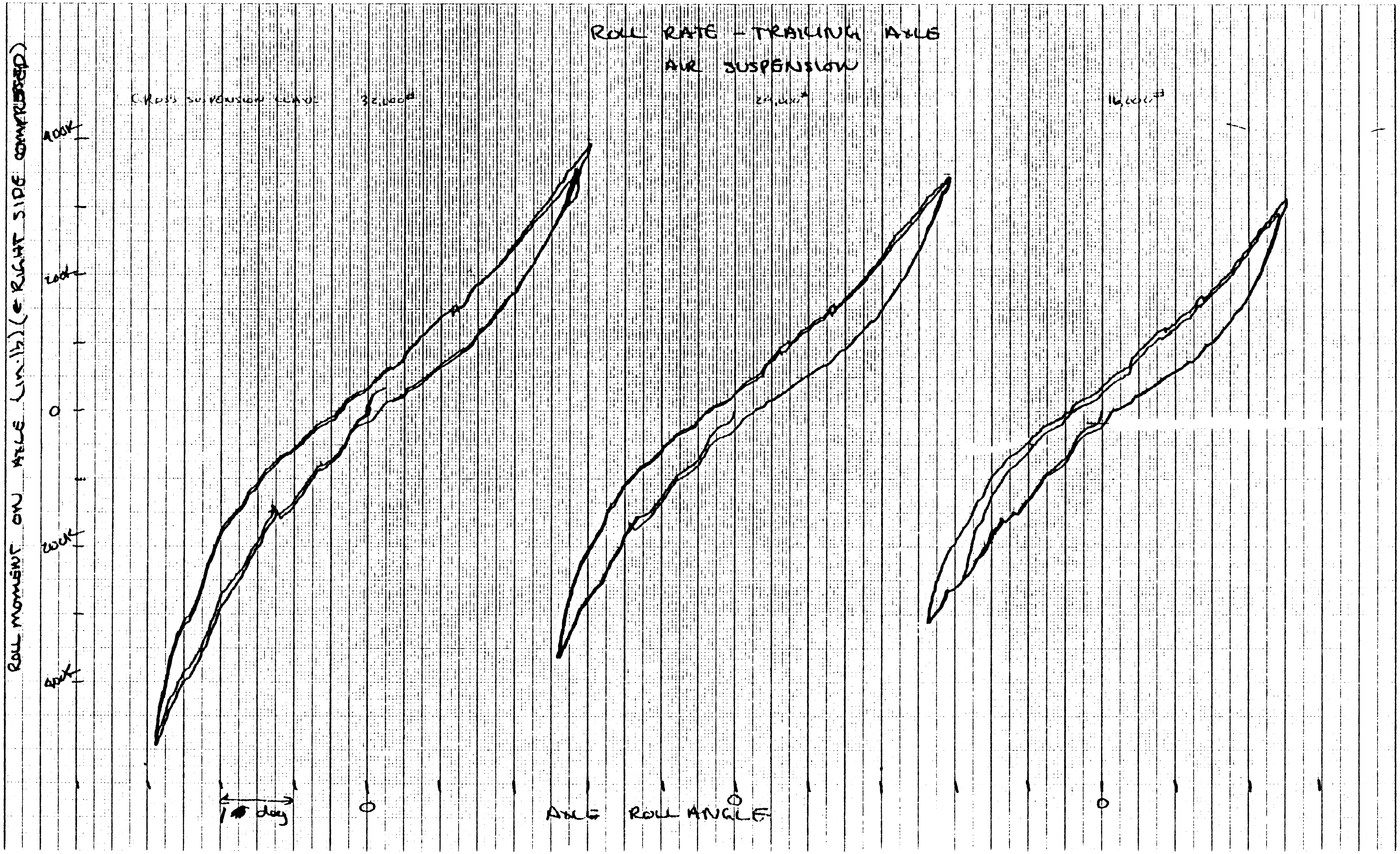
ROLL RATE - LEADING AXLE

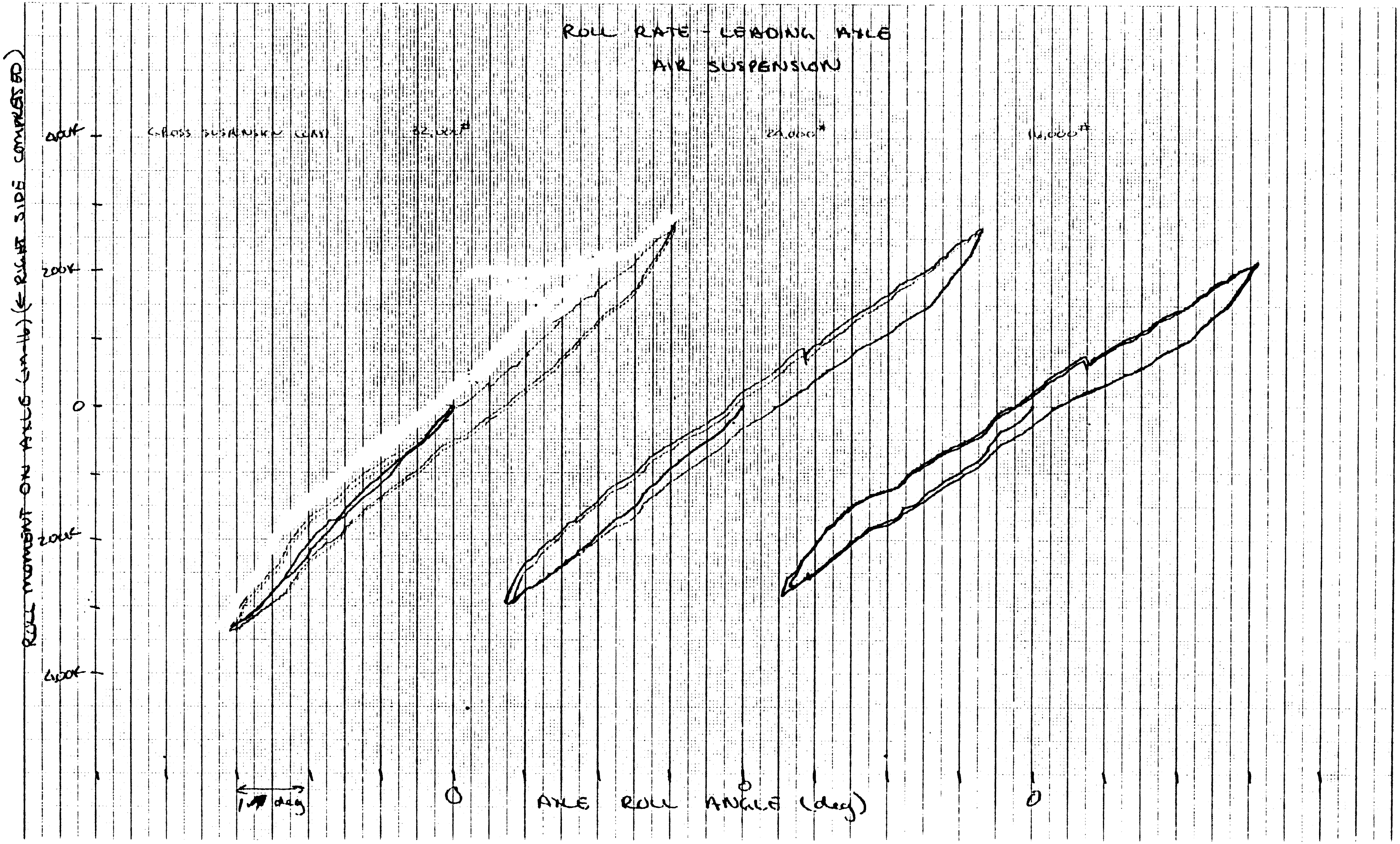
CHALMERS SUSPENSION


ROLL RATE: TRAILING AXLE
CHALMERS SUSPENSION

A.7 Neway Air Suspension


VERTICAL RATE
NEWAY AIR SUSPENSION
CROSS SUSPENSION LOAD 32,000#
24,000#
16,000#
2K
1K
0
1K
2K
.25"
0
0
0
0
47 1510
KEUFFEL & ESSER CO.


ROLL RATE - TRAILING AXLE
AIR SUSPENSION
GROSS SUSPENSION LOAD 32,000#
24,000#
16,000#
ROLL MOMENT ON AXLE (in·lb) (← RIGHT SIDE COMPRESSED)
400K
200K
0
200K
400K
1° deg
0
0
0
AXLE ROLL ANGLE


ROLL RATE - LEADING AXLE
AIR SUSPENSION

APPENDIX B

EXAMPLE LISTING OF VEHICLE PARAMETERS

(See Reference [2] for reference to the details of this computer model)

```
-9999.000
        8300 GAL NITROGEN TANKER WITH NEWAY, PETERBUILT TRACTOR

 WU1 =  1200.  WU2 =  4600.  WU3 =  3000.  WAXL1 =  12000.  WAXL2 =  34000.  WAXL3 =  34000.

T1 =  40.50 A1 =   0.0  T2 =  29.00 A2 =  13.00 T3 =  29.00 A3 =  13.00 S1 =  16.00 S2 =  19.00 S3 =  19.00

 ZS1 =  44.00 ZS2 =  40.00 ZS3 =  90.21 Z1 =  20.00Z2 =  20.00 Z3 =  20.00

 HR1 =  22.00 HR2 =  28.00 HR3 =  17.00 Z5 =  48.00 ZFR =  35.00

 KT11 =    5000.0 KT21 =   10000.0 KT31 =   10000.0 KRS1 =          0. KRS2 =     25000. KRS3 =    200000.

 MFR =     9000.0 COULFR =    10000.0 M5 =  1000000.0 MOMSEP = 495000.0

 LASH5 =    3.3 W5 =  27500.0 WS2 =   1000.0

 KYT1 =    3000.0 KYT2 =    6000.0 KYT3 =    6000.0

 KOVT1 =    1000.0 KOVT2 =    2000.0 KOVT3 =    2000.0
 DELPH =   0.02 XPRINT =   0.50

  SPRING TABLE:  1
NO. OF DATA POINTS IN TABLE :   2

   FORCE        DEFLECTION
-15000.000        -10.000
 15000.000         10.000

  SPRING TABLE:  2
NO. OF DATA POINTS IN TABLE :  10




   FORCE        DEFLECTION
-11000.000         -4.627
    0.0            -1.627
    0.0            -1.127
  2200.000         -0.752
  4300.000         -0.502
  9400.000         -0.125
 14800.000          0.0
 19000.000         -0.125
 20700.000          0.248
 36700.000          1.248

  SPRING TABLE:  3
NO. OF DATA POINTS IN TABLE :   2

   FORCE        DEFLECTION
-16000.000         -8.000
 16000.000          8.000
DATA FROM:
    0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.850      0.850      0.850      0.850      0.850      0.850      0
```

```
           6000 GAL OXYGEN TANKER WITH CHALMERS, MACK TRACTOR

  WU1 =  1200.  WU2 =  4600.  WU3 =  3000.  WAXL1 =  12000.  WAXL2 =  34000.  WAXL3 =  34000.

 T1 =  40.50 A1 =    0.0  T2 =  29.00 A2 =  13.00 T3 =  29.00 A3 =  13.00 S1 =  16.00 S2 =  19.00 S3 =  19.00

  ZS1 =  44.00 ZS2 =  40.00 ZS3 =  85.60 R1 =  20.00R2 =  20.00 R3 =  20.00

  HR1 =  22.00 HR2 =  32.20 HR3 =  30.00 Z5 =  48.00 ZFR =  35.00

  KT11 =    5000.0 KT21 =   10000.0 KT31 =   10000.0 KRS1 =          0. KRS2 =     32000. KRS3 =     35000.

  MFR =     9000.0 COULFR =    10000.0 M5 =  1000000.0 MOMSEP = 513000.0

  LASH5 =    3.3 W5 =  28500.0 WS2 =   1000.0

  KYT1 =    3000.0 KYT2 =    6000.0 KYT3 =    6000.0

  KOVT1 =    1000.0 KOVT2 =    2000.0 KOVT3 =    2000.0
  DELTH =   0.02 XPRINT =   0.50

   SPRING TABLE:  1
 NO. OF DATA POINTS IN TABLE :    2

    FORCE        DEFLECTION
 -15000.000         -10.000
  15000.000          10.000

   SPRING TABLE:  2
 NO. OF DATA POINTS IN TABLE :  10

    FORCE        DEFLECTION
 -16000.000          -3.325
      0.0            -1.825
      0.0            -1.275
   1200.000          -1.000
   2700.000          -0.750
   7400.000          -0.250
  14900.000           0.0
  16800.000           0.063
  17800.000           0.100
  34900.000           0.740

   SPRING TABLE:  3
 NO. OF DATA POINTS IN TABLE :  10

    FORCE        DEFLECTION
 -16000.000          -6.125
      0.0            -4.125
      0.0            -2.500
   3800.000           1.500
   6630.000          -1.000
  13600.000          -0.125
  15500.000           0.0
  17800.000           0.125
  19440.000           0.220
  31000.000           0.890
 DATA FROM:
     0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.850       0.850       0.850       0.850       0.850       0.850       0.8
     0.034       0.439       0.434       0.520       0.052       0.164       0.063       0.730       0.767       0.933       0.970       0.804       0.818       0.8
```

```
          8300 GAL NITROGEN TANKER WITH 4 LEAF, FREIGHTLINER TRACTOR

 WU1 =  1250.  WU2 =  4600.  WU3 =  3000.  WAXL1 =  12000.  WAXL2 =  34000.  WAXL3 =  34000.

 T1 =  40.50 A1 =    0.0  T2 =  29.00 A2 =  13.00 T3 =  29.00 A3 =  13.00 S1 =  16.00 S2 =  19.00 S3 =  19.00

 ZS1 =  44.00 ZS2 =  40.00 ZS3 =  90.21 Z1 =  20.00Z2 =  20.00 Z3 =  20.00

 HR1 =  22.00 HR2 =  29.00 HR3 =  28.00 ZS =  48.00 ZFR =  35.00

 KT11 =    5000.0 KT21 =   10000.0 KT31 =   10000.0 KHS1 =          0. KHS2 =     50000. KHS3 =     44000.

 MFR =     9000.0 COULFR =    10000.0 MS =  1000000.0 MOMSEP = 495000.0

 LASHS =    3.3 WS =  27500.0 WS2 =   1000.0

 KYT1 =    3000.0 KYT2 =    6000.0 KYT3 =    6000.0

 KOVT1 =    1000.0 KOVT2 =    2000.0 KOVT3 =    2000.0
 DELTH =   0.02 XPRINT =   0.50

  SPRING TABLE:  1
NO. OF DATA POINTS IN TABLE :   2

  FORCE        DEFLECTION
-15000.000        -10.000
 15000.000         10.000

  SPRING TABLE:  2
NO. OF DATA POINTS IN TABLE :  10

  FORCE        DEFLECTION
-10000.000         -4.625
     0.0           -2.625
     0.0           -1.875
  2400.000         -1.250
  5900.000         -0.750
 10400.000         -0.250
 15000.000          0.0
 17500.000          0.100
 18000.000          0.163
 30000.000          1.663

  SPRING TABLE:  3
NO. OF DATA POINTS IN TABLE :  10

  FORCE        DEFLECTION
-16000.000         -5.560
     0.0           -3.560
     0.0           -1.756
  2600.000         -1.060
  4700.000         -0.756
 12300.000         -0.125
 15500.000          0.0
 18600.000          0.125
 19600.000          0.244
 33200.000          1.244
DATA FROM:
     0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.850      0.850      0.850      0.850      0.850      0.850      0.85
     0.048      0.473      0.464      0.520      0.068      0.159      0.187      0.734      0.770      0.930      0.966      0.713      0.756      0.94
```

```
>          13250 GALLON HELIUM TANKER (W/CHASSIS), MACK TRACTOR

> WU1 =  1200.  WU2 =  4600.  WU3 =  3000.  WAXL1 =  10000.  WAXL2 =  33000.  WAXL3 =  33000.

>T1 =  40.50 A1 =   0.0  T2 =  29.00 A2 =  13.00 T3 =  29.00 A3 =  13.00 S1 =  16.00 S2 =  19.00 S3 =  19.00

> ZS1 =  44.00 ZS2 =  40.00 ZS3 =  95.97 R1 =  20.00R2 =  20.00 R3 =  20.00

> HR1 =  22.00 HR2 =  32.20 HR3 =  28.00 ZS =  48.00 ZFR =  35.00

> KT11 =    3700.0 KT21 =    7400.0 KT31 =    7400.0 KRS1 =          0. KRS2 =     32000. KRS3 =     44000.

> MFR =     9000.0 COULFR =     10000.0 MS =  1000000.0 MUMSEF = 453708.0

> LASHS =    3.3 WS =  25206.0 WS2 =   1000.0

> KYT1 =    3000.0 KYT2 =    6000.0 KYT3 =    6000.0

> KOVT1 =    1000.0 KOVT2 =    2000.0 KOVT3 =    2000.0
> DELPH =   0.02 XFRINT =   0.50

>  SPRING TABLE:  1
>NO. OF DATA POINTS IN TABLE :   2

>   FORCE       DEFLECTION
>-15000.000       -10.000
> 15000.000        10.000

>  SPRING TABLE:  2
>NO. OF DATA POINTS IN TABLE :  10

>   FORCE       DEFLECTION
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>     0.0          -1.825
>     0.0          -1.275
>  1200.000        -1.000
>  2700.000        -0.750
>  7400.000        -0.250
> 14900.000         0.0
> 16800.000         0.063
> 17800.000         0.100
> 34900.000         0.740

>  SPRING TABLE:  3
>NO. OF DATA POINTS IN TABLE :  10

>   FORCE       DEFLECTION
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>     0.0          -3.560
>     0.0          -1.756
>  2600.000        -1.060
>  4700.000        -0.756
> 12300.000        -0.125
> 15500.000         0.0
> 18600.000         0.125
> 19600.000         0.244
> 33200.000         1.244
>DATA FROM:
>    0.0        0.0        0.0        0.0        0.0        0.0        0.0      1.115      1.115      1.115      1.115      1.115      1.115
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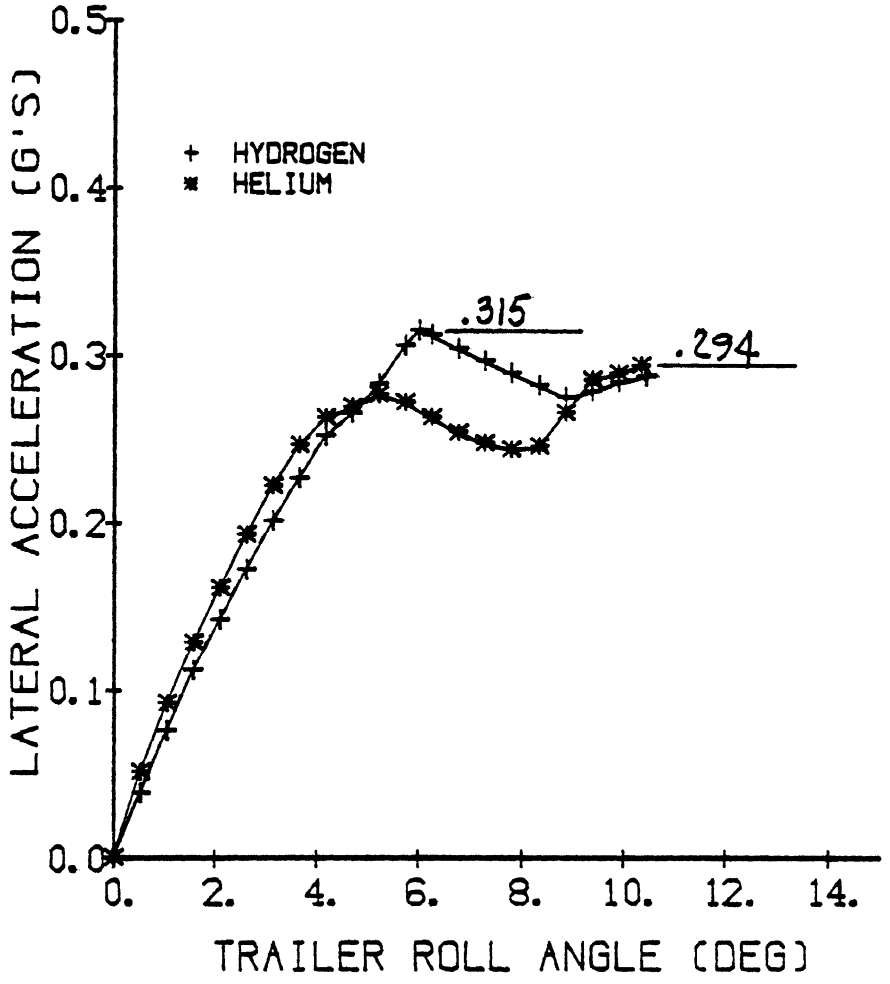
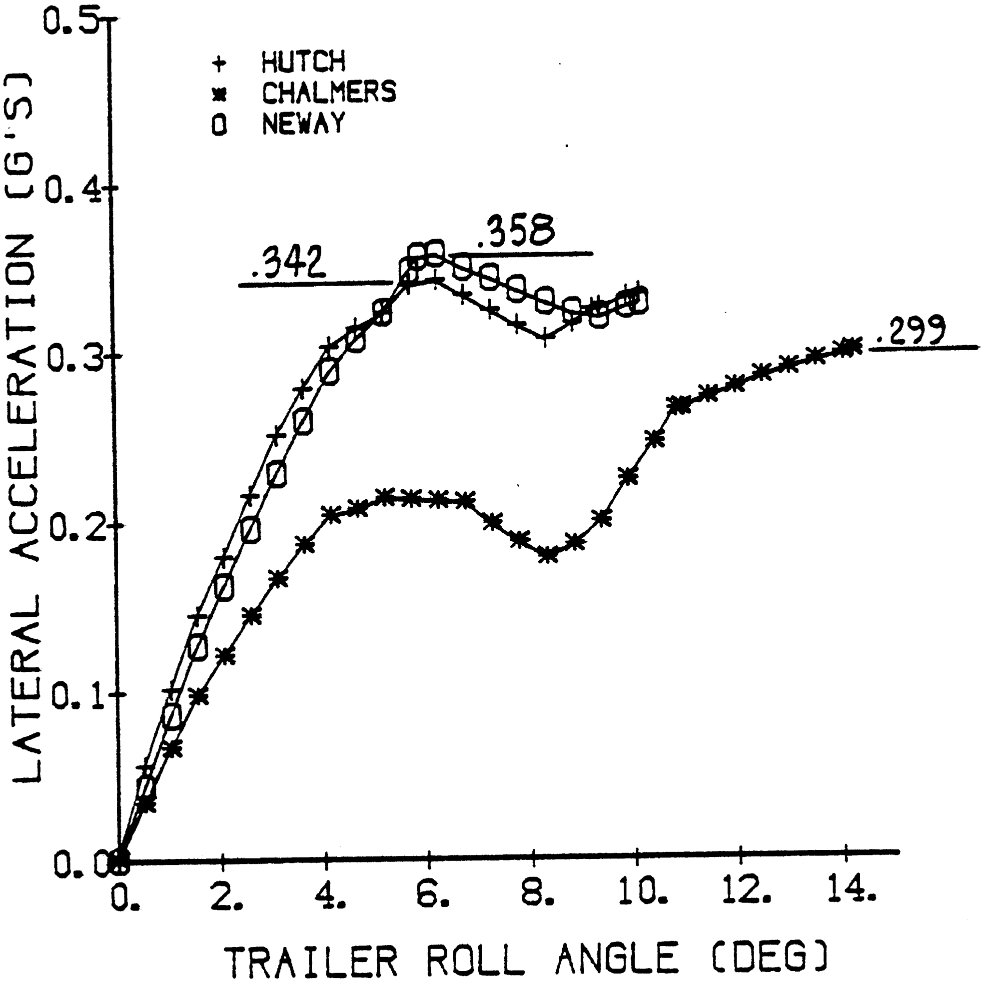
APPENDIX C

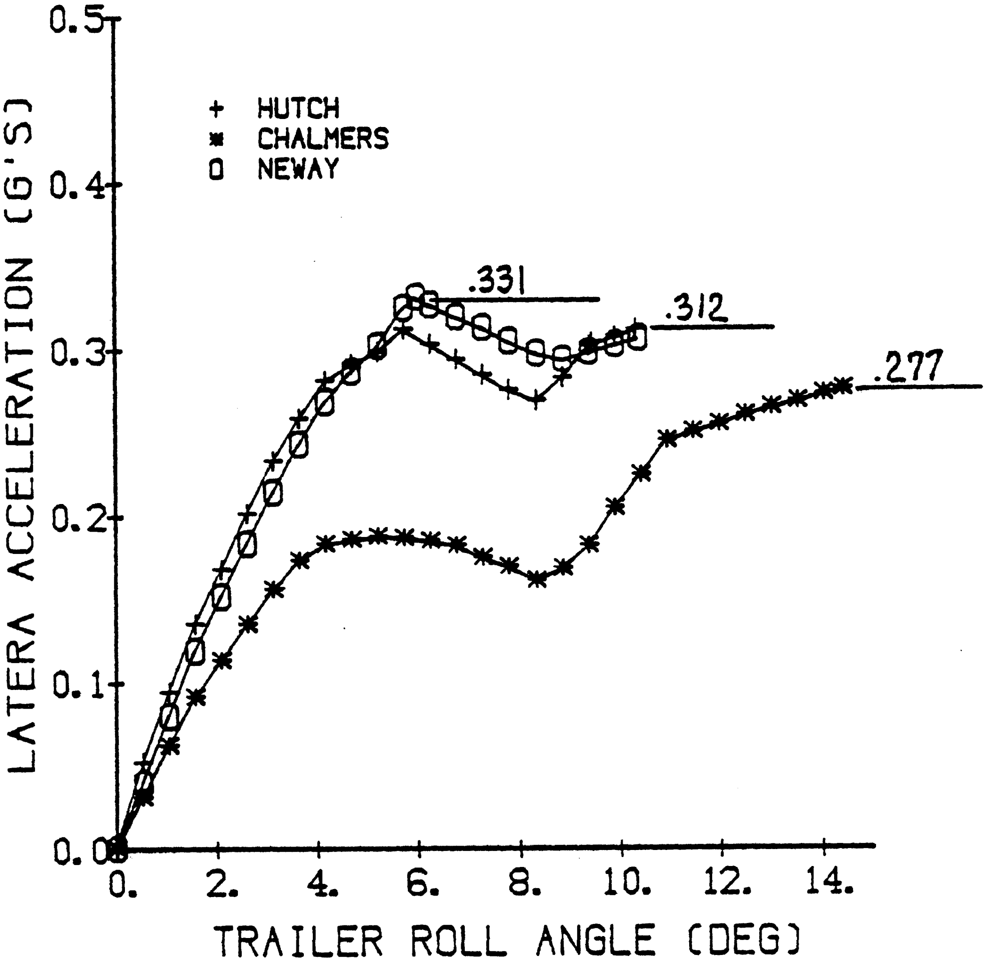
COMPUTER PLOTS OF LATERAL ACCELERATION VERSUS TRAILER ROLL ANGLE FOR VEHICLES IN THE <u>CURRENT FLEET</u>



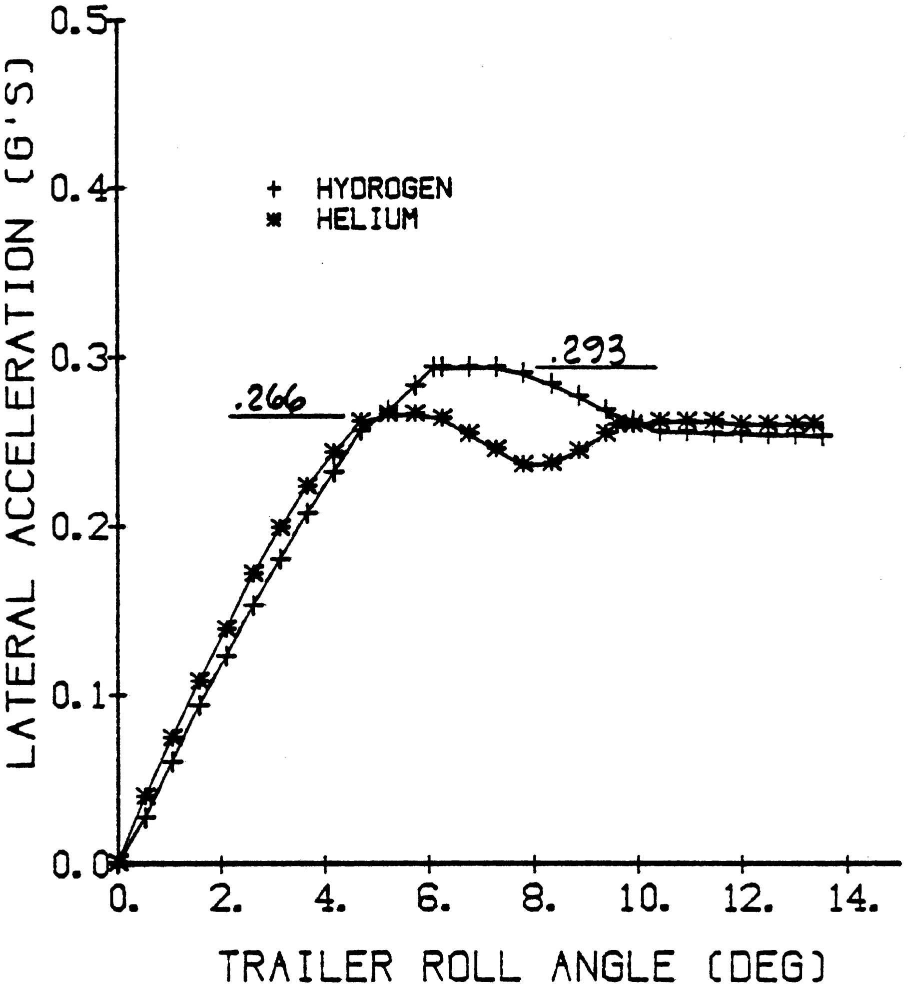
MACK TRACTOR



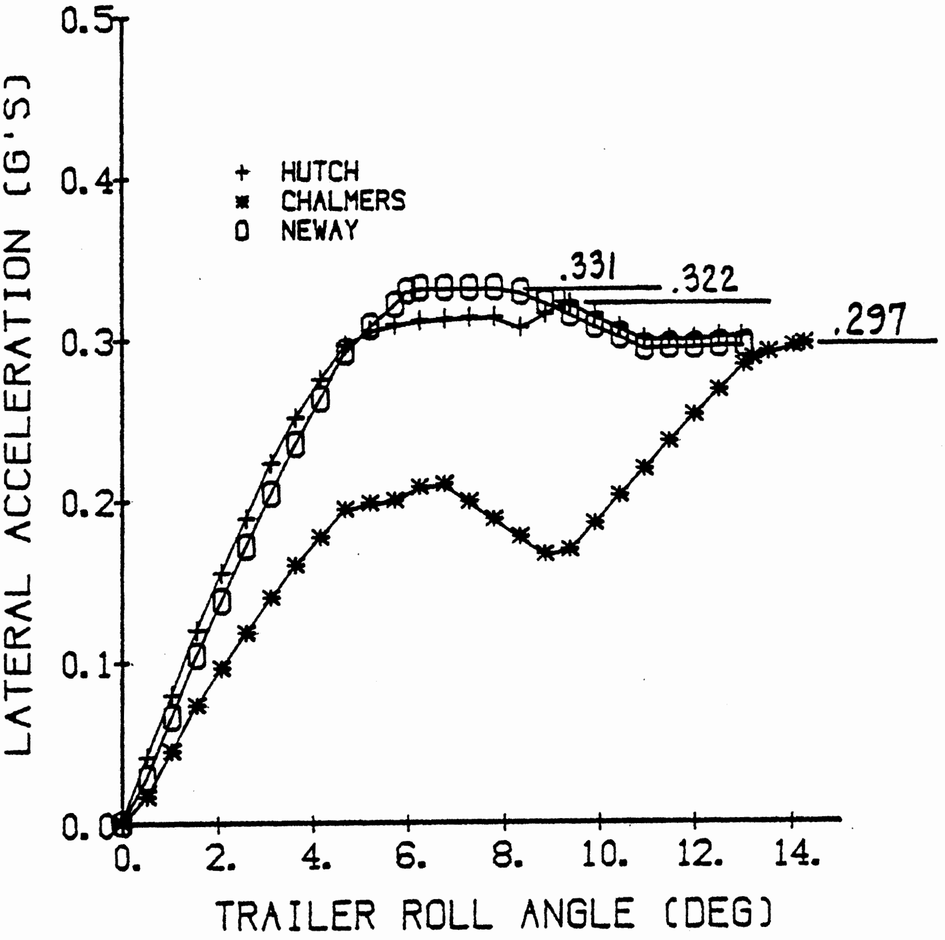
MACK TRACTOR, OXYGEN



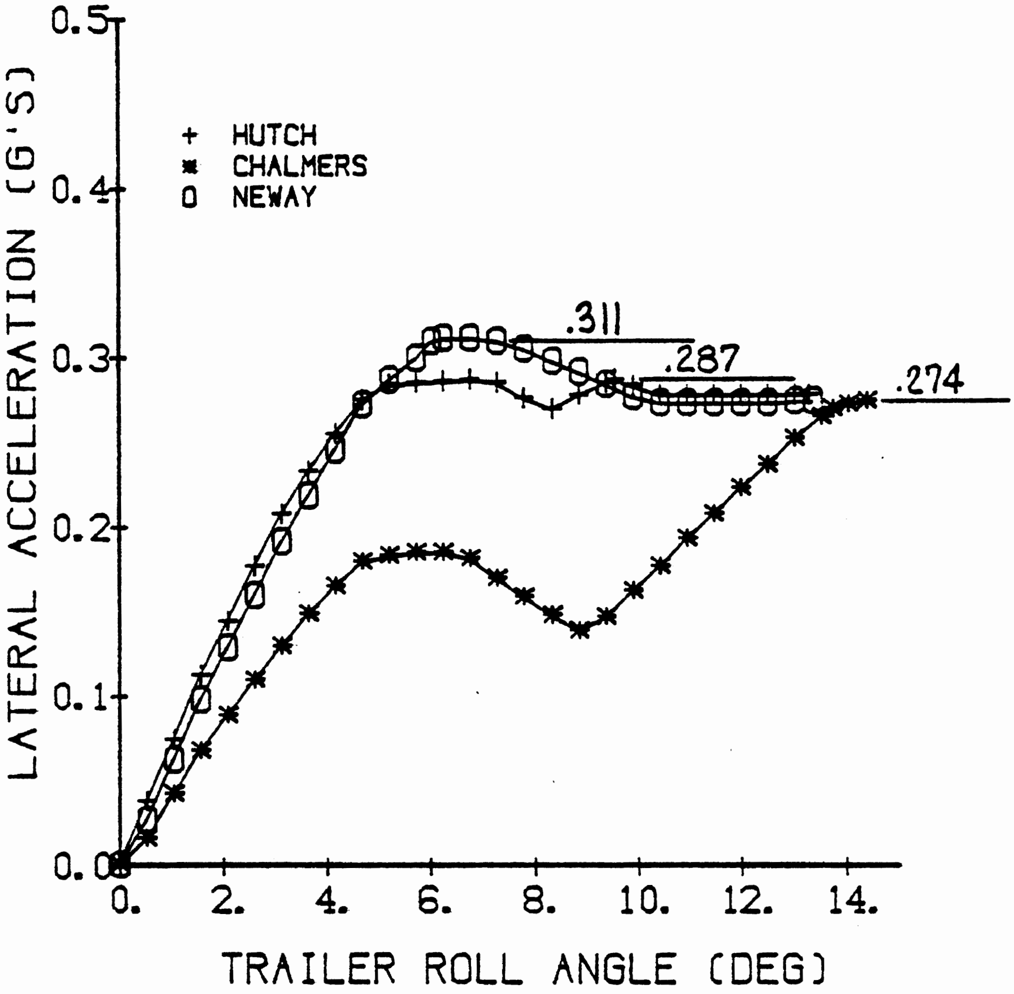
MACK TRACTOR, NITROGEN



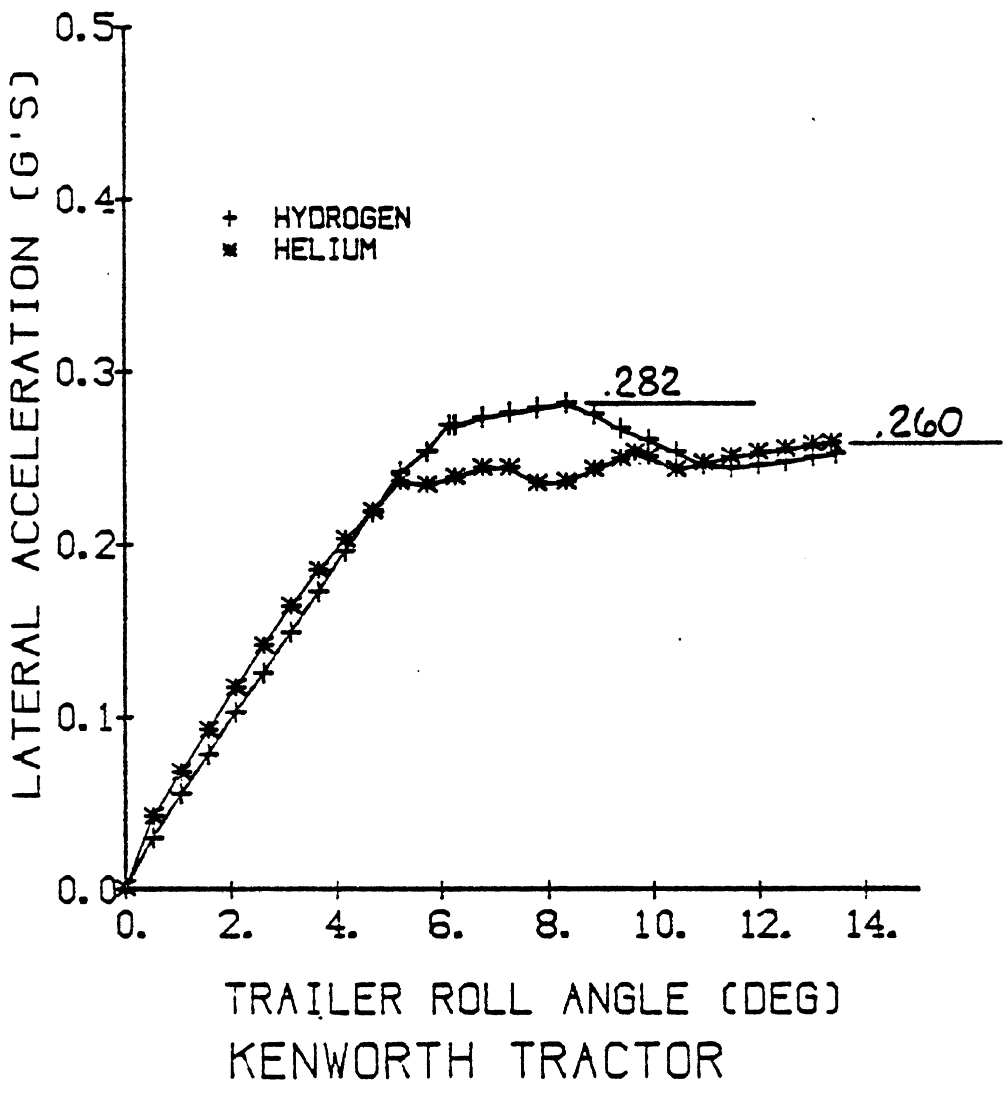
PETERBUILT TRACTOR

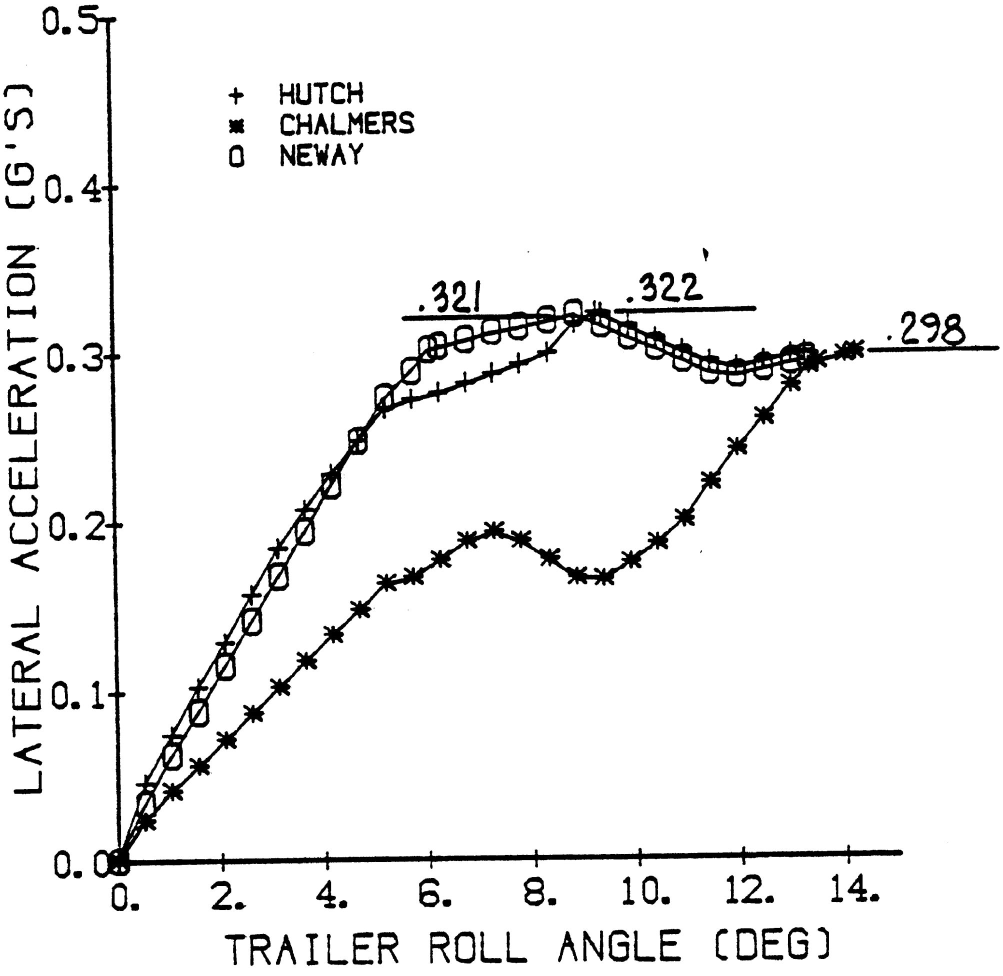


PETERBUILT TRACTOR, OXYGEN

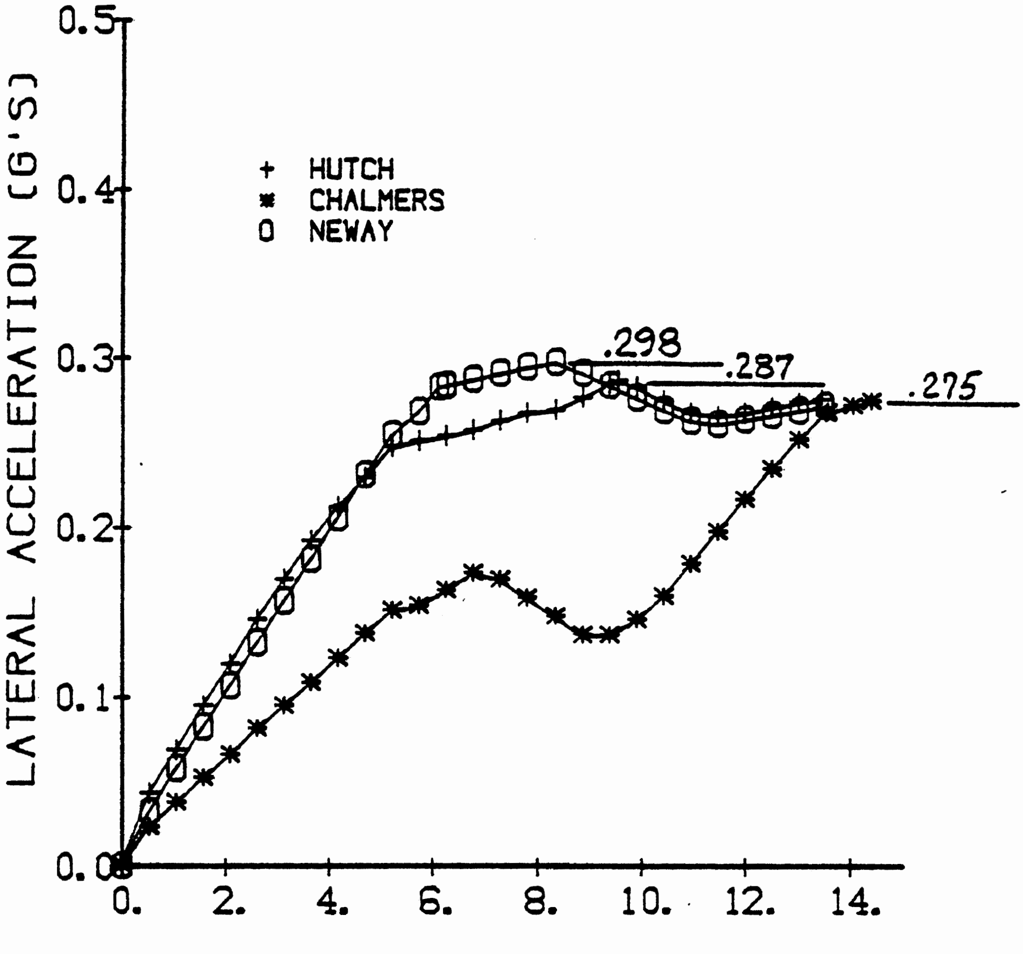


PETERBUILT TRACTOR, NITROGEN

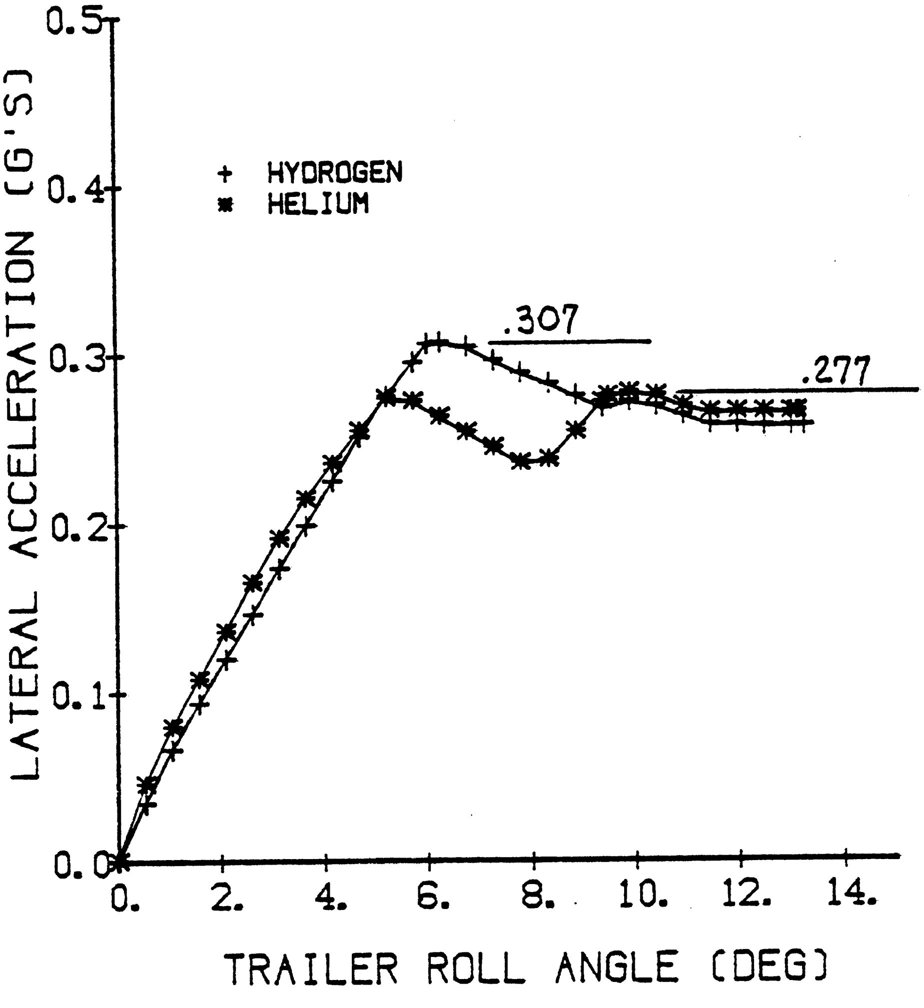

LATERAL ACCELERATION (G'S)
0.0
0.1
0.2
0.3
0.4
0.5
+ HYDROGEN
✱ HELIUM
.282
.260
0.
2.
4.
6.
8.
10.
12.
14.
TRAILER ROLL ANGLE (DEG)
KENWORTH TRACTOR



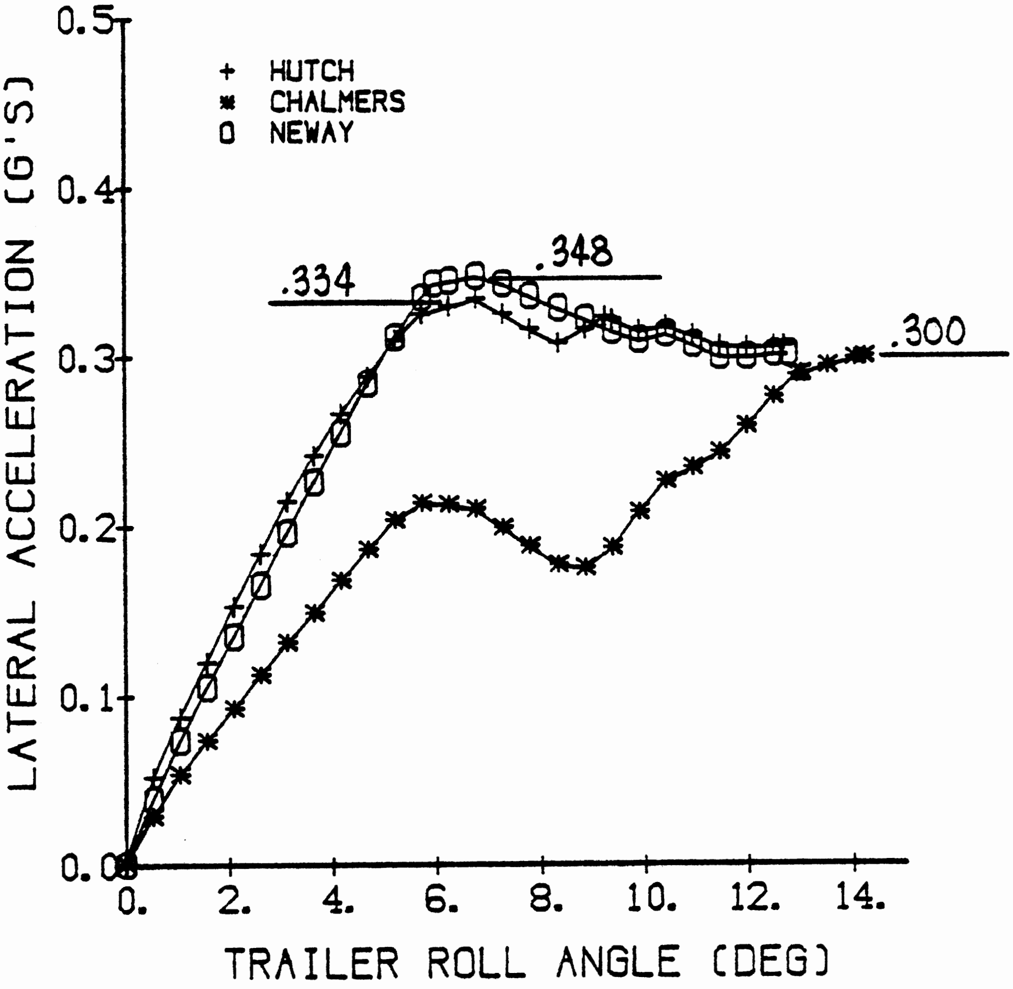
KENWORTH TRACTOR, OXYGEN



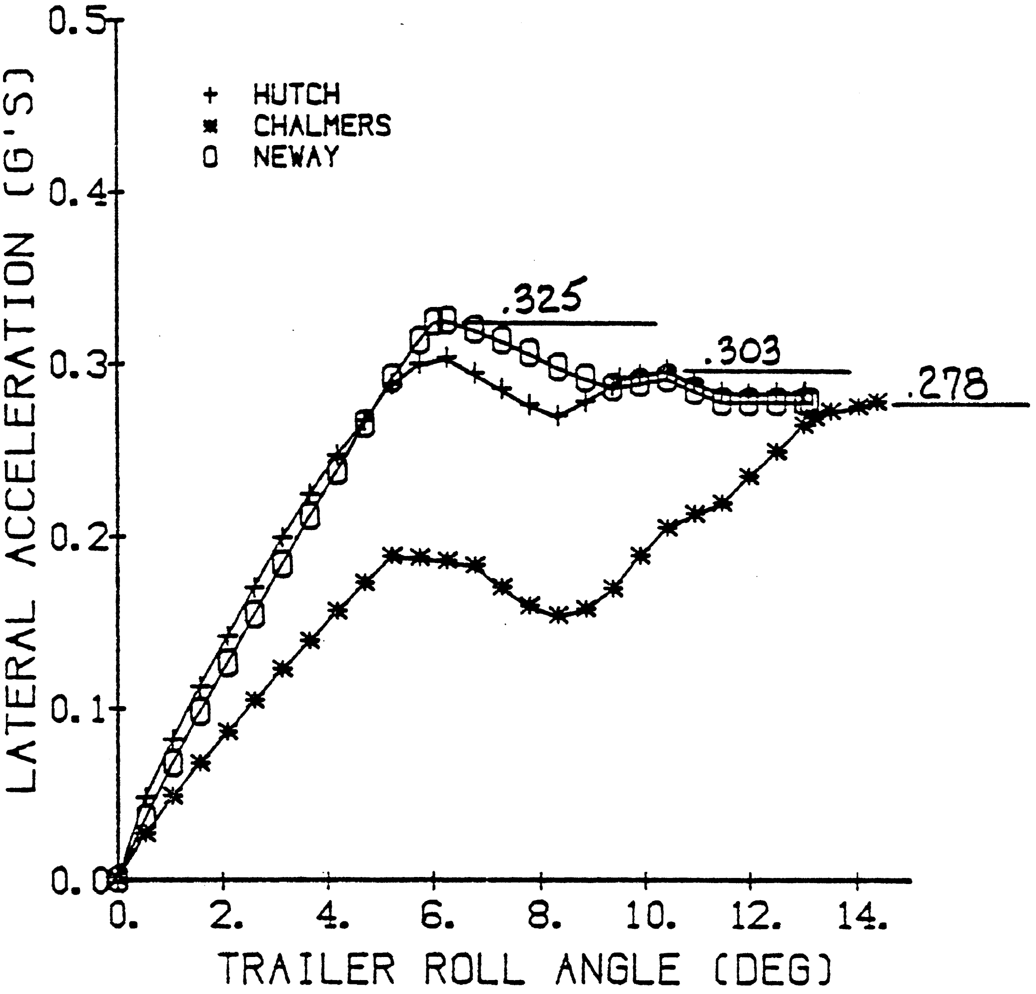
KENWORTH TRACTOR, NITROGEN



FREIGHTLINER TRACTOR



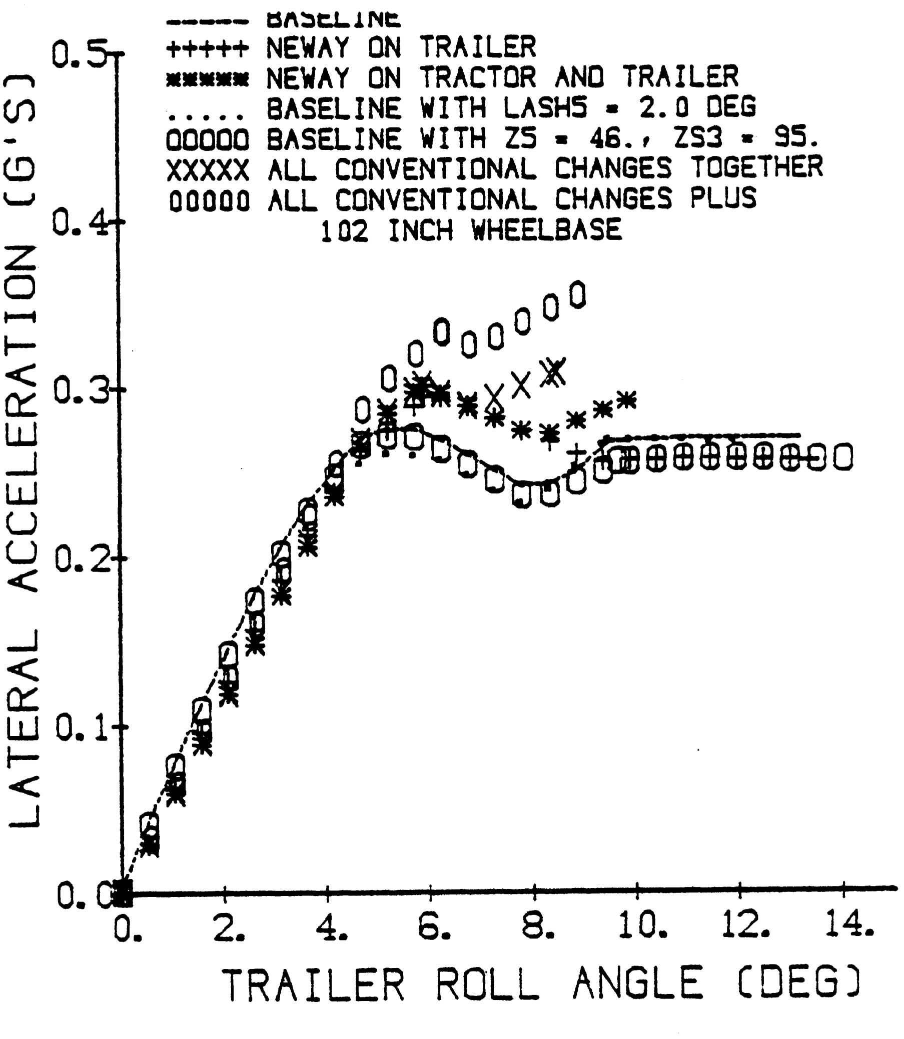
FREIGHTLINER TRACTOR, OXYGEN



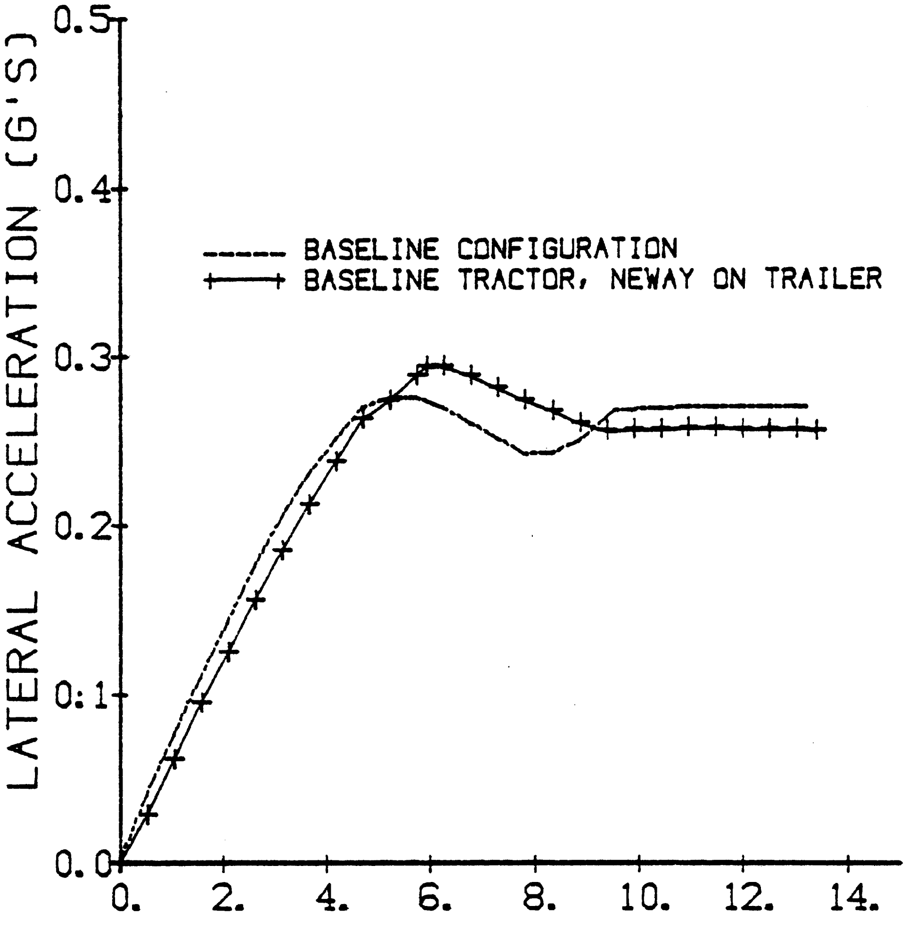
FREIGHTLINER TRACTOR, NITROGEN

APPENDIX D

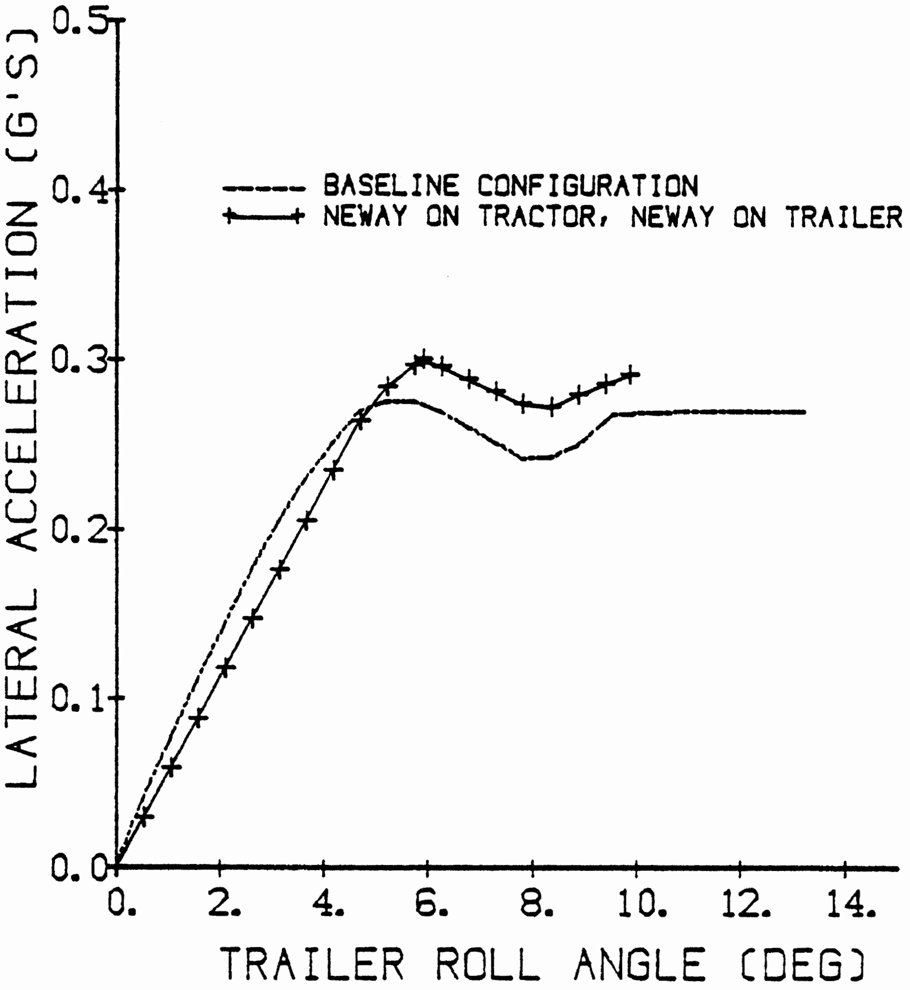
COMPUTER PLOTS OF LATERAL ACCELERATION VERSUS TRAILER ROLL ANGLE SHOWING INFLUENCE OF DESIGN CHANGES



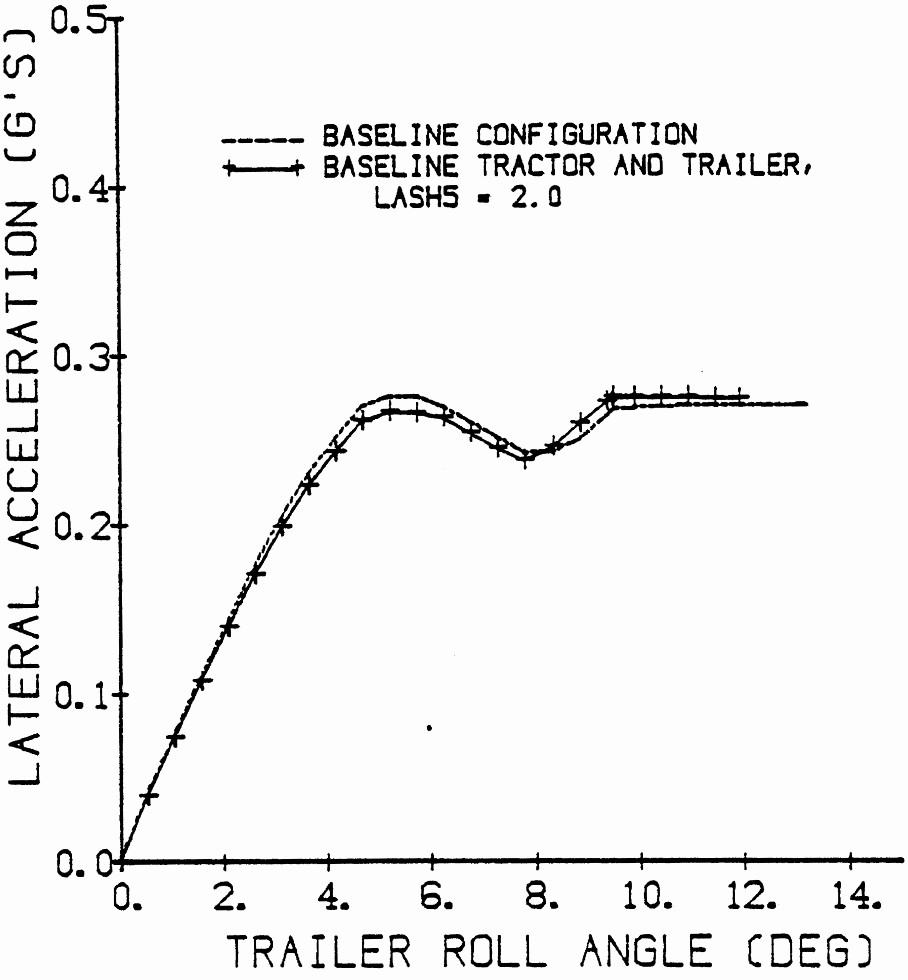
PETERBILT TRACTOR / HELIUM TRAILER



PETERBILT TRACTOR / HELIUM TRAILER



PETERBILT TRACTOR / HELIUM TRAILER



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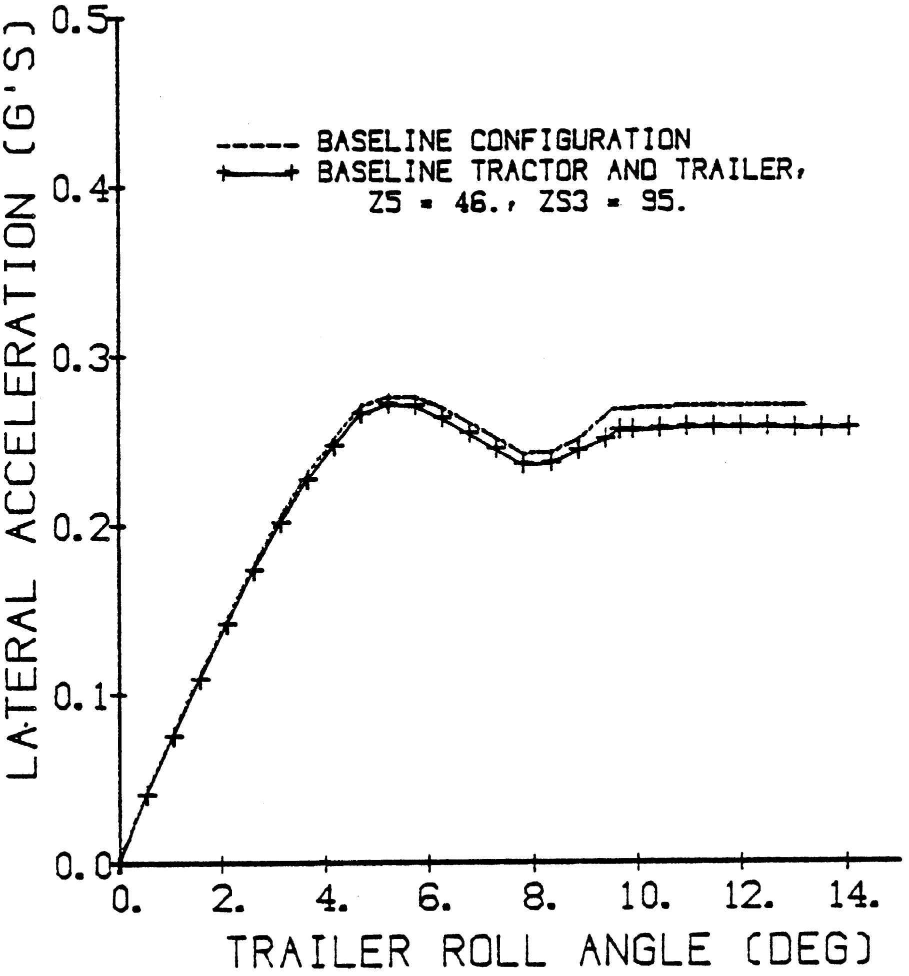
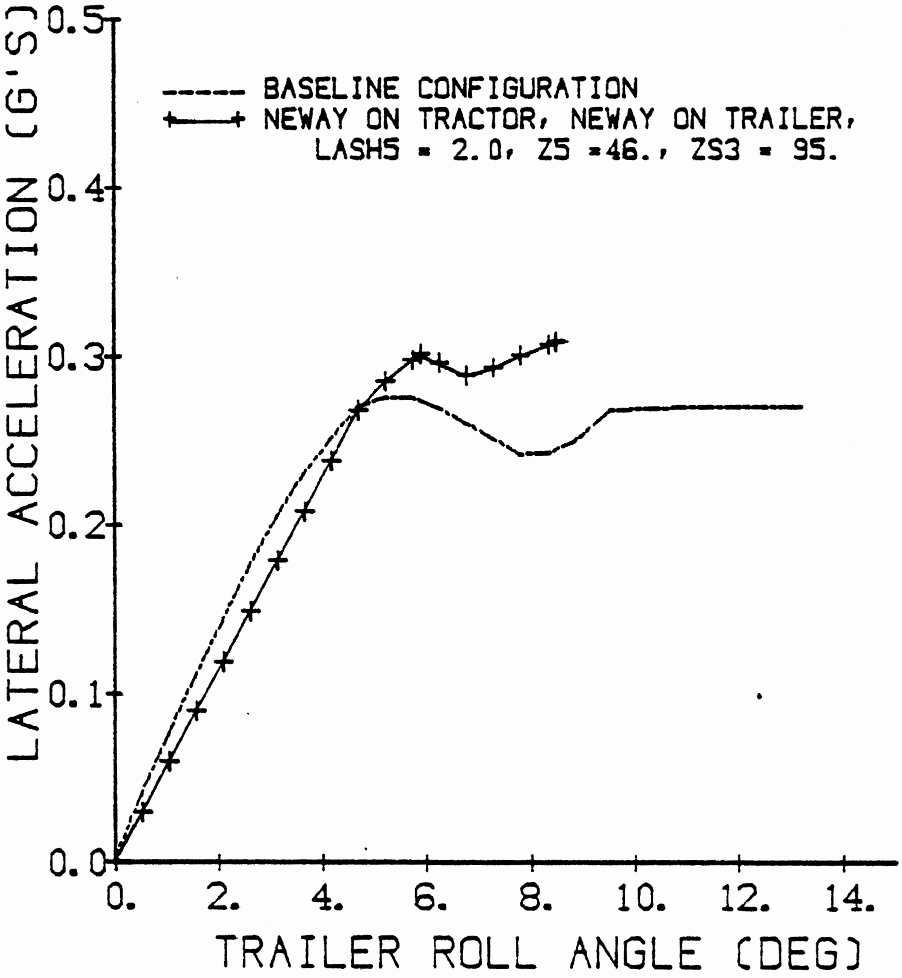
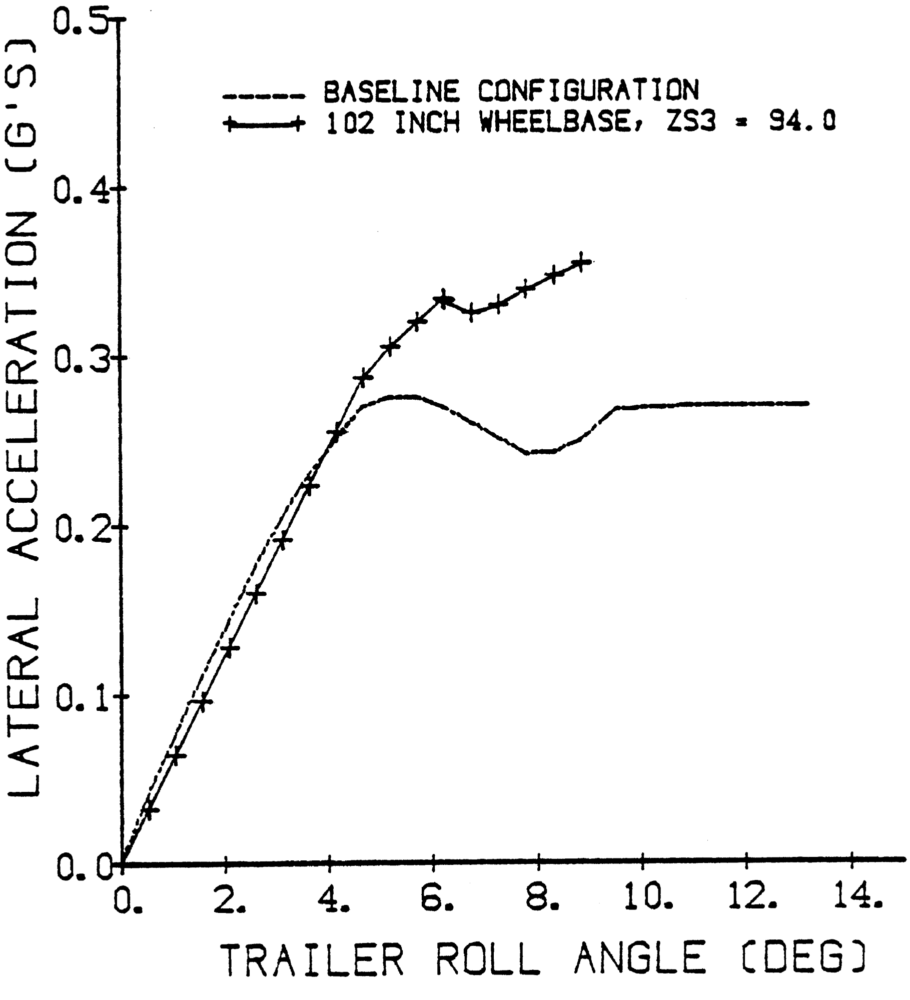


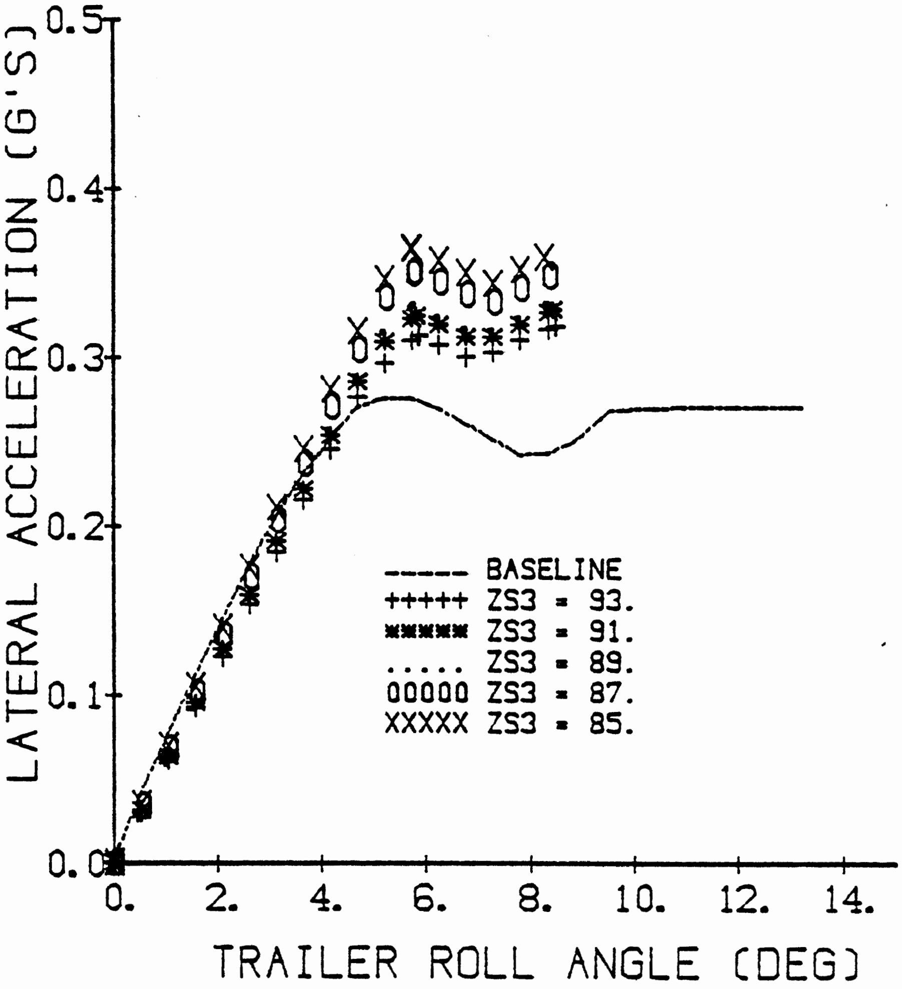
PETERBILT TRACTOR / HELIUM TRAILER



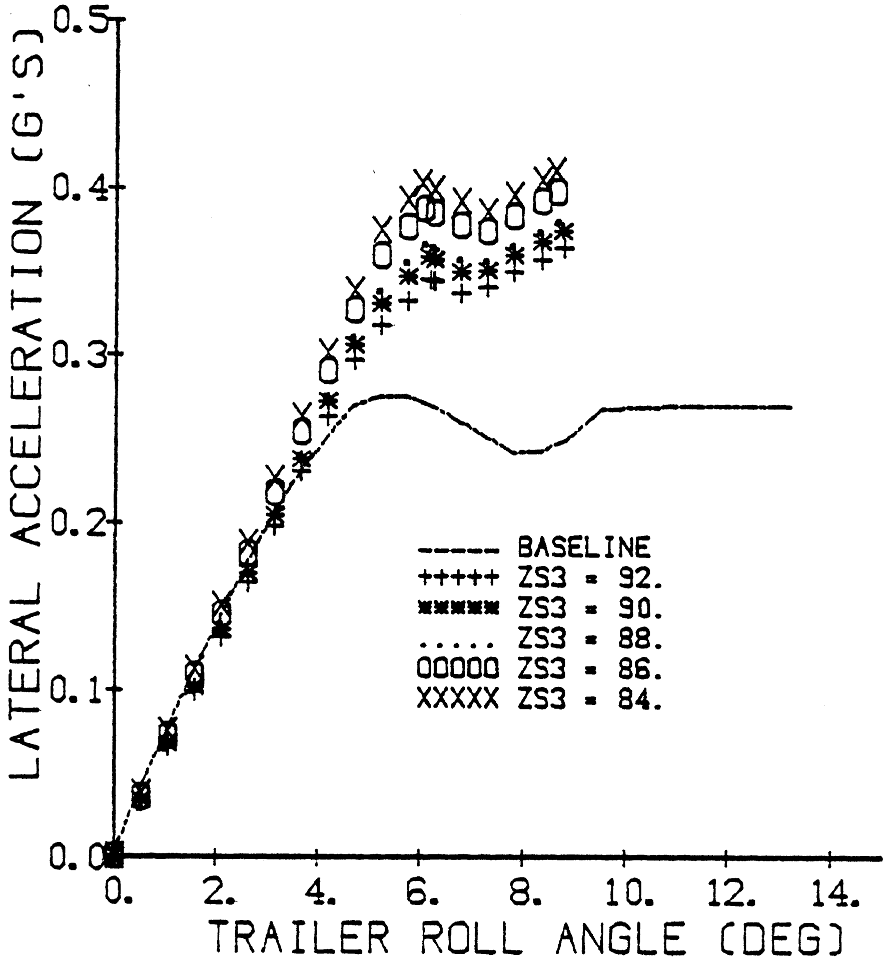
PETERBILT TRACTOR / HELIUM TRAILER



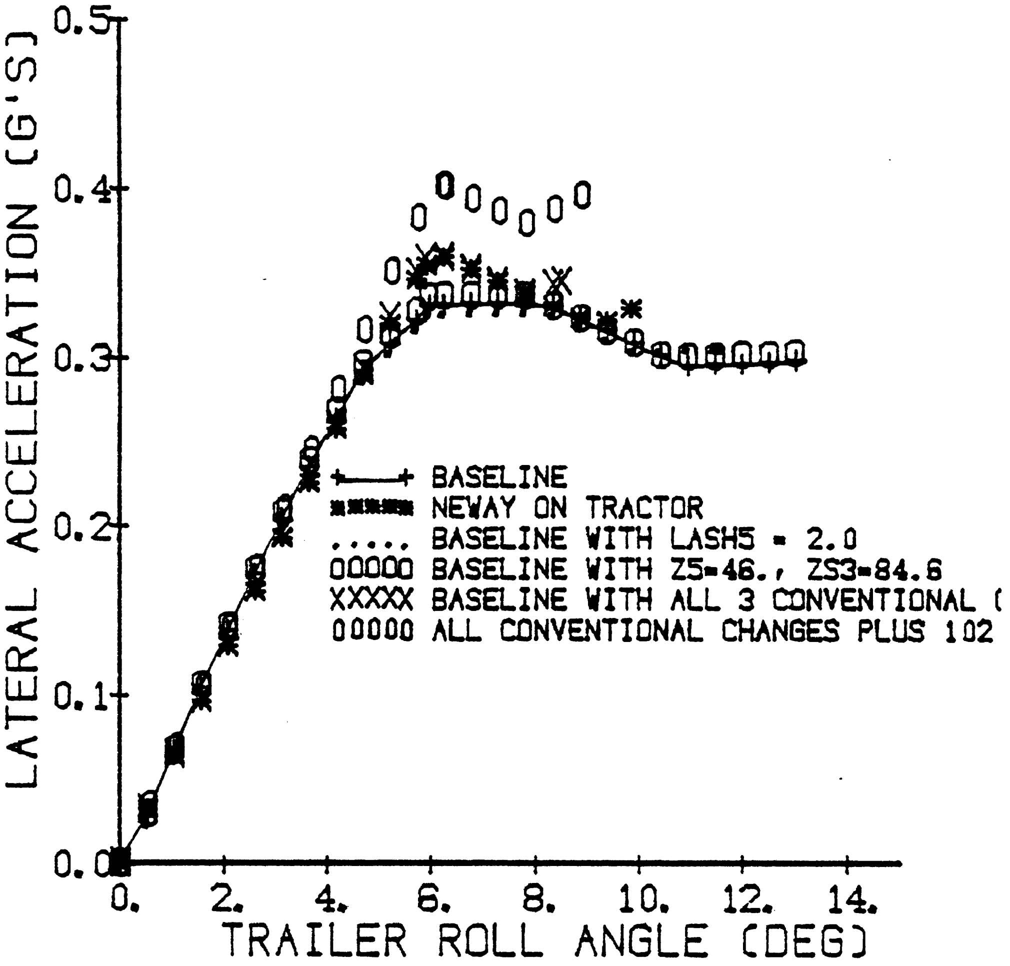
PETERBILT TRACTOR / HELIUM TRAILER



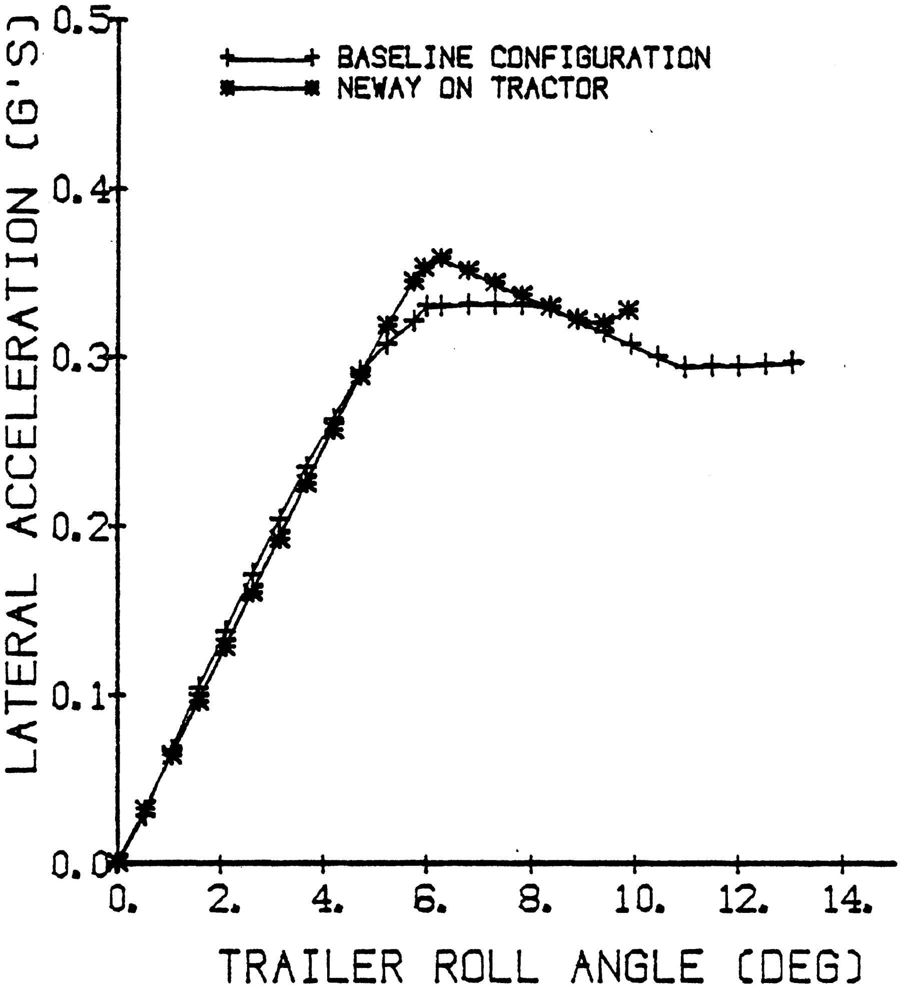
C.G. REDUCTION
WITH ALL CONVENTIONAL CHANGES



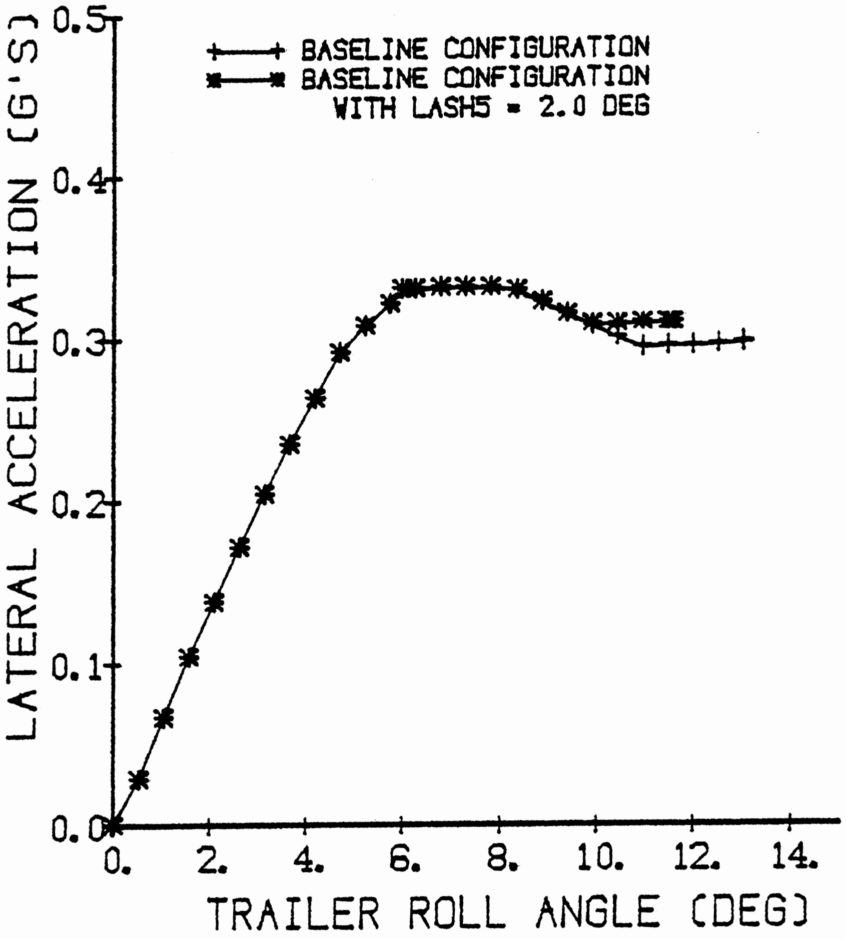
C.G. REDUCTION
WITH CONVENTIONAL CHANGES
PLUS 102 INCH WHEELBASE



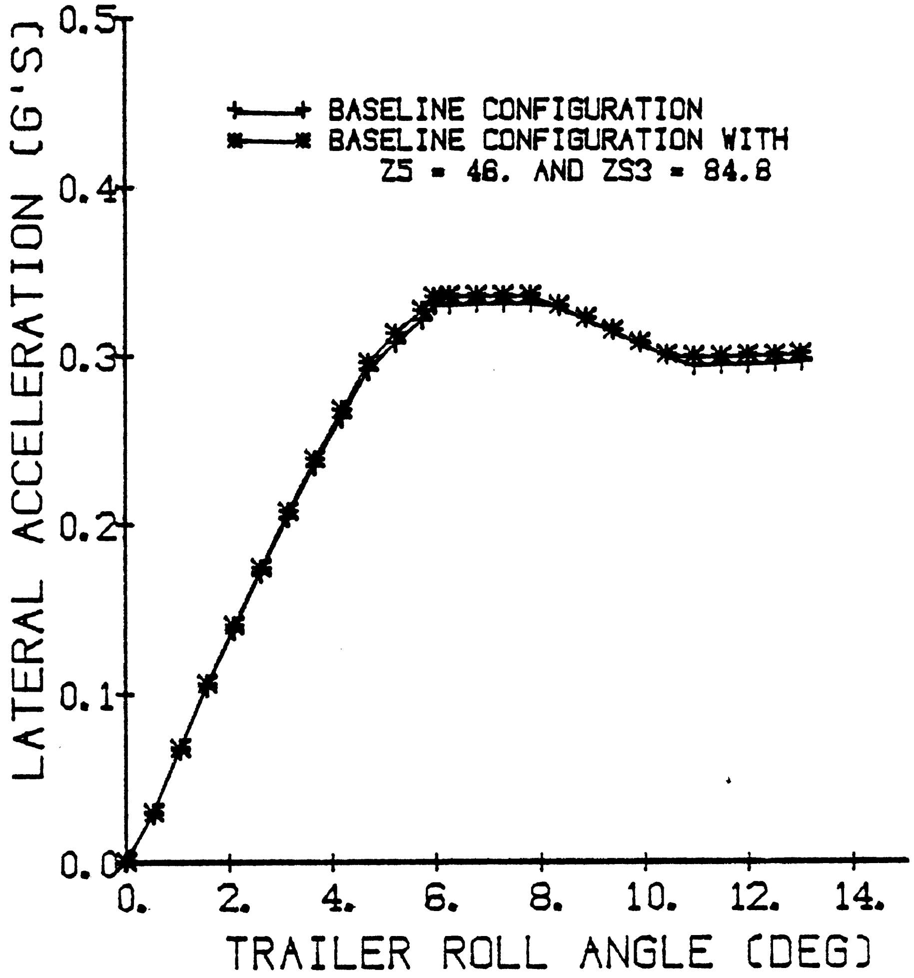
PETERBILT TRACTOR / OXYGEN TRAILER



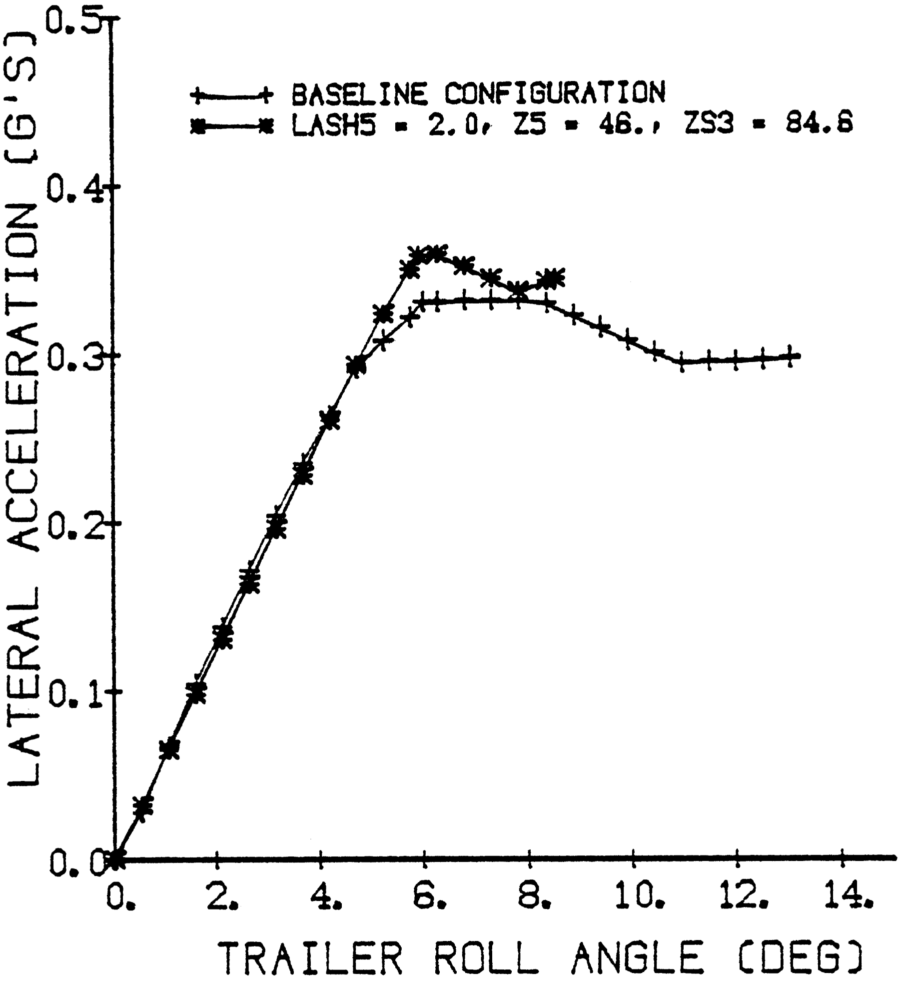
PETERBILT TRACTOR / OXYGEN TRAILER



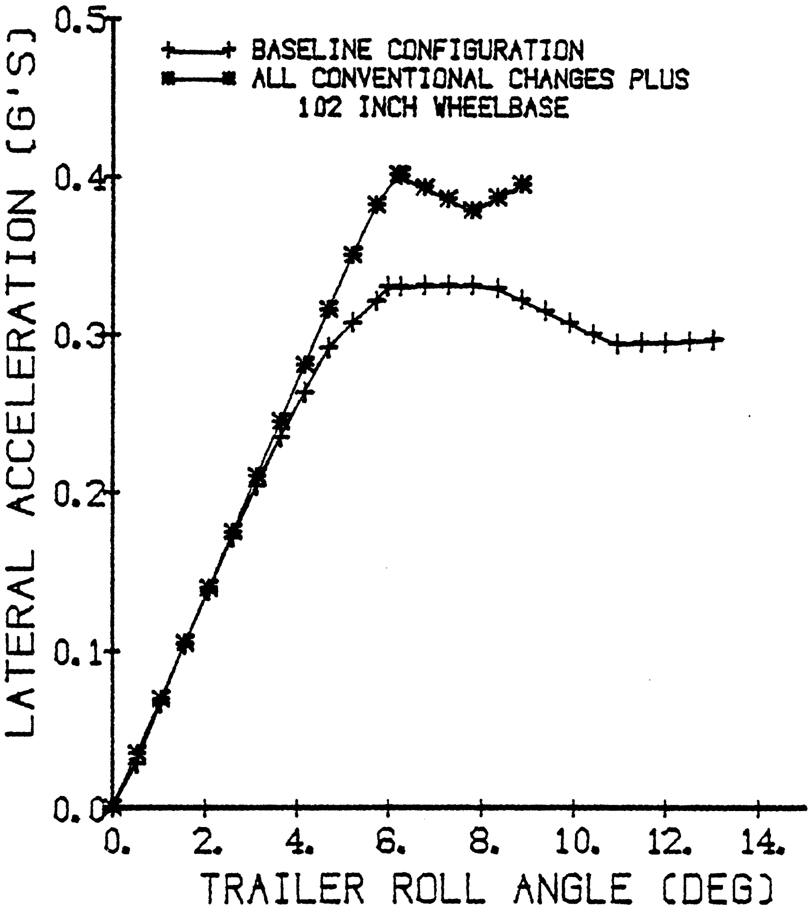
PETERBILT TRACTOR / OXYGEN TRAILER



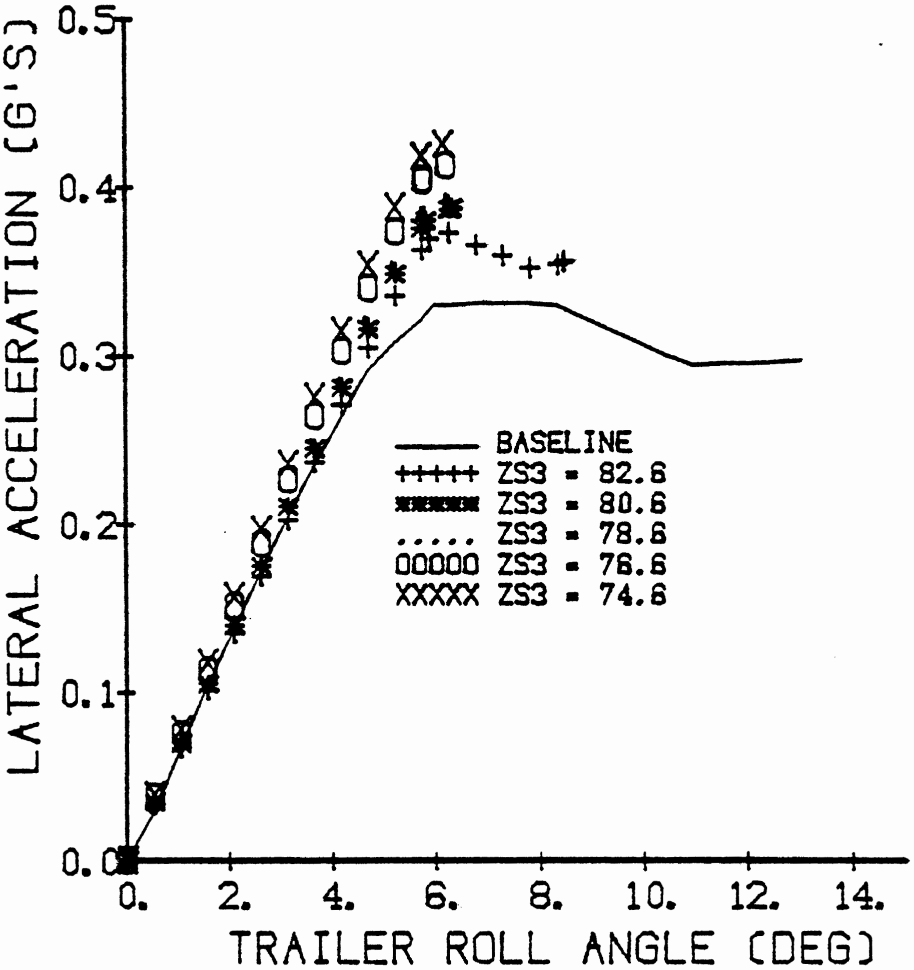
PETERBILT TRACTOR / OXYGEN TRAILER



PETERBILT TRACTOR / OXYGEN TRAILER

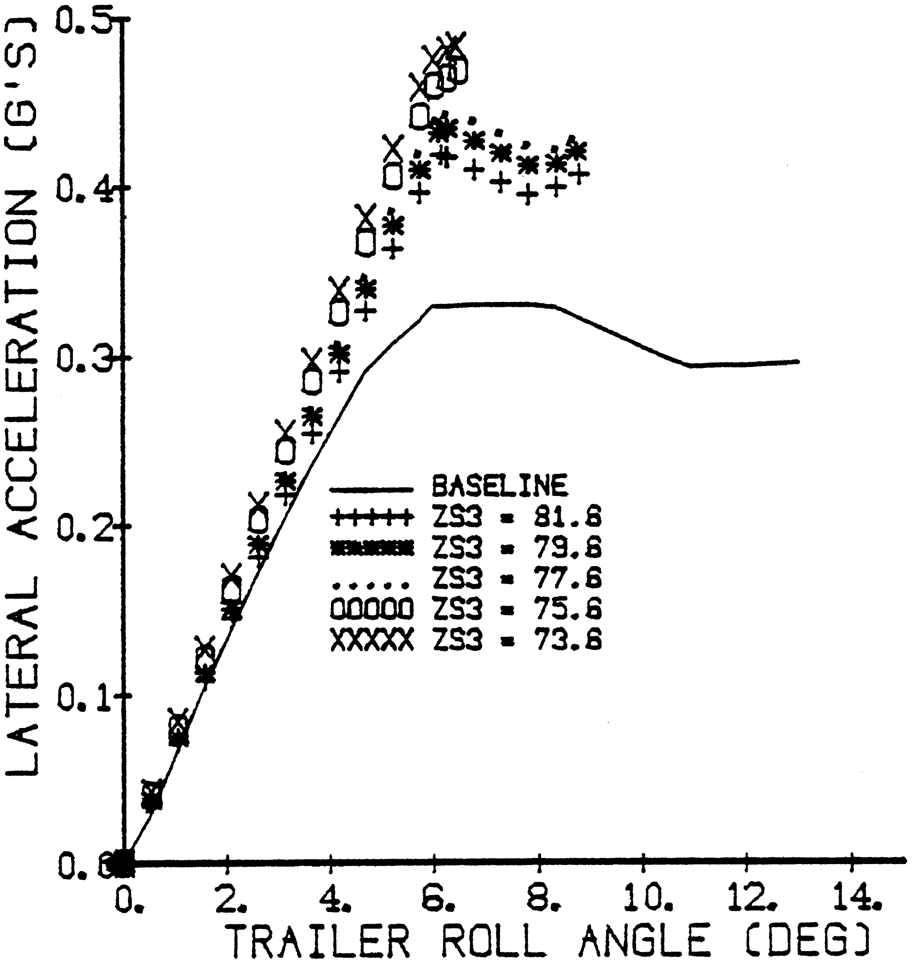


PETERBILT TRACTOR / OXYGEN TRAILER



C.G. REDUCTIONS

WITH ALL CONVENTIONAL CHANGES



C.G. REDUCTIONS
WITH CONVENTIONAL CHANGES
PLUS 102 INCH WHEELBASE

APPENDIX E

DESCRIPTIVE ROLLOVER ACCIDENT SUMMARIES COVERING LINDE FLEET OPERATIONS DURING THE PERIOD 4/25/76 THROUGH 8/16/81

DATE	TRACTOR #	TRAILER # TYPE & YEAR	FULL/EMPTY & PRODUCT	ACCIDENT SPEED POSTED SPEED	DESCRIPTION
4/25/76	5507	1428 '65 Cosmodyne	Full LN_2	45-50 50	Vehicle left straight 4 lane divided highway and crossed over berm at roadside. Sudden attempt to return to road, jackknife. Hit leading edge of guardrail. Trailer began to roll upon crossing berm. Rolled 90°. Conditions: wet, light rain, dark
10/28/76	3538	1309 '62 LOX	Full LO_2	50 55	Vehicle left straight highway. No corrective action taken and after approx. 120', drove into ditch (2' wide x 1-1/2' deep), causing trailer to lay over. Tire marks at scene indicated no braking action prior to leaving road. Conditions: clear, dry, light
11/29/76	4359	1496 '66 Cosmodyne	Full LN_2	58 40	Vehicle was traveling on 4 lane divided highway. Just after clearing bridge, driver came upon slight curve to right and upshifted. At same time, right front trailer wheel skid off road onto soft shoulder, causing vehicle to veer right. Brakes applied momentarily. Attempt made to steer back to road. Vehicle jackknifed and right rear tractor wheels dropped into a hole. Trailer flipped - almost end over end. Conditions: snow, icy, dark
2/2/77	1780	1470 '66 Cosmodyne	Full LO_2	45 50	Driver pulled over to extreme right of narrow 2 lane road to avoid collision. Very soft shoulder. Tractor skidded and could not be steered back to road. Vehicle came to complete stop before right tires sank into shoulder. Rig laid over 90° on its side. Conditions: clear, wet, dark
2/4/77	Private Owner	1380 (?) Serial #6345	Full LN_2	? Reports indicate excessive speed	Vehicle traveling on straight 2 lane highway. Driver downshifted on approach to intersection. Brakes applied, hand brake applied, tractor protection valve pulled. Took right turn off highway to avoid intersection and vehicle swung onto divided 4 lane road. After making turn too wide and contacting divider, trailer rolled and pulled tractor with it. Trailer brake O.K.; tractor brake out of adjustment as found in post-accident investigation. Conditions: clear, dry, dawn

DATE	TRACTOR #	TRAILER # TYPE & YEAR	FULL/EMPTY & PRODUCT	ACCIDENT SPEED POSTED SPEED	DESCRIPTION
10/11/77	Internat. D2137GGA -11354	1366 '64 LAP	Full LN_2	?	Vehicle veered left off of 4 lane divided highway onto exit after having applied brakes 100-125' before exit ramp. after going into turn, driver felt weight of trailer shift and entire rig rolled. Conditions: clear, dry, dawn
12/13/77	8772	1828 '73 LOX	Full LO_2	48-50 55	Vehicle was traveling on a 4 lane divided highway Driver began to slow down after cresting hill and seeing cars on roadside because of bad road conditions. Brakes gently applied; immediately caused fishtail due to glare ice. Unit drifted toward right shoulder despite efforts to steer toward center. Tractor slid beyond shoulder. Unit almost stopped, then started to tip, settled back then tipped over - rolled twice down steep embankment. Conditions: ice, snow, dark
12/16/77	4703	1893 '75 Russell	Full LN_2	50-51 55	Vehicle traveling approximately 51 mph on straight section of interstate highway. Driver's statement indicates brakes applied when road became icy. Tach chart analysis by expert consulting firm (VDO-Argo Instrument) reports that brakes were applied rapidly, reducing speed to 28 mph. Vehicle swerved left; jackknifed. Brakes released once and again applied. Trailer slid completely around, hit shoulder, and rolled. Conditions: icy, clear, dawn
1/19/78	819	1218 '61 Linde	Full LH_2	55-60 55	Truck traveling on straight stretch of 4 lane divided highway. Driver got over onto shoulder covered with 12-18" of snow. Traveled on shoulder for approx. 350' before rolling 90° down and embankment. Conditions: clear, wet, snow, daylight
6/16/78	2979	1313 LOX	1/2 Full Ar	55-58 55	Upon cresting hill on 2 lane highway, driver began to apply brakes. On feeling load shift forward, brakes applied harder. Tractor and trailer brakes applied 782' from intersection. Emergency brake switch also applied. Vehicle was suddenly steered to berm on right side of road. Trailer slid into ditch and rolled 90°. Speed at time of rollover approx. 11 mph. Conditions: clear, dry, daylight

DATE	TRACTOR #	TRAILER # TYPE & YEAR	FULL/EMPTY & PRODUCT	ACCIDENT SPEED POSTED SPEED	DESCRIPTION
8/28/78	Owner Operator	1821	? LO_2	?	Driver pulled over to stop. Got truck onto shoulder and tried to steer back. No success. Started down embankment. Correction made to aim vehicle at an angle to roll but no success. Rolled 90°. Conditions: clear, dry, dark
10/2/78		1999	Full LHe	N/A	Driver had exited right from a 4 lane divided highway. Went left under overpass and made left hand turn onto highway in opposite direction. Upon making left turn onto entrance ramp, unit layed over on right side - 90° roll. Conditions: dry, clear, daylight
12/1/78	8701	1812 '73 Process	Full LN_2	N/A	Driver had backed unit down a hill on a service road parallel to hill in order to turn vehicle around. Unit was in a 75° to 90° jackknife when he tried to pull forward. As he moved forward, 5th wheel frame broke and trailer rolled, free of tractor. Conditions: dry, clear, dark
2/20/79	3509	1436 Cosmodyne	Full LN_2	37 55	Vehicle rounded slight curve in snow covered highway. Driver suddenly applied brakes and swerved left to avoid object. Made contact with object on attempt to return to right lane. Vehicle slid and jackknifed, went off road and climbed embankment. Trailer, with 5th wheel attached, rolled 180°. Conditions: snow, ice, daylight
5/10/79	69187	1759 '71 Russell	Full LN_2	Not a factor	On making left turn out of parking lot, rear trailer wheels slid over and rolled over soft shoulder and onto a ditch just beyond, causing trailer to roll 90° while tractor remained upright. Conditions: dry, clear, daylight

DATE	TRACTOR #	TRAILER # TYPE & YEAR	FULL/EMPTY & PRODUCT	ACCIDENT SPEED POSTED SPEED	DESCRIPTION
6/28/79	3517	7148 '73 LOX	Full LO_2	50-55 40	Driver took left hand exit ramp from major 2 lane highway at approx. 50-55 mph. Exit ramp curves left. Vehicle drifted into breakdown lane on right side (outside of curve). Left side trailer wheels lifted and trailer began to roll against guardrail. Tractor & trailer slid 91' on guardrail before hitting bridge abutment and rolling down embankment. Reports indicate exit ramp designed with 7° pitch to left and shoulder with 3° pitch to right. Conditions: clear, dry, daylight
8/4/79	3668	7167 '79 Budd	Empty LHe	No Tach Chart	Vehicle had gone off road onto shoulder and traveled approx. 800' along shoulder and embankment in upright position. Vehicle had almost come to complete stop in soft mud when it rolled 90°. Conditions: rain, fog, dark
8/6/79	Private Owner	1328 LOX	Full LO_2	Appr 50-60 55	Vehicle came to shallow, long radius curve to left running over a bridge. Before coming out of curve, vehicle came out of control and skidded toward right side making contact with guardrail. At end of guardrail, tractor and trailer rolled 90° on left side. Conditions: cloudy, dry, daylight
8/8/79	8834	7120 Russell	1/4 Full LN_2	55 35	Vehicle was entering major highway at speed above that posted. Made right hand turn too wide and rolled tractor 180°. Conditions: cloudy, dry, light
11/15/79	8898	7131 '79 Linde	Full LN_2	33 25	Vehicle was making right hand exit from 4 lane divided highway. Exit ramp makes 180° bend. It was determined through expert tach chart analysis (VDO Argo Instrument) that brakes were suddenly applied at approx. 33 mph. This was after vehicle had entered exit ramp and just before it rolled 90° on its left side. Conditions: clear, dry, dawn

DATE	TRACTOR #	TRAILER # TYPE & YEAR	FULL/EMPTY & PRODUCT	ACCIDENT SPEED POSTED SPEED	DESCRIPTION
1/21/80	4709	7073 '77 Russell	Full Ar	50 55	Vehicle had just topped a hill when very rough road conditions were encountered (washboard like surface). Vehicle went out of control and verred sharply left. Driver turned sharply right to compensate. Vehicle left roadway (rear of trailer first) then rolled 90° on embankment in Median. Conditions: dry, cloudy, daylight
2/14/80	4664	1798 '74 Ryan	Empty LN_2	50 55	Vehicle was traveling straight on 4 lane divided highway. Road conditions changed from wet to icy and control was lost. Vehicle slid sideways into median and, after sliding through mud and snow, rolled. Conditions: rain, wet/icy, dark
4/27/80	8850	1934 year ?	Full LN_2	50 55	Vehicle left a 4 lane divided highway and ran onto shoulder on right side. After traveling along shoulder, vehicle jackknifed into a ditch next to shoulder. Trailer then rolled onto its left side and came to rest on left bank of ditch approx. 12' from shoulder. Conditions: clear, dry, dawn
6/4/80	Ryder	1830 '74 Russell	Full Ar	40-45	Vehicle was entering slight curve to the left on 2 lane highway. Swerved to the left (inside of curve) to avoid object in road. Skidded to a sideways position for 150' before trailer began to roll. Tractor and trailer separated. Trailer rolled 3-3/4 times. Conditions: clear, dry, daylight
6/11/80	D2137	1699 '71 Russell	Full LN_2	40 40	Driver approached blind curve to the left. Tractor ran off roadway onto shoulder at beginning of curve. Struck guardrail and rolled 90°. Slid approx. 100'. Conditions: clear, dry, dark
9/28/80	8880	7085 '77 Russell	Empty LN_2	53 55	Vehicle began descent down long, steep grade. Road surface became rough and curved to the right. Brakes were applied to slow down. Brakes released, then reapplied. At this point, jackknife occurred after 320', tractor came to shoulder. After 106', tractor hit rock and trailer rolled. Conditions: rain, wet, dawn

DATE	TRACTOR #	TRAILER # TYPE & YEAR	FULL/EMPTY & PRODUCT	ACCIDENT SPEED POSTED SPEED	DESCRIPTION
11/24/80	Ryder 305745	1584 '68 LOX	Full LO_2	40-50 Not Post.	Vehicle traveling on straight, icy road. Upon deceleration, trailer began to fishtail. Vehicle slid toward right shoulder. Brakes applied as vehicle left shoulder and hit dirt. Entire unit rolled 90°. Conditions: icy, snow, fog, dark
12/7/80	8851	7121 '78 Russell	Empty LN_2	40 55	Vehicle traveling on straight, icy road. Upon deceleration, trailer began to fishtail. Vehicle slid toward right shoulder. Brakes applied as vehicle left shoulder and hit dirt. Entire unit rolled 90°. Conditions: icy, snow, fog, dark
12/27/80	8952	7070 '76 Russell	Full Ar	50-55 55	Vehicle drove off right side of road surface at approx. 50 mph and drove across 10' wide shoulder in 314' before rolling 90° on left side. Only corrective action reported on part of driver was to steer back toward road before hitting piled up dirt. Conditions: dry, clear, dark
1/13/81	4628	1886 '74 Process	Empty LN_2	40-45 55	Vehicle traveling on straight stretch of interstate. Ran off road onto shoulder at approx. 45 mph. Trailer pulled tractor into ditch causing 90° roll. Conditions: clear, dry, dark
2/11/81	8891	1442 '65 Cosmodyne	Full LO_2	37 35	Vehicle was in extreme right lane of 4 lane divided highway to make right hand exit. Entered 45° exit ramp at approx. 37 mph. Vehicle struck curbed island in middle of exit ramp which divides it into 2 lanes of traffic. Trailer flipped over island after striking it and rolled 90°. Conditions: wet, rain, dark
3/3/81	495	7251 '80 Gardner	Empty He	5 Not Post.	Vehicle was traveling on township (dirt) road at slow speed. Wet, muddy conditions. Trailer wheels slid to right shoulder of high crowned road pulling tractor to the right. Right side wheels sank in mud and rig rolled 90°. Conditions: rain, mud, dark

DATE	TRACTOR #	TRAILER # TYPE & YEAR	FULL/EMPTY & PRODUCT	ACCIDENT SPEED POSTED SPEED	DESCRIPTION
4/3/81	536	7299 '74 Frue	Full He	45	Vehicle was traveling on straight stretch of 2 lane highway. Swerved left, then quickly verred right with brakes on to avoid object. Contact with object caused jackknife and 90° roll. Conditions: dry, clear, dark
4/15/81	3681	7352 LOX	1/6 Full	50 55	Vehicle was traveling straight on a 4 lane divided interstate. Vehicle went off roadway onto 6' paved shoulder with asphalt berm. Beyond berm is 6°, 30-40' slope downward. Rear trailer wheels slid over berm and down bank causing it to roll on its side. tractor remained upright on shoulder. Conditions: clear, dry, dark
5/21/81	8803	7076 '77 Russell	Partially Full Ar	10-15	Driver of vehicle was negotiating 90° turn on customer property. Vehicle got too wide around turn and trailer rolled 90° on its side. Conditions: rain, fog, dark
8/16/81	J.B.Kelly	8763 '79 Budd	Full He	15-20	Vehicle was traveling 50-55 mph on 2 lane exit ramp. Slowed down on approach to S turn. Negotiated 1st turn (to the right) at approx. 25 mph with no problem. Took second turn (to the left) too wide. Vehicle got out on outside of curve and rolled 90°. Shoulder here, drops off at an incline to roadway. Conditions: dry, clear, daylight