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Pavement Damage Attributable to Four Axle Single Unit Trucks

Thomas J. Parsons

Final Report

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16. Abstract

The objective of the study was to investigate and define the types of pavement damage which may be attributed to four axle single unit trucks and identify and define applicable terms and uses of the truck. Assessment of pavement damage was accomplished by determining average EALs associated with each class of trucks. Also, truck traffic patterns on Arkansas highways and percent of equivalent axle loads (EALs) generated by each class of trucks on rural arterials were determined. A test plate was developed which measured the resultant tire forces produced by the four axle single unit truck during tight turns. A national survey of state highway departments, weight and permit divisions and enforcement divisions was conducted. The survey asked for information concerning the usage and restrictions associated with four axle single unit trucks. Truck and lift axle manufacturers were surveyed for information on the manufacture and sale of lift axles. Recommendations were made concerning four axle single unit trucks which could reduce the EALs associated with these trucks by a factor of two to three. These recommendations would impose a minimal economic hardship on the truck owners and operators.

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PAVEMENT DAMAGE ATTRIBUTABLE

to

FOUR AXLE SINGLE UNIT TRUCKS

by

Thomas J. Parsons, Ph.D., P.E.

Final Report

HIGHWAY RESEARCH PROJECT TRC-8804

CONDUCTED FOR THE

ARKANSAS STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

The opinions, findings, and conclusions are those of the author and not necessarily those of the Arkansas State Highway and Transportation Department or the Federal Highway Administration.

January 1989

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PREFACE

The objective of the study was to investigate and define the types of pavement damage which may be attributed to four axle single unit trucks and identify and define applicable terms and uses of the truck. Assessment of pavement damage was accomplished by determining average EALs associated with each class of trucks. Also, truck traffic patterns on Arkansas highways and percent of equivalent axle loads (EALs) generated by each class of trucks on rural arterials were determined. A test plate was developed which measured the resultant tire forces produced by the four axle single unit truck during tight turns. A national survey of state highway departments, weight and permit divisions and enforcement divisions was conducted. The survey asked for information concerning the usage and restrictions associated with four axle single unit trucks. Truck and lift axle manufacturers were surveyed for information on the manufacture and sale of lift axles. Recommendations were made concerning four axle single unit trucks which could reduce the EALs associated with these trucks by a factor of two to three. These recommendations would impose a minimal economic hardship on the truck owners and operators.

EXECUTIVE SUMMARY

The objective of the study was 1) to investigate and define the types of pavement damage which may be attributed to four axle single unit trucks, 2) define applicable terms, and 3) define uses of the trucks.

Assessment of pavement damage was accomplished by determining the average equivalent axle loads (EALs) generated with each class of trucks, percent of EALs generated by each class of trucks on rural arterials, and determination of resultant tire forces from field tests.

A national survey of state highway departments, weight and permit divisions and enforcement divisions was conducted. The survey obtained information concerning the usage and restrictions associated with four axle single unit trucks. Also, a survey of truck and lift axle manufacturers was conducted.

Findings:

1) The analysis of pavement damage revealed that the four axle single unit truck had the highest EAL generated per trip when compared to the two axle and three axle single unit trucks and the five axle two unit trucks. The average four axle truck EAL was 3.23 when calculated by the Kentucky approach, which accounted for non-uniform axle loadings on tri-axles.

2) The four axle single unit truck EAL was 3.2 times an ideal EAL for this truck (a truck weighing the legal limit having equally loaded tri-axle axles).

3) A review of the four axle data revealed that 20 percent of the trucks in the data sample had tri-axles nearly uniformly loaded or a variance of 3000 lb. between the heaviest and lightest axle along with a legal front

axle. The EAL for this group was calculated to be 1.18 as compared to an average of 3.23 for the four axle trucks.

4) By just considering the tri-axle evenly loaded, the four axle truck EAL reduced to 1.53.

5) An analysis of the truck traffic by class of truck and functional class of roadway revealed that the four axle single unit truck averaged 2.2 percent of the truck traffic on interstates and arterials. Also, over 90 percent of the four axle single unit truck traffic was on interstates and rural arterials. A study of rural arterials revealed that 16 counties had over twice the average four axle single unit truck traffic. An analysis limited to these counties determined that the four axle single unit truck accounted for over nine percent of the pavement damage on rural arterials.

6) An analysis by county revealed that the four axle single unit truck traffic was concentrated in three regions of the state. They were the Southwestern quarter, Northcentral region and the Central counties along the Mississippi River. The four axle single unit truck had approximately the same damage impact, over nine percent of the total EALs generated, on the pavement as the three axle truck even though there were 1.8 times more three axle trucks on rural arterials.

7) The test plate data revealed that the four axle single unit truck generated similar resultant forces with the lift axle raised or lowered. There was no significant increase in the resultant forces per tire when the lift axle was lowered. However, there was a significant reduction in the front tire forces measured when the lift axle was raised.

8) An analysis of pavement resistive forces to sliding revealed that the front tire was about to slide during a tight turn on wet pavement.

9) The effect of varying the lift axle air bag pressure on pavement damage

revealed that when the air pressure was changed from 70 to 100 psi, the truck's EAL changed from 2.1 to 6.2.

10) The national survey revealed that the common uses of the trucks were transporting garbage, asphalt, gravel, concrete, grain or agricultural products, forest products or any loose material.

11) The survey revealed that several states have increased restrictions on this type of four axle single unit trucks. Six states have imposed severe restrictions or banned the use of four axle single unit trucks. Twenty-one states impose restrictions by the use of the bridge formula and 33 states have set maximum weight limits on the tri-axle and/or four axle single unit trucks. One state requires a tell-tale device which indicates when the lift axle is fully engaged and six require the pressure regulator to be located outside the cab. Five states require or encourage the use of castering lift axles and 12 states specify a maximum axle load in terms of maximum tire load per inch of tire tread width .

12) Recent movements in AASHTO and several states tend to impose more restrictions on the use of four axle single unit trucks. The restrictions require uniform axle loadings within the tri-axle, pressure regulators outside the cab, minimum capacity ratings of the lift axle, castering lift axle wheels and maximum axle loads based on tire load ratings.

13) The major truck manufacturers do not install the lift axles on the truck. The lift axle generally is installed by the dealer or truck body shop. The dealers or body shops usually buy a complete unit from a lift axle manufacturer. The units come with castering or non-castering wheels. Also, each unit has a rated capacity between 12,000 lb. and 22,500 lb. The castering lift axle has many advantages over the non-casterings units. They reduce tire and bearing wear, improve maneuverability of the truck and reduce fuel

consumption. The cost differential between the castering and non-castering lift axle is between $1000 and $2000.

Recommendations

Four axle single unit trucks make up a small percentage of the state's truck traffic, but in some areas of the state they cause over nine percent of the rural arterial pavement damage. In order to minimize the damage, the following recommendations are made:

1. Require each axle of the tri-axle unit to carry its share of the load. The difference between the heaviest and lightest axles should not exceed 3000 lbs.
2. Require the pressure regulator for the lift axle air bags to be located outside the truck's cab. An off/on or up/down control could be located inside the truck's cab.
3. Require the lift axle to have castering or self-steering wheels.
4. Restrict a castering lift axle from being raised during turning maneuvers.
5. Restrict the load on the lift axle to the rated capacity, the legal limit, or 600 to 650 lbs. per inch of tire tread width.
6. Require that the minimum capacity of the lift axle be 18,000 lbs.

These restrictions would impose a minimum economical hardship on the four axle single unit truck owners and operators. However, they would reduce the damage to the state highways caused by these trucks. For a $2000 increase in the cost of the lift axle and uniform axle loadings, the damage to the state's highways by these trucks could be reduced by a factor of two to three.

IMPLEMENTATIONS

In order to implement the recommendations concerning four axle single unit trucks, section 75-801 of the Arkansas Motor Vehicle and Traffic Laws and State Highway Commission Regulation needs to be amended. The amendment should address the following issues:

1. Penalties should be imposed for axle weights in excess of legal limits.
2. Each axle of the tri-axle unit should support its share of the gross vehicle weight. The weight differential between the heaviest and lightest axle of the tri-axle unit should not exceed 3000 lb.
3. The pressure regulator which regulates the air pressure in the lift axle air bags should be placed outside the cab of the vehicle. It should not be accessible to the driver when the truck is in motion. An up/down or off/on switch could be located in the cab which would raise or lower the lift axle, until January 1, 1995.
4. All lift axles installed after January 1, 1990 should have self-steering or castering wheels. All lift axles should be castering by January 1, 1995.
5. All castering or self-steering lift axles should be restricted from being raised during turning maneuvers.
6. All lift axles should have a minimum capacity rating of 18,000 lb.
7. Axle weights should be restricted to the axle capacity, legal limit or 600 to 650 lb. per in. of tire tread width in contact with the pavement surface.

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METRIC CONVERSION TABLE

SYMBOL	KNOWN UNIT	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	30.48	centimeters	cm
ft	feet	0.30	meters	m
yd	yards	0.91	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.45	square cm	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.84	square meters	m^2
mi^2	square miles	2.59	sq. kilometers	km^2
	acres	0.40	hectares	ha
	acres	4046.87	square meters	m^2
		VOLUME		
in^3	cubic inches	16.39	cubic cm	cm^3, cc
ft^3	cubic feet	0.03	cubic meters	m^3
ft^3	cubic feet	28317.0	cubic cm	cm^3, cc
yd^3	cubic yards	0.76	cubic meters	m^3
gal	gallon (U.S.)	3.79	liter(1000 cc)	l
qt	quart (U.S.)	0.95	liter	l
oz	ounce fluid)	29.57	cubic cm	cm^3, cc
		WEIGHT		
lb	pound(avoirdupois)	0.45	kilogram	kg
lb	" "	453.59	grams	g
oz	ounces(")	28.35	grams	g
	short ton(2000 lb)	0.91	tonnes(1000kg)	t
		FORCE, PRESSURE		
lbf	pounds-force	4.45	newtons	N
psi,lbf/in^2	pound-force/square inch	6.89	kilopascals	kPa
	foot of water(39.2°F)	2.99	"	kPa
	inch of mercury(32°F)	3.39	"	kPa
		ANGLE		
°	degrees	0.017	radians	rad
'	minutes	2.91×10^{-4}	radians	rad
"	seconds	4.85×10^{-6}	radians	rad
		TEMPERATURE		
°F	degrees Fahrenheit	t°C=(t°F-32)/1.8	degrees Celcius	°C
°C	degrees Celcius	ADD 273.15	degrees Kelvin	°K

CHAPTER 1

INTRODUCTION

1.1 THE PROBLEM

New truck designs and demands for higher payloads have resulted in the introduction of four axle single unit trucks, consisting of a steering axle, tandem and an extra load carrying axle. The extra axle may be operated by air bags, hydraulics or affixed to the frame for constant load bearing after a "threshold" load is applied. Considerable pavement abrasion may result from tight turns with the tri-axle configuration. As increased loads are permitted, failure to use the third axle may cause overloads on other axles. Since enforcement is dependent upon gross load rather than axle load, there is, at present, no means of penalizing axle overloads. A further defining of variances which are granted and the ambivalent meaning of "Load Bearing Axle" is required.

1.2 PROJECT OBJECTIVES

The research project consisted of five major objectives. They were as follows:

1. Identify and define all applicable terms associated with four axle single unit trucks.
2. Define the uses and types of trucks which make up the "Four Axle Single Units".
3. Investigate and define the types of pavement damage which may be attributed to four axle single unit trucks. The study defined which mechanisms could cause the damage and quantified the damage attributed to the mechanisms. Emphasis was placed on abrasion and

distortion of flexible pavements. The mechanisms which cause axle overloads were investigated and defined, and the effects which they had on the pavements were investigated.

4. Identify vehicles with alternative axle configurations, which are permitted in other states.
5. Make recommendations which would reduce the pavement damage attributable to four axle single unit trucks.

1.3 METHODOLOGY

In order to achieve the objectives of this research, the following procedure was observed.

Phase 1. Investigation of the uses and types of four axle single unit trucks in Arkansas.

This phase was accomplished in two steps. The first step was to survey the usage of four axle single unit trucks in Arkansas. The sub-committee decided that the survey was not required and the survey was not completed. The second step consisted of surveying the manufacturers for design information and was completed. This included design load per axle, spacing of axles, intended usage and manufacture of lift axle.

Phase 2. Investigation into the restrictions imposed on four axle single unit trucks by other states.

A survey of all fifty states was conducted concerning the use of four axle single unit trucks and trucks or trailers which could have similar effects on pavements, for example, trailers with widely spaced tandem wheels. The states were asked if they impose any restrictions on these trucks and trailers and what justification they have for the restrictions or lack of restrictions. The survey also asked if they have any documentation or experience with flexible or rigid pavement damage caused by these trucks and axle overloads. Lastly, the states were asked for the types and uses of these trucks within their state.

Phase 3. Identification and definition of all applicable terms.

A literature search was conducted concerning four axle single unit trucks and terms related to their usage. The results of phases one and two were incorporated and the terms were defined. From this, a comprehensive definition of four axle single unit truck, load bearing axle and other related terms were identified.

Phase 4. Investigation into possible mechanisms of pavement damage.

Static and dynamic models of four axle single unit trucks identified in phases one and two were developed. These models predicted the forces imposed on the pavement, that is, the vertical, horizontal and tangential wheel loads. This provided a means of documenting the pavement loads caused by the four axle single unit trucks.

Phase 5. Verification of models.

To verify the results of the models, physical tests were conducted. This was accomplished by developing an instrumented steel plate which was placed on a test roadway. Trucks passed over the plate and horizontal and tangential wheel loads were recorded. A complete data base was developed for comparison purposes. Three and four axle single unit trucks were driven over the plate.

Phase 6. Assessment of pavement damage.

From the developed data base, the pavement damage produced by four axle single unit trucks was assessed.

Phase 7. Recommendations were made on how to reduce the effects that four axle single unit trucks have on the highway. Also, legislation changes were recommended along with the appropriate course of action for the Arkansas State Highway and Transportation Department.

1.4 LITERATURE REVIEW

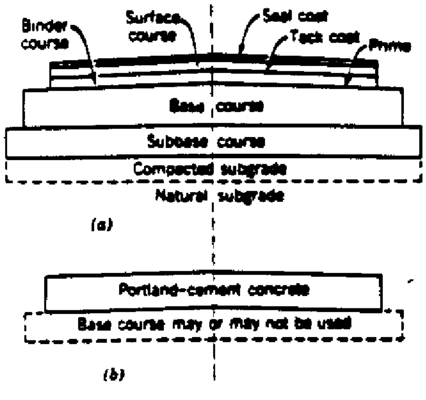
1.4.1 BACKGROUND.

Pavement damage can be divided into two classes of failure, structural and functional. Structural failure is when there is a breakdown of pavement components which make the pavement incapable of supporting the imposed surface loads. Functional failure is when the roughness of the pavement causes discomfort to the passengers or high stresses in the vehicle. The following example will distinguish between the two types of failure. If the road surface is rough and still carries the intended loads, this is a functional failure. The road could be resurfaced to restore a smooth ride. If the road is rough and continues to break up by the intended loads, this is a structural failure. If the road is resurfaced, the intended loads will continue to break up the road. The road could only be repaired by reconstructing it.

The causes of structural or functional failures are related to either of the following: overloading by excessive gross loads, high repetitions of loads, and/or increased tire pressures. A second means of failures could be climatic conditions and environmental conditions that may cause surface irregularities and structural weaknesses to develop such as the disintegration of paving materials due to freezing and thawing and/or wetting and drying (1). Pavement design procedures take into account the factors which may cause these failures. The magnitude and number of loads the pavement is subjected to is addressed by the number of equivalent axle loads (EAL) the pavement is designed for. The tire pressure is addressed by amount of contact area used in the development of pavement design curves. Climatic and environmental conditions along with disintegration of paving materials are addressed by the mix design, type of aggregates, drainage, maintenance procedures and other means.

Design of pavements is a complex process based on engineering principles and experience. The flexible or asphalt pavements are assumed to be a multi-layered elastic system characterized by the modulus of elasticity and Poisson's ratio associated with the different pavement and subgrade layers. The different layers commonly considered are given in Fig. 1.1. The strength of the pavement is a result of the layers distributing the surface load over the subgrade. Rigid pavements or concrete pavements are considered to be very stiff or rigid, thus, have a high modulus of elasticity which results in the major portion of the structure capacity provided by the slab, Fig. 1.1. Therefore, the surface load is distributed by the slab over a relatively wide area of subgrade soil.

In the design of flexible pavements, several factors are considered. They include subgrade properties, material properties, traffic values, environmental factors and other factors. The material properties of asphalt mixtures are characterized by modulus of elasticity or dynamic modulus. The resilient modulus is used to characterize the elastic and dynamic properties of untreated granular base material and soil materials. Environmental factors are taken into account by the selection of the grade of asphalt (2). Different asphalt grades are selected for different mean annual air temperatures. Traffic values are expressed in terms of the number of repetitions of an 18,000 lb single axle load (EAL) applied to the pavement. The axle is assumed to consist of two sets of dual tires. The number of EALs is a function of traffic volume, percent of trucks, type of trucks and future growth. Research based on road tests and other factors has determined that the EAL can be correlated to the life expectancy of flexible pavements. It was also determined that an axle load of any mass can be represented by an EAL.



Components of (*a*) flexible and (*b*) rigid pavements. Base courses under rigid pavements are often called subbase courses. For these illustrations the base and subbase courses are shown in a "trench" section.

Fig. 1.1 Flexible and Rigid Pavements (1)

Due to the weight difference between automobiles and heavy trucks, heavy trucks account for the greatest share of the EALs in most cases. Exceptions include parkways, shoulders or other roadways where truck traffic is restricted. Truck traffic damage by type of vehicle for the different classes of highways is given in Table 1.1. Statistical data available for 1974 indicate that the volume of heavy trucks on all classes of highways average about 11 percent of total traffic volume in the United States. However, regional averages of truck traffic could range from two to 25+ percent (2). The number of EALs a road is designed for is determined by (1) estimating the number of vehicles or trucks expected to travel over the design lane during the design life of the pavement for each weight class, 2) multipling by the appropriate truck factor, Table 1.2, for each weight class, and 3) summing the results.

Asphalt pavement design charts have been developed for each asphalt mix type and aggregate base thickness. The design curves are a function of subgrade resilient modulus and the number of repetitions of EALs, see Fig. 1.2. By knowing these factors, one can determine the required thickness of asphalt required. The resilient modulus can be determined in the laboratory under controlled conditions or estimated by other tests. The number of repetitions of EALs should be determined by local traffic surveys and accurate assessments of EAL per axle per type of truck.

1.4.2 DETERMINATION OF LOAD EQUIVALENCY FACTORS

The load equivalency factors is defined as the number of EALs per passage of an axle. It is a function of the number of tires per axle, load imposed on the pavement by the axle and axle grouping (single, tandem or triple axles at a close spacing). The American Association of State Highway Officials (AASHO) developed an equivalency factor equation based on road tests. This equation

Table 1.1 Distribution of Trucks on Different Classes of Highways-United States*(2)

Truck Class	Percent Trucks									
	Interstate Rural		Other Rural		All Rural		All Urban		All Systems	
	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
Single-unit trucks										
2-axle, 4-tire	39	17-64	58	40-80	47	23-68	61	33-84	49	28-67
2-axle, 6-tire	10	5-15	11	4-18	10	4-16	13	4-26	11	5-20
3-axle or more	2	1-4	4	1-6	2	1-4	3	1-7	3	1-8
All single-units	51	30-71	73	50-88	59	38-77	77	55-94	63	38-81
Multiple-unit trucks										
3-axle	1	<1-2	1	<1-3	1	1-3	1	<1-4	1	<1-2
4-axle	5	1-10	3	<1-8	4	1-10	4	1-13	4	1-10
5-axle or more**	43	24-59	23	8-40	36	16-57	18	5-37	32	15-58
All multiple-units	49	31-71	27	13-50	41	23-60	23	6-44	37	20-67
All trucks	100		100		100		100		100	

*Compiled from data supplied by the Highway Statistics Division, U.S. Federal Highway Administration.

**Including full-trailer combinations in some states.

Table 1.2 Distribution of Truck Factors (TF) for Different Classes of Highways and Vehicles-United States*(2)

Vehicle Type	Truck Factors									
	Rural Systems						Urban Systems		All Systems	
	Interstate Rural		Other Rural		All Rural		All Urban			
	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
Single-unit trucks										
2-axle, 4-tire	0.02	0.01-0.08	0.02	0.01-0.09	0.03***	0.02-0.08	0.03***	0.01-0.05	0.02	0.01-0.07
2-axle, 6-tire	0.19	0.13-0.30	0.21	0.14-0.34	0.20	0.14-0.31	0.26	0.18-0.42	0.21	0.16-0.32
3-axle or more	0.56	0.08-1.56	0.73	0.31-1.57	0.67	0.23-1.53	1.03	0.52-1.98	0.73	0.29-1.59
All single-units	0.07	0.02-0.16	0.07	0.02-0.17	0.07	0.03-0.16	0.08	0.04-0.21	0.07	0.02-0.17
Tractor semi-trailers										
3-axle	0.51	0.30-0.86	0.47	0.29-0.82	0.48	0.31-0.80	0.47	0.24-1.02	0.48	0.33-0.78
4-axle	0.62	0.40-1.07	0.83	0.44-1.55	0.70	0.37-1.34	0.89	0.60-1.84	0.73	0.43-1.32
5-axle or more**	0.94	0.67-1.15	0.98	0.58-1.70	0.95	0.58-1.64	1.02	0.69-1.69	0.96	0.63-1.53
All multiple units	0.93	0.67-1.38	0.97	0.67-1.50	0.94	0.69-1.43	1.00	0.72-1.58	0.96	0.71-1.39
All trucks	0.49	0.34-0.77	0.31	0.20-0.62	0.42	0.29-0.67	0.30	0.15-0.59	0.40	0.27-0.63

*Compiled from data supplied by the Highway Statistics Division, U.S. Federal Highway Administration.

**Including full-trailer combinations in some states.

***See Article 4.06 for values to be used when the number of heavy trucks is low.

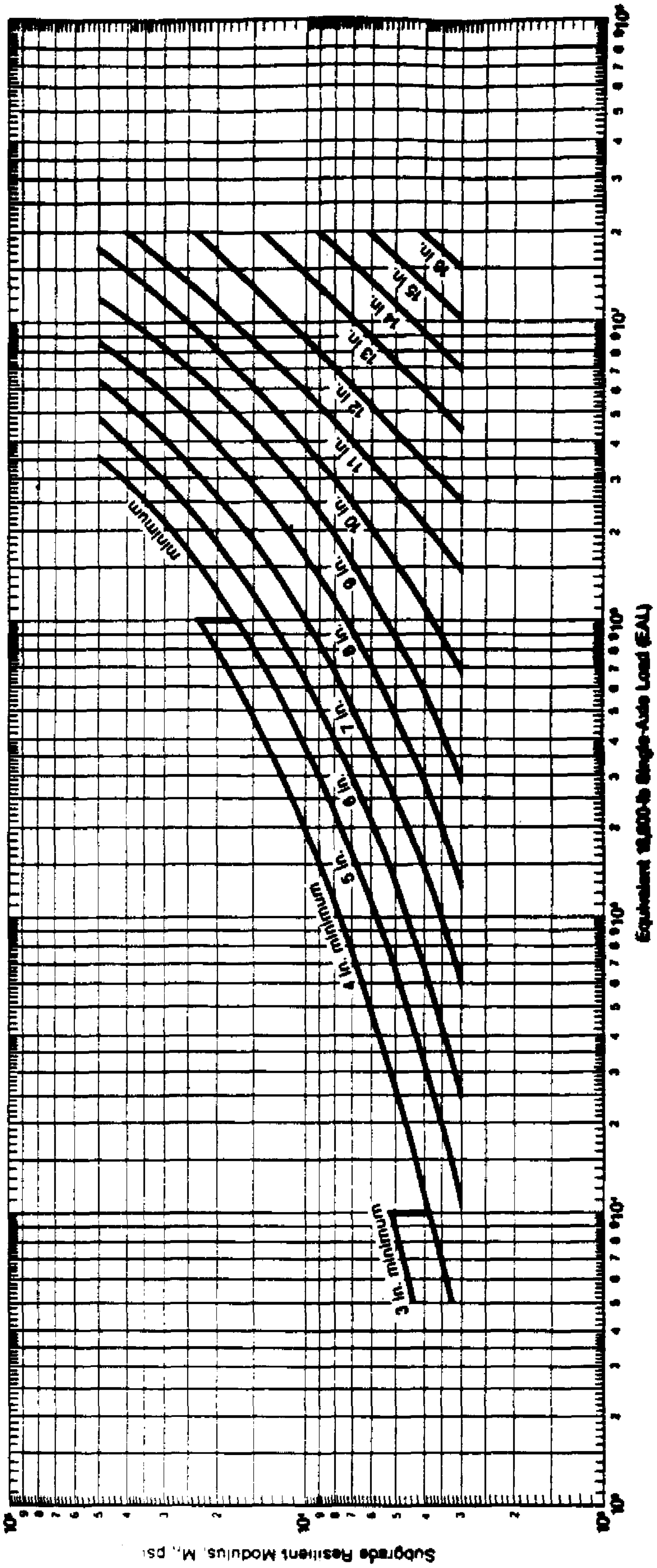


Fig. 1.2 Design Chart for Untreared Aggregate Base 6.0 in. Thickness (2)

relates the number of repetitions of EALs to produce failure of the pavement in terms of pavement rigidity or stiffness value associated with rigid (D) or flexible pavements (SN), load characteristics and the terminal level of serviceability (Pt) selected as the pavement failure point (1). Tables of equivalency factors for single, tandem and triple axles based on the AASHO equation are available. Several other equivalency factor equations have been developed and are given in Fig. 1.3.

The AASHO equivalency factor equation was developed for a total load on a tandem or triple axle group. The axles were assumed to be uniformly loaded. A recent study by the Kentucky Transportation Research Program (3) examined the effects of non-uniform axle loads within the axle group. The work determined how the magnitude of loading, tire and axle configurations and tire pressures affected the values of EALs or load equivalency factors. Load equivalency factors were recalculated by setting the strain energy, or the work done internally by the pavement, equal to the work done by the applied axle loads. The Chevron N-layer program was modified in order to perform the calculations.

Load equivalency factors were determined for equally loaded and unequally loaded axle groups. The different types of pavements considered in the AASHO Road tests were considered. The relationships developed for equally loaded axle groups are given in Fig. 1.4. The curves shown in Fig. 1.4 were approximated by

$$\text{Log (DF)} = a + b\,(\text{Log(load)}) + c\,(\text{Log(load)})^2 \qquad 1.1$$

where

DF = EAL for axle group relative to an 18-kip four-tire axle load

Load = Load imposed by axle group in kips

a,b,c = regression coefficients.

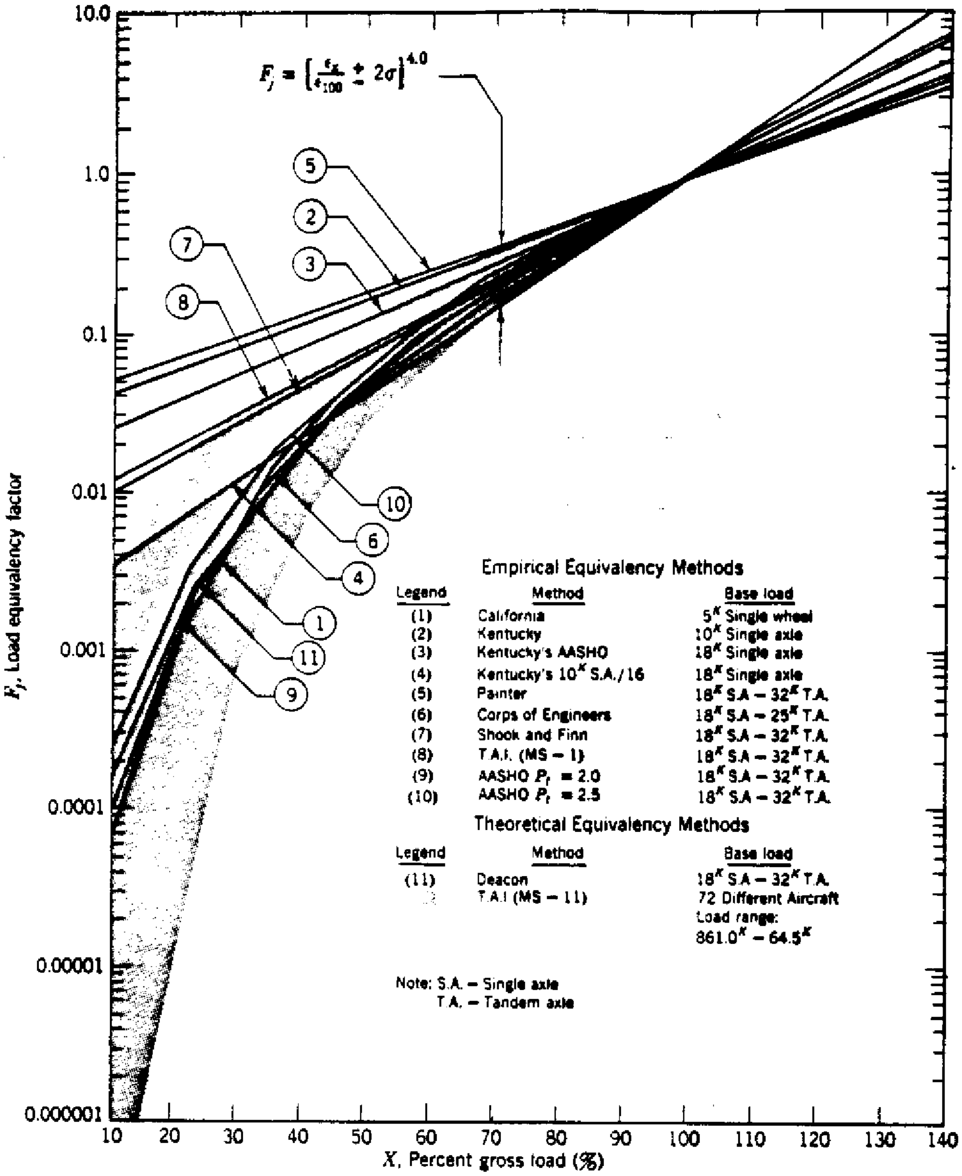


Fig. 1.3 Comparison of Various Load Equivalency Methods as a Function of Percent of Gross Load (1).

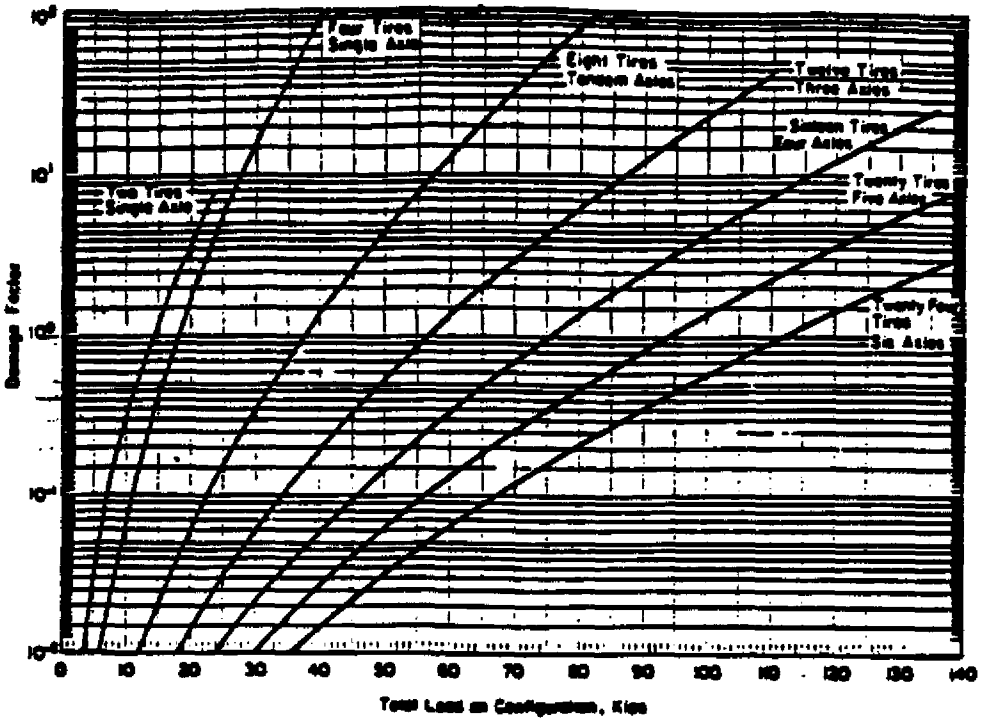


Fig. 1.4 Relationship Between Load Equivalency and Total Load on the Axle Group and Evenly Distributed on All Axles (3).

The regression coefficients are given in Appendix A.

The effects of uneven load distributions on the axle groups were accounted for by the use of multiplicative factors (MF). The MF factor for a 36 kip tandem axle group with uneven loads is given by:

$$\text{Log(MF)} = 0.00186354 + 0.0242189\ (\text{percent}) - 0.0000906996(\text{percent})^2 \qquad 1.2$$

where

MF = factor to multiply the EAL given by Equation 1 in order to adjust for uneven loadings

Percent = $\left|\ (\text{Axle Load No. 1} - \text{Axle Load No. 2})\ \right|$ x 100/(Axle Load No. 1 + Axle Load No. 2).

The MF factors for the triaxle group were developed based on a 54 kip tri-axle load. Thirteen loading patterns were considered for tri-axle group. The resulting MF equations are given in Appendix A.

The state of Maine has a similar approach to account for tridem axles which are unbalanced. They have a computer program which generates EALs from unbalanced tridem axles. They make three types of corrections depending on the distribution of imbalances on the triaxle group.

Case 1 - if the heaviest axle is more than three times the weight of the middle weighted axle, the group is treated as a single axle.
ex. 20 - 5 - 2.5 (kip) = single axle 27.5 kips.

Case 2 - If the heaviest axle is more than three times the weight of the smallest axle, Case 1 is not applicable, the group is treated as a tandem axle.
ex. 16 - 10 - 5 (kip) = tandem axle 31 kip.

Case 3 - If the heaviest axle is more than 1.05 times the smallest axle, two-thirds of the difference between the largest and smallest axles is added to the weight of the tri-axle.
ex. using Case 2 (16 - 5) x 2/3 = 7.3 kip added to the above weight as correction.

1.4.3 COMMONWEALTH OF PENNSYLVANIA

In Pennsylvania a typical tri-axle truck can legally carry up to 73,280 bs even though the legal axle load permits 76,400 lbs or 22,400 lbs on the steering axle and 54,000 lbs on the tri-axle (4). The reduced weight is due to a state statue that states "no vehicle shall, when operated upon a highway shall have a gross weight exceeding 73,280 lbs, and no combination driven upon a highway shall have a gross weight exceeding 80,000 lbs" (4). In Pennsylvania it was noted that "the damage caused by overweight trucks is most apparent in those areas where trucks hauling natural resources are making numerous short trips each day on the same roads. The overweight natural resource trucks generally haul large volumes of heavy cargo, such as coal, logs, and gravel for short distances" (4). Also stated was that "a 1978 DOT study concluded that adverse impacts on Appalachian coal highways have already occurred and the projected sharp increase in coal production will ruin these highways. Much of the coal is hauled by large three and four axle dump trucks".

The problem associated with four axle trucks is due to practical limitations of the truck design, the practical/legal limits are reached when the body of the truck is only about 60 percent full. This results from the following:

1. The legal limit for the steering axle is 22,400 lb, but due to tire limitations and/or work capacity for a front steering axle, a reasonable front axle weight is 12,000 to 14,000 lbs. This is the range of the front axle for most four axle trucks in the state.
2. Each individual axle of the tri-axle configuration can carry up to 18,000 lbs. However, the lift axle usually carries approximately 11,000 lbs. to 13,000 lbs. due to limited ability of the air pressure system. Surveys in Pennsylvania have indicated that the lift axle carries about 19 percent of the gross vehicle weight. Therefore, if the tri-axle carries 54,000 lbs., the legal limit, the resulting load on the lift axle will be 14,000 lbs.
3. Assuming 14,000 lbs. on the front and lift axle, 36,000 lbs. on the tandem and subtracting 26,000 lbs on the average weight of vehicle,

produces a resulting cargo weight of 38,000 lbs. This is approximately 60 percent of capacity of the truck body.

Also presented was the results of a limited investigation into 18,000 lb. equivalent axle study. It was determined that a tri-axle group loaded with approximately 55,000 lbs. had an 18-kip equivalent damage effect of 0.94 to 1.51 depending on the season of the year, assuming equal distribution of the load among the three axles. To simulate actual field practice, where the lift axle carries approximately 14,000 lbs., the damage effect was approximately four. It was also reported if the lift axle was raised for turning and not lowered after the turn, the EAL increased to 13.

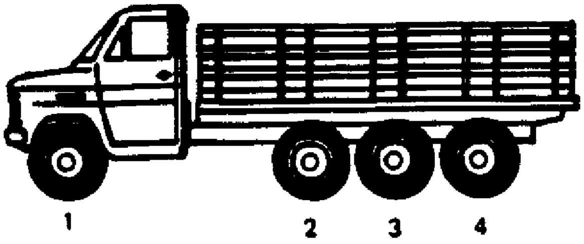
It was noted that tri-axle trucks tend to raise the lift axle during turns. The reason given for raising the lift axle during turning maneuvers was because the tri-axle configuration does not lend itself to easy turning since the tri-axle configuration tries to force the truck to follow a straight path even when the front wheels are turned.

A statistical analysis of axle weights for tri-axle dump trucks, was reported by selected gross vehicles weights. The results are given in Table 1.3.

Lastly, the results of a U.S. General Accounting Office in-depth evaluation of excessive truck weights and damage done to pavements were reported. "It was concluded that heavy and overweight trucks are a major cause of highway deterioration. Damaging effects by these vehicles and their increasing number and weight over the last 10 years make it clear that these trucks are the principal cause of traffic-related deterioration on the highways. While eliminating excessively heavy trucks will not stop highway damage, it will reduce it.

Because of the exponential impact of excessive weight on highways, a small percentage of overweight trucks will significantly decrease serviceable life of the Nation's highways."

Table 1.3 GVW Percentage per Axle



GVW average percent of weight per axle

GVW lb.	Truck Axle No. 1	2	3	4
67,000 to 69,000	21	16	31	32
69,000 to 71,000	19	18	32	31
71,000 to 74,000	19	19	31	31
Field Typical	19	19	31	31

1.4.4 VEHICLE WEIGHT AND DIMENSIONS STUDY

A comprehensive vehicle weight and dimension study was conducted by the Roads and Transportation Association of Canada. The main areas of research were vehicle stability and pavement response to truck loadings (5,6,7). Vehicle stability and control characteristics of various tractor-trailer configurations were determined or evaluated by 1) using computer models, 2) roll over analysis performed by tilt table tests, 3) full scale field testing and, 4) actual demonstrations.

The relative damaging effects of various truck axle load conditions were determined for different pavement structures. Fourteen sites in Canada were instrumented so that pavement strain and deflections produced by the different axle loadings could be measured. The loading program was carried out at each site by the use of a specially designed tractor-trailer. This tractor-trailer combination produced the following axle loads:

Single axle, single tire loadings from 7,700 lbs. to 12,100 lbs.
Single axle, dual tire loadings from 19,800 lbs. to 24,200 lbs.
Tandem axle loading from 12,100 lbs to 48,400 lbs.
Triaxle loadings from 44,000 lbs. to 70,400 lbs.
Tandem axle plus belly axle configuration loadings from 55,000 to 70,400 lbs.

Also, the vehicle speed on pavement response was determined for each loading condition.

The general conclusions and observations of the study were as follows:

1. Based on load equivalency factors derived from both pavement strain and deflection data, it is evident that the potential damaging effect of a particular axle configuration for a given load varies greatly between the 14 sites tested. Overall average load equivalency

factors for all configurations tested based on deflection data are presented in Fig. 1.5.

2. A wide variation in actual load equivalency factors were obtained at the different sites. The relative damaging effects of single axles, tandem axles and tridems at comparable load levels remained consistent.
3. In comparison with the AASHO load equivalency factors, the single axle correlated closely in the 17,600 lb. to 26,400 lb. range. The tandem axles group correlated closely at 44,000 lb. and above. The load equivalency factor determined was higher than AASHO in the 11,000 lb. to 33,000 lb. range. The results are presented in Fig. 1.6.
4. A single axle with single tires appeared to have the same destructive effect as a single axle with dual tires at twice the loading in the 7,700 lb. to 12,100 lb. range.
5. An increase of 2200 lb. on a single axle with dual tires in the 17,600 lb. to 26,400 lb. would, on average, increase the potential damaging effect by approximately 25 to 30 percent.
6. An increase of 2200 lb. on a tandem axle group in the 35,200 lb. to 52,800 lb. range, on average, would increase potential damaging effect by approximately 10 to 15 percent.
7. An increase of 2200 lb. on a tridem axle group load in the 44,000 lb. to 70,400 lb. range would, on average, increase potential damaging effect by approximately 6 to 10 percent.
8. In the 55,000 lb. to 70,400 lb. range, a tandem axle group plus a belly axle (wide spread single axle) with a 192 in. spread appeared to be approximately 15 percent more destructive than an equally loaded, symmetrical tridem with a 144" overall spread.

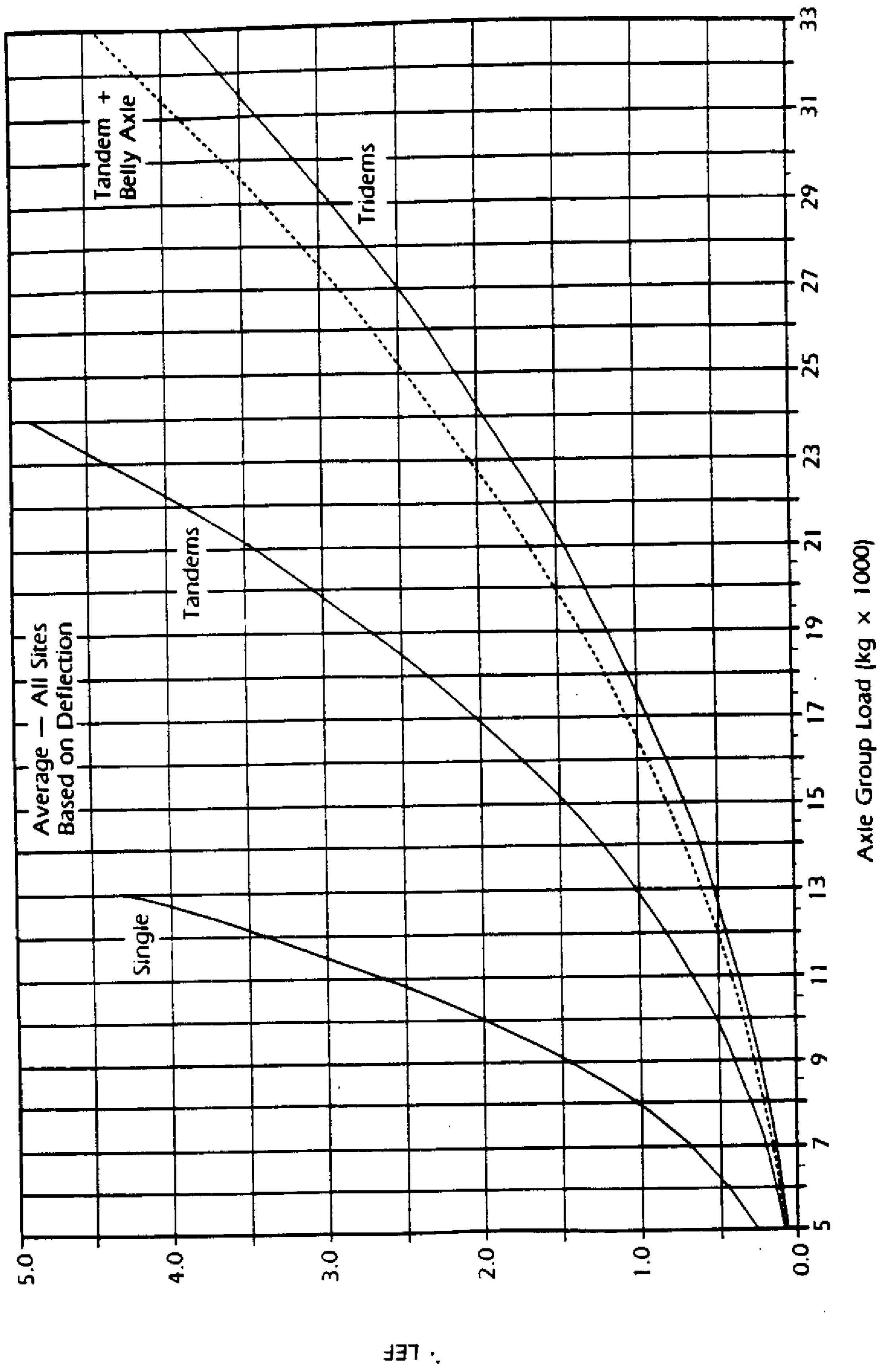


Fig. 1.5 Load Equivalency Factors (5).

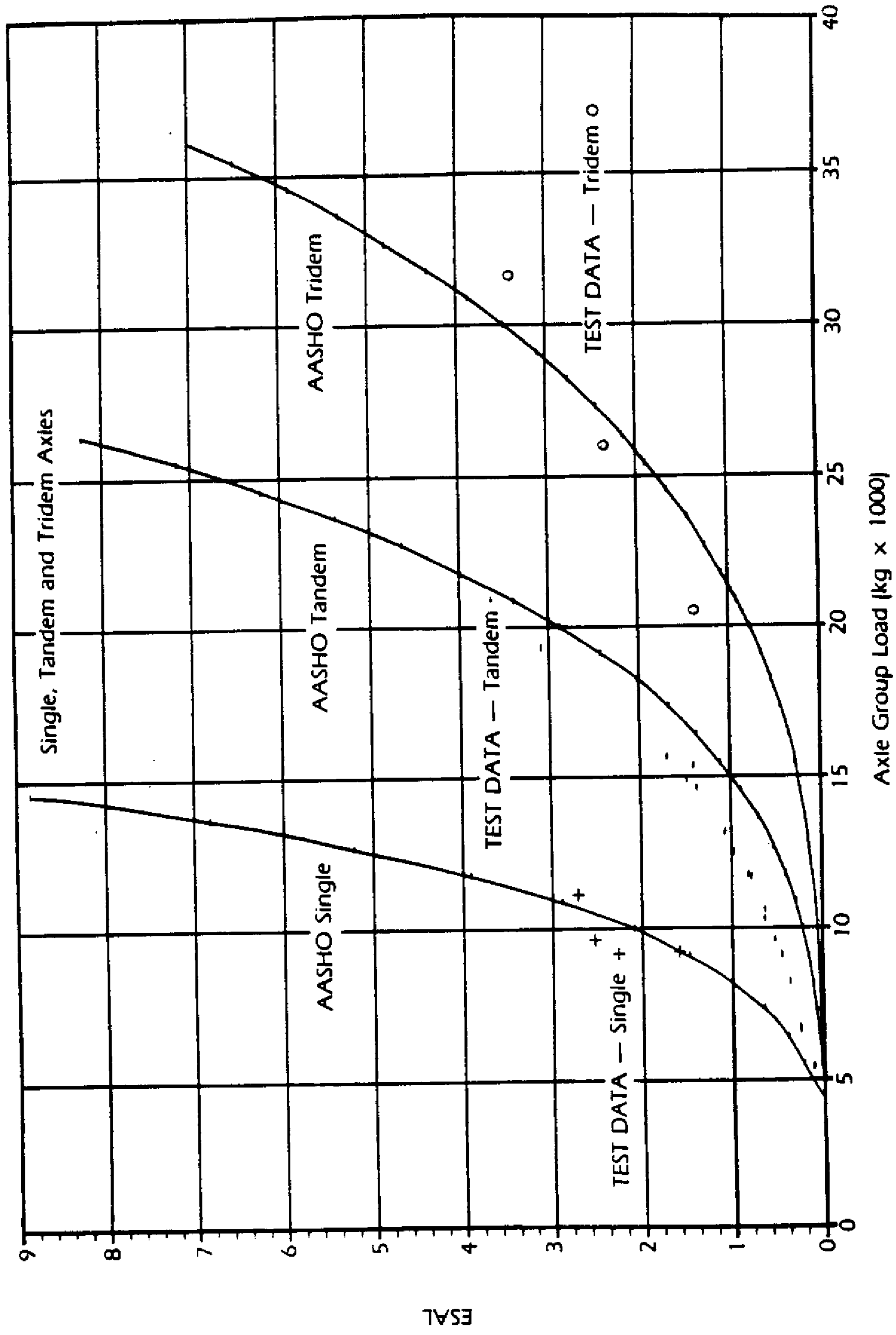


Fig. 1.6 Comparison of Equivalency Factors with AASHO (5).

9. Maximum pavement strains and deflections occurred at the slowest vehicle speed tested. At speeds above 9 mph., a 10 to 15 percent reduction in peak pavement strains and deflections were observed.

1.4.5 STATE OF NEW YORK

The state of New York conducted a study to determine the effect of overweight permits issued in the state on the performances of highway pavements and bridges. The study was based on the data obtained from 13 weigh in motion (WIM) sites in the state and a survey of truck owners who were issued permits. It was determined that there was a high percentage of vehicles operating in the state above the legal limit (8). A summary of survey results by truck class is presented in Table 1.4. The survey revealed the following truck usage for different functional class of highways. The results are based on reported traveled miles.

Interstate (all)	23%
Principle Arterial (all)	43%
All major Arterial and major collectors	33%
All other	1%

Also, the equipment number of legal trucks needed to carry permit payloads was determined. They were found to be:

2-axle 6 tire single units - 1.43

3-axle single unit - 1.63

4-axle single unit - 1.48

4 or less axle double unit

  (1 unit is truck) - 1.38

5 axle double unit

  (1 unit is truck) - 1.45

Table 1.4 Analysis of Trucks From Survey Results (8).

Number	Vehicle Type	Description	% of Permit Trucks
126	1-3-0	3 axle truck	51.9
48	3-2-0	3 axle truck, 2 axle semi trailer	19.6
22	1-4-0	4 axle truck	9.1
15	3-3-0	3 axle truck, 3 axle semi trailer	6.2
13	1-2-0	2 axle truck	5.3
4	2-2-0	2 axle truck, 2 axle semi trailer	1.6
2	2-1-0	2 axle truck, 1 axle semi trailer	.8
2	3-4-0	3 axle truck, 4 axle semi trailer	.8
2	1-4-2	4 axle truck, 2 axle trailer	.8
2	2-3-0	2 axle truck, 3 axle semi trailer	.8
1	1-3-2	3 axle truck, 2 axle trailer	.4
1	4-2-0	4 axle truck, 2 axle semi trailer	.4
2	1-6-0	6 axle split truck	.8
2	1-5-0	5 axle truck	.8
1	1-4-4	4 axle truck, 2 axle trailer	.4
243			99.7

Table 1.5 Percentage of Vehicles Holding Permits by Type (8).

Vehicle Type (class) % of Survey	Estimated Permit Vehicles % Of Survey	Estimated Number of Permit Vehicles	Estimated Permit Eligible Vehicles	Permitted Truck % of Truck Type
Single Unit Truck				
2 axle (1-2-0)	5.3	557	64240	1
3 axle (1-3-0)	51.9	5450	14965	36
4 axle (1-4-0)	9.1	956	1095	87
Combinations				
3 axle truck, 2 axle semi-trailer (3-2-0)	19.6			
3 axle truck, 3 axle semi-trailer (3-3-0)	6.2			
	25.8	2709	18371	15
2 axle truck, 2 axle semi-trailer (2-2-0)	1.6	168	10828	2
All other	6.3	662	6205	11
Totals	100.0	10529	115704	

The truck population eligible to obtain permits in New York was estimated to be:

Single unit truck	
2 axles	64,240
3 axles	14,965
4 axles	1,095
Single unit Truck with trailer	
3 axles	1,825
5 axles or more	1,460
Truck tractor single trailer	
3 axles	2,920
4 axles	10,828
5 axles or more	18,371

The percentage of vehicles holding permits by type of truck is given in Table 1.5.

To determine whether the loadings of the permit trucks are significant enough to cause an increase in pavement deterioration the EAL concept was used. In order to make the comparison, the EALs generated by the total WIM traffic streams were calculated. For comparison purposes, the number of vehicles that had permits were estimated and the EALs associated with these vehicles were obtained. Next the EALs associated with these vehicles were subtracted from the total EALs. It was assumed the commodities carried by permitted vehicles will still be carried by legal vehicles. So the number of EALs generated by the estimated legal vehicles needed to replace the permitted vehicles were added back into the total EALs. The difference between the two EALs represents the relative pavement damage caused by permit vehicles. Axle group configurations were checked for weight imbalance conditions and corrections were made to account for the imbalance effect. The results are presented in Table 1.6. They are expressed in terms of the total estimated increase in traffic and decrease in pavement damage if the annual permit vehicles were replaced with legal weight vehicles.

Table 1.6 Changes in Truck Traffic and Pavement Damage (3).

	% Increase in Truck Traffic (1)	% Decrease in Pavement Damage (ESALs)				
		PCC		Asphalt		
		9"	8"	10.5"	8.5"	5.5"
Minor Arterial/ Collectors	2.2	- (3)	.1	-	-.6	-.6
Principal Arterial	2.2	3.0	3.0	3.3	2.1	2.2
Interstate	.9	.5	.6	.6	.4	-

1. Based on estimated traffic stream if current permit users carried cargo in equivalent legal trucks divided by current number of trucks which includes annual permit trucks.

The table indicates that the damage would decrease on principal arterials. However, the pavement damage would increase for minor arterials/collectors if the annual permits were not available and cargo shifted to legal trucks. It was noted that the two, three, and four axle single unit trucks make up about 59 percent of the truck traffic on minor arterial/collectors and 34 and 17 percent of the principal arterial and interstate truck traffic, respectively. By this method of analysis, a net increase in EALs occurred for all functional classes of two axle, six tired, single unit trucks. An increase was noted for three axle single unit trucks on minor arterials/collectors and an increase on the interstate with the four axle single unit trucks.

The process of shifting freight from overweight to equivalent legal weight trucks and comparing EALs generated, revealed that the effect of the processing truck permits is small. However, the single most important reason for this is that the annual permit trucks are a very small percentage of the total overweight truck traffic.

An economic study revealed that the cost of operations in the permit vehicle fleet had decreased by approximately $690 million per annum after the introduction of the permit system. The main beneficiaries of the savings are operators in the construction industry, operators of four axle trucks, and operators of trucks having special permits (9). The construction industry is estimated to experience 62 percent of the total direct cost savings arising from the current weight-permit system. These savings are passed on to virtually every other industry.

1.4.6 OTHER RELATED STUDIES.

"An Investigation of Truck Size and Weight Limits" by the Federal Highway Administration in 1981, examined the effect of lower gross vehicle weights and lower axle loads imposed by several states (10). Also, the restrictions on trailer size and configurations were studied. Some of the conclusions of the study were:

> "Pavement wear increased sharply with increases in axle weights. Thus, higher axle weight limits tend to accelerate pavement wear even though they reduce truck miles by allowing higher average payloads...Modest increases in axle weights can decrease the serviceability of the highway and substantial increases can result in serious deterioration. Thus, changes in vehicle standards can result in needs for additional surfacing or reconstruction of pavements, strengthening or replacement of bridge structures, increased levels of maintenance, and increased financial burdens and commitments of public funds."

A study by Paxson and Glickert showed that the calculated damage costs to pavements imposed by overweight trucks, based on EAL per miles traveled was \$0.03/EAL/Mile in Tennessee (11). Also, a study in Alabama using WIM equipment, found that the average number at 18-kip EALs per truck were much greater than estimated from static measurements (12). An investigation by Mason on the effect of oil field truck traffic on low volume roads revealed that the additional truck traffic produced by the drilling operation reduced the service life from 7.5 years to 4.2 years. The estimated annual cost went from \$14,000/mile to \$26,560/mile due to the effect of the oil operation (13,14). Also, the number of oil wells in a given area affected the life of the road. It was shown that truck traffic from 20 wells could reduce the time of failure from 82 months to 52 months.

Work by Fernardo, Luhr and Saxena determined the effect of axle loads under a variety of conditions (15,16). This was done by modeling different pavement thicknesses and material properties subjected to various load magnitudes. It was found that single, tandem and triple axle assemblies did not have a significant effect on pavement response when the load per tire remained constant. Since pavement response can be correlated to pavement performance, it can be inferred that axle configuration will not have a significant effect on performance as long as the load per tire is constant.

Work by Skok provides an excellent example of the effect of equivalent axle loads (EALs) on pavement life and fatigue (17). A piece of metal bent once usually won't break. But if it is bent many times, it might eventually break. The number of times it takes to break the metal also depends on how far it is bent. If it is bent only slightly, it will take many bends in order to fatigue and break the metal. If it is bent more each time, it will take fewer bends to break it. Also, there is a load which will break it with one loading.

Pavement fatigue is measured by the number and weight of axle loads needed to make the pavement unserviceable. If each axle load is increased, there will be fewer applications before the road breaks up. If the axle loads are decreased, the pavement will carry more vehicles before it will fail. The amount of pavement deflection can be correlated to an EAL. An increase in EALs will not fail the pavement immediately, but the time until the road will need significant maintenance is shortened.

Skok provided the following example on the cost associated with increased EALs caused by increased axle loadings. If the general level of loading was increased by ten to eleven percent, such as from a 9-ton to a 10-ton single axle load, the increased wheel loading would cause about a 50 percent increase in damage. If one and one-half inch of asphalt overlay costs about $20,000 per mile, and it was expected to last 20 years, this would represent an annual investment of $1,000 per year per mile. For the increased damage of 50 percent, the life expectancy is reduced to thirteen years. The cost per year is then more than $1,500. This represents more than a 50 percent increase in annual maintenance cost.

He also addressed the effect of tri-axles. He states that a 42,000 lb., evenly loaded tridem axle will have an EAL of 1.0. The load must be the same on each of the axles or a higher EAL will result. If a truck consisting of a front axle, tri-axle and tandem has GVW of 80,000 lb. it will have an EAL two-thirds of that with a truck composed of a front axle and two tandems. The tri-axle will spread the load over more axles and thus do less pavement damage.

1.5 COMMON TERMS

One of the objectives of the study was to define the terms associated with four-axle single unit trucks. All terms used by the other states and manufacturers to describe the lift axle were noted. They are as follows: lift, tag, cheater, variable load, third, pusher, retractable, booster, hydraulic load, air ride, drop, add on, movable, and belly. Terms associated with the tri-axle unit, tandem set plus a lift axle, were as follows: tri-axle, tridem axle and triple axle.

Another term encountered with the lift axle was the pressure control device. This device controls the air pressure in the lift axle air bags or load which the lift axle carries. Other terms for this device were activating device, regulator and pressure control.

1.5.1 DEFINITION OF TERMS

Lift Axle - An add-on variable load, retractable axle.

Air Bag - A device activated by air pressure which applies a variable load on the lift axle.

Pressure Control - A device consisting of a pressure regulator and a pressure gage which regulates the air pressure in the air bag.

Control Switch - A switch which can only activate the air bag at a preset air pressure. The pressure cannot be regulated by the switch.

Drop - The vertical distance the lift axle can travel between the raised and loaded position.

Suspension - The mechanism which raises or lowers axle and connects axle to frame.

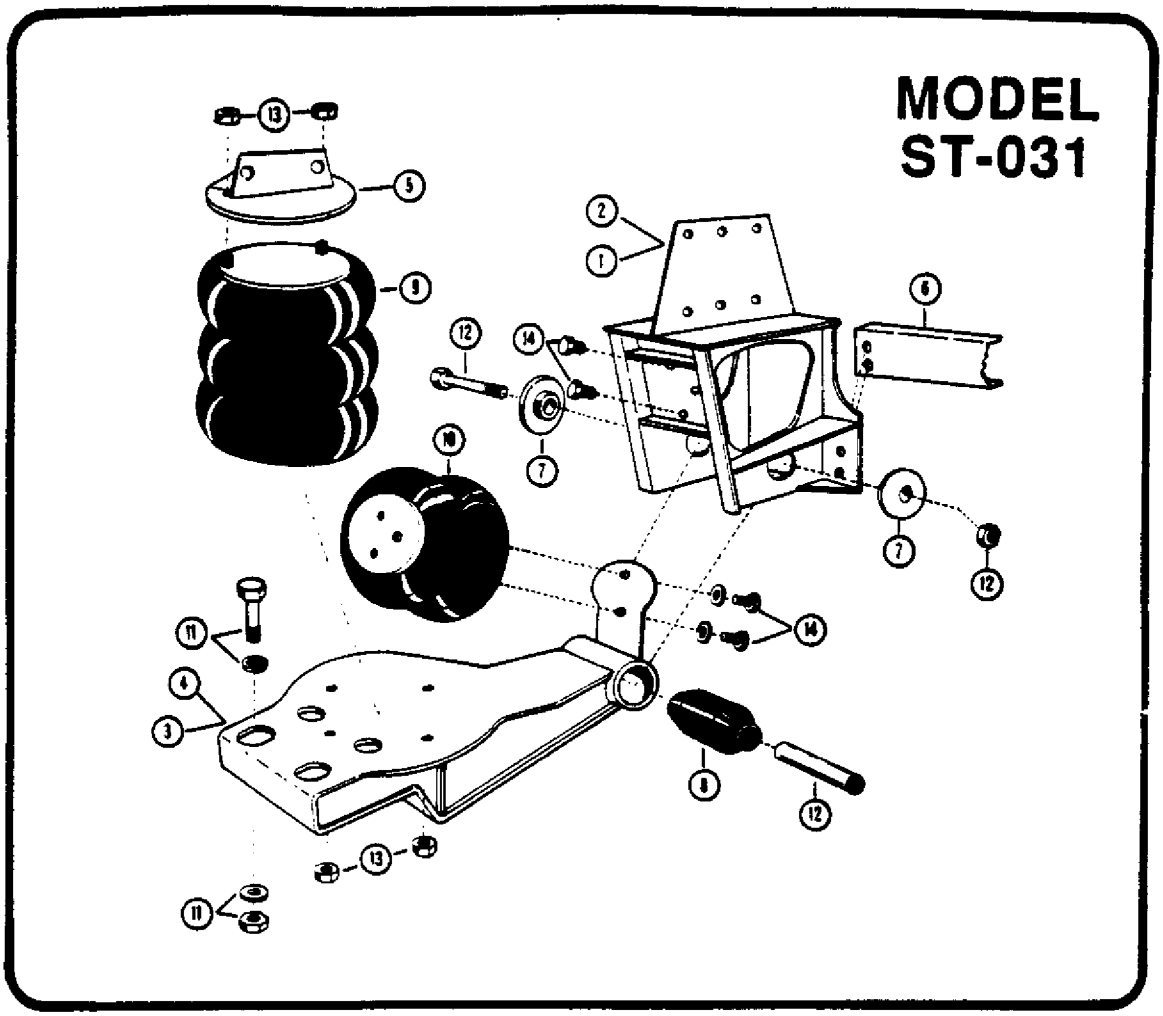
Arm Suspension - A suspension system with a pivoting arm assembly to which the lift axle is attached (Fig. 1.7).

Spring Lift Suspension - A positive lift system where the lift axle is mounted on a positive return spring and the axle is loaded by an air bag (Fig. 1.8).

Castering - A lift axle which permits the wheels to pivot during turning maneuvers (Fig. 1.9 to 1.11).

Tag Lift Axle - Lift axle placed behind tandem.

Pusher Lift Axle - Lift axle placed in front of tandem.

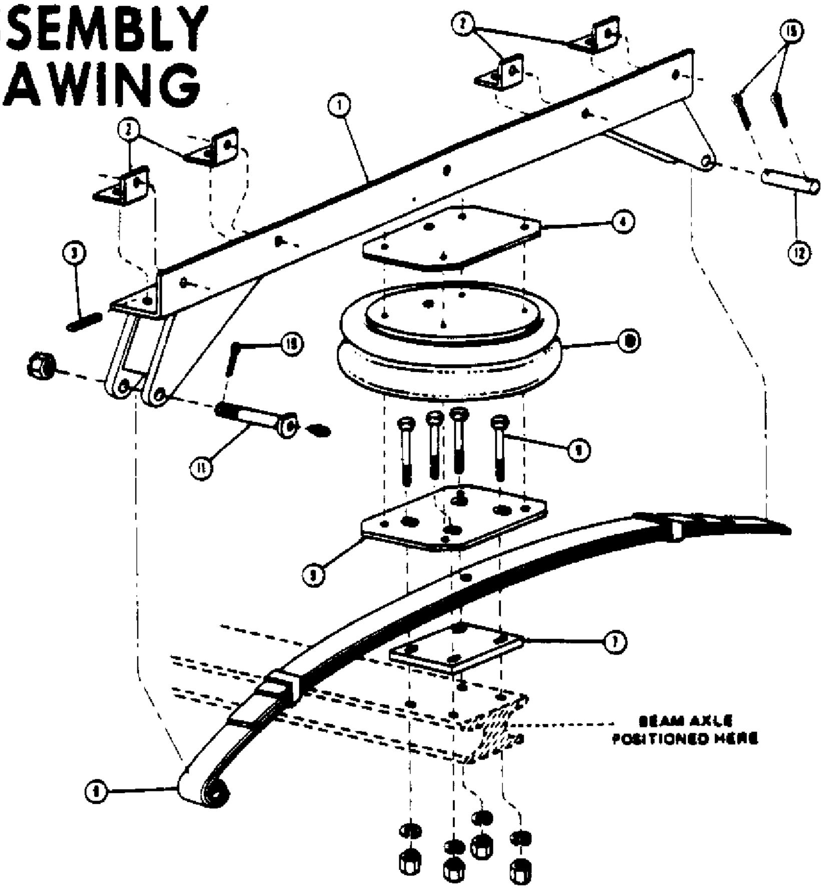


MODEL NO. ST-031 PARTS LIST NO. 50-031 DRAWING NO. D-7190

ITEM NO.	PART NUMBER	QTY.	DESCRIPTION
1	C-6272-1	1	HANGER ASSEMBLY
2	C-6272-2	1	HANGER ASSEMBLY
3	D-7373	1	BEAM, AXLE SEAT & BUSHING R.H.
4	D-7373	1	BEAM, AXLE SEAT & BUSHING L.H.
5	C-6176	2	UPPER BAG PLATE
6	A-1631-14	1	CHANNEL
7	B-5331	4	ALIGNMENT COLLAR
8	B-2841-1	2	BUSHING
9	B-7853	2	AIR SPRING (RIDE)
10	B-2630	2	AIR SPRING (LIFT)
11	A-7379	1	AXLE BOLT KIT
11A	SA-1000-27	8	3/4-10X 3 1/2 HHCS GR-8
11B	SA-1300-7	8	3/4-10 HEX NUT
11C	SA-1500-6	8	3/4 FLAT WASHER
11D	SA-1600-5	8	3/4 LOCKWASHER
12	A-5332	2	BEAM BOLT KIT
12A	SA-1000-34	2	1 1/8-7X 8 1/2 HHCS GR-8
12B	SA-1300-17	2	1 1/8 STOVER LOCK NUT
12C	A-2068-2	2	DELRIN BUSHING 4.97"
13	A-6575	2	AIR SPRING BOLT KIT (RIDE)
13A	SA-1300-4	8	1/2X 13 HEX NUT
13B	SA-1300-8	4	3/4-16 FIN. HEX NUT
13C	SA-1600-4	8	1/2 MED. LOCKWASHER
13D	A-2300-3	2	1/4-20 NPTF PLUG (FIRESTONE ONLY)
14	A-2849	2	AIR SPRING BOLT KIT (LIFT)
14A	SA-1100-6	8	3/8-16X 1 HHCS GR-2
14B	SA-1600-1	8	3/8 MED. LOCKWASHER

Fig. 1.7 Arm Suspension System

ASSEMBLY DRAWING

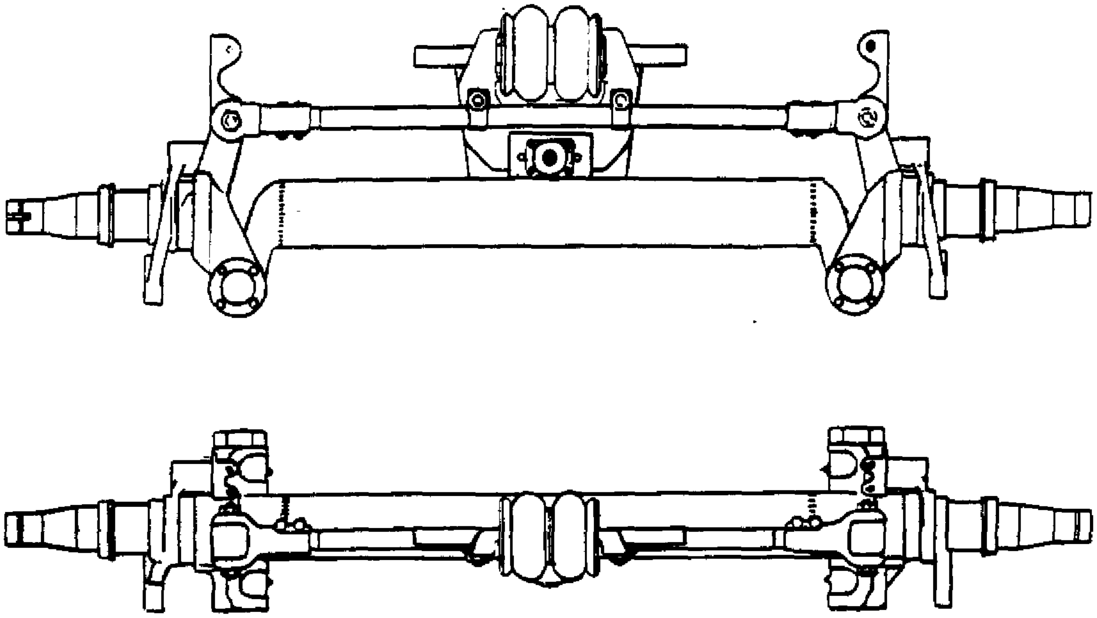


PARTS LIST – MODEL WM-100

ITEM NO.	PART NAME	PART NO.	REQUIRED
1	Side Rail Assembly	C-1061	2
2	Side Rail Clip Angles	A-1079	8
3	Side Rail Clip Angle Spacers	A-1046	8
4	Top Bag Plate	C-1062	2
5	Bottom Bag Plate Weldment	B-1090	2
6	Positive Return Spring	C-1092	2
7	Axle Plate	A-1088	2
8	Spring Spacers (not shown)	A-1078	6
9	5/8 x 7 Hex Head Bolts w/Nuts & Washers	A-1136	1
10	3/8 x 1 Bolts w/lockwasher (not shown)	A-1134	2
11	Shackle Bolts w/grease fittings & nuts	A-1132	2
12	Free End Pin	A-1011	2
13	Hand Control Valve (see Detail 4)	A-1127	1
14	Cotter Pins	SA-1700-2	6
15	Brake Protection Valve (see Detail 4)	A-1128	1
16	Air-ride	B-1080	2
17	Quick Release Valve (see Detail 4)	A-1129	1
18	Air Gauge (see Detail 4)	A-1130	1
19	Spring Center Bolt (not shown)	A-1081	2

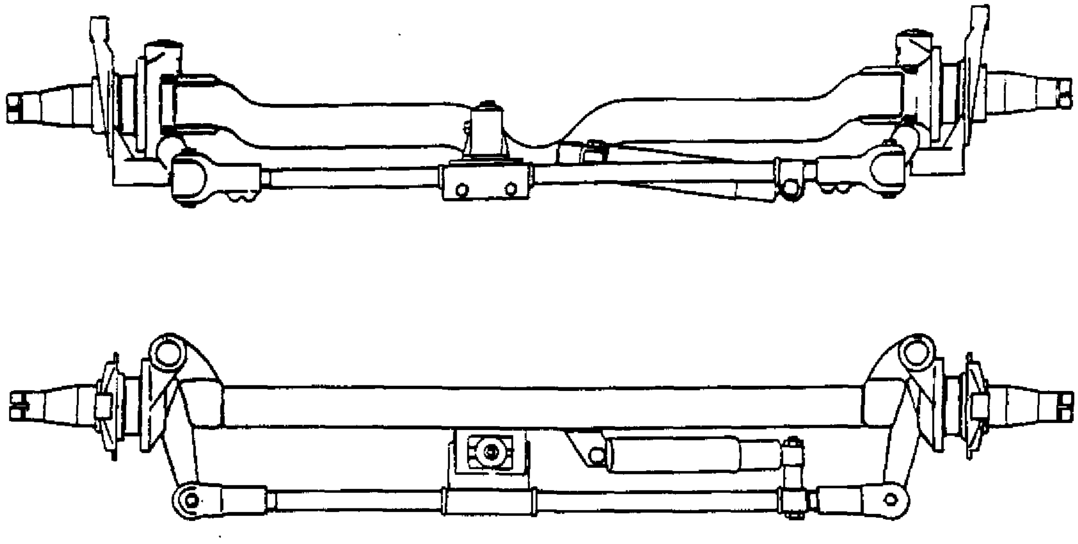
NOTE: When ordering part, be certain to specify item number, part number, serial number and model.

Fig. 1.8 Spring Lift System



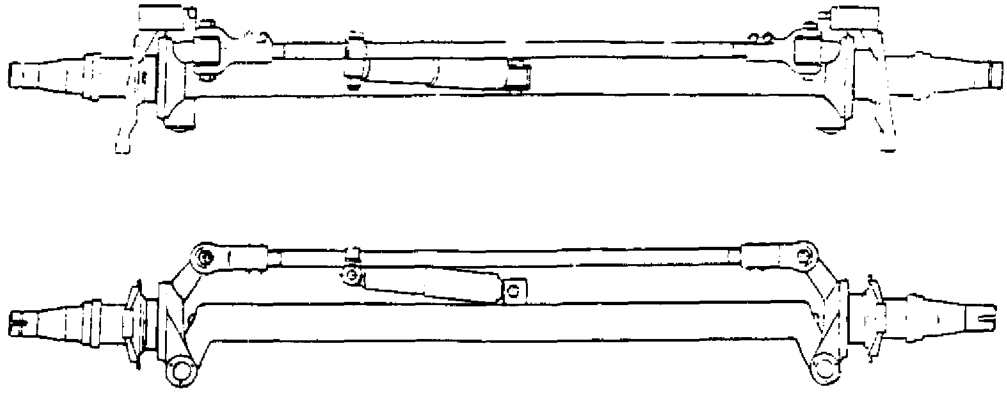
TRACK AVAILABLE	C188SS715 - 71 1/2" C187SS755 - 75 1/2"
CAPACITY	22,500 lbs.
STABILIZER	Air Operated
REVERSE LOCK	Air Operated
BEARING CONES	663 Inner HM212049 Outer
BRAKES	16 1/2" x 7"
WHEELS AVAILABLE	All Wheels Available for IMT A19 Series Axle i.e. 20" 5 Spoke Wheel 10 Stud Hub
SUSPENSION	Can be used with most Air Ride Suspensions using a trailing beam. Will fit most mechanical suspensions.
APPLICATION	Pusher or Tag Axle for Trailer Use. Tag Axle for Trucks.

Fig. 1.9 Castering Air Stabilizer Tag Axle



TRACK	80"
CAPACITY	12,000 lbs.
REVERSE LOCK	Air Operated
BEARING CONES	663 Inner HM212049 Outer
BRAKES	12-1/4" x 5-1/2"
WHEELS AVAILABLE	All Wheels available for IMT A19 Series Trailer Axles
APPLICATION	Light Duty Pusher Axle for Trucks

Fig. 1.10 Castering Shock Absorber Pusher Axle



TRACK AVAILABLE	78"
CAPACITY	15,000 lbs.
STABILIZER	Single Shock Absorber
BEARING CONES	663 Inner HM212049 Outer
BRAKES	16 1/2" x 7" Air Operated
WHEELS AVAILABLE	All Wheels Available for IMT A19 Series Trailer Axle i.e. 20" 5 Spoke Wheel 10 Stud Hub
APPLICATION	Has Been Used Mounted Behind and In Front of Tandem Axles on Trucks and Trailers.

Fig. 1.11 Castering Shock Absorber Tag Axle

Chapter 2

Surveys

2.1 INTRODUCTION

Two surveys were conducted in order to obtain background information on four axle single unit trucks. The first survey investigated the use of these trucks in other states and how the states responded to their use. The second survey investigated the manufacturers of the four axle trucks and lift axles for design and other related information.

2.2 NATIONAL SURVEY OBJECTIVE

The survey objective was to investigate the use, restrictions and pavement damage associated with the four axle single unit truck. A survey letter was sent to all the State Police, Weights and Permits Directors and Chief Engineers of the Highway Departments in the United States. The letter asked for responses to the following questions:

1. Does your state permit the use of four axle single unit trucks or similar triple axle configurations?
2. What restrictions do you impose on their usage?
3. The justification you have for the restrictions or lack of restrictions.
4. Provide any documentation or experience with flexible or rigid pavement damage caused by these trucks.
5. Types or uses of these trucks or related axle configuration in your state.

2.3 NATIONAL SURVEY RESPONSE

At least one agency from each state responded to the survey. A summary of the survey is as follows:

2.3.1 STATES WHICH SEVERELY RESTRICT THE USE OF THE LIFT AXLE.

1. Alaska - The maximum weight permitted on a tandem is 38,000 lb as compared to 42,000 lb on a tri-axle. Other restrictions are that any axle within 10 ft. of another axle is considered part of tandem and a tell-tale device shall be visible on the left side of the truck to show the axle is fully loaded. Also, after 11/30/87 the lift axle would be restricted to ready-mix trucks only.
2. California - The use of the self-steering lift axles is permitted only on ready-mix trucks.
3. Florida - The maximum weight on the tandem is 44,000 lb and the maximum weight on the tri-axle is 44,000 if the distance between first and third axles is less than 10 ft. Additional weight on the triaxle is governed by a bridge formula.
4. Georgia - Lift axles will be banned after April 1, 1988 because of abuse by the trucking industry - running with the axle up.
5. New Mexico - The GVW for a tri-axle truck is 46,220 lb. The state permits a weight of 12,000 lbs on the steering axle and 34,320 lb on the tandem axles. The lift axle is considered part of the tandem set.
6. Oregon - If the weight placed upon an axle can be varied, it is not counted as an axle.

2.3.2 BRIDGE FORMULAS

The following states regulated the permissible load on the tri-axle by the bridge formula: Alabama, Arizona, California, Colorado, Florida, Idaho, Illinois, Indiana, Iowa, Maryland, Michigan, Minnesota, Mississippi, Nevada, New Jersey, Oklahoma, Tennessee, Texas, Vermont, Virginia, and Wisconsin.

2.3.3 DISTANCE SPECIFICATIONS

Many states had a minimum distance between the first and third axles of the tri-axle in order to be considered a tri-axle set. Some examples are as follows:

(1) ARKANSAS

Maximum weight.

48,000 lb if distance is less than 8 ft.

50,000 lb if distance is more than 8 ft.

(2) CALIFORNIA (Part of bridge formula)

Distance	Max Weight
8′	34,000 lb
9′	42,500 lb
10′	43,500 lb

(3) FLORIDA (Part of bridge formula)

Distance	Max Weight
8′	44,000 lb
9′	44,000 lb
10′	44,000 lb
11′	44,500 lb

(4) KANSAS

Distance between first and third axles must be 97 inches or more to be considered a triple.

(5) MARYLAND (Part of bridge formula)

Distance	Max Weight
8′	34,000 lb
8′ plus (97")	42,000 lb
9′	42,500 lb
10′	43,500 lb

(6) MICHIGAN

Distance	Max Weight Per Axle
0 - 3 1/2′	9,000 lb
Tandem	17,000 lb
3 1/2 - 9′	13,000 lb
9′ or more	20,000 lb

(7) MINNESOTA (Part of bridge formula)

Distance	Max Weight
7′	41,500 lb
8′	42,000 lb
9′	43,000 lb

(8) MISSOURI (Part of bridge formula)

Distance	Max Weight
8′	34,000 lb
8′ plus (97")	42,000 lb
9′	42,500 lb
10′	43,500 lb

(9) NEBRASKA

Distance	Max Weight
96" or less	34,000 lb
97" or more	54,000 lb

(10) NEW JERSEY (Part of bridge formula)

Distance	Max Weight
8′	34,000 lb
9′	42,500 lb
10′	43,500 lb

(11) OHIO

Max Weight - 48,000 lb and 4′ centers and less than 9′

(12) VERMONT (Part of bridge formula)

Distance	Max Weight
8′	36,000 lb
9′	42,500 lb
10′	43,500 lb

or 54,000 lb in tri-axle group with no two axles supporting over 42,000 and no single axle over 22,400 lb.

(13) WYOMING

Maximum weight on tri-axle group is 42,500 lb and the distance between the first and third axles must be less than 108 in.

2.3.4 LIFT AXLE SPECIFICATIONS

The following states had specifications on the lift axle in order to be considered as an axle

(1) COLORADO - Lift axle must carry 10 percent of the gross weight.

(2) ILLINOIS - Lift axle must carry enough weight so that the tandem set is not overloaded.

(3) MAINE - No single axle of a tri-axle unit shall support more than 40 percent of the weight supported by the tri-axle unit.

(4) MARYLAND - The lift axle must carry its share of the weight.

(5) MINNESOTA - No axle in a group of three may carry more than 15,000 lb.

(6) NEBRASKA - Lift axle must carry at least 8 percent of the gross vehicle weight.

(7) OHIO - Lift axles must equalize load over all three axles.

(8) OKLAHOMA - Lift axle must carry its share of the weight.

(9) SOUTH CAROLINA - All axles must make contact with the highway. No lifting during turns.

(10) WEST VIRGINIA - Lift axle must have less than 20,000 lb and lift axle plus adjacent axle must be less than 34,000 lb.

(11) WISCONSIN - Lift axle must carry at least 8 percent of gross vehicle weight.

(12) WYOMING - Lift axle must assume about same weight as the other axles.

2.3.5 MAXIMUM WEIGHT

The maximum weight permitted on the tri-axle group specified by the different states or gross vehicle weights are as follows:

(1) ALASKA - GVW of tri-axle truck - 70,000 lb.

(2) ARIZONA - GVW of tri-axle truck - 74,000 lb.

(3) CONNECTICUT - GVW of tri-axle truck:

76,500 pressure control outside cab.

73,000 pressure control inside cab.

(4) DELAWARE - GVW of four axle truck:

73,280 lb (lift axle lowered).

70,000 lb (lift axle raised).

(5) FLORIDA - GVW of four axle truck - 70,000 lb.

(6) IDAHO - GVW of four axle truck - 66,000 lb.

(7) ILLINOIS - GVW of four axle truck - 60,000 lb

Tri-axle unit - 42,500 lb.

(8) INDIANA - GVW of four axle truck - 70,000 lb.

(9) KENTUCKY - GVW of four axle truck - 70,000 lb

Tri-axle unit - 50,000 lb.

(10) LOUISIANA - GVW of four axle truck - 60,000 (with permit)

Tri-axle unit - 42,000 with no axle over 16,000 lb.

(11) MAINE - GVW of four axle truck - 69,000 lb

Tri-axle unit - 48,000 lb hauling grain

54,000 lb hauling gravel

64,000 lb hauling forest products with a GVW of 75,900 lbs.

(12) MARYLAND - GVW of four axle truck - 66,000 lb

Tri-axle unit - 42,000 lb.

(13) MASSACHUSETTS - GVW of four axle truck - 73,000 lb

60,000 lb without lift axle down.

(14) MISSOURI - GVW of four axle truck - 73,280 lb.

(15) MONTANA - GVW of four axle truck - 74,000 lb.

(16) NEBRASKA - GVW of four axle truck - 74,000 lb

Tri-axle unit - 54,000 lb.

(17) NEVADA - GVW of four axle truck - 74,000 lb.

(18) NEW HAMPSHIRE - GVW of four axle truck - 60,000 lb. off interstate

47,500 lb. on interstate

Tri-axle unit - 48,000 lb.

(19) NEW JERSEY - GVW of four axle truck - 60,000 lb.

(20) NEW MEXICO - GVW of four axle truck - 46,320 lb.

(21) NEW YORK - GVW of four axle truck - 76,400 lb

Tri-axle unit - 54,000 lb.

(22) NORTH DAKOTA - GVW of 4 axle truck - 61,000 lb.

GVW of 4 axle truck - 64,000 lb. if 14′ or more from front to lift axle

Tri-axle set - 51,000 lb or 17,000 max per axle

(23) OHIO - GVW of 4 axle truck - 68,000 lb

Tri-axle unit - 48,000 lb.

(24) OKLAHOMA - GVW of 4 axle truck - 70,000 lb.

(25) PENNSYLVANIA - GVW of 4 axle truck - 73,280 lb.

Tri-axle unit - 60,000 lb.

Class 20 - 21,400 lb/axle

Class 19 or less - 18,000 lb/axle.

(26) RHODE ISLAND - GVW of 4 axle truck - 76,650 lb.

(27) SOUTH CAROLINA - GVW of 4 axle truck - 69,850 lb.

(28) TENNESSEE - GVW of 4 axle truck - 74,000 lb.

(29) VERMONT - GVW of 4 axle truck - 60,000 lb.

(30) VIRGINIA - GVW of 4 axle truck - 62,500 lb.

(31) WEST VIRGINIA - GVW of 4 axle truck - 63,000 lb

Tri-axle unit - 42,500 lb.

(32) WYOMING - GVW of 4 axle truck - 62,500 lb

Tri-axle unit - 42,500 lb.

2.3.6 PRESSURE REGULATOR

Many states specified that the pressure regulator must be located outside the cab or have a device to show that the axle is loaded. They are as follows:

(1) ALASKA - Tell-tale device visible on left side to show the axle is fully loaded.

(2) ARIZONA - Pressure control present and outside cab.

(3) CONNECTICUT - 3,500 lb increase in GVW if pressure control outside cab.

(4) IDAHO - Pressure switch outside cab (excluding ready-mix trucks).

(5) LOUISIANA - Pressure control must be outside of cab.

(6) MINNESOTA - Pressure control must be outside of cab.

(7) SOUTH DAKOTA - Pressure control outside of cab and raise-lower control inside cab.

2.3.7 CASTERING LIFT AXLE

Some states specify or encourage the lift axle to be self-steering or castering, they are:

(1) ARIZONA - Lift axle must be self-steering.

(2) CALIFORNIA - Lift axle must be self-steering.

(3) IDAHO - Lift axle must be self-steering after 1990.

(4) UTAH - Encourages self-steering lift axle.

(5) WASHINGTON - Lift axle must be self-steering.

2.3.8 WIDTH OF TREAD REGULATIONS

Many states specify a maximum weight on axle as a function of load per inch width of tread.

They are:

(1) ALABAMA - 550#/1" width.

(2) ALASKA - 550#/1" width.

(3) FLORIDA - 605#/1" width.

(4) KENTUCKY - 600#/1" width.

(5) MAINE - 600#/1" width.

(6) MASSACHUSETTS - 600#/1" width.

(7) MICHIGAN - 700#/1" width.

(8) MONTANA - 600#/1" width.

(9) NEW HAMPSHIRE - 600#/1" width.

(10) NEW JERSEY - 800lb/1" width.

(11) OHIO - 650lb/1" width.

(12) VERMONT - 600lb/1" width.

2.3.9 OTHER RESTRICTIONS

Other restrictions by state included the following:

(1) CONNECTICUT - Lift axle must be rated at least 15,000 lb.

(2) LOUISIANA - Lift axle must not be raised while transporting a load unless making a turn.

(3) SOUTH CAROLINA - No lifting during turns.

(4) SOUTH DAKOTA - Annual permit for lifting axle when making a turn.

(5) WASHINGTON - Lift axle must be rated 10,000 lbs.

2.4 AASHTO RECOMMENDATIONS

An AASHTO Policy Resolution concerning four axle single unit trucks has been prepared by the Highway Subcommittee on Highway Transport, which is part of the American Association of State Highway and Transportation Officials (AASHTO) organization. The resolution recommends the following restrictions on four axle single unit trucks.

In computation of gross vehicle or axle weight limits for highway legal vehicles not requiring oversize/overweight permits, no allowance will be made for any retractable or variable load suspension VLS axle not meeting the following criteria:

1. All controls must be located outside of and be inaccessible from the driver's compartment.
2. The gross axle weight rating of all VLS (Variable Load Suspension) devices must conform to the expected loading of the suspension and shall in no case be less than 9000 pounds.
3. Axles of all retractable or VLS devices manufactured or mounted on a vehicle after January 1, 1990 shall be engineered to be self-steering in a manner that will guide or direct the VLS mounted wheels through a turning movement without tire scrubbing or pavement scuffing.
4. Tires in use on all such axles shall conform in load rating capacity with relevant state regulations or with Federal Motor Vehicle Safety standards or with both as is deemed appropriate.
5. The VLS suspension system shall, at all times for the weight computation, proportionately distribute the load for the axle group being considered.

2.5 TRUCK MANUFACTURER SURVEY

Ford, GMC, Dodge and International personnel were interviewed in order to obtain technical information on their trucks. Information on suspension, axle and frame capacity was reviewed from each manufacturer. It was noted that the manufacturers do not manufacture or install the lift axle. The lift axles are generally installed by dealers or body shops. It was also learned that the manufacturer will still honor the trucks' warranty after a lift axle is installed.

Further investigation into structural strengths and characteristics of lift axles was limited to lift axle manufacturers.

2.6 MANUFACTURED LIFT AXLE SURVEY

Three lift-axle manufacturers (Watson and Chalin, Hendrickson Turner, and Ingersoll Machine and Tool Co. Limited) were surveyed for information concerning the design specifications of the axle. The capacity of the lift axle varied from 12,000 lbs to 22,500 lbs. The manufacturers built axles with castering and non-castering wheels. That is, the wheels would caster or turn as the trucks turned. They had the same capacity rating as the non-castering axle. The size of tires which could be placed on the castering axle varied by manufacturer. One manufacturer used balloon or very wide tires (22") while another used dual tires on the axle. The cost differential between the castering and non-castering axle ranged from $1000 to $2000, depending on the manufacturer.

The advantages of the castering axles are as follows:

1. Makes driving safer because the vehicle negotiates turns easier.
2. Reduces tire wear since the tires are not scuffing across the pavement.

3. Reduces critical stress on chassis, axles, springs and bearings during turning maneuvers.
4. Reduces fuel consumption as less power is needed to overcome the dragging effect of turns.
5. Protects road pavements because the pavement is not scuffed and reduces stress in pavement.
6. Does not require any special maintenance on the vehicle.
7. Improvement in stabilizers has prevented the wobbling effect with consequent wear of tires and bushings as observed on earlier versions.

Chapter 3

DETERMINATION OF EALS

3.1 INTRODUCTION

Equivalent axle load (EAL) is one of the major terms used in pavement design and damage analysis. Pavement design is based on the number of EALs expected to pass over the roadway in a given time period, along with other factors. Therefore, EALs are a good measure of pavement damage or the reduced life of pavement.

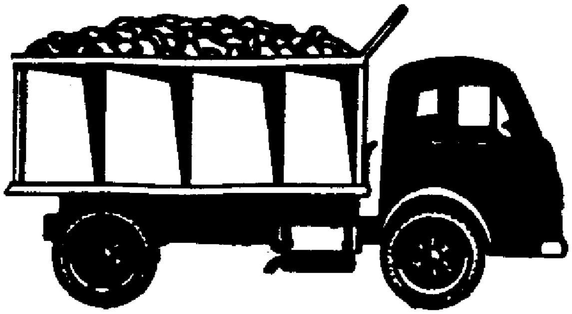
One means to assess the damage caused by different trucks is to determine the average EALs per class of truck. The EALs for each of the major truck axle configurations were determined from data obtained from the Arkansas Highway Police.

3.2 FIELD DATA

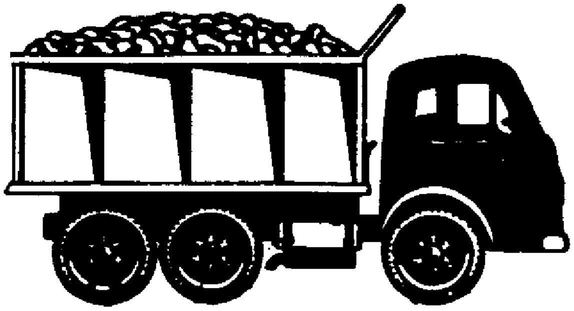
Data used to determine the axle weights for the EALs was obtained from the random weighing of trucks by the Arkansas Highway Police using portable scales. When each truck was weighed, a weight slip, AHP-49, was filled out listing wheel weights, axle weights and total gross weight. A random data set was obtained from weigh slips filled out between September 1987 and April 1988. The number of observations for each class of trucks (Fig. 3.1) is given in Table 3.1.

Table 3.1 Observations per Class of Truck.

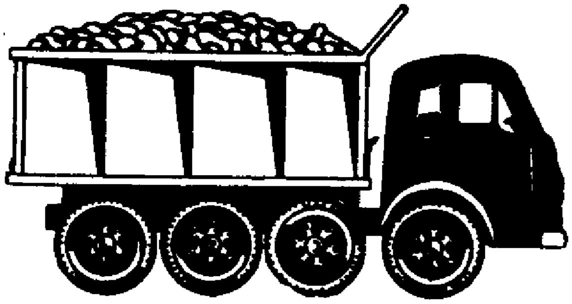
Class of Truck	Number of Observations
2 axle single unit	61
3 axle single unit	97
4 axle single unit	74
5 axle double unit	98
Total	330



Two Axle



Three Axle



Four Axle

Fig. 3.1 Single Unit Trucks

3.3 TRUCK CLASS EALs

The EALs associated with each truck were calculated by two methods. The first method was using the AASHO Tables for flexible pavements using a structural number (SN) of 4.0 and terminal level of serviceability (Pt) of 3.0. These tables assume dual tires on all axles and equal axle loads on tandems and tridems. The second method used to determine the EALs was based on work by Southgate and Deen of the Kentucky Transportation Research Program. Their work assumes single tires for front axle, dual tires on single rear axles, tandems and tridems and non-uniform loading of axles. This results in a truck EAL associated with the truck's true axle weight for tandems and tridems subjected to non-uniform loadings. The results are given in appendix B.

3.4 PRESENTATION OF RESULTS

An average EAL was calculated for each class of truck by each method. They are presented in Table 3.2.

Table 3.2 Average Truck EALs

Class	AASHO	Ideal	Kentucky Approach	Ideal
2 axle single unit	1.64	1.64	2.86	2.28
3 axle single unit	1.49	1.41	1.70	1.17
4 axle single unit	1.71	1.41	3.23	1.01
5 axle double unit	2.51	2.56	1.94	1.80

A graph of the four classes of trucks in terms of EALs and weights is presented in Fig. 3.2.

The ideal truck EAL was calculated for each method by assuming a truck with a front axle loaded to 12,000 lb and the maximum legal uniformly loaded rear axle or axles.

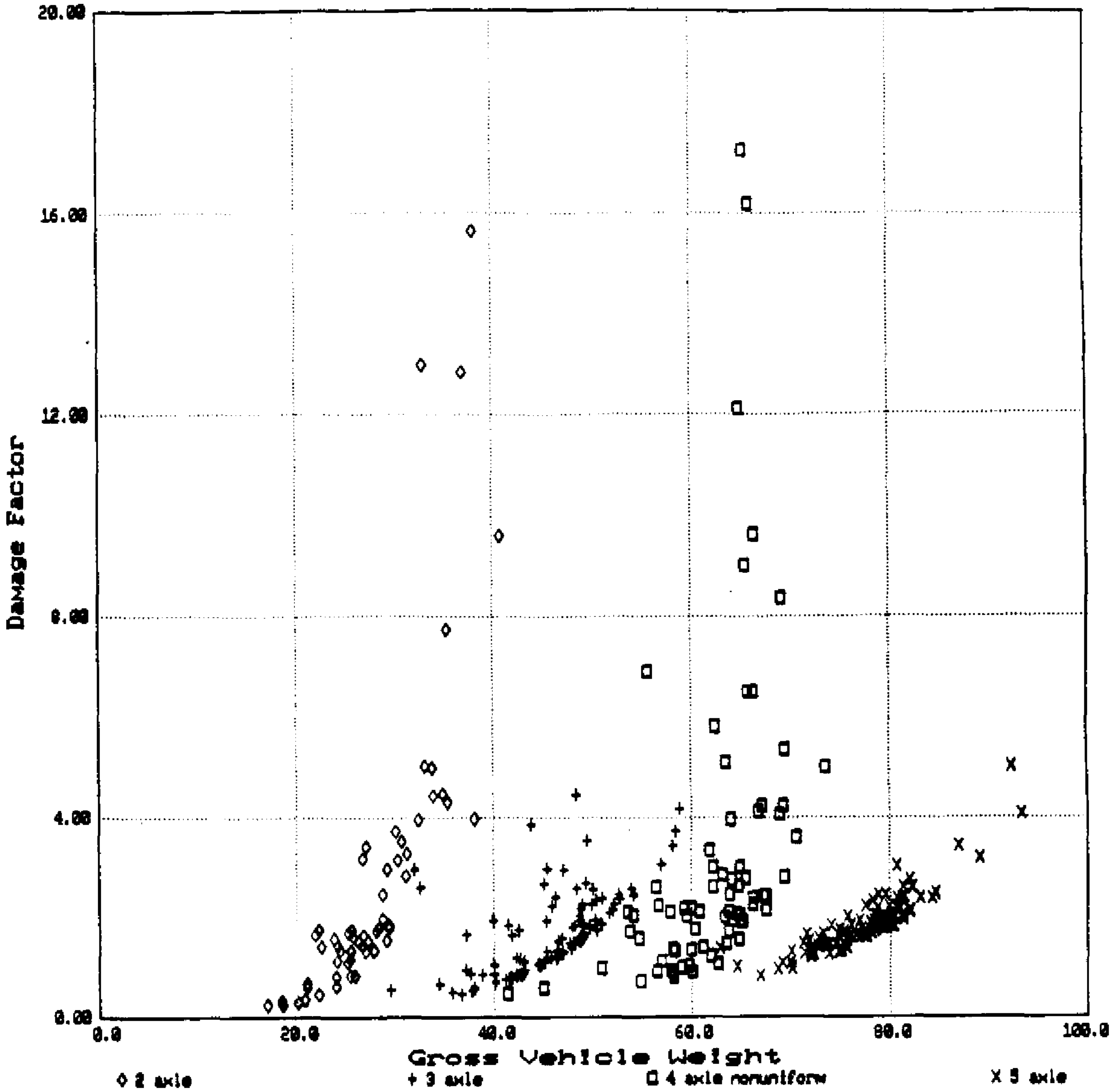


Fig. 3.2 Truck EALs

The percentage of trucks which were overweight in each class of vehicles is presented in Table 3.3.

Table 3.3 Percent of Trucks Overweight

Class	% Overweight	Accepted Legal Limit, Kips	Average GVW Kips
2 axle single unit	15	33.5	27.6
3 axle single unit	41	47.5	45.5
4 axle single unit	47	63.5	61.9
5 axle double unit	12	81.5	78.3

It should be noted that the legal limit was increased by 1.5 kips to account for the accepted 1.5 kip variance of the portable scales.

To further investigate the effect of the four axle truck, a statistical analysis was performed on the data using the "LIMDEP" statistical routines. The analysis revealed that the best fit curve which would describe the behavior of the data was of the form:

$$\ln(\text{Truck EAL}) = A + B * \text{Weight} \qquad 3.1$$

where

A and B are constants.

Weight is the Gross Vehicle Weight.

Truck EAL is the EAL calculated for each truck.

The constants associated with the regression equation for each class of trucks are given in Appendix A.

The analysis of variance revealed that when looking at the mean EAL, the least damaging truck was the three axle. The five axle and two axle truck produced higher EALs, respectively. The truck with the highest EAL was the four axle truck. Taking into account the weight of the vehicle, the least damaging was the five axle truck and the three axle and four axle trucks were more damaging, respectively. The most damaging was the two axle truck. The analysis also revealed that the confidence level for the analysis was 99^+ percent.

A review of the best fit curves, Equation 3.1, revealed that for a unit increase in load, the greatest increase in the truck's EAL was introduced by the two axle truck since it had the steepest slope. The next damaging truck in terms of slope was the four axle, followed by the two axle and five axle, respectively.

An analysis of four axle trucks revealed that 18 out of the 74 (24%) had tri-axles with individual axle weights difference between the heaviest and lightest axle of 3,000 lbs or less. An analysis was performed on those trucks whose front axle was under 18,000 lbs and tri-axle within a 3000 lb axle difference. The results are given in Table 3.4. If the weight difference was 3000 lbs or less, the axle was considered uniformly loaded since the truck's EAL was close to the ideal value of 1.01.

Table 3.4 Uniforms Tri-axle Weights

Axle Weight Difference	Sample Size	Avg. Weight (lbs)	Four Axle Avg Weight	EALs (Kentucky Method)	Four Axle Avg EAL
1500	7	58,600	61,900	1.06	3.23
3000	15	59,500	61,900	1.18	3.23

A second analysis was performed on the four axle data where the front axle was limited to 12,000 lbs and the remaining weight was transferred to the tridem. Also, the tridem was considered uniform loaded. The analysis revealed that the truck EAL calculated by the Kentucky approach would change from 3.23 to 1.13. This would produce a reduction in the EALs by a factor of slightly under three. A graph of this data compared to all trucks is given in Fig. 3.3. A third analysis was performed by the Kentucky approach which considered a uniformly loaded tri-axle and the actual front axle weight. The four axle truck EAL reduced from 3.23 to 1.53, just by considering the tri-axle uniformly loaded.

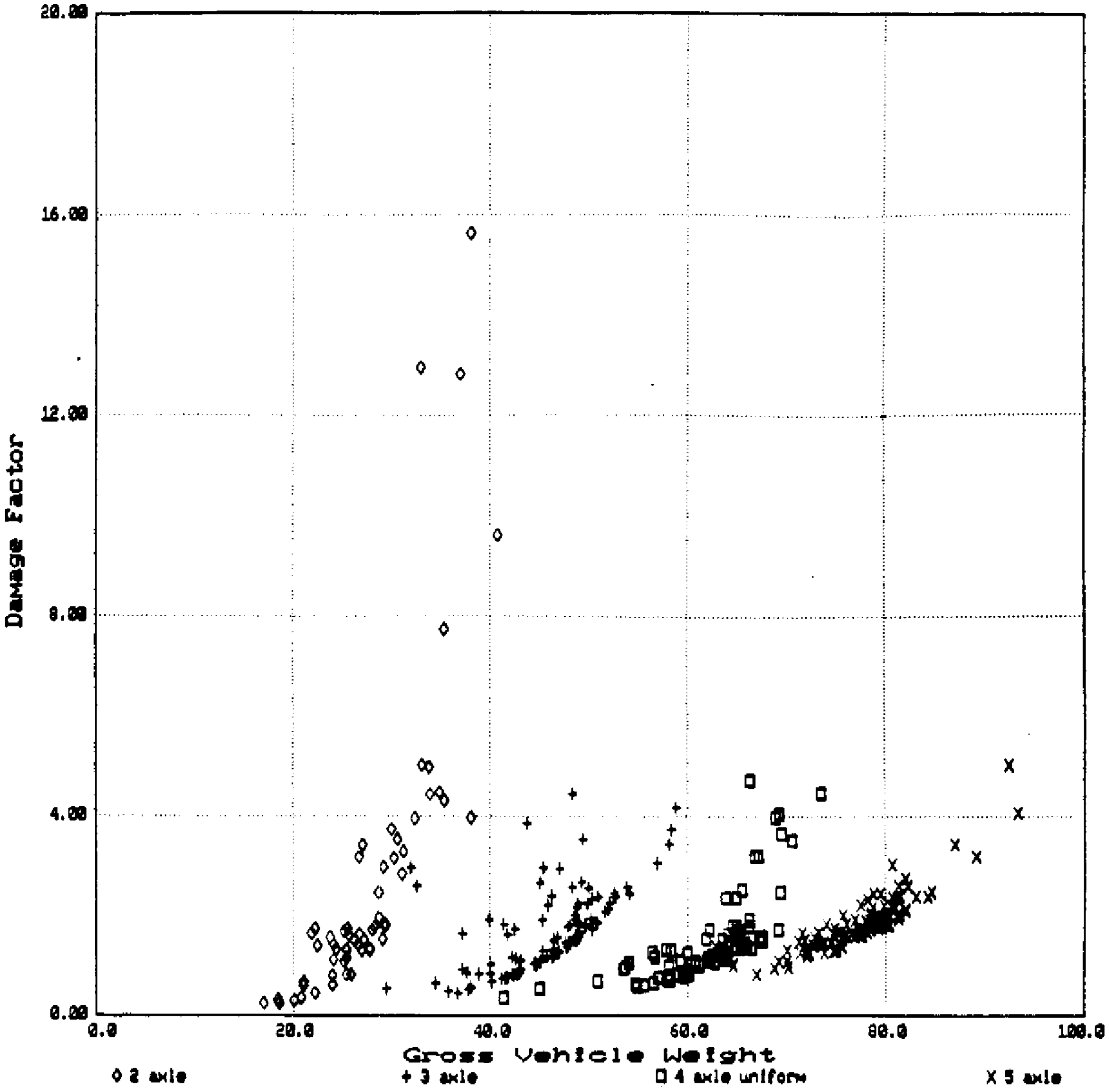


Fig. 3.3 Truck EALs with Uniformly Loaded Tri-axles

CHAPTER 4

IMPACT OF FOUR AXLE TRUCKS

4.1 INTRODUCTION

In order to estimate the impact the four-axle single unit trucks have on the roads in Arkansas, vehicle classification data was reviewed over a four year period, 1984 to 1987. The review considered county, function class of road, class of truck, and total truck count. The review determined the percentage of trucks by class on each functional class of roadway for each county within the state.

4.2 FOUR AXLE SINGLE UNIT TRUCK TRAFFIC.

The function of roadways was divided into 18 classes. They are:

- Rural
  - Interstate
  - Other Principal Arterials
  - Minor Arterial
  - Major Collector
  - Minor Collector
  - Collector
- Small Urban (5000-50,000 population)
  - Interstate
  - Other Freeway and Expressway
  - Other Principal Arterials
  - Minor Arterials
  - Collectors
  - Local

Urbanized (over 50,000 population)

- Interstate
- Other Freeways and Expressways
- Other Principal Arterials
- Minor Arterials
- Collectors
- Local

The percentage of four axle single unit truck traffic within the total truck count for each functional class of roadway by year is given in Table 4.1. These trucks averaged 2.2 percent of the total truck traffic. On interstates and arterials, the four axle single unit truck also averaged 2.2 percent of the truck traffic.

The percentage of four axle single unit trucks within the truck stream by county is given in Fig. 4.1. The percentage in some counties were not reported due to lack of data. The shaded counties denote where four axle single unit trucks compose more than three percent of the total truck traffic.

Table 4.1 Four Axle Single Unit Truck Traffic Percentage

	Percentage of Trucks					Percentage by Classification
	1984	1985	1986	1987	Avg.	
All Roads	1.18	3.03	2.49	2.29	2.20	100.0
Interstates	0.9	2.7	2.3	4.1	2.2	65.4
Arterials	1.5	3.5	2.1	1.9	2.2	30.4
Rural	1.2	3.5	2.1	1.7	2.0	24.8
Small Urban	3.9	4.6	3.0	0.9	3.3	3.0
Urbanized	2.2	2.6	1.3	4.9	2.8	2.6
Collectors	3.1	3.3	1.7	2.1	2.9	4.2

The regions of above average four axle truck traffic are the Southwest quarter, the North Central area and the Central Counties along the Mississippi River. Ten counties have over three times the average four axle truck traffic and 13 counties had over twice the average four axle truck traffic.

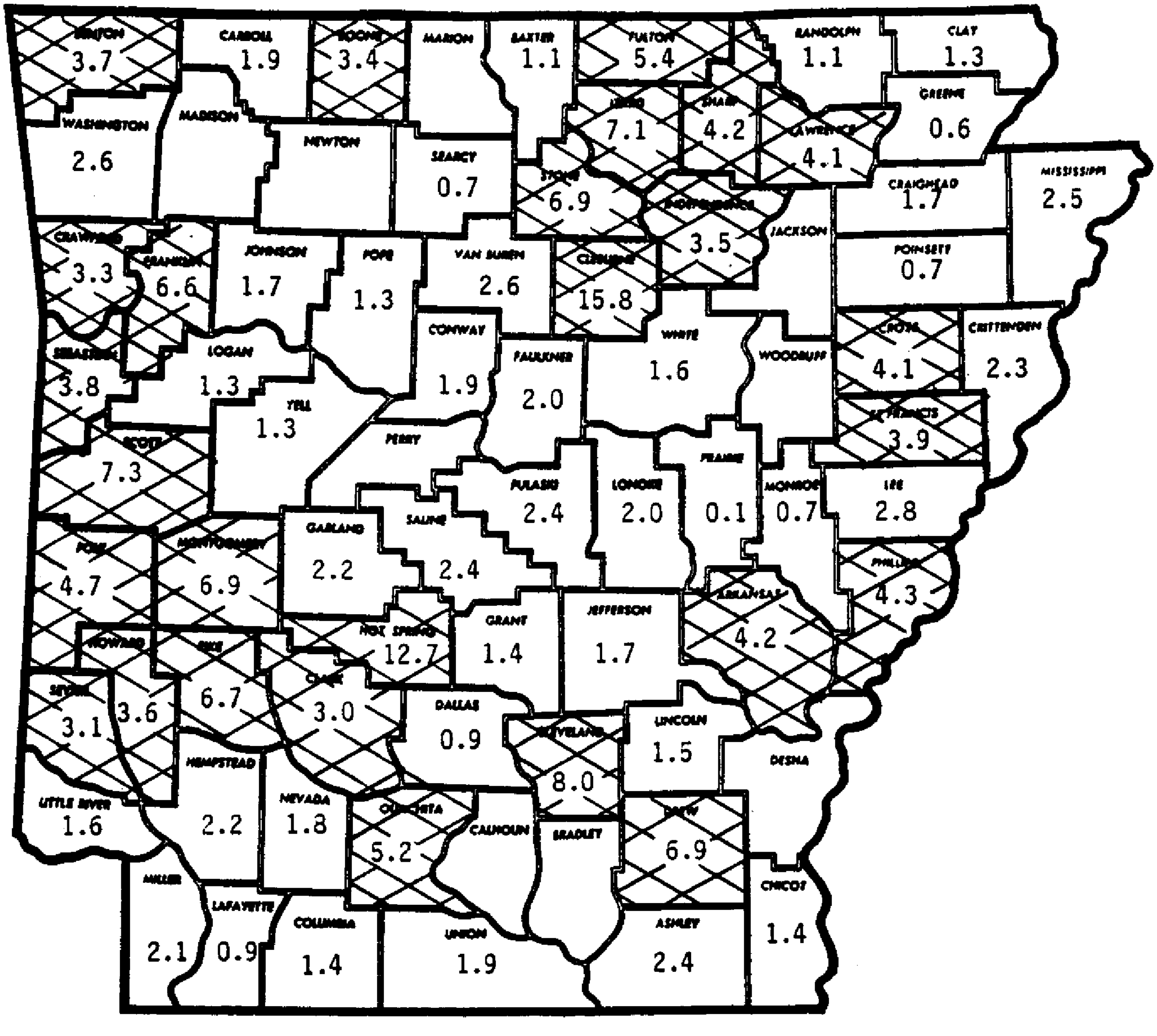


Fig. 4.1 Percent of Truck Traffic

The percentage of four axle single unit truck traffic on the interstates is given in Fig. 4.2 and the percentage on Arterials is given in Fig. 4.3 to 4.4. Again, above average, four axle single unit truck traffic is noted in the same regions of the state, on arterials and rural arterials as compared to overall truck traffic. Ten counties had over three times the average traffic and 16 had over twice the average traffic on rural arterials. It should be noted that 90.2 percent of the four axle single unit truck traffic was on interstates and rural arterials.

4.3 IMPACT OF FOUR AXLE SINGLE UNIT TRUCKS

The percentage of EALs generated by each class of truck was determined by multiplying the percentage of truck traffic for each class of vehicle by the vehicle EAL determined in Chapter 3. From Highway Police weighing data, the four axle two unit truck EAL was determined to be 4.0. A table summarizing the four axle two unit truck data for the EAL calculation is presented in Appendix C. Also, included in Appendix C is a sample set of calculations for determining the average number of EALS generated by each class of truck within the 16 counties studied. The EAL used for the other class of truck was estimated at 2.0 since no data on this class of truck was available. It was assumed that they will have similar properties as the five axle two unit truck.

The percentage of EALs for each class of truck on rural arterials by county is given in Table 4.2. The two axle percentage varied from 12 to 38 percent, three axle varied from 5 to 15 percent, four axle single unit varied from 6 to 19 percent, four axle two unit varied from 11 to 42 percent and five axle two unit truck varied from 20 to 49 percent of the total EALs produced.

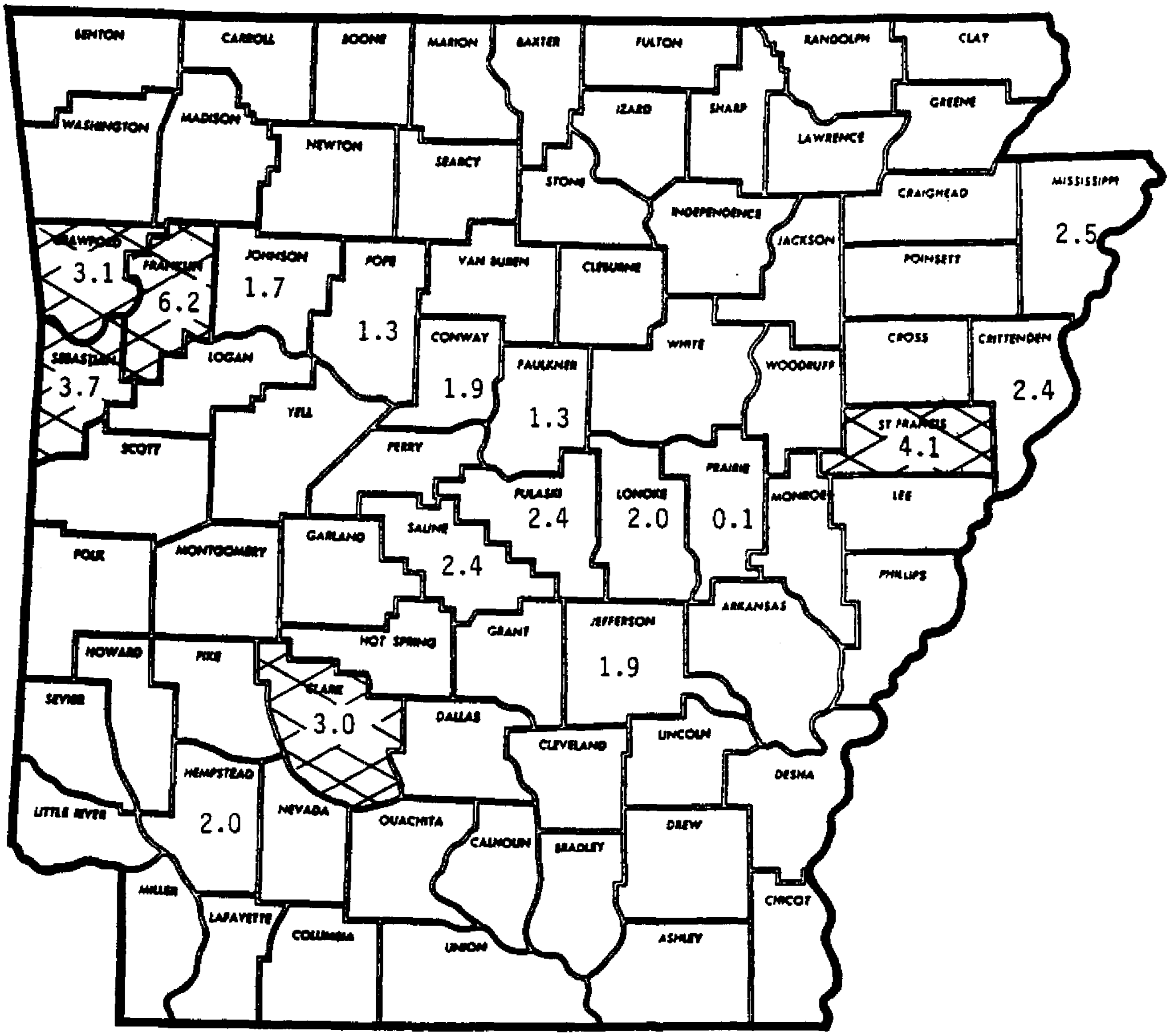


Fig. 4.2 Percent of Truck Traffic on Interstates

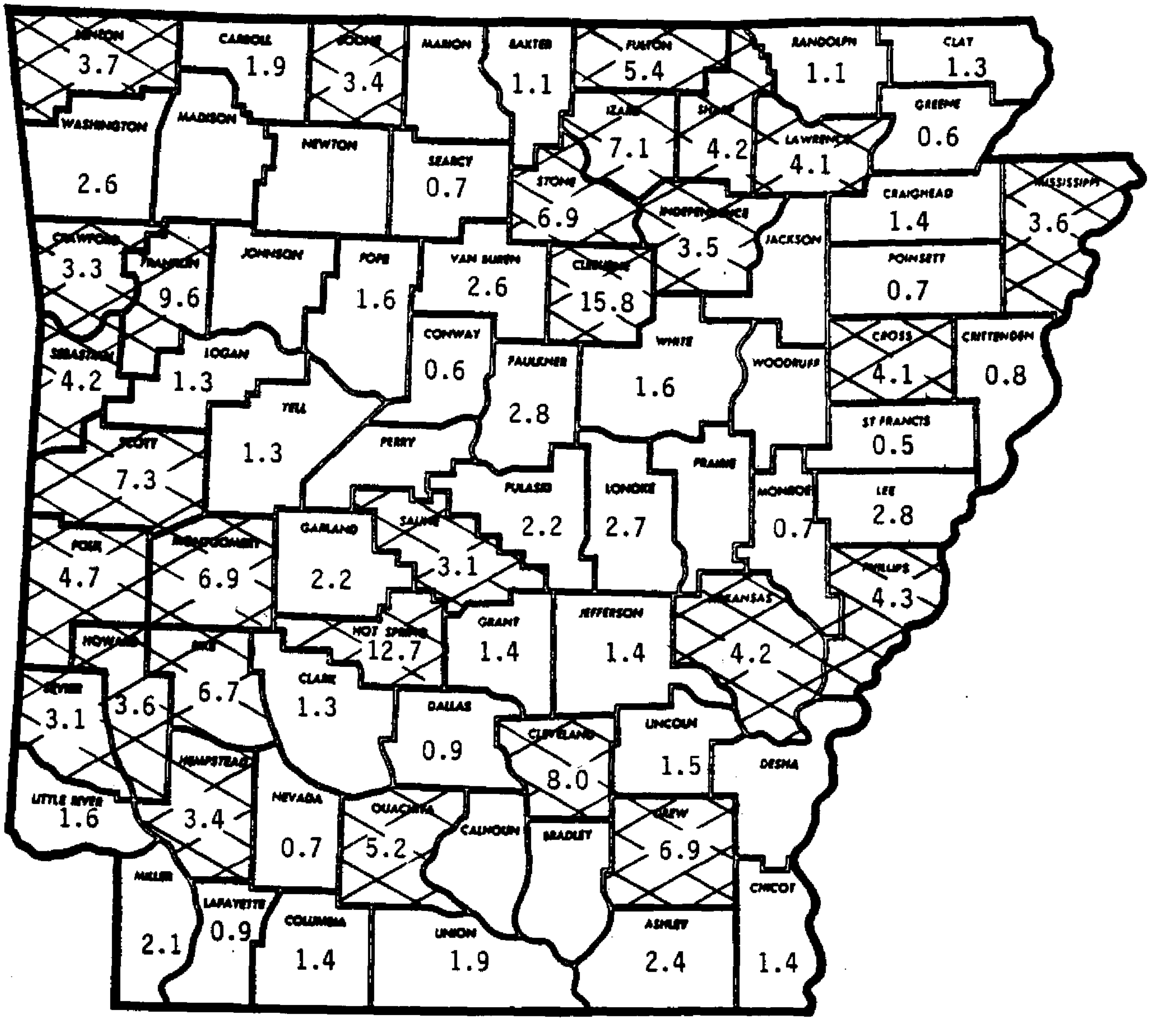


Fig. 4.3 Percent of Truck Traffic on Arterials

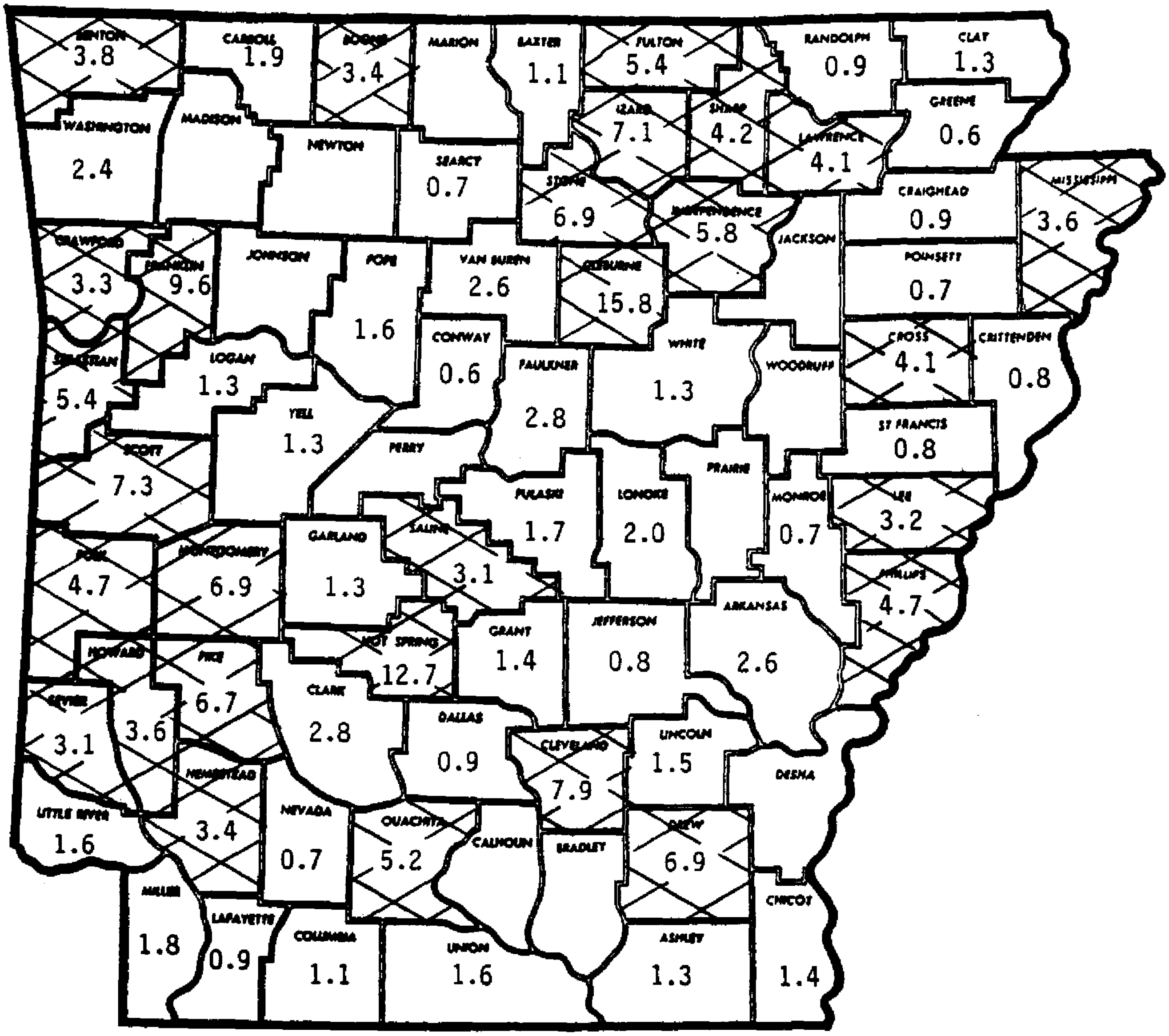


Fig. 4.4 Percent of Truck Traffic on Rural Arterials

Table 4.2 Truck Class Percentage of EALs on Rural Arterials

Percent of EALs

County	Single Unit Truck			Two Unit Truck		
	2 axle	3 axle	4 axle	4 axle	5 axle	Others
Cleburne	35.9	12.1	19.3	17.4	15.3	-
Cleveland	15.2	8.9	17.1	36.2	36.2	11.7
Drew	12.3	9.9	9.6	19.9	44.7	3.8
Franklin	30.4	11.5	11.8	25.7	20.2	0.5
Fulton	18.0	6.3	7.1	26.0	37.4	5.3
Hot Springs	26.0	8.4	15.9	21.6	27.3	0.8
Independence	23.5	10.3	7.7	19.9	32.0	6.6
Izard	38.0	8.0	8.7	23.6	20.8	1.0
Montgomery	29.2	10.6	8.9	21.2	28.4	1.6
Ouachita	16.2	9.9	6.9	25.5	39.6	1.8
Phillips	29.6	4.7	6.3	14.7	43.8	0.9
Pike	20.5	14.7	9.5	11.3	42.4	1.6
Polk	17.9	7.2	6.6	15.8	48.9	3.6
Scott	17.4	9.8	10.5	10.5	47.0	4.8
Sebastian	19.2	10.1	6.4	41.7	21.6	1.1
Stone	37.2	10.2	9.0	14.3	27.6	1.8
Average	21.7	9.5	9.1	20.5	35.5	3.7

4.4 FINDINGS

The four axle single unit truck averaged 9.1 percent of the EALs generated on rural arterials in the 16 counties studied with over 4.4 percent of the truck traffic being four axle single unit trucks. The four axle single unit truck had approximately the same damage impact on rural arterials as the three axle truck even though there were 1.8 times more three axle trucks than four axle single unit trucks.

CHAPTER 5

PAVEMENT LOADS

5.1 INTRODUCTION

The main objective of the study was to assess the pavement damage attributed to four axle single unit trucks. One means of assessment was to measure the forces transmitted to the pavement by the truck tires. There are two basic forces involved. The first force transmitted is the gravity load of the tire, that is, each tire's share of the gross vehicle weight. This force can be measured by scales when the truck is moving or static. The other force transmitted is a resultant force consisting of the horizontal or drive force, the force required to move or stop the vehicle, and a tangential force, or the force present when the vehicle turns. Tangential forces are present in the front wheels as they turn the vehicle and in the tri-axle wheels as they resist the turning forces.

In order to determine the forces produced in the pavement when a four axle single unit truck makes a tight turn, a test plate was developed and placed in a roadway to measure the resultant force. The gravity loads on each axle was obtained by static platform scale measurements.

5.2 TEST PLATE

A test plate was developed which measured the resultant force produced between the pavement and tires (Fig. 5.1). The plate was designed to measure the forces produced by a single wheel.

The plate was constructed in the following manner.

1. One-half inch mild steel was used for the base and floating plate.
2. The base plate and floating center plate were surfaced and BBs were placed between the plates to maintain freedom of movement.

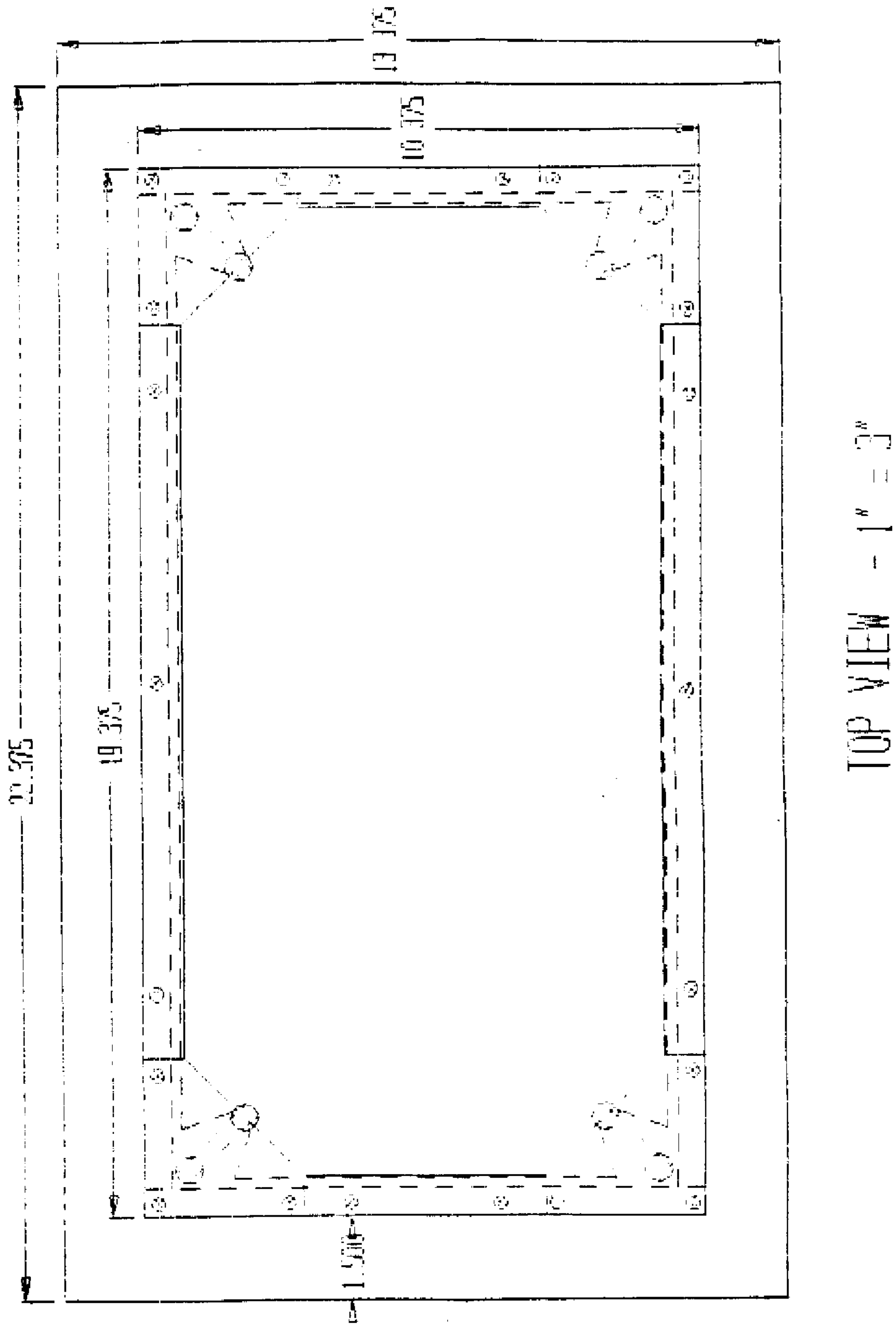


Fig. 5.1 Test Plate

3. A machined steel border strip was bolted to the base plate. It held the floating plate in place. This strip was designed to permit the plate to float and hold the BBs in place.
4. Rods, 3/8" in diameter, were placed in each corner of the floating plate. The rods could pivot on both ends and had left and right hand threads in the pivoting blocks. This would permit the rods to be tightened in order to remove any play in the floating plate. (Fig. 5.2)
5. The rods were machined on opposite surfaces to permit mounting of strain gages on each surface. (Fig. 5.3). The rods were calibrated in tension before they were placed in the plate.
7. A steel plate cover was bolted on top of the border strip and over the edges of the floating plate. This plate protected the strain gages and kept dirt away from the edges of the floating plate and BBs.
8. A diamond pattern was welded on the floating plate to simulate the frictional surfaces of pavement.
9. The plate was calibrated with a variable force applied in four directions. The forces were applied at the center of the floating plate and parallel to the long and short sides of the plate.
10. The strain gage readings were collected by a Keithley data acquisition system with the strain gage module. A Zenith Model 13 computer recorded and stored the strain gages readings. The strain gage module could support up to four strain gage bridges. This resulted in readings being obtained from each corner of the plate.
11. The calibration device used to calibrate the plates was a hydraulic jack designed to remove pullout inserts. A pressure transducer and readout were mounted on the jack. The hydraulic pressure within the

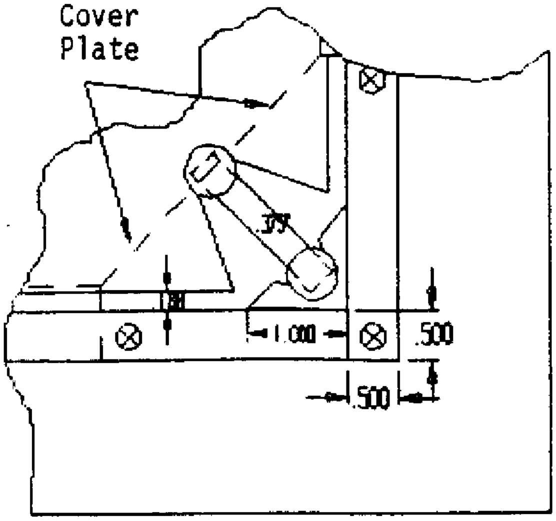


Fig. 5.2 Rod Details

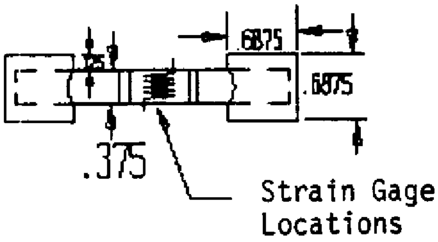


Fig. 5.3 Strain Gage Locations

jack could be measured to within 1 psi. The hydraulic jack had been calibrated before it was used to calibrate the plate.

12. The strain gage bridge consisted of the two strain gages mounted on the steel rod (120 ohm, HBM 3/120 Ly11) and two highly accurate 120 ohm resistors.
13. A 50 ft. cable consisting of nine pairs of individually shielded twisted wires was used to transmit the strain gage signals to the data acquisition system.
14. The orientation of the plate's reference axis is given in Fig. 5.4.

5.3 DETERMINATION OF FORCES

The test plate and computer system was transported to a local ready mix supplier who loaned a truck for use in the study. The truck was a Crane Carrier Model 4424-4EX equipped with a dual tire lift axle. The axle spacings are given in Fig. 5.5.

5.3.1 AXLE LOADING

Six axle loading conditions were evaluated during the tests. Air pressure in the lift axle air bags was varied from 60 to 100 psi in 10 psi increments. Also, there was a loading condition with the lift axle up. Axle weights were determined by driving the truck onto a certified platform scale and noting the changes in loading as each axle entered the scale. Results are given in Table 5.1

5.3.2 FIELD CONDITIONS

To simulate the turning of a four axle single unit truck, the test plate was mounted in a level gravel roadway at the ready mix supplier. The truck

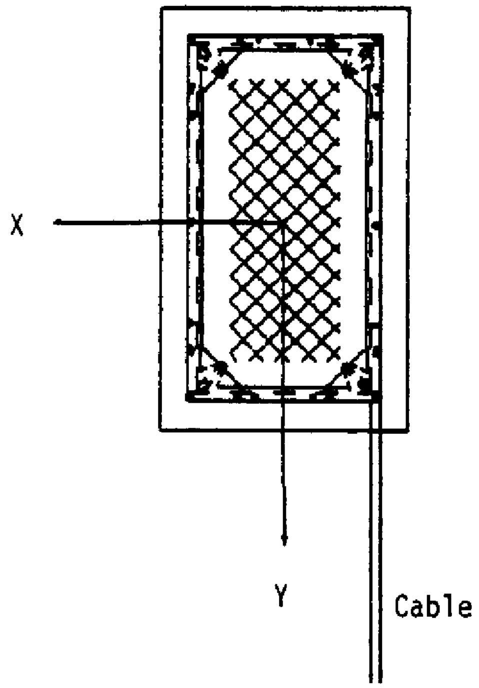


Fig. 5.4 Plate Reference Axis

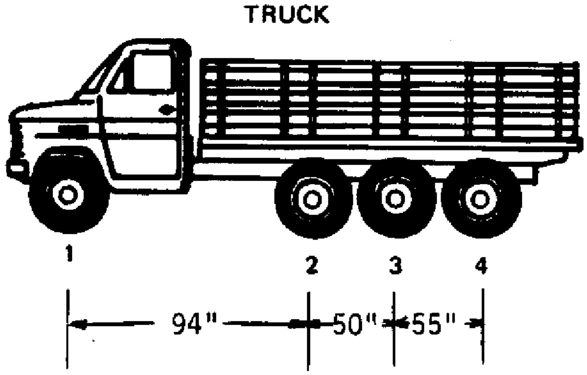


Fig. 5.5 Truck Dimensions

simulated a hard right turn, with a turning radius of approximately 45 ft. The radius was under 45 ft. when the lift air bags were operated at 60 to 80 psi loadings. As the air pressure increased in the air bag the turning radius increased. Also, when the lift axle was up, the turning radius was less than 45 ft. The plate was mounted flush in the gravel and secured in place with eight 3/8 x 8 in. steel spikes. The cable was buried in the gravel in order to prevent damage to it.

5.3.3 DATA

The turning maneuvers were repeated nineteen times. They were video recorded in order to record which tires passed over the plate and the percentage of plate coverage by the tires. A description of lift axle loading conditions for each turning maneuver in order of runs is given in Table 5.2 along with the percentage of plate coverage by tires.

The data was analyzed by calculating the magnitude of the resultant force for each wheel and the direction of force with respect to the X axis of the plate. The positive X-axis was in the direction of travel. The results are presented in graphic form in Appendix D.

The test plate was positioned so that the Y-axis was parallel to the radius of curvature. However, due to unforeseen circumstances, the Y axis was not parallel to the radius. The orientation is given in Fig. 5.6. Magnitude and direction of the resultant forces for each wheel with respect to the vehicle's long axes are given in Appendix D for each turning maneuver.

TABLE 5.1 Axle Weights

Lift Axle Air Bag (psi)	Axle Weights Front	Lift	1st Axle of Tandem	2nd Axle of Tandem
60	17,460	10,660	17,840	16,640
70	16,160	13,020	16,960	16,460
80	15,620	16,000	13,640	17,340
90	12,840	19,760	12,300	17,700
100	12,480	21,920	10,920	17,280
0 (UP)	21,680	0	20,800	20,120

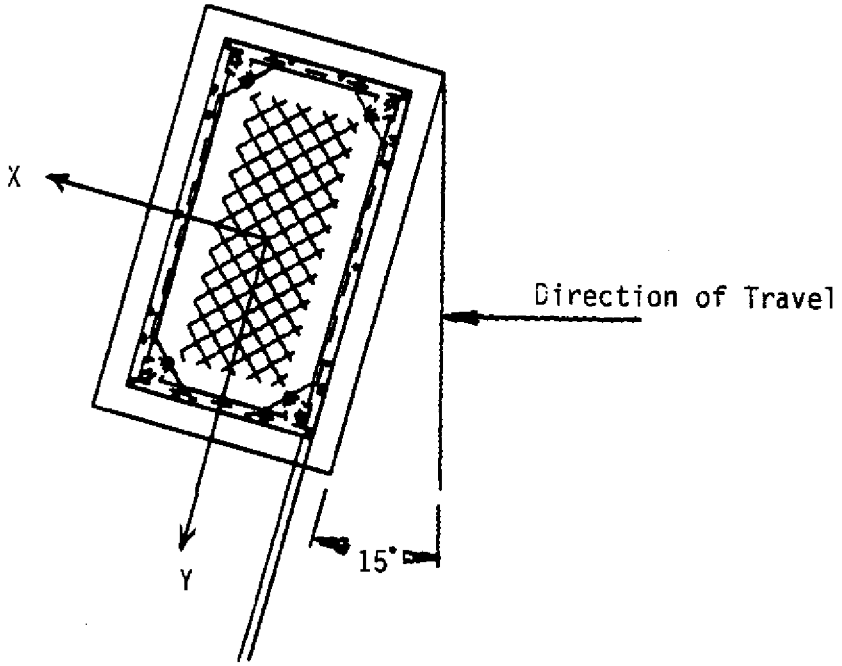


Fig. 5.6 Plate Orientation

Table 5.2 Turning Maneuvers

Lift Axle Air Bag Force (psi)	Wheel Studied	Plate Coverage	Data Code
60	Front	Full	T160
	Front	*	TF60
	Tri-axle	Full (both duals)	TT160
70	Front	2/3	TF70
	Tri-axle	Full (outside dual + 2"inside)	TT170
	Tri-axle	Full (both duals)	TT270
80	Front	2/3	TF80
	Tri-axle	Full (outside dual)	TT180
	Tri-axle	3/4 (outside dual)	TT280
90	Front	1/3 Front 3/4 Tri-axle	TF190
	Tri-axle	Full (outside dual)	TT290
	Front	Full (front) 1/4 Tri-axle	TF290
	Tri-axle	3/4 (outside dual)	TT290
100	Tri-axle	Full (outside dual)	TT1100
	Tri-axle	*	TT2100
	Front	1/2 Front 1/2 Tri-axle	TF1100
0 (UP)	Tandem	Full (both duals)	TT10
	Front	*	TF10
	Front	1/2	TF20

* No video documentation

5.4 FINDINGS

The resultant force (Fig. 5.7) measured by the test plate ranged from 1350 lb for 60 psi air bag loading on lift axle to 2100 lb for 100 psi loading on lift axle. For 70 to 100 psi air bag pressures on the lift axle, the resultant force varied from 1750 lb to 2100 lb or 16% of the maximum force. The force was oriented toward the center of rotation in all cases. The angle between the force and the truck's long axis or center line was 75° for 60 to 90 psi loadings. The 100 psi loading was approximately 60° toward the center of rotation. The first axle of the tandem set had a resultant force in the same direction as the lift axle. The magnitude of the force ranged from 1075 to 1350 lbs for 60 to 90 psi loadings and 350 to 900 lbs. for the 100 psi loadings. The front steering axle had a resultant force of a magnitude ranging from 150 to 2700 lbs. The 150 lb force was for a 60 psi air bag pressure on the lift axle and 2200 to 2700 lbs were noted for 80 to 100 psi air bag pressure. The orientation of the front axle resultant force was away from the center of rotation. When the lift axle was raised the resultant force on the

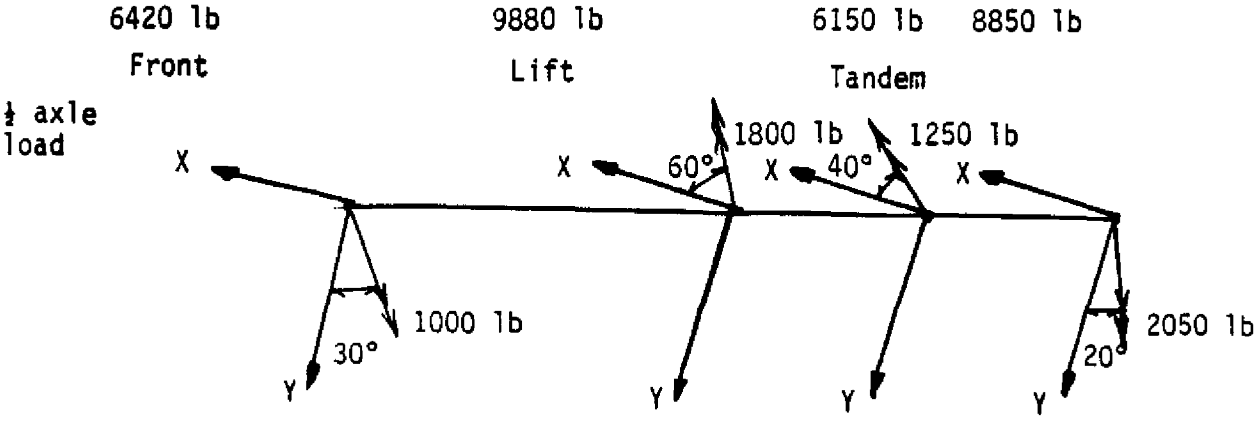


Fig. 5.7 Resultant Forces

first axle of the tandem set increased by approximately 300 lbs. to 1450 lbs. The resultant force on the second axle of the tandem set remained at 2000 lbs. and the front axle resultant force decreased to 550 lbs. This is about one-fifth of the maximum resultant force noted on the front axle with the lift axle lowered.

The resultant forces recorded were the force per tire. A review of the data reveals that when the outside tire of the dual set or when both tires of the dual set covered the plate, similar forces were obtained.

One of the important observations made from the data was that the maximum resultant force produced by the tri-axle was measured at 2700 lbs. The force was on the rear axle of the tandem set. The maximum resultant force produced by a lift axle tire was measured at 2100 lbs. The front tire resultant force had a maximum measured value of 2700 lbs. This was when the tire's gravity load was 6240 lbs. for a lift axle air bag pressure of 100 psi and 6420 for a 90 psi air bag pressure.

The maximum frictional force provided by a road surface can be estimated by multiplying the gravity load by the coefficient of friction. For a 30 mph stopping speed, the coefficient of friction for a wet road is 0.36 and 0.62 for a dry road (18). These frictional values are commonly used in calculating stopping distances. The resulting pavement resistive forces for the front tire with a 100 psi air bag pressure is 2250 lbs. for a wet road and 3850 for dry conditions. The pavement resistive force for dry conditions is greater than the front tire resultant force of 2700 lbs. On a wet roadway the front tire resultant force is greater than the pavement resistive force.

To estimate the resistive force for a 5 mph turn, the coefficient of friction needs to be increased. The coefficient of friction varied by 0.03 for speeds of 30 and 40 mph. The coefficient, therefore, should be increased by 0.03 x (30 mph - 5 mph)/10 mph or to 0.44 for a 5 mph turn. The pavement resistive force would therefore increase to 2750 lbs for wet conditions. This is approximately equal to the measured front tire resultant force.

5.5 CALCULATED TRUCK EALs

The effect of varying the air bag pressure on road damage was studied by calculating the truck EAL associated with each air bag loading condition. The results are given in Table 5.3. The lowest EAL was obtained for 70 and 80 psi air bag pressures. The highest value was obtained for 100 psi air bag pressure. The effect of running with the axle up and a 100 psi air bag pressure in terms of EALs is about the same. It was noted that the ready mix supplier generally runs with a 90 to 100 psi pressure in the air bags.

Table 5.3 Truck EAL Vs. Air Bag Pressure

Air Bag Pressure (psi)	Truck EAL
60	2.8
70	2.1
80	2.1
90	2.8
100	6.2
0 (UP)	5.9

CHAPTER 6

SUMMARY AND DISCUSSION OF RESULTS

6.1 INTRODUCTION

The main objectives of the research were to investigate and define the types of pavement damage which may be attributed to four axle single unit trucks and identify uses and terms associated with the truck. The assessment of pavement damage was accomplished by determining average EAL associated with each class of truck. Also, truck traffic patterns on Arkansas highways and percent of EALs generated by each class of trucks on rural arterials were determined. A test plate was developed which measured the resultant tire forces produced by the four axle single unit truck during tight turns. A national survey of state highway departments, weight and permit divisions and enforcement divisions was conducted. The survey obtained information concerning the usage and restrictions associated with four axle single unit trucks. Also, truck and lift axle manufacturers were surveyed.

6.2 PAVEMENT DAMAGE

The analysis of pavement damage revealed that the four axle single unit truck had the highest EAL generated per trip when compared to the two axle and three axle single unit trucks and the five axle two unit trucks. The average EAL was 3.23 when calculated by the Kentucky approach. This approach accounted for non-equal axle loading on tandems and tri-axles. Data obtained from Highway Police weighings of trucks was used in generating the EAL associated with each truck. The four axle single unit truck's EAL was 3.2 times its ideal EAL or a truck weighing the legal limit and having equally loaded tri-axle axles. A review of the four axle data revealed that 20 percent of the trucks had a tri-axle with a variance of 3000 lbs. between the heaviest and lightest axle and a legal front axle. The average EAL for this group of four axle single unit trucks was 1.18 as compared to the group average EAL of 3.23.

A second analysis of four axle single unit truck data was performed where the front axle was limited to 12,000 lb. and the tri-axle was assumed evenly loaded. Under these conditions, the average EAL was 1.13. Also, by just considering the tri-axle evenly loaded, the EAL associated with the four axle truck reduced to 1.53. Therefore, a substantial reduction in the EAL associated with the four axle single unit truck could be achieved by having the axles of the tri-axle evenly loaded.

An analysis of the truck traffic by class of truck and functional class of roadway revealed that the four axle single unit truck averaged 2.2 percent of the truck traffic on interstates and arterials in Arkansas. It was also revealed that over 90 percent of the four axle single units truck traffic was on interstates and rural arterials. An analysis by counties revealed that the four axle single unit truck traffic was concentrated in three regions of the state. They were the Southwestern quarter, North Central region and the central counties along the Mississippi River. A study of rural arterials revealed that 16 counties in these regions had over twice the average four axle single unit truck traffic. An analysis limited to these counties determined the percentage of EALs produced by the different classes of trucks for rural arterials. The four axle single unit truck had approximately the same damage impact on the pavement as the three axle truck even though there were 1.8 times more three axle trucks on rural arterials.

Though the four axle single unit trucks compose only 2.2 percent of truck traffic statewide, in the areas where they are concentrated they account for over nine percent of the pavement damage on rural arterials.

The analysis of the test plate data indicates that the four axle single unit truck generated similar resultant forces with the lift axle raised or lowered. There was no significant increase in the resultant forces per tire when the lift axle was lowered. However, there was a significant reduction in the front tire resultant forces when the lift axle was raised. An analysis of pavement resistive forces to sliding revealed that the front tire was about to slide during a tight turn on wet pavements. Castering lift axle wheels would make the truck more maneuverable, thus reducing front tire resultant forces. Therefore, the truck's safety would be improved by installing the castering wheels. Also, the drivers would not have to raise the lift axle for tight turns, thus reducing pavement damage. An EAL analysis of the truck used in the study revealed that a truck's EAL went from 2.1 to 5.9 when the lift axle was raised.

The effect of varying the lift axle air bag pressure was studied. When the air pressure was changed from 70 to 100 psi, the truck's EAL changed from 2.1 to 6.2. This was caused by the imbalance of the tri-axle axle loads. The driver reported he generally ran with 90 to 100 psi air pressure. Also, the air pressure varied by over ±5 psi during a run. Therefore, the EAL associated with the four axle single unit truck is dependent upon the lift axle air bag pressure. A pressure too low or too high would greatly change the truck's EAL.

6.3 NATIONAL SURVEY

A national survey was conducted to investigate the use and restrictions of four axle single unit trucks in other states. The common uses of the trucks were transporting garbage, asphalt, gravel, concrete, grain or agricultural products, forest products or any loose material. The survey results indicated several states have imposed restrictions on these trucks. Six states have imposed severe restrictions or banned the use of four axle single unit trucks. This was accomplished by not considering a lift axle as a load carrying axle or restricting the lift axle use only to ready mix trucks. Twenty one states impose restrictions by the use of the bridge formula and 33 states have set maximum weight limits on the tri-axle and/or four axle single unit truck. One state requires a tell-tale device which indicates when the lift axle is fully engaged and six require the pressure regulator to be located outside the cab. Five states require or encourage the use of castering lift axles and twelve states specify a maximum axle load in terms of maximum tire load per inch of tread width.

There have been recent movements in AASHTO and several states to impose more restrictions on four axle single unit trucks. The restrictions require uniform axle loadings within the tri-axle, pressure regulators outside the cab, minimum capacity ratings of the lift axles, castering lift axle wheels and maximum axle loads based on tire load ratings. These restrictions are made in order to limit the damage effect of the vehicle and to improve the vehicle's safety.

6.4 MANUFACTURER SURVEY

The major truck manufacturers do not install the lift axles on the trucks. They are usually installed by the dealer or truck body shop. The dealer or body shop generally purchase a pre-engineered and fabricated unit from a manufacturer. The units come with castering or non-castering wheels. Also, each unit has a rated capacity between 12,000 lbs. and 22,500 lbs. The castering lift axle has many advantages over the non-casterings units. They reduce tire and bearing wear, improve maneuverability of the truck and reduce fuel consumption. The cost differential between the castering and non-castering lift axle is between $1000 and $2000. This is a small price to pay for improved safety, reduced tire wear and reduced damage to the pavement.

CHAPTER 7

RECOMMENDATIONS

The transportation of agriculture and forest products, natural resources and cement is vital to the growth of Arkansas. However, these goods need to be transported with a minimum damage to the highway system. Presently, one form of moving these goods is by the four axle single unit truck. These trucks make up a small percentage of the state's truck traffic, but in some areas of the state they cause over nine percent of the pavement damage on rural arterials. In order to minimize the damage, the following recommendations are made:

1. Require each axle of the tri-axle unit to carry its share of the load. The difference between the heaviest and lightest axles should not exceed 3000 lbs.
2. Require the pressure regulator for the lift axle air bags to be located outside the truck's cab. An off/on or up/down control could be locate inside the truck's cab.
3. Require the lift axle to have castering or self-steering wheels.
4. Restrict a castering lift axle from being raised during turning maneuvers.
5. Restrict the load on the lift axle to the rated capacity, the legal limit, or 600 to 650 lbs. per inch of tire tread width.
6. Require that the minimum capacity of the lift axle be 18,000 lbs.

These restrictions would impose a minimum economical hardship on the four axle single unit truck owners and operators. However, they would reduce the damage to the state highways caused by these trucks. For a $2000 increase in the cost of the lift axle and uniform axle loadings, the damage to the state's highways by these trucks could be reduced by a factor of two to three.

Many questions were raised during the research efforts which could not be answered. To answer these questions the following research is recommended:

1. What effect does the resultant forces have on the pavement behavior? A larger test plate should be constructed and a highly controlled study should be conducted which would determine the resultant forces associated with two, three, four and five axle trucks. Once the resultant forces are determined, the effect they have on the pavement should be studied. These forces would impose an additional shear force to the pavement and the effect of additional shear on the bonding of overlays should be investigated.
2. How much pavement damage is attributed to two axle single unit and four axle two unit trucks? This research effort has identified these trucks as producing a truck EAL greater than the four axle single unit truck. A new research study should investigate the impact that these trucks have on highway pavements and the study should provide a means of reducing the impact of the trucks.

CHAPTER 8

IMPLEMENTATION OF PROCEDURE AND BENEFITS

In order to implement the recommendations concerning four axle single unit trucks, Section 75-801 of the Arkansas Motor Vehicle and Traffic Laws and State Highway Commission Regulations needs to be amended. The amendment should address the following issues:

1. Penalties should be imposed for axle weights in excess of legal limits.
2. Each axle of the tri-axle unit should support its share of the gross vehicle weight. The weight differential between the heaviest and lightest axle of the tri-axle unit should not exceed 3000 lbs.
3. The pressure regulator which regulates the air pressure in the lift axle air bags should be placed outside the cab of the vehicle. It should not be accessible to the driver when the truck is in motion. An up/down or off/on switch could be located in the cab which would raise or lower the lift axle until January 1, 1995.
4. All lift axles installed after January 1, 1990 should have self-steering or castering wheels. All lift axles should be castering by January 1, 1995.
5. All castering or self-steering lift axles should be restricted from being raised during turning maneuvers.
6. All lift axles should have a minimum capacity rating of 18,000 lbs.
7. Axle legal capacity should be restricted to the axle capacity, legal limit, or 600 to 650 lbs. per inch of tire tread width in contact with the pavement surface.

These changes in the motor vehicle and traffic laws would produce the following benefits:

1. Research has shown that the amount of pavement damage is a function of the individual axle weights and gross vehicle weight. Thus, enforcement by axle weights and gross vehicle weight would reduce pavement damage. This reduction in pavement damage would increase the time before pavement maintenance is required, thus, producing a cost savings for the people of Arkansas.
2. By requiring each axle of the tri-axle unit to equally share the load, the amount of pavement damage imposed by the four axle single unit truck would be reduced by a factor of two to three.
3. Mounting the lift axle air bag pressure regulator outside the cab would prevent the driver from altering the lift axle load. This would insure that the lift axle would carry it's share of the gross vehicle weight, thus reducing the damage effect of the vehicle.
4. The introduction of castering or self-steering lift axles would improve the turning maneuverability of the vehicle, thus improving the safe operation of the vehicle. Other benefits would include reduced tire and bearing wear and reduced fuel consumption.
5. In the state of Arkansas, the average load imposed on the lift axle is 18,000 lbs. Therefore, setting a minimum axle capacity of 18,000 lbs. for the lift axle would insure the safe operation of the four axle single unit truck.
6. The safe load carrying capacity of an axle is governed by the axle's rated capacity and capacity of the tires. By calculating the capacity of the axle in terms of load per inch of tire tread width, safe vehicle operation and reduced pavement damage would be insured. An

axle with an 18,000 lb. load with single tires would produce approximately twice the pavement damage as an axle with dual tires. It was observed that many of the four axle single unit trucks in Arkansas operate with lift axles with single tires. Therefore, they are doing more pavement damage than their counterparts who have dual tires on the lift axle. This regulation coupled with the lift axle carrying it's share of the gross weight would help to minimize the pavement damage caused by the four axle single unit trucks.

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APPENDIX A

Regression Equations

REGRESSION COEFFICIENTS TO CALCULATE DAMAGE FACTORS FOR VARIOUS AXLE CONFIGURATIONS

$$\log(\text{Damage Factor}) = a + b(\log(\text{Load})) + c(\log(\text{Load}))^2$$

AXLE CONFIGURATION	COEFFICIENTS a	 b	 c
Two-Tired Single Front Axle	-3.540112	2.728860	0.289133
Four-Tired Single Rear Axle	-3.439501	0.423747	1.846657
Eight-Tired Tandem Axle	-2.979479	-1.265144	2.007989
Twelve-Tired Tridem Axle	-2.740987	-1.873428	1.964442
Sixteen-Tired Quad Axle	-2.589482	-2.224981	1.923512
Twenty-Tired Quint Axle	-2.264324	-2.666882	1.937472
Twenty-four Tired Sextet Axle	-2.084883	-2.900445	1.913994

COEFFICIENTS FROM REGRESSION ANALYSES OF UNEQUAL LOAD DISTRIBUTION ON INDIVIDUAL AXLES OF TRIDEM AXLE GROUP

$$\log(\text{Multiplying Factor}) = a + b(\text{Ratio}) + c(\text{Ratio})^2$$

in which Ratio = (M − L) / I

M = Maximum Axleload, kips,
I = Intermediate Axleload, kips,
L = Least Axleload, kips, and
a,b,c = coefficients

Load Pattern: 1. L,I,M 2. M,I,L 3. M,E,E 4. E,E,M	
Constant a	0.468782731
Coefficient b	1.093207072
Coefficient c	-0.1503124207
Standard Error of Estimate	0.073149
Correlation Coefficient, R	0.96024
F Ratio	1183.4
Sample Size	648

Load Pattern: 1. I,L,M 2. M,L,I 3. E,L,E	
Constant a	-0.1161216122
Coefficient b	1.507954095
Coefficient c	0.377814882
Standard Error of Estimate	0.069341
Correlation Coefficient, R	0.92765
F Ratio	326.9
Sample Number	343

Load Pattern: 1. L,M,I 2. I,M,L 3. E,M,E	
Constant a	-0.0235937584
Coefficient b	1.283412872
Coefficient c	-0.2187655038
Standard Error of Estimate	0.088165
Correlation Coefficient, R	0.92395
F Ratio	710.7
Sample Size	478

Load Pattern: 1. L,E,E 2. E,E,L	
Constant a	0.0004399421
Coefficient b	0.8053052125
Coefficient c	0.2363591702
Standard Error of Estimate	0.05634
Correlation Coefficient, R	0.96827
F Ratio	1037.4
Sample Size	282

Load Pattern: All Patterns Above	
Constant a	-0.198429071
Coefficient b	1.20191282
Coefficient c	-0.1746353238
Standard Error of Estimate	0.09792
Correlation Coefficient, R	0.9240
F Ratio	2085.4
Sample Size	1951

Damage Factor Regression Equations from Statistical Analysis

Two axle truck

$$\mathrm{Ln(DF)} = 0.1647\ (\mathrm{GVW}) - 3.9368$$

$$R^2 = 0.83$$

Three axle truck

$$\mathrm{Ln(DF)} = 0.06282\ (\mathrm{GVW}) - 2.4565$$

$$R^2 = 0.46$$

Four axle single unit truck

$$\mathrm{Ln(DF)} = 0.08357\ (\mathrm{GVW}) - 4.3105$$

$$R^2 = 0.39$$

Five axle truck

$$\mathrm{Ln(DF)} = 0.05359\ (\mathrm{GVW}) - 3.5838$$

$$R^2 = 0.85$$

APPENDIX B

Damage Factor for Different Classes of Trucks

Two axle single unit truck

Number	Axle-1	Axle-2	GVW	D. F.	AASHO
1	9.1	7.9	17.0	0.247	0.151
2	4.4	14.0	18.4	0.318	0.454
3	8.5	10.0	18.5	0.244	0.206
4	7.5	12.5	20.0	0.294	0.353
5	9.4	11.4	20.8	0.363	0.331
6	5.0	16.0	21.0	0.592	0.704
7	4.5	16.5	21.0	0.674	0.777
8	2.0	19.8	21.8	1.642	1.342
9	9.8	12.4	22.2	0.452	0.422
10	2.2	20.0	22.2	1.731	1.381
11	3.2	19.2	22.4	1.406	1.231
12	4.1	19.6	23.7	1.573	1.309
13	7.2	16.7	23.9	0.794	0.841
14	9.0	14.9	23.9	0.610	0.651
15	4.8	19.2	24.0	1.426	1.238
16	5.9	18.2	24.1	1.117	1.055
17	5.4	18.9	24.3	1.330	1.185
18	7.2	17.9	25.1	1.080	0.995
19	5.3	19.8	25.1	1.679	1.355
20	7.1	18.2	25.3	1.161	1.076
21	9.0	16.3	25.3	0.826	0.833
22	6.5	18.8	25.3	1.328	1.179
23	6.7	18.7	25.4	1.302	1.164
24	5.6	19.9	25.5	1.730	1.376
25	6.0	19.6	25.6	1.613	1.322
26	10.0	15.8	25.8	0.827	0.800
27	7.0	19.2	26.2	1.492	1.265
28	7.6	18.9	26.5	1.411	1.219
29	7.2	19.5	26.7	1.618	1.325
30	4.3	22.4	26.7	3.178	1.948
31	8.5	18.4	26.9	1.300	1.150
32	4.3	22.7	27.0	3.415	2.032
33	8.0	19.1	27.1	1.505	1.264
34	9.5	18.2	27.7	1.317	1.151
35	8.4	19.6	28.0	1.725	1.374
36	8.5	19.7	28.2	1.773	1.397
37	8.6	20.1	28.7	1.957	1.481
38	7.5	21.2	28.7	2.467	1.696
39	10.4	18.6	29.0	1.530	1.272
40	7.1	22.0	29.1	2.964	1.868
41	9.7	19.5	29.2	1.786	1.408
42	9.7	19.6	29.3	1.827	1.424
43	6.9	23.0	29.9	3.735	2.145
44	8.0	22.2	30.2	3.153	1.941
45	7.8	22.7	30.5	3.528	2.077
46	9.4	21.6	31.0	2.842	1.849
47	8.8	22.3	31.1	3.280	2.000
48	9.2	23.1	32.3	3.961	2.239
49	4.1	28.8	32.9	12.959	4.363
50	8.8	24.2	33.0	5.018	2.545

Two axle single unit truck

Number	Axle-1	Axle-2	GVW	D. F.	AASHO
51	8.8	24.2	33.0	5.018	2.545
52	8.8	24.2	33.0	5.018	2.545
53	9.6	24.1	33.7	4.974	2.541
54	10.3	23.5	33.8	4.432	2.401
55	11.4	23.4	34.8	4.471	2.444
56	12.2	23.1	35.3	4.316	2.417
57	9.1	26.2	35.3	7.740	3.262
58	8.2	28.7	36.9	12.839	4.367
59	17.4	20.6	38.0	3.969	2.423
60	8.3	29.7	38.0	15.651	4.906
61	13.8	26.9	40.7	9.619	3.891
	7.7	19.9	27.6	2.855	1.638

Three axle single unit trucks

Number	Axle-1	Axle-2	Axle-3	GVW	Total
1	9.8	12.9	6.8	29.5	0.540
2	5.5	21.7	4.7	31.9	2.963
3	8.1	20.8	3.6	32.5	2.598
4	12.0	11.3	11.1	34.4	0.651
5	8.9	12.7	14.1	35.7	0.477
6	7.8	14.2	14.7	36.7	0.450
7	5.7	17.9	13.6	37.2	0.937
8	16.3	10.6	10.3	37.2	1.635
9	8.8	16.7	12.1	37.6	0.853
10	5.6	16.0	16.1	37.7	0.526
11	10.4	13.9	13.7	38.0	0.585
12	10.6	15.7	12.5	38.8	0.837
13	9.0	10.8	20	39.8	1.914
14	7.5	15.1	17.4	40.0	0.852
15	13.5	13.1	13.4	40.0	1.027
16	12.8	14.8	12.4	40.0	1.037
17	9.5	14.0	16.5	40.0	0.830
18	10.3	14.7	15.1	40.1	0.689
19	10.1	15.2	15.8	41.1	0.755
20	8.9	12.5	20	41.4	1.827
21	8.0	17.0	16.5	41.5	0.774
22	8.6	16.7	16.3	41.6	0.759
23	8.1	17.0	16.7	41.8	0.777
24	10.2	16.0	15.6	41.8	0.790
25	8.0	14.0	19.8	41.8	1.626
26	10.0	16.4	15.8	42.2	0.831
27	13.9	14.0	14.3	42.2	1.183
28	10.0	16.0	16.3	42.3	0.812
29	15.4	15.5	11.6	42.5	1.743
30	13.5	14.7	14.4	42.6	1.135
31	10.3	16.3	16.1	42.7	0.842
32	10.3	16.5	16.1	42.9	0.875
33	11.2	15.5	16.2	42.9	0.940
34	10.2	15.3	17.6	43.1	1.097
35	9.2	17.4	16.5	43.1	0.939
36	7.7	23.5	12.5	43.7	3.863
37	10.9	17.1	16.4	44.4	1.051
38	9.7	17.8	17.1	44.6	1.063
39	11.0	17.0	16.6	44.6	1.041
40	10.9	17.0	16.8	44.7	1.026
41	11.8	16.6	16.6	45.0	1.076
42	11.9	16.6	16.5	45.0	1.092
43	10.0	21.6	13.5	45.1	2.661
44	13.5	16.1	15.7	45.3	1.304
45	13.4	18.7	13.2	45.3	1.925
46	8.4	22.4	14.6	45.4	2.967
47	11.8	17.2	16.7	45.7	1.188
48	9.1	15.7	21.1	45.9	2.218
49	17.7	13.7	14.8	46.2	2.403
50	10.9	17.8	17.6	46.3	1.184

Three axle single unit trucks

Number	Axle-1	Axle-2	Axle-3	GVW	Total
51	10.6	18.5	17.3	46.4	1.331
52	10.8	17.5	18.2	46.5	1.271
53	14.2	16.0	16.3	46.5	1.485
54	10.9	16.6	19	46.5	1.527
55	14.4	15.9	16.5	46.8	1.567
56	11.2	17.6	18.1	46.9	1.294
57	11.5	21.8	13.7	47.0	2.945
58	13.4	17.3	17	47.7	1.482
59	11.5	18.3	18	47.8	1.380
60	11.2	17.0	19.7	47.9	1.793
61	10.9	19.0	18.1	48.0	1.498
62	10.6	19.0	18.5	48.1	1.456
63	15.5	16.3	16.3	48.1	1.820
64	9.9	16.7	21.7	48.3	2.572
65	10.6	13.7	24	48.3	4.454
66	9.3	19.6	19.7	48.6	1.542
67	10.1	17.9	20.6	48.6	2.006
68	15.3	17.2	16.2	48.7	1.928
69	10.6	19.2	18.9	48.7	1.512
70	13.1	17.5	18.1	48.7	1.599
71	6.1	21.6	21.1	48.8	2.177
72	15.3	16.9	16.7	48.9	1.863
73	12.2	18.7	18	48.9	1.594
74	16.6	16.8	15.5	48.9	2.265
75	13.2	18.3	17.5	49.0	1.669
76	11.3	21.6	16.4	49.3	2.687
77	7.4	23.5	18.5	49.4	3.541
78	14.7	17.6	17.3	49.6	1.838
79	13.7	17.5	18.4	49.6	1.797
80	16.7	16.6	16.6	49.9	2.248
81	17.6	16.4	16	50.0	2.557
82	9.4	20.7	20.1	50.2	1.940
83	10.3	20.0	20	50.3	1.742
84	16.4	17.6	16.4	50.4	2.348
85	13.8	18.6	18.4	50.8	1.860
86	16.9	17.0	17	50.9	2.387
87	14.9	18.5	18.3	51.7	2.097
88	11.0	20.2	20.8	52.0	2.151
89	10.4	21.2	20.5	52.1	2.264
90	11.2	21.4	20	52.6	2.469
91	16.0	18.4	18.3	52.7	2.385
92	15.8	19.3	18.8	53.9	2.582
93	12.7	20.9	20.5	54.1	2.446
94	16.0	20.5	20.5	57.0	3.065
95	14.9	21.9	21.3	58.1	3.425
96	17.4	20.1	20.9	58.4	3.736
97	16.9	22.1	19.8	58.8	4.188
ave	11.6	17.3	16.6	2.6	1.701

			Four axle truck			Non unif.	
Number	Axle-1	Axle-2	Axle-3	Axle-4	GVW	D. F.	AASHO
1	9.7	7.2	12.6	11.8	41.3	0.465	0.387
2	11.2	10.3	12.3	11.1	44.9	0.574	0.548
3	11.7	12.3	11.4	15.4	50.8	0.975	0.821
4	13.0	3.6	18.6	18.2	53.4	2.113	1.000
5	13.2	5.9	17.5	17.0	53.6	1.712	1.020
6	13.7	6.4	17.6	16.3	54.0	2.034	0.669
7	10.1	7.5	18.8	18.2	54.6	1.570	1.020
8	9.1	16.3	15.3	14.1	54.8	0.702	1.080
9	5.7	22.3	13.5	14.0	55.5	6.883	1.310
10	14.4	6.8	18.9	16.3	56.4	2.615	1.240
11	9.0	13.3	17.3	16.9	56.5	0.912	1.200
12	13.9	5.9	18.0	18.8	56.6	2.240	1.220
13	10.7	12.2	16.6	17.5	57.0	1.118	1.200
14	14.5	10.7	18.1	14.5	57.8	2.113	1.330
15	8.7	17.4	17.3	14.5	57.9	0.906	1.330
16	12.5	11.4	17.2	16.9	58.0	1.353	1.270
17	8.7	15.1	17.2	17.1	58.1	0.857	1.340
18	10.7	16.3	15.1	16.0	58.1	0.809	1.280
19	14.3	14.9	14.9	14.2	58.3	1.331	1.360
20	10.3	14.7	17.3	16.7	59.0	0.997	1.360
21	13.0	8.1	19.5	18.6	59.2	2.190	1.370
22	8.9	10.0	20.5	20.0	59.4	2.006	1.440
23	8.5	15.3	17.8	18.1	59.7	1.025	1.490
24	13.7	8.5	19.1	18.6	59.9	2.181	1.430
25	10.7	12.7	18.2	18.3	59.9	1.339	1.420
26	8.6	17.7	17.0	16.7	60.0	0.896	1.510
27	12.0	14.3	19.5	14.5	60.3	1.763	1.430
28	12.4	9.8	18.7	19.8	60.7	2.107	1.450
29	11.4	13.7	18.5	17.5	61.1	1.404	1.510
30	14.8	6.0	20.9	20.1	61.8	3.340	1.620
31	12.5	16.8	16.6	16.0	61.9	1.210	1.570
32	11.8	7.8	21.6	20.9	62.1	3.000	1.580
33	15.5	8.9	19.1	18.6	62.1	2.613	1.680
34	12.8	1.5	24.2	23.9	62.4	5.794	1.610
35	10.9	17.1	17.3	17.3	62.6	1.071	1.640
36	12.8	8.9	20.2	21.2	63.1	2.860	1.670
37	13.2	12.5	18.2	19.4	63.3	1.991	1.690
38	14.3	4.8	20.9	23.4	63.4	5.099	1.720
39	12.4	15.5	17.1	18.4	63.4	1.470	1.690
40	10.6	12.9	19.5	20.7	63.7	2.110	1.750
41	11.5	14.0	19.5	18.7	63.7	1.722	1.730
42	17.4	14.1	16.2	16.1	63.8	2.454	1.940
43	10.6	19.8	17.0	16.5	63.9	3.967	1.770
44	13.9	13.0	18.5	18.6	64.0	1.944	1.760
45	14.7	9.4	20.1	19.8	64.0	2.761	1.790
46	15.4	14.0	17.3	17.8	64.5	2.072	1.860
47	12.9	10.5	20.8	20.5	64.7	2.633	1.810
48	14.0	16.9	17.2	16.6	64.7	1.554	1.820
49	5.5	25.3	17.1	16.9	64.8	12.136	2.220
50	14.6	11.5	19.8	18.9	64.8	1.923	1.850

Four axle truck Non unif.

Number	Axle-1	Axle-2	Axle-3	Axle-4	GVW	D. F.	AASHO
51	17.3	13.5	17.0	17.0	64.8	3.009	2.000
52	15.3	14.2	17.5	17.8	64.8	2.053	1.380
53	14.8	15.7	17.9	16.7	65.1	1.716	1.880
54	5.4	26.8	17.2	15.9	65.3	17.279	2.280
55	12.7	12.0	18.0	22.7	65.4	9.037	1.870
56	17.7	13.3	17.3	17.2	65.5	2.783	2.090
57	5.5	22.0	19.8	18.4	65.7	6.485	2.320
58	6.8	26.5	16.7	15.9	65.9	16.215	2.240
59	15.6	13.7	17.9	18.9	66.1	2.392	2.000
60	14.9	13.9	19.1	18.3	66.2	2.265	1.980
61	22.0	4.5	20.4	19.4	66.3	6.491	2.720
62	8.0	24.1	17.5	16.8	66.4	9.649	2.160
63	19.2	9.0	19.3	19.3	66.8	4.129	2.350
64	19.2	9.0	19.6	19.3	67.1	4.226	2.370
65	13.2	13.5	20.5	20.0	67.2	2.421	2.030
66	12.2	13.9	21.0	20.3	67.4	2.435	2.050
67	13.0	14.8	20.0	19.6	67.4	2.153	2.050
68	20.6	15.2	16.8	16.3	68.9	4.073	2.690
69	7.2	23.3	19.8	18.8	69.1	8.383	2.550
70	20.7	14.4	17.0	17.1	69.2	4.243	2.726
71	16.9	17.7	19.1	15.6	69.3	2.797	2.350
72	19.9	7.5	21.1	21.0	69.5	5.348	2.640
73	19.5	16.2	17.4	17.4	70.5	3.593	2.680
74	21.0	13.9	19.4	19.2	73.5	5.003	3.130
averag	12.9	13.1	18.1	17.8	61.9	3.234	1.714

Five axle truck

Number	Axle-1	Axle-2	Axle-3	Axle-4	Axle-5	GVW	Total
1	8.4	16.4	9.0	13.0	16.1	62.9	1.382
2	8.8	14.1	14.0	13.8	13.9	64.6	0.698
3	6.0	15.5	15.6	15.1	14.8	67.0	0.827
4	8.3	15.5	15.4	15.3	14.3	68.8	0.951
5	10.1	16.7	16.1	13.1	13.2	69.2	1.082
6	8.6	16.9	16.2	14.3	14.1	70.1	1.074
7	8.0	15.9	13.2	17.2	15.8	70.1	1.315
8	8.4	15.9	15.9	14.9	15.1	70.2	0.976
9	8.8	15.8	14.9	14.0	17.7	71.2	1.474
10	9.4	16.0	14.5	16.4	15.0	71.3	1.272
11	9.6	12.0	12.0	18.5	19.5	71.6	1.643
12	10.3	18.1	15.5	13.6	14.3	71.8	1.507
13	10.0	17.1	16.9	14.0	14.0	72.0	1.194
14	8.0	17.0	16.0	15.0	16.0	72.0	1.259
15	8.7	13.2	15.8	17.3	17.1	72.1	1.346
16	9.6	16.6	15.5	15.6	15.0	72.3	1.251
17	10.1	17.1	15.0	15.6	14.8	72.6	1.405
18	10.5	18.1	14.9	14.6	14.7	72.8	1.573
19	8.5	13.7	13.3	18.7	18.9	73.1	1.464
20	12.0	17.1	13.8	15.5	14.8	73.2	1.657
21	9.8	17.2	16.2	16.0	14.3	73.5	1.442
22	9.5	17.8	16.6	15.1	14.6	73.6	1.412
23	8.9	16.1	15.9	16.2	16.7	73.8	1.264
24	9.2	18.6	18.0	14.0	14.0	73.8	1.460
25	9.6	13.4	12.3	19.8	19.0	74.1	1.829
26	9.2	16.4	16.8	15.2	16.9	74.5	1.452
27	9.9	16.7	16.7	15.8	15.7	74.8	1.301
28	10.3	16.3	15.0	15.6	17.6	74.8	1.627
29	8.8	18.2	16.2	14.8	16.9	74.9	1.740
30	9.0	16.8	17.0	16.2	16.0	75.0	1.334
31	9.3	16.7	16.4	16.4	16.2	75.0	1.337
32	9.5	15.6	15.6	15.9	18.6	75.2	1.688
33	9.8	15.0	13.4	18.9	18.3	75.4	1.707
34	9.6	16.9	16.7	16.3	16.1	75.6	1.381
35	9.1	15.2	15.0	18.5	17.8	75.6	1.545
36	8.4	17.4	18.2	13.5	18.2	75.7	2.024
37	9.1	17.7	17.6	14.7	16.8	75.9	1.601
38	9.3	17.0	18.3	15.3	16.0	75.9	1.627
39	9.2	18.4	17.0	14.5	17.0	76.1	1.835
40	10.2	18.5	17.5	15.2	15.1	76.5	1.649
41	8.9	17.4	16.9	17.3	16.4	76.9	1.601
42	12.0	16.0	14.0	18.1	16.8	76.9	1.913
43	9.6	18.5	18.1	16.3	14.6	77.1	1.747
44	11.1	17.5	16.7	16.0	16.0	77.3	1.619
45	9.9	18.1	17.2	16.5	15.6	77.3	1.704
46	8.9	18.5	18.8	15.7	15.5	77.4	1.664
47	10.0	16.6	15.1	19.6	16.2	77.5	2.215
48	8.5	17.2	16.7	17.7	17.5	77.6	1.605
49	8.8	15.8	15.0	19.4	18.9	77.9	1.858
50	10.8	15.7	17.7	17.4	16.3	77.9	1.894

Five axle truck

Number	Axle-1	Axle-2	Axle-3	Axle-4	Axle-5	GVW	Total
51	9.1	16.9	16.0	18.1	18.0	78.1	1.688
52	10.2	18.2	19.5	17.3	13.0	78.2	2.339
53	9.8	18.5	19.5	15.4	15.1	78.3	1.926
54	10.3	16.4	16.5	17.1	18.1	78.4	1.736
55	8.6	19.5	19.2	14.5	16.6	78.4	2.011
56	9.2	19.7	18.4	16.0	15.2	78.5	2.029
57	8.7	16.7	15.4	18.7	19.1	78.6	1.899
58	9.3	18.5	17.7	16.0	17.2	78.7	1.873
59	9.0	20.5	19.8	14.9	14.5	78.7	2.163
60	9.2	19.0	16.5	18.8	15.3	78.8	2.453
61	11.7	17.1	16.9	16.1	17.1	78.9	1.805
62	9.2	19.5	19.3	15.8	15.1	78.9	1.915
63	10.8	17.9	15.9	16.6	17.7	78.9	2.000
64	10.1	18.2	18.0	16.2	16.7	79.2	1.764
65	8.1	19.7	15.7	18.3	17.7	79.5	2.446
66	9.4	18.5	18.4	17.6	15.7	79.6	1.962
67	9.2	18.1	17.7	16.9	17.8	79.7	1.877
68	8.7	19.1	18.6	17.1	16.2	79.7	1.965
69	10.9	16.9	17.7	17.0	17.3	79.8	1.854
70	9.7	20.3	19.4	15.4	15.0	79.8	2.201
71	9.5	18.4	18.7	16.0	17.3	79.9	1.956
72	7.8	19.7	19.1	16.8	16.6	80.0	2.037
73	11.4	17.1	18.1	16.0	17.4	80.0	2.048
74	9.6	18.0	17.7	17.6	17.2	80.1	1.837
75	9.7	18.2	17.4	17.4	17.4	80.1	1.855
76	9.4	18.8	18.4	17.4	16.1	80.1	1.996
77	10.7	17.9	17.7	17.0	17.0	80.3	1.805
78	7.4	20.2	20.0	16.6	16.5	80.7	2.156
79	8.5	18.4	18.5	19.3	16.0	80.7	2.364
80	9.3	14.2	13.9	22.3	21.0	80.7	3.026
81	9.1	19.7	18.9	17.0	16.2	80.9	2.171
82	7.4	16.8	16.8	20.6	19.5	81.1	2.362
83	9.9	16.8	18.8	16.3	19.4	81.2	2.618
84	9.8	16.3	16.3	19.5	19.3	81.2	2.030
85	10.0	19.0	19.0	16.6	16.7	81.3	1.957
86	9.8	17.0	18.4	17.0	19.2	81.4	2.408
87	9.0	19.0	18.7	17.3	17.9	81.9	2.113
88	9.0	17.1	16.8	21.0	18.0	81.9	2.735
89	9.0	18.1	17.1	18.9	18.9	82.0	2.132
90	9.9	18.5	18.5	15.7	19.6	82.2	2.590
91	10.4	19.5	17.9	17.8	17.4	83.0	2.394
92	9.5	19.4	18.9	18.4	18.0	84.2	2.395
93	10.2	20.1	19.7	17.2	17.4	84.6	2.475
94	11.0	21.4	18.7	18.5	17.3	86.9	3.438
95	8.8	20.5	20.6	19.8	19.3	89.0	3.189
96	6.6	22.2	22.2	22.2	19.1	92.3	5.020
97	10.6	21.9	21.7	20.0	19.1	93.3	4.062
98	10.3	24.4	24.9	20.7	20.6	100.9	6.585
ave	9.4	17.6	17.0	16.8	16.7	77.5	1.9

APPENDIX C

Sample Calculation
of
Damage Impact Factor

and

Damage Factor Calculation
for
Four Axle Two Unit Truck

Four axle two unit truck

Number	Axle-1	Axle-2	Axle-3	axle-4	GVW	D. F.
1	6.4	10.7	12.2	11.4	40.7	0.302
2	8.2	18.1	9.8	7.3	43.4	1.361
3	13.4	12.1	13.2	14.0	52.7	1.210
4	5.6	20.0	14.4	13.7	53.7	2.065
5	10.7	18.1	13.8	11.4	54.0	1.670
6	5.4	20.9	14.5	13.8	54.6	2.520
7	10.2	15.3	15.3	14.9	55.7	1.152
8	6.0	16.5	17.3	16.4	56.2	1.400
9	8.8	13.4	17.7	17.0	56.9	1.209
10	5.1	22.0	15.3	14.7	57.1	3.283
11	6.0	17.9	16.8	16.5	57.2	1.626
12	6.0	18.0	17.3	16.0	57.3	1.760
13	9.0	26.0	11.7	11.1	57.8	7.531
14	10.3	17.6	14.1	16.1	58.1	1.736
15	5.8	21.7	15.8	15.0	58.3	3.161
16	5.5	21.4	16.7	15.7	59.3	3.099
17	6.4	26.9	13.8	14.6	61.7	9.116
18	7.5	22.6	16.0	15.8	61.9	3.898
19	5.5	24.0	16.8	16.0	62.3	5.247
20	6.3	20.8	17.9	17.7	62.7	2.997
21	7.3	27.5	16.2	12.4	63.4	10.573
22	4.9	23.2	18.0	17.3	63.4	4.689
23	5.2	24.8	17.2	17.0	64.2	6.222
24	6.5	23.8	17.7	16.7	64.7	5.245
25	7.4	20.3	18.7	18.3	64.7	2.987
26	7.0	22.6	18.0	18.0	65.6	4.234
27	8.2	26.8	17.2	13.7	65.9	9.429
28	5.9	20.0	20.5	19.6	66.0	3.400
29	8.9	29.0	14.5	14.1	66.5	13.974
30	11.1	19.7	18.4	18.3	67.5	2.946
31	5.2	22.3	21.5	20.5	69.5	5.193
32	15.7	13.2	22.7	21.6	73.2	4.363
Ave	7.5	20.5	16.3	15.5	59.9	4.047

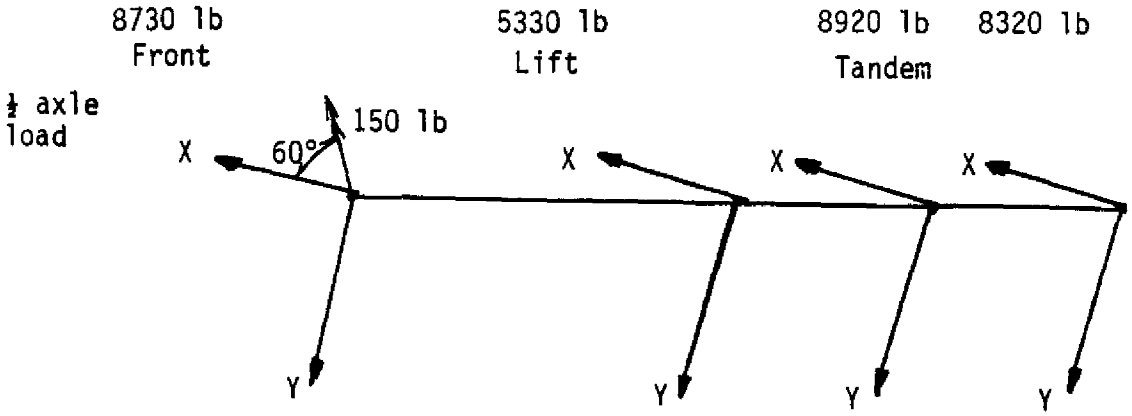
Sixteen County Average

	Number	Truck Percent	D. F.	EALs	EAL Percent
Single Unit Truck					
Two-Axle	3713	18.4	2.86	52.6	21.7
Three-Axle	2739	13.5	1.70	23.0	9.5
Four-Axle	1385	6.8	3.23	22.0	9.1
Two Unit Truck					
Four Axle	2504	12.4	4.0	49.6	20.5
Five Axle	8980	44.4	1.94	86.1	35.5
Other	900	4.5	2.0	9.0	3.7
Total	20221	100.0		242.3	100.0

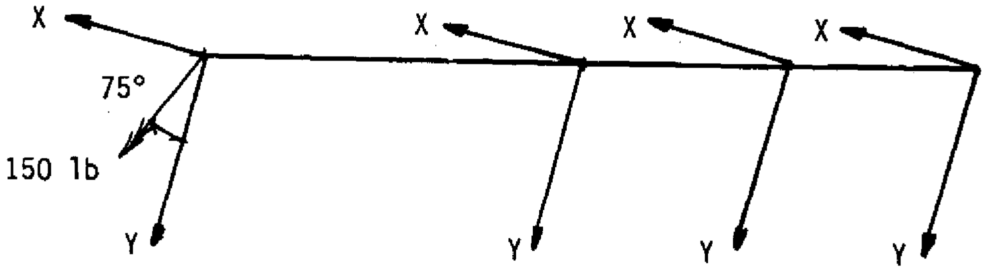
EALs = Truck Percent x Damage Factor (DF)

APPENDIX D

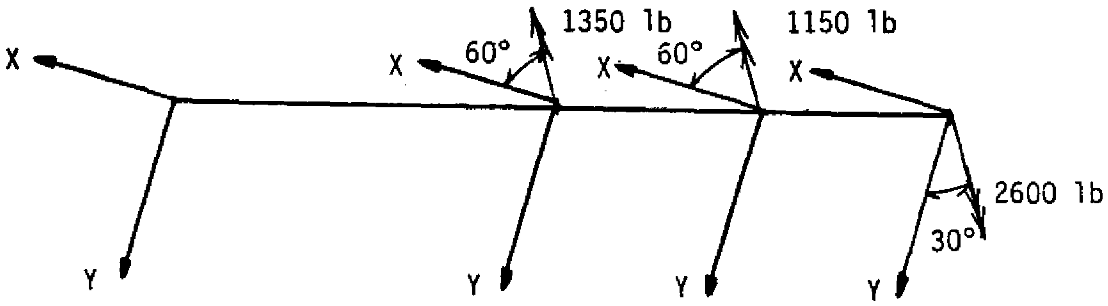
Test Plate Data



Run T160

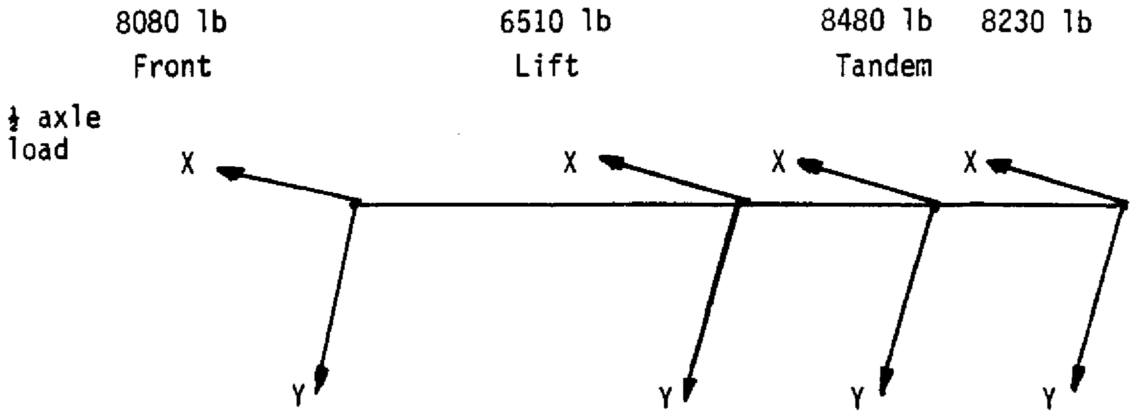


Run TF60

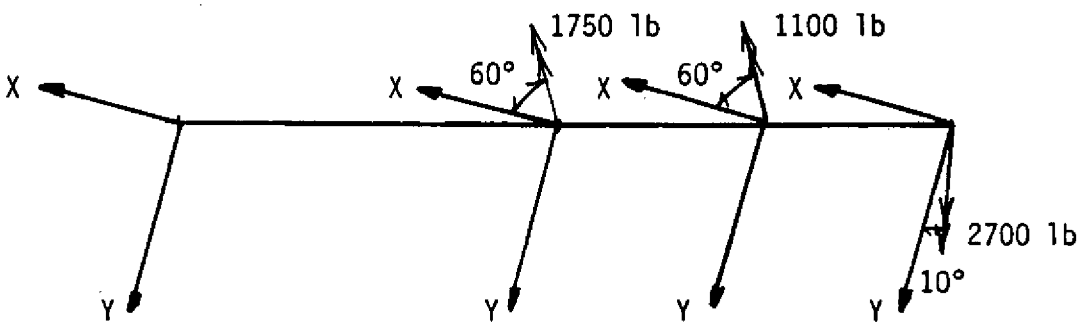


Run TT160

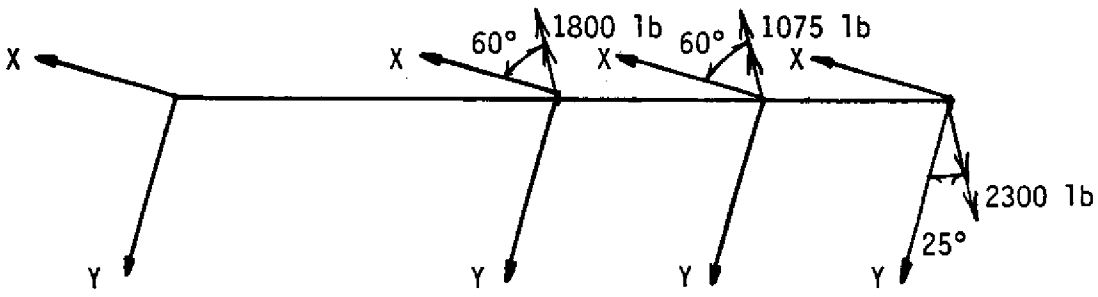
Lift Axle at 60 psi



Run TF70

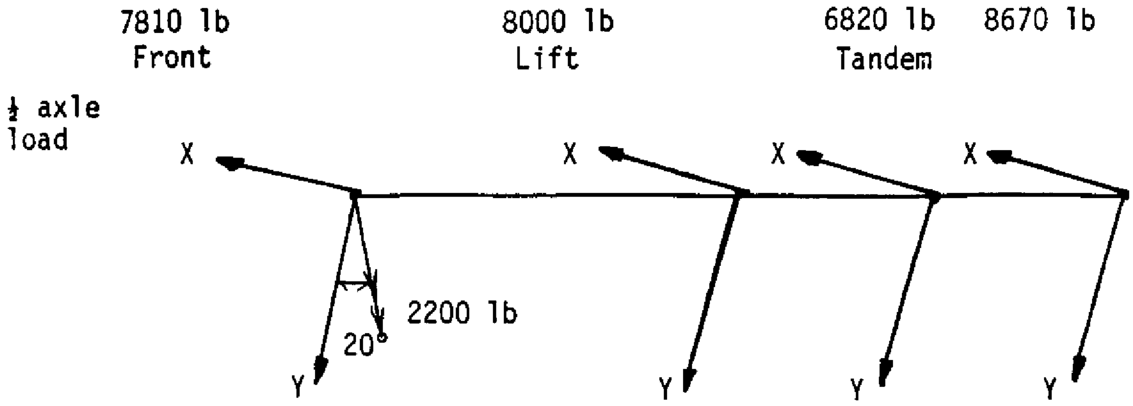


Run TT170

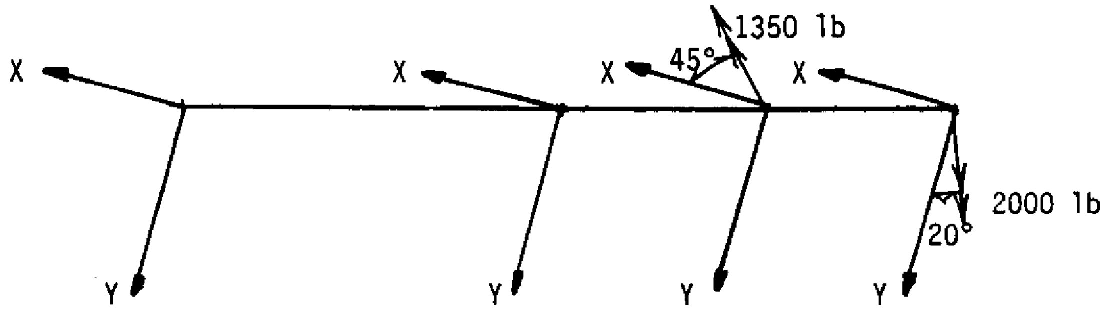


Run TT270

Lift Axle at 70 psi



Run TF80



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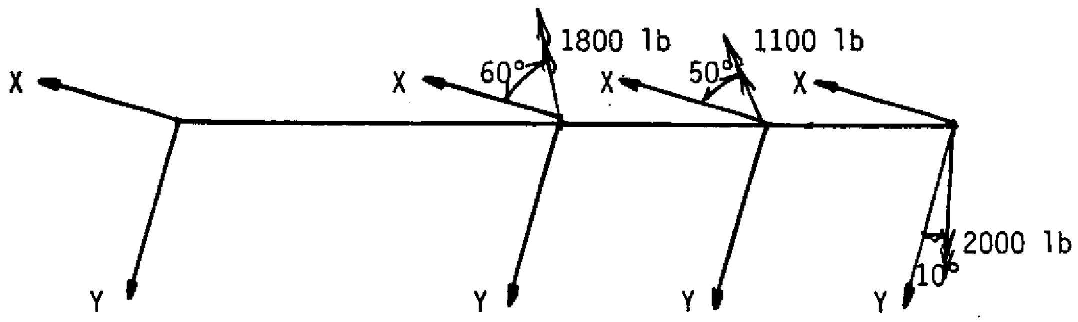
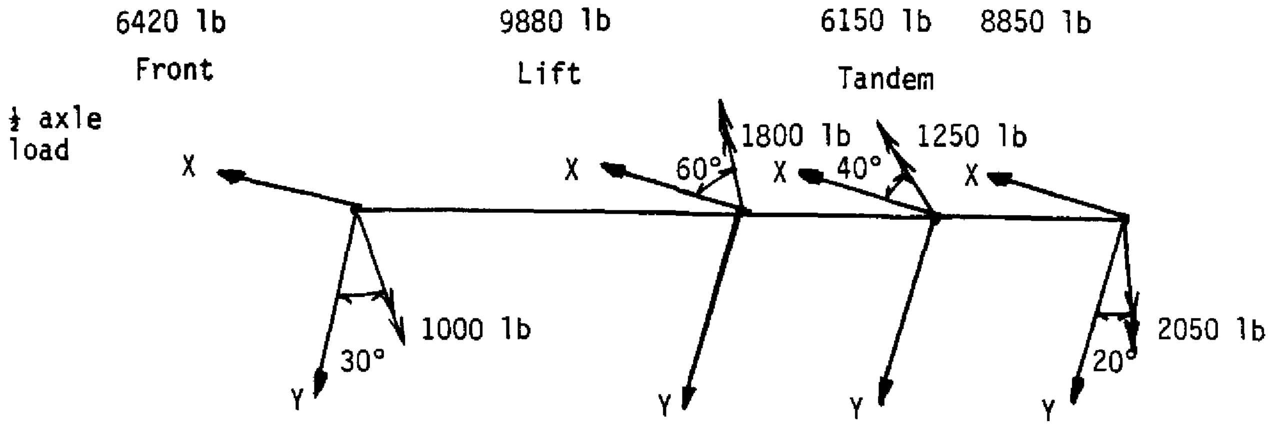


Run TT280

Lift Axle at 80 psi



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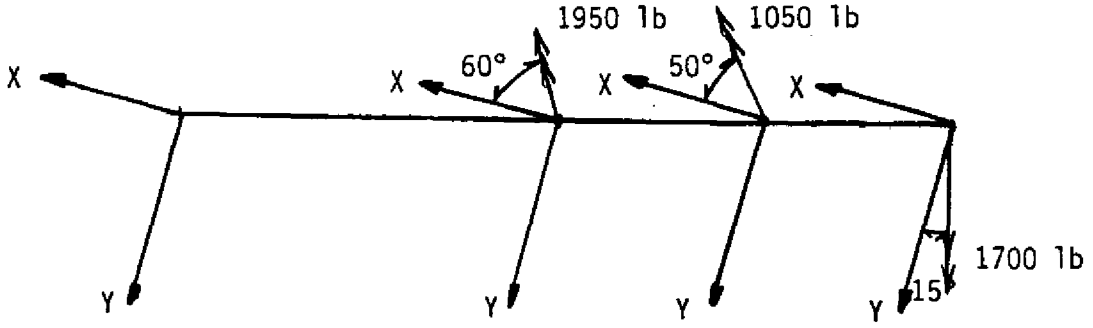

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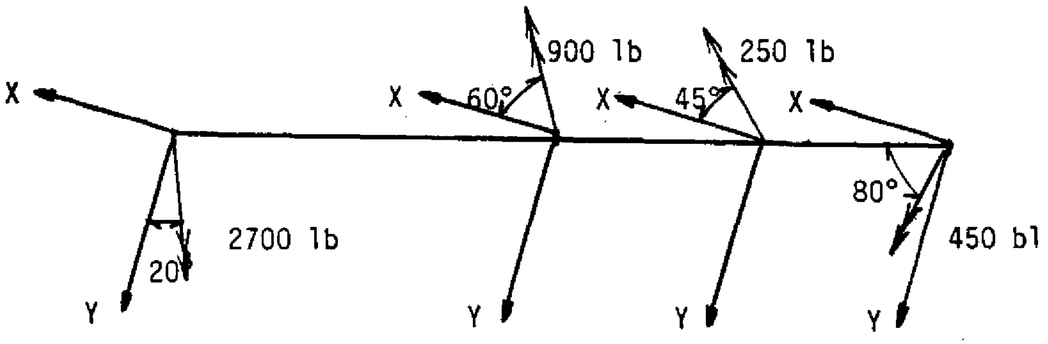
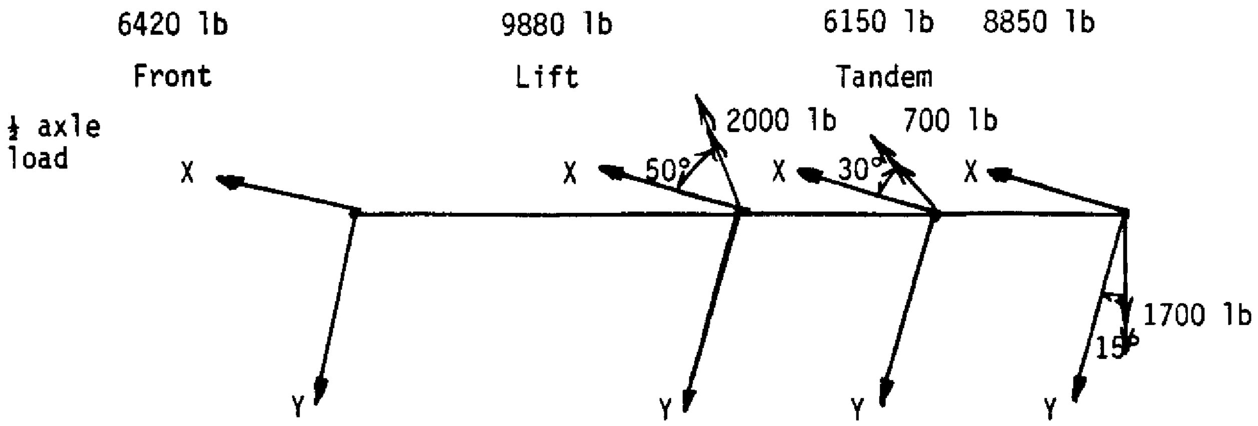


Run TF290

Lift Axle at 90 psi



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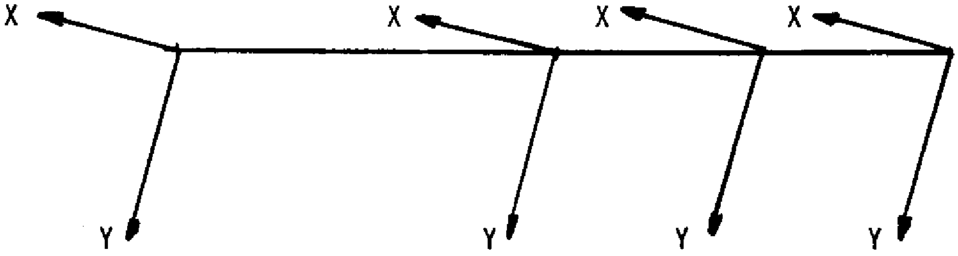

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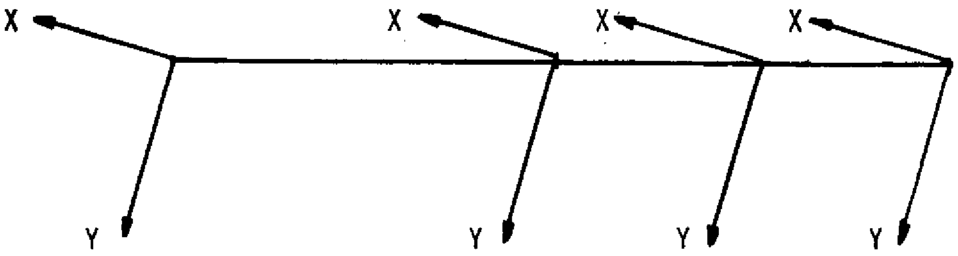
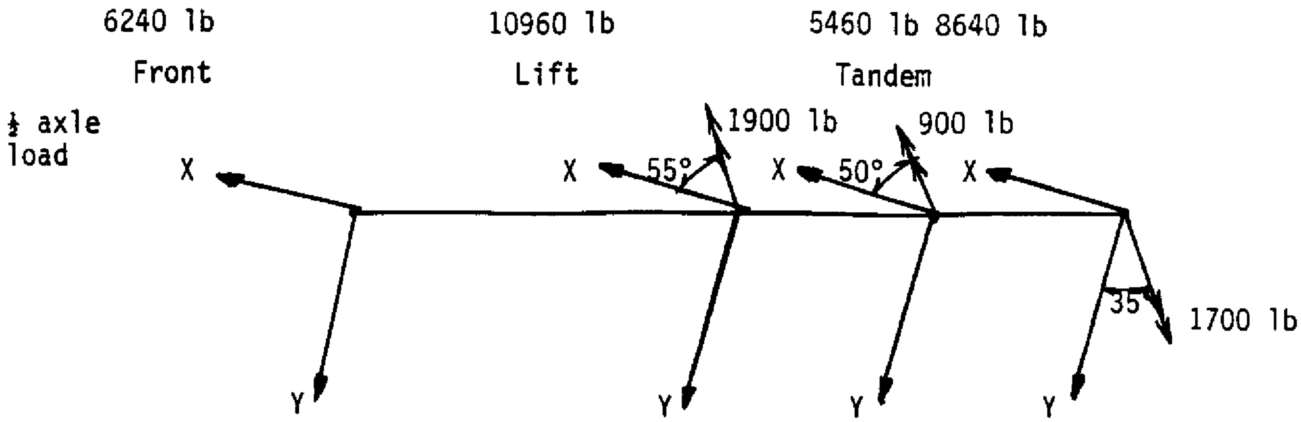
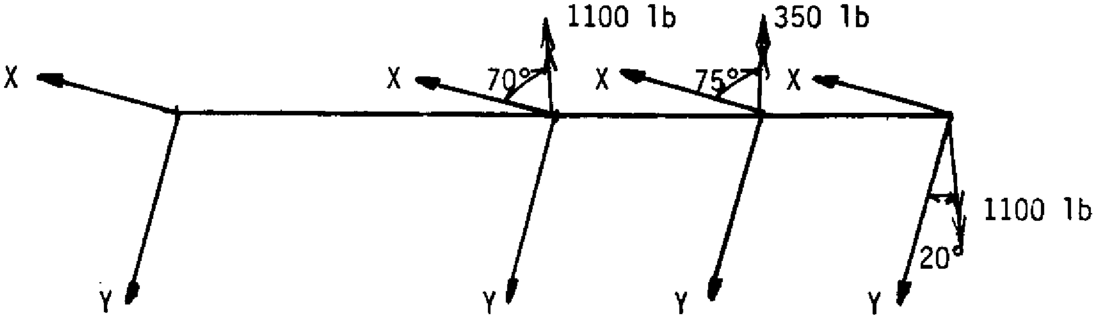


Run

Lift Axle at 90 psi



Run TT1100



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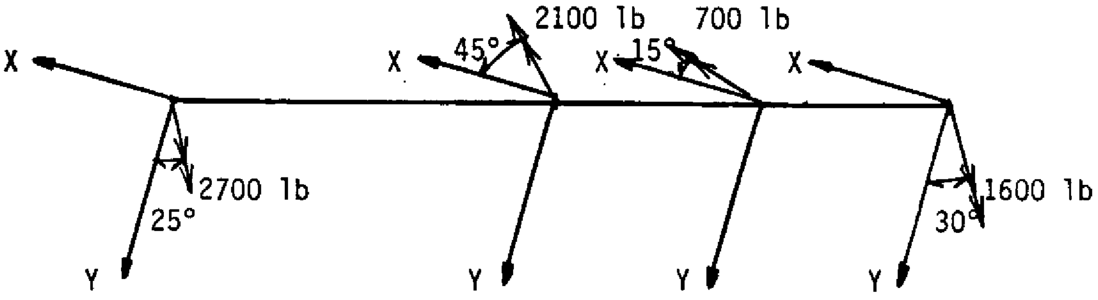
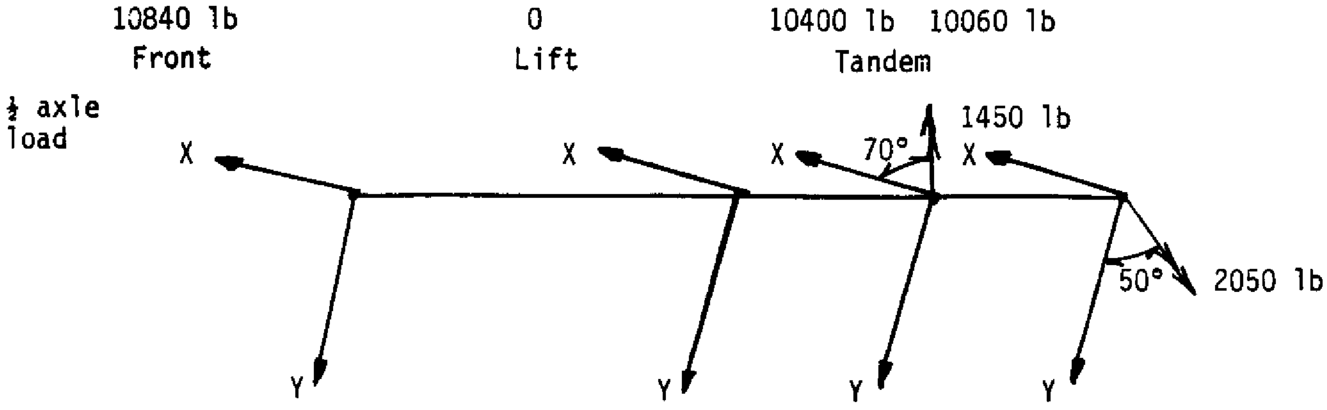


Run TF1100

Lift Axle at 100 psi



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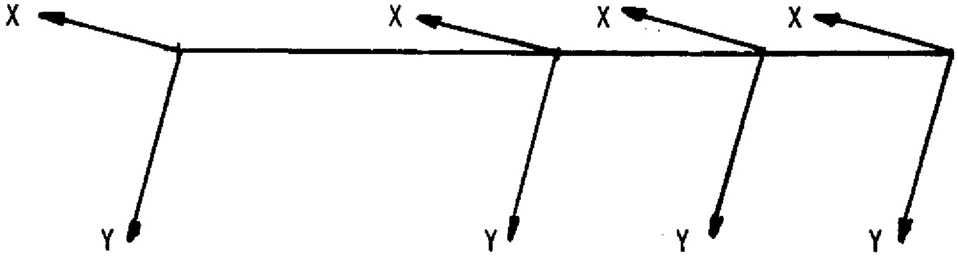

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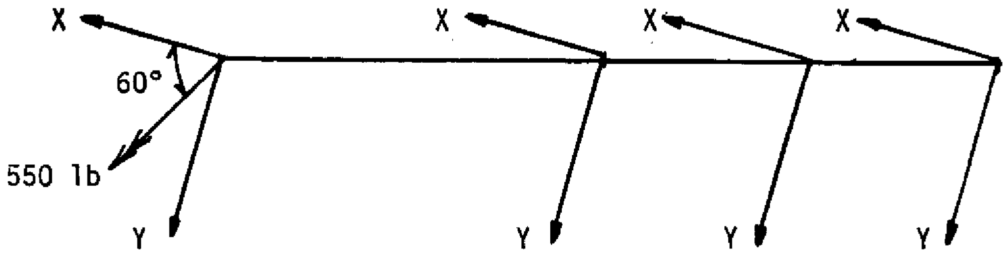

Run TF20

Lift Axle at 0 psi

T160.DAT

MAGNITITUDE OF
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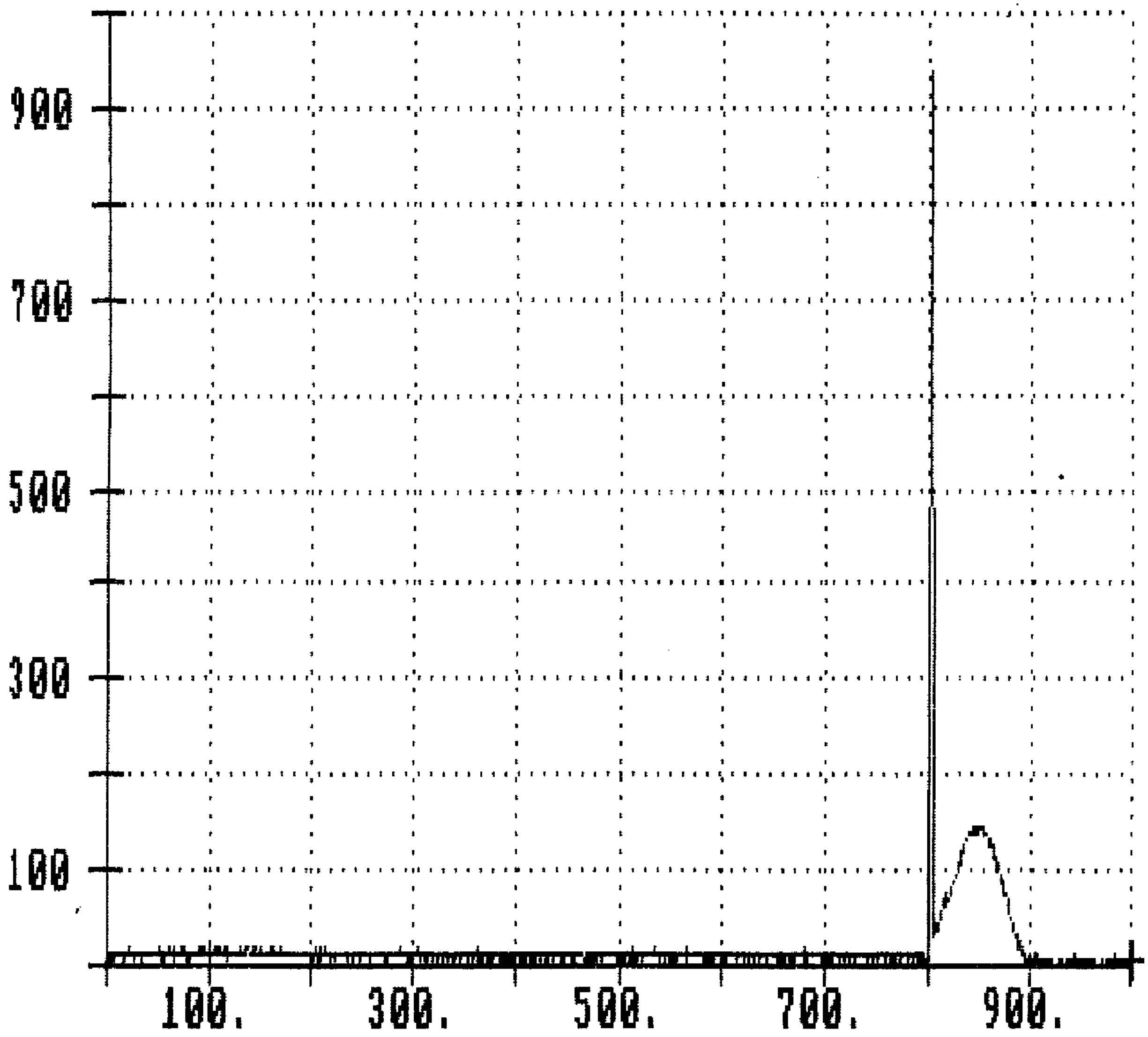

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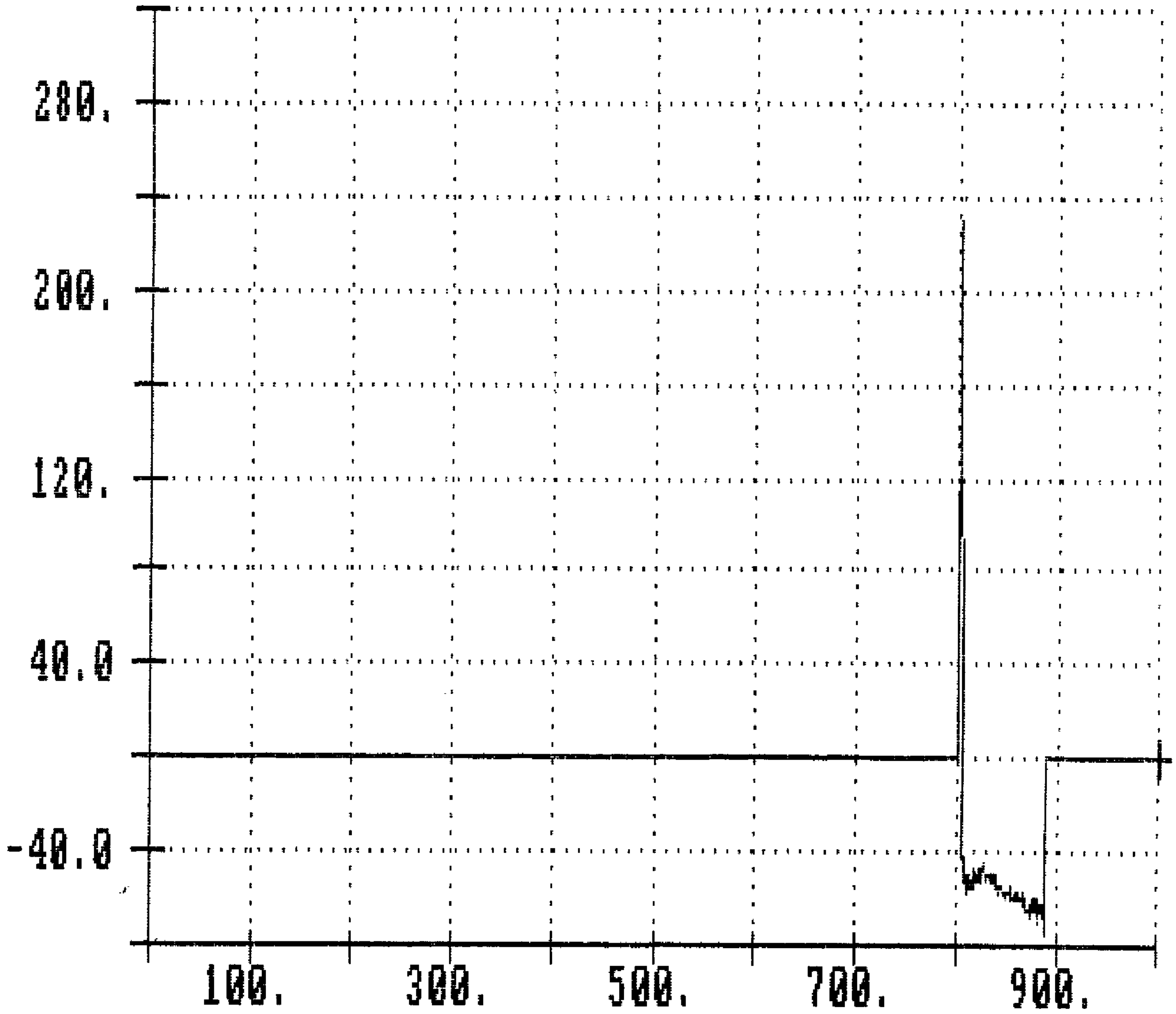

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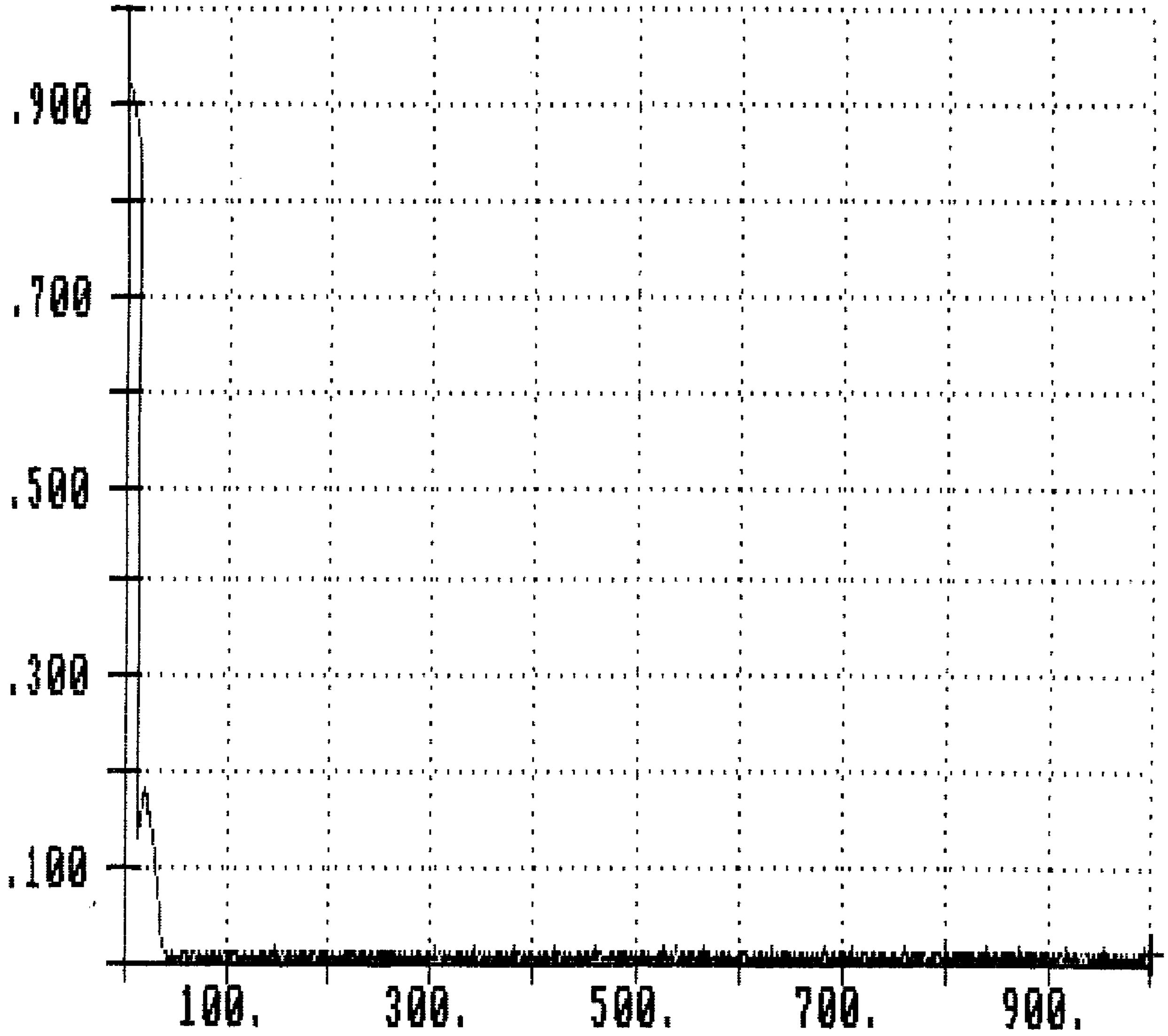

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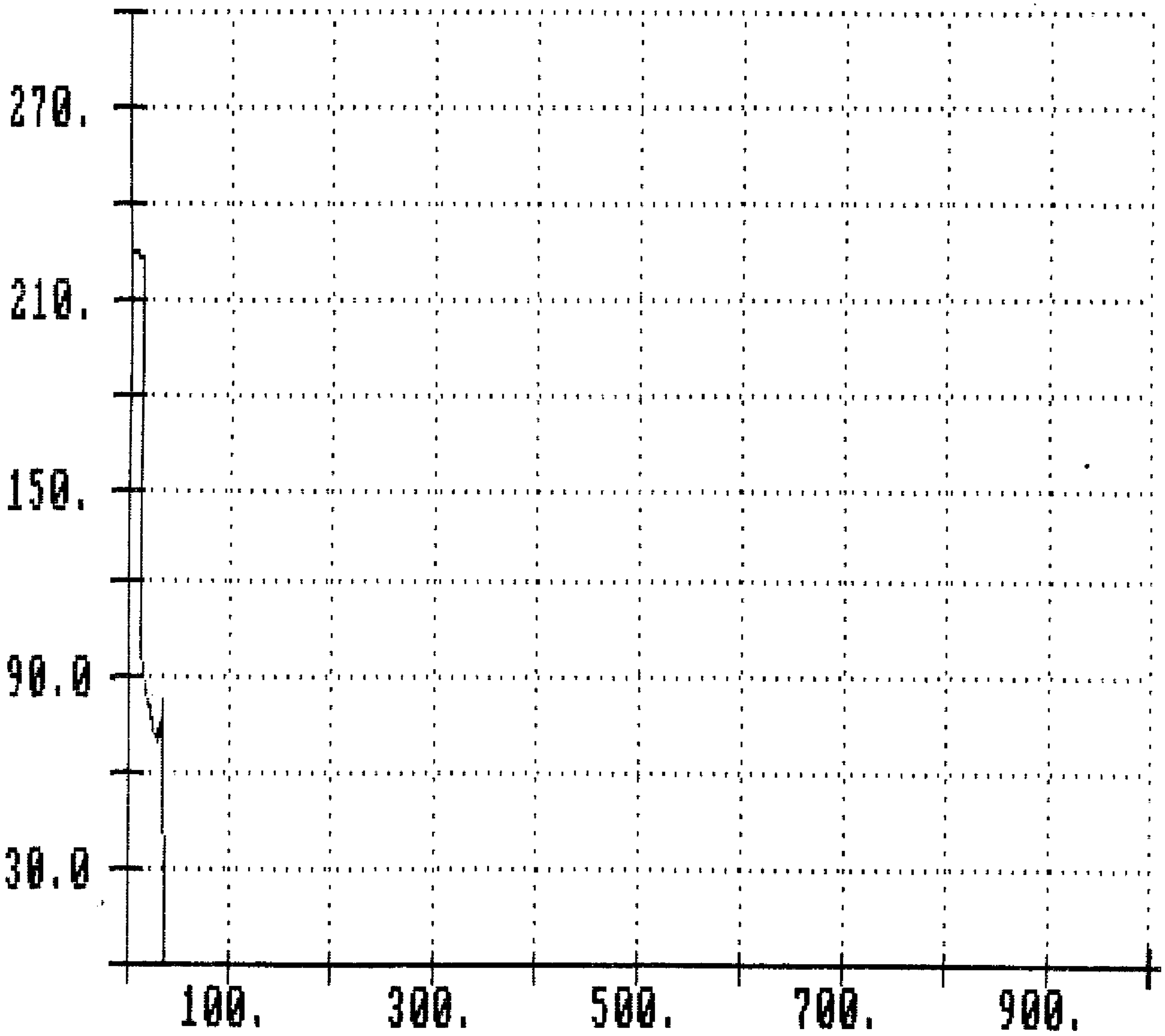

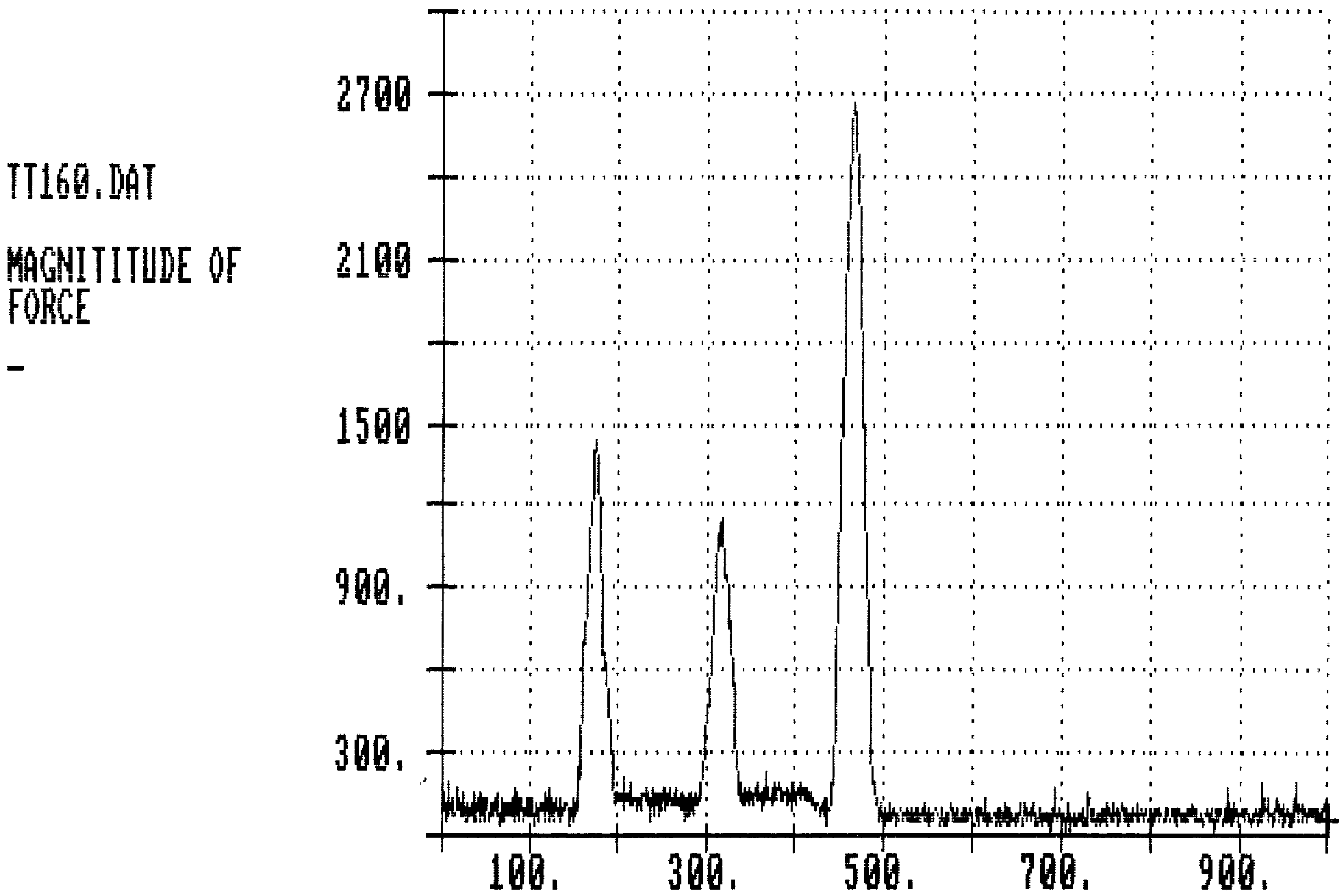
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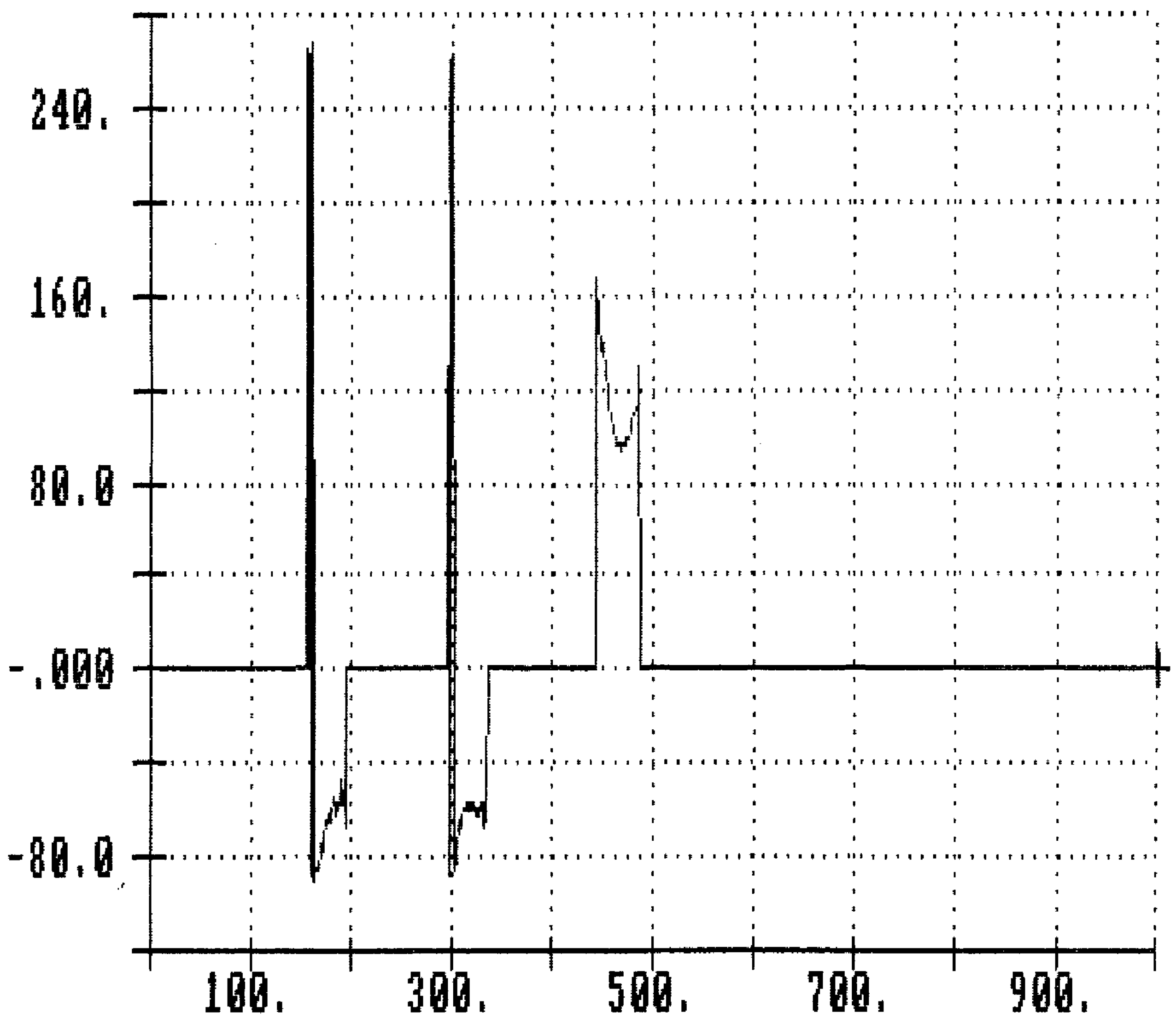
700.
900.

TT160.DAT

ANGLE OF FORCE

-



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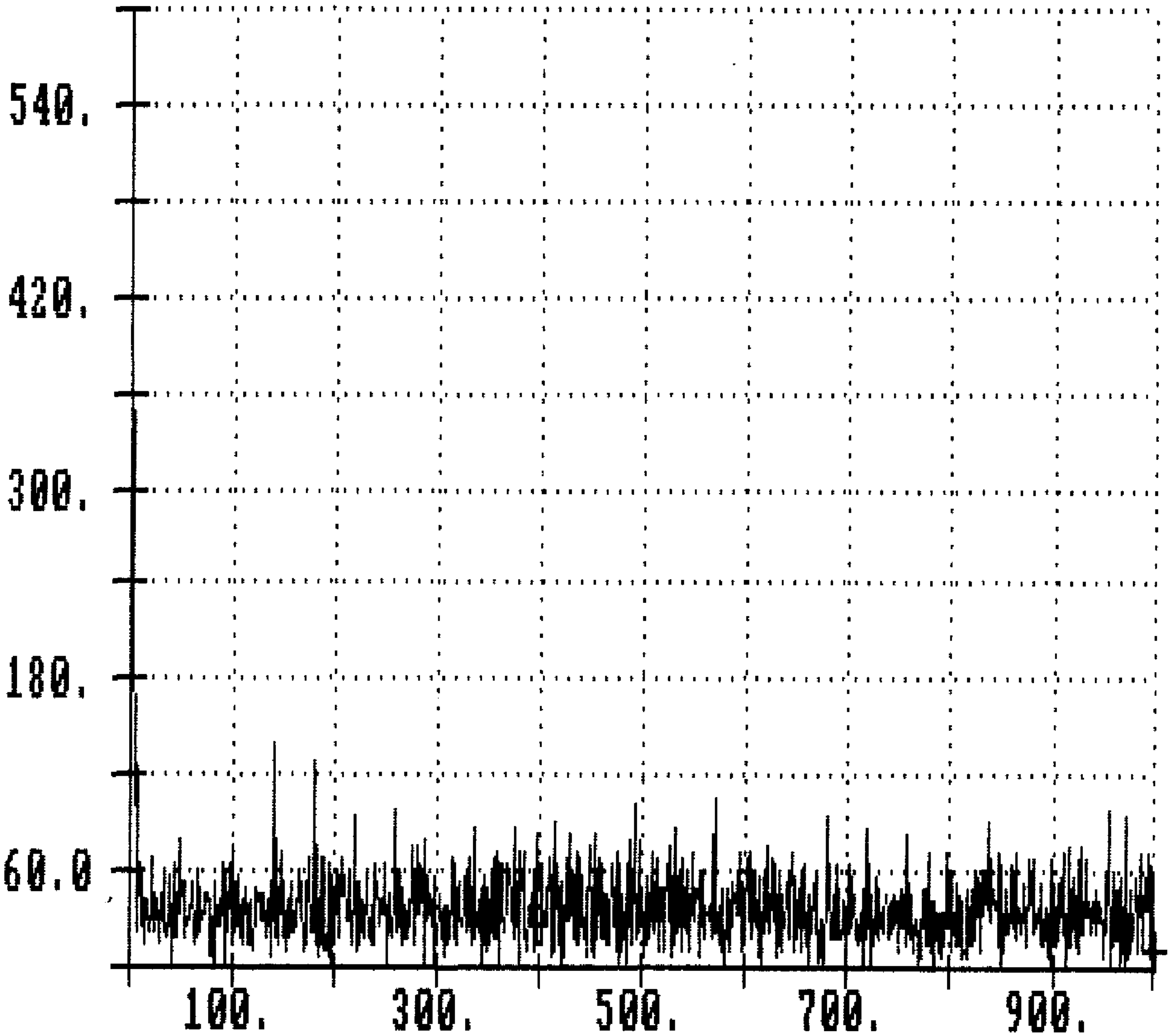

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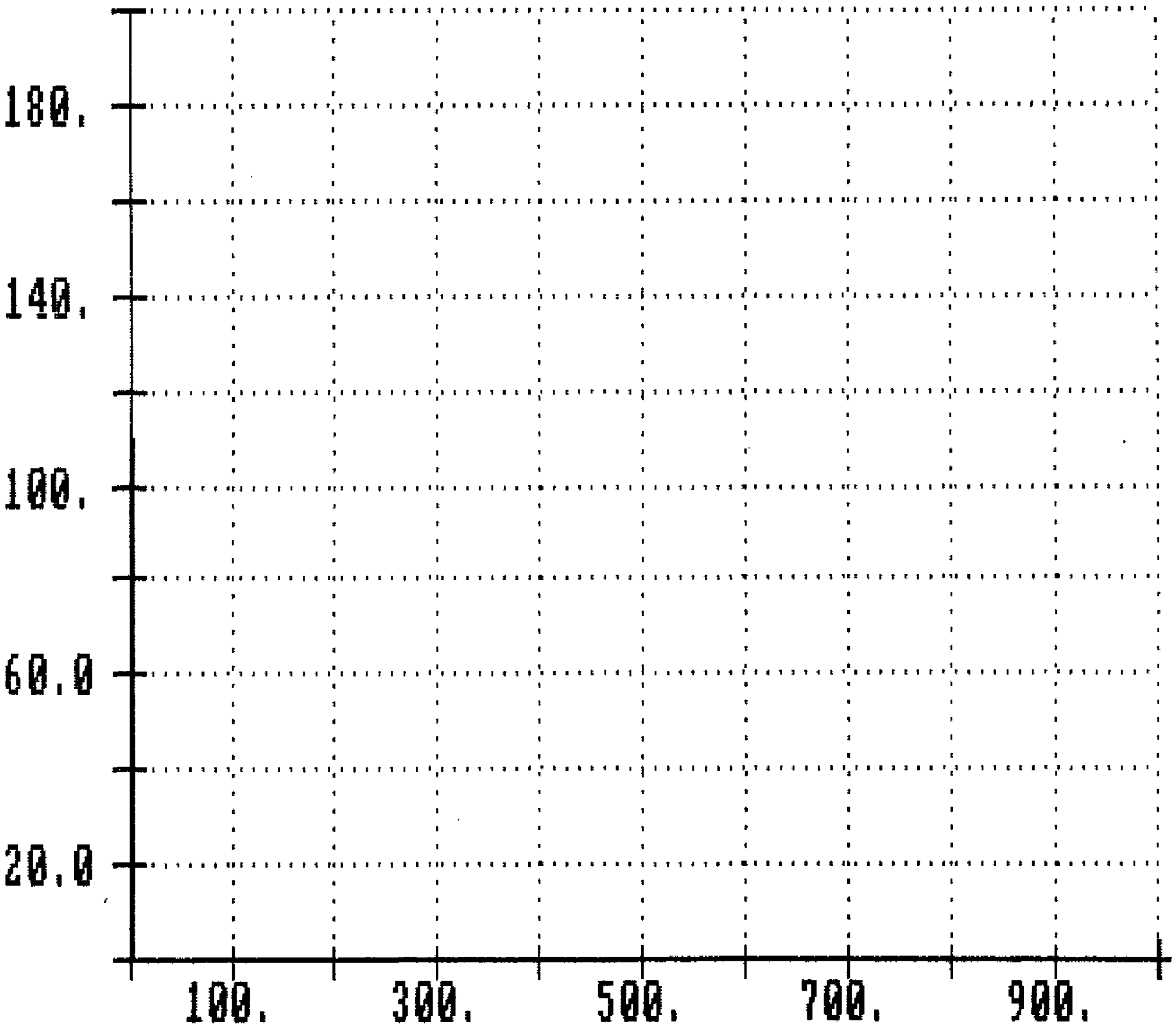

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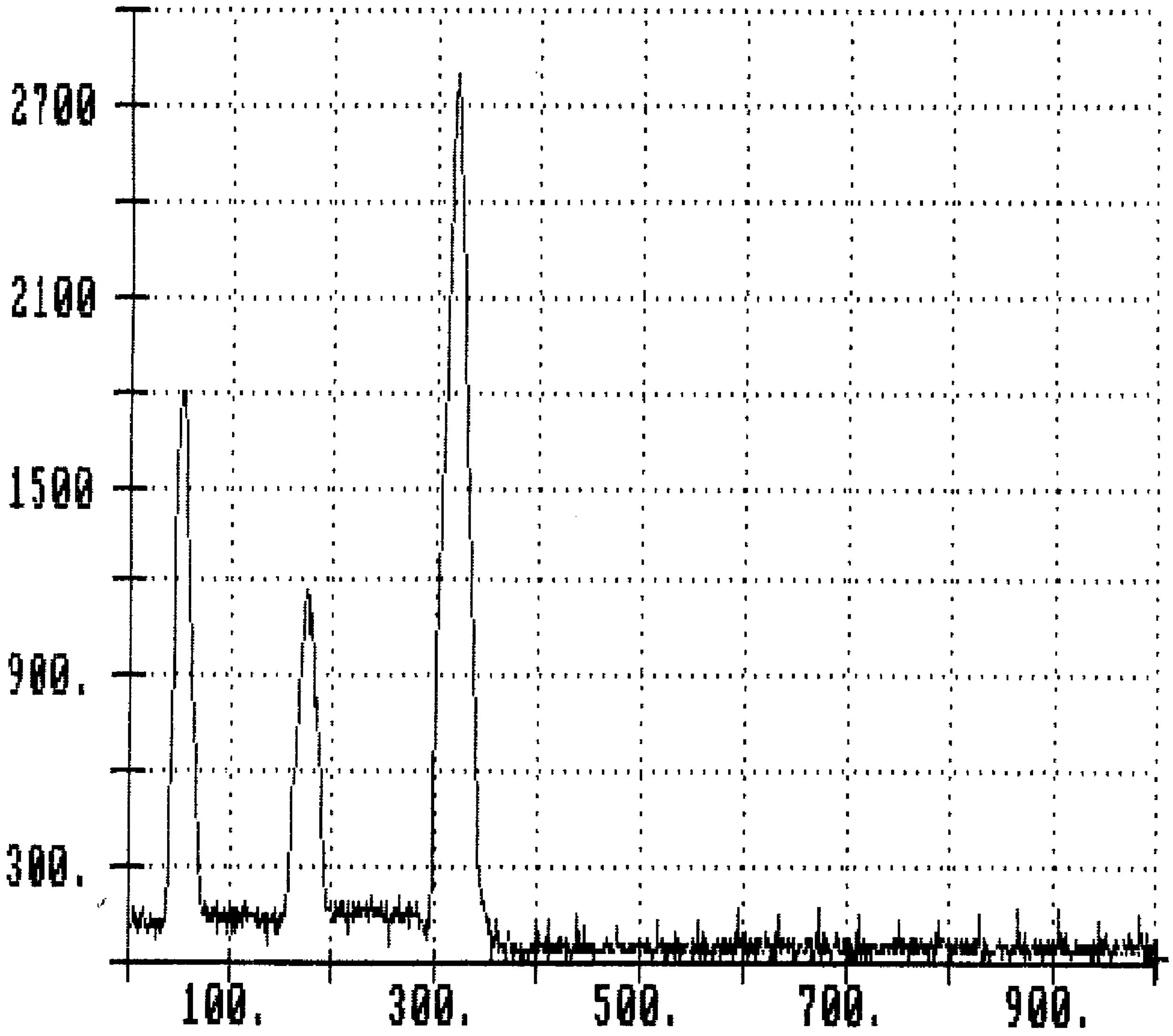

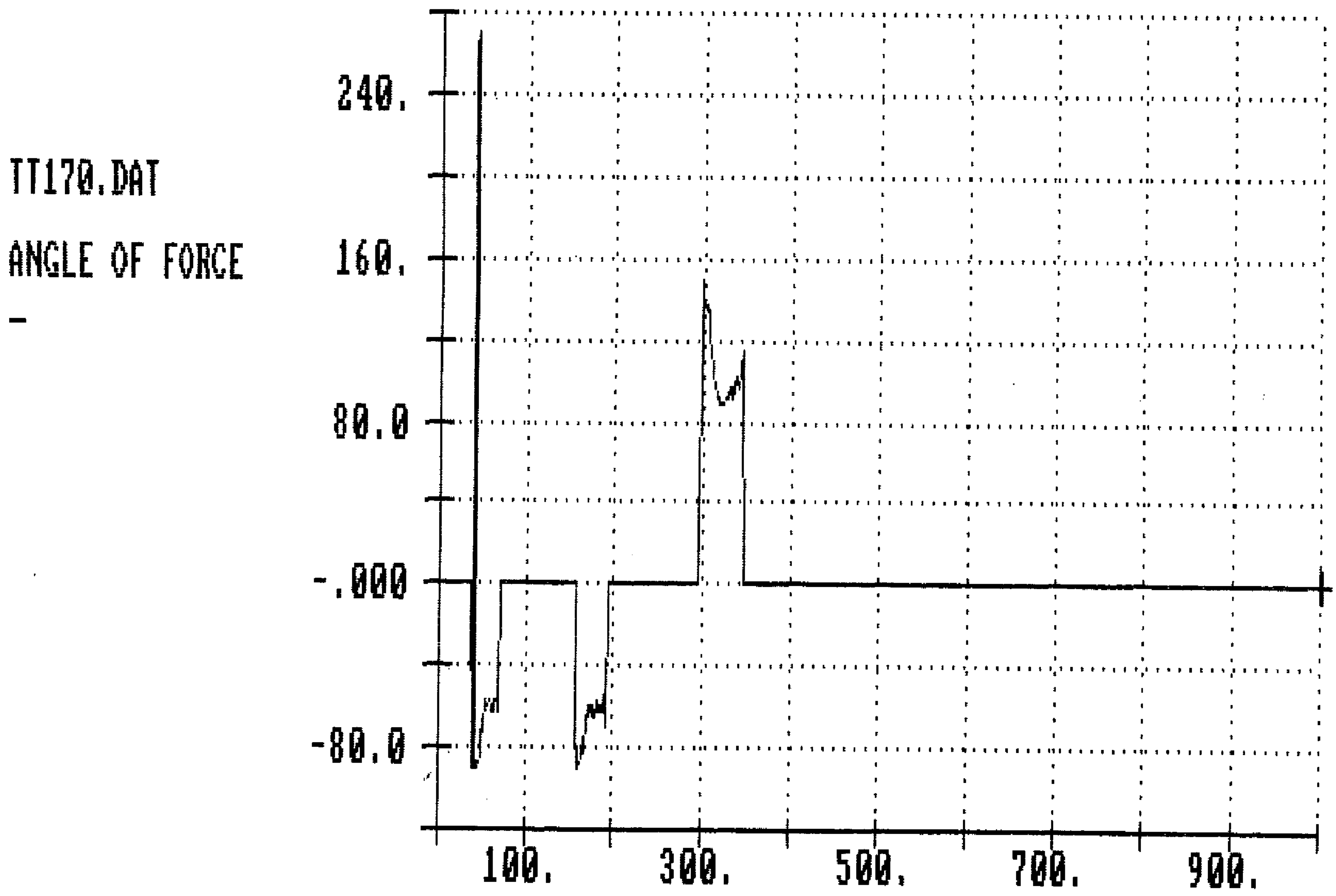
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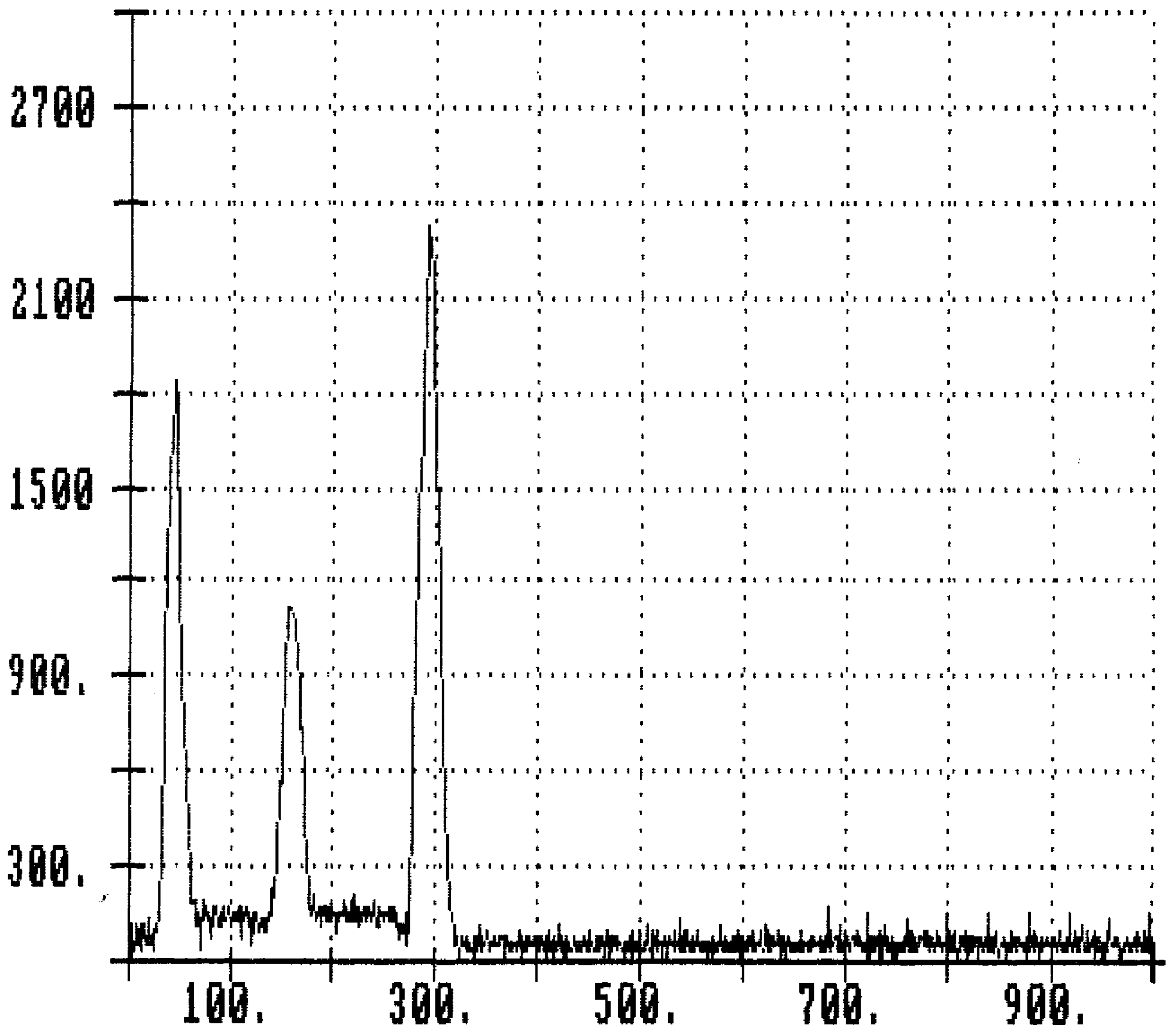

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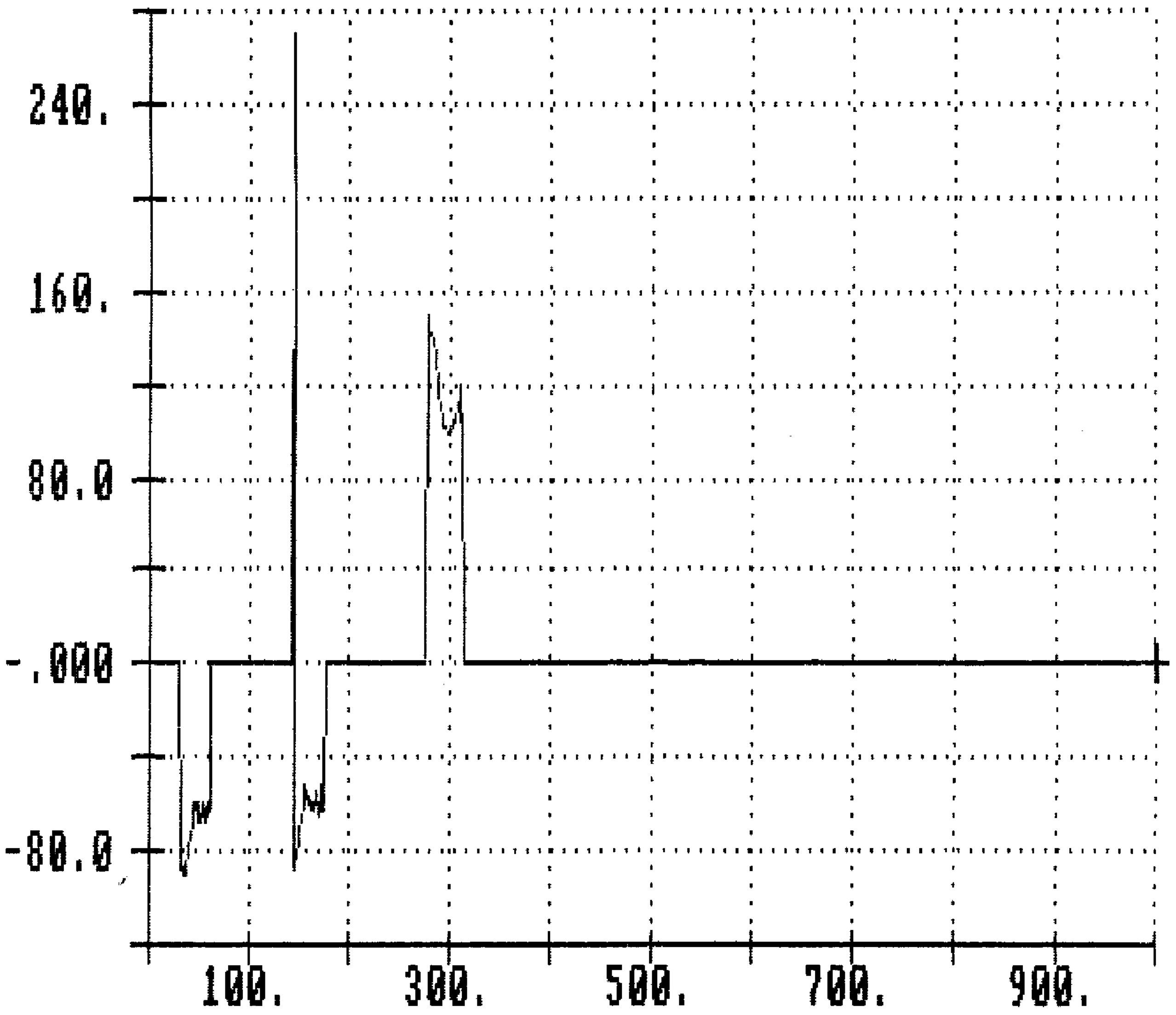

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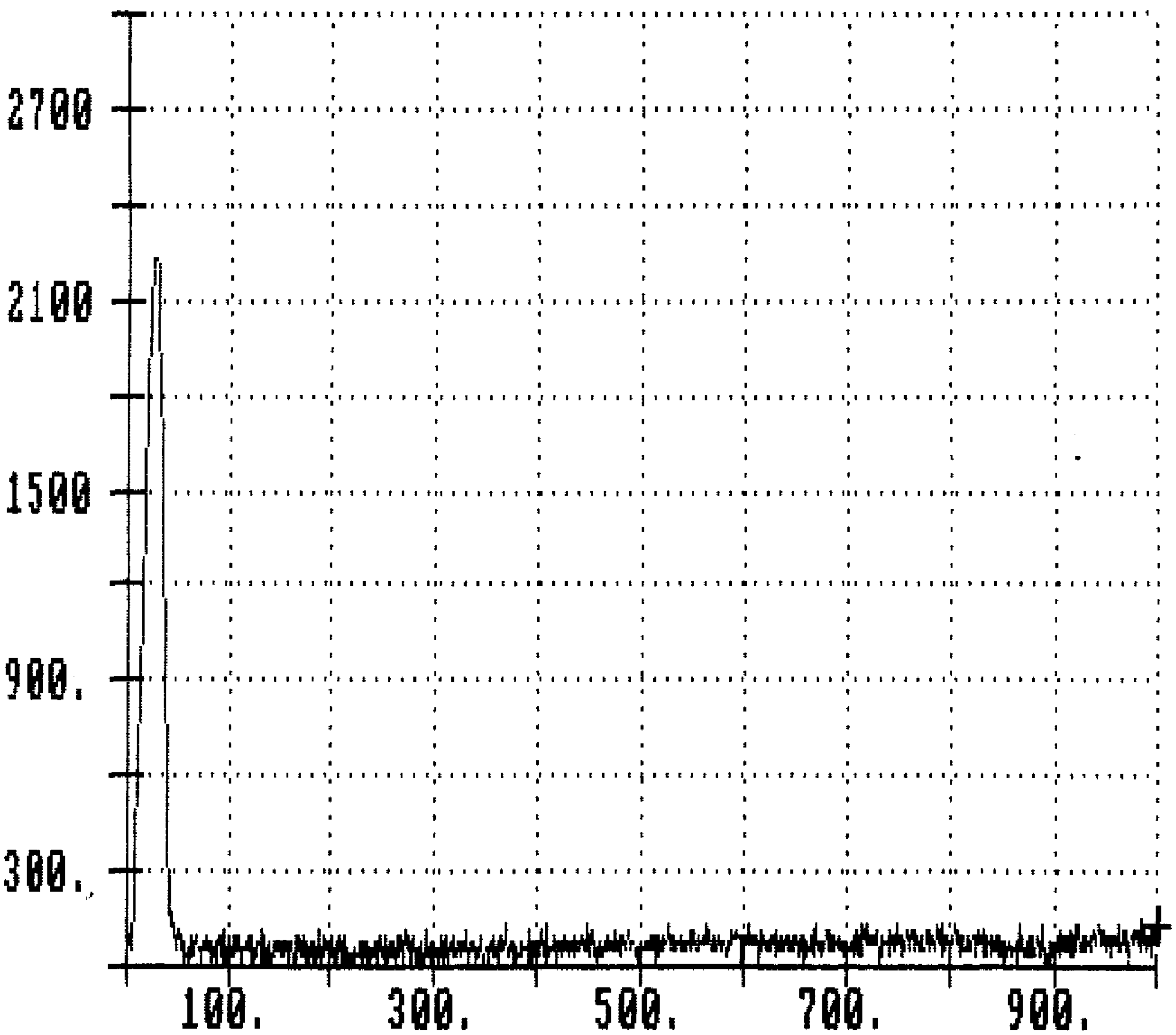

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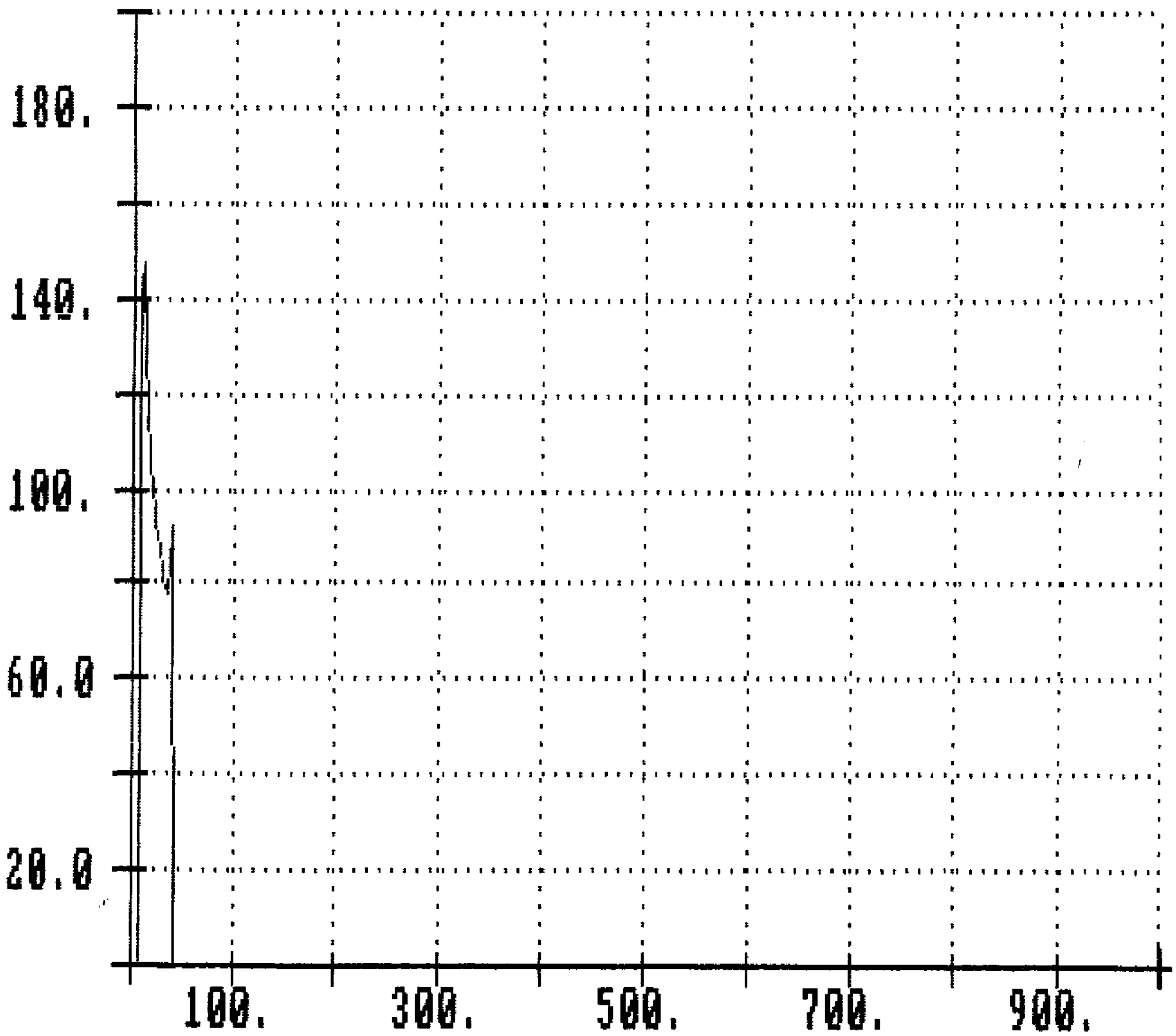

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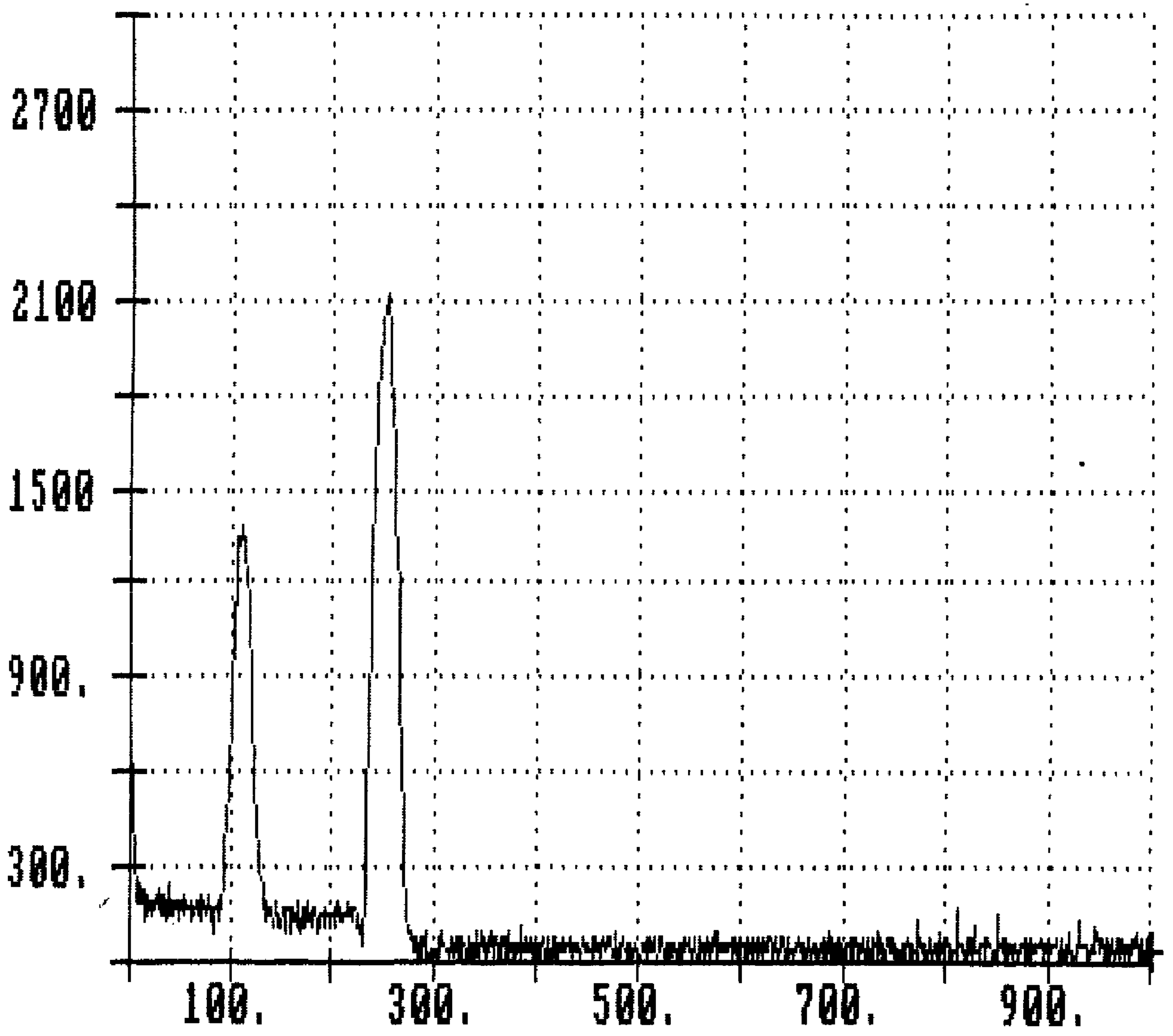

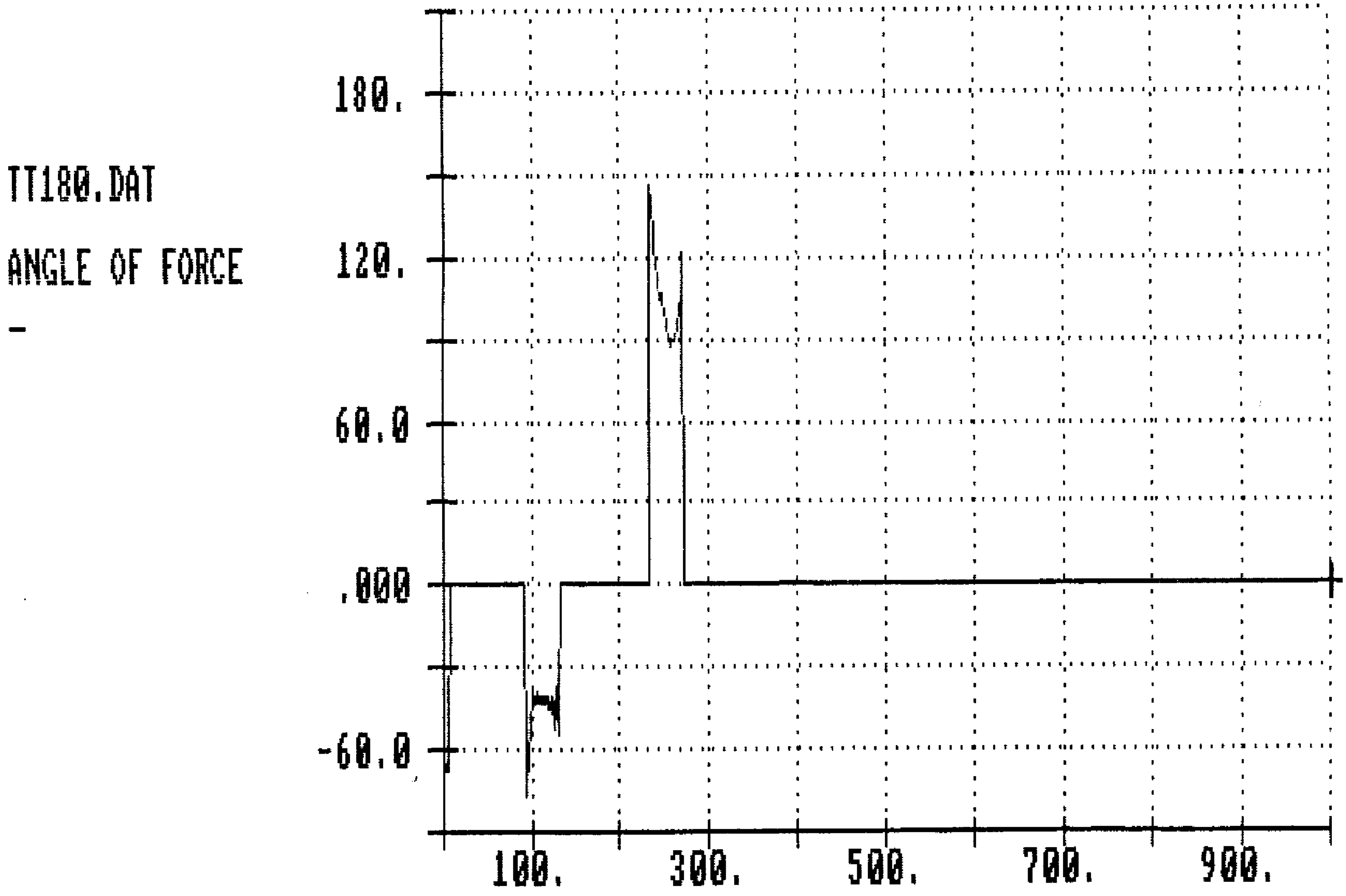
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500.
700.
900.

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MAGNITITUDE OF
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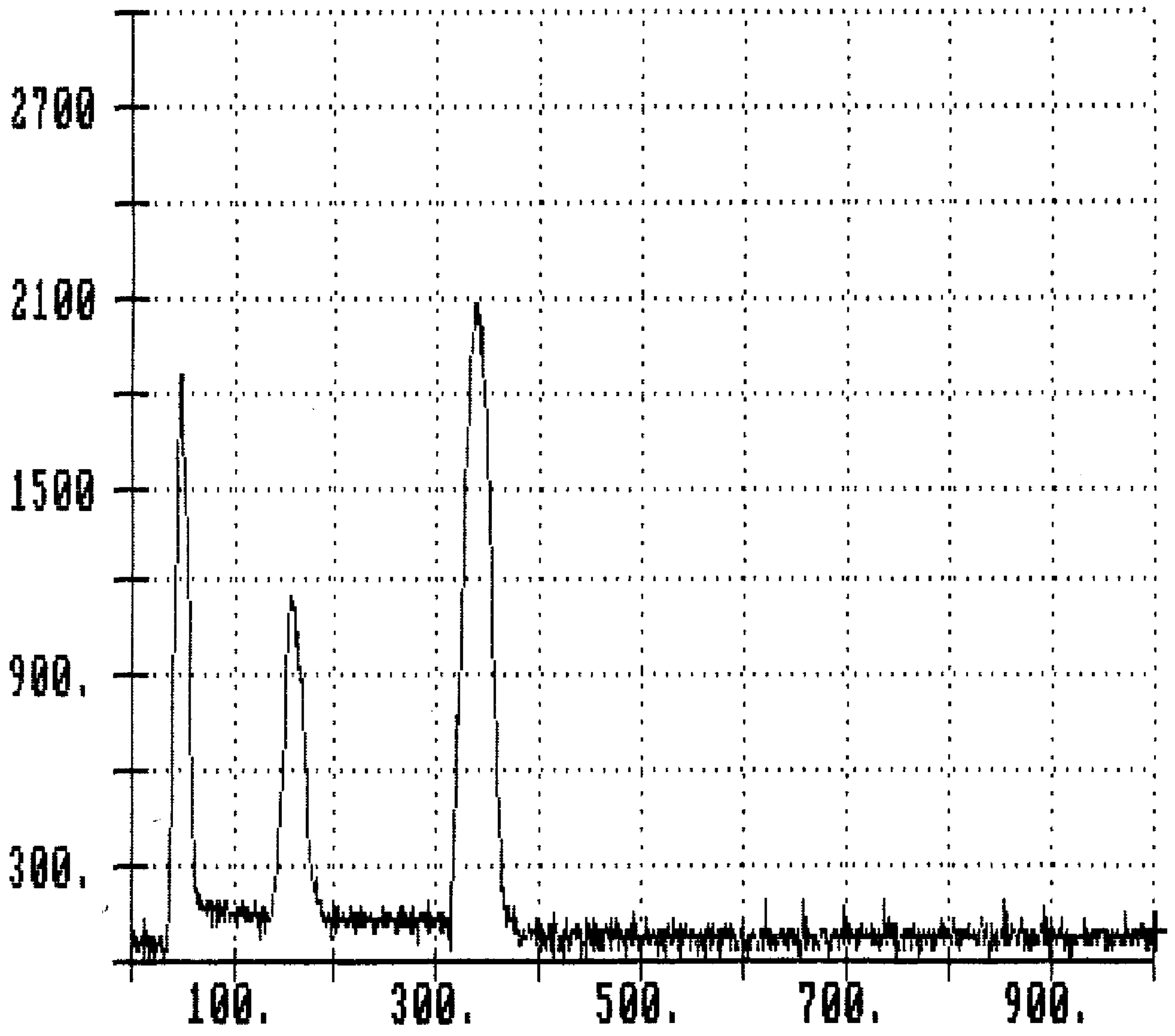

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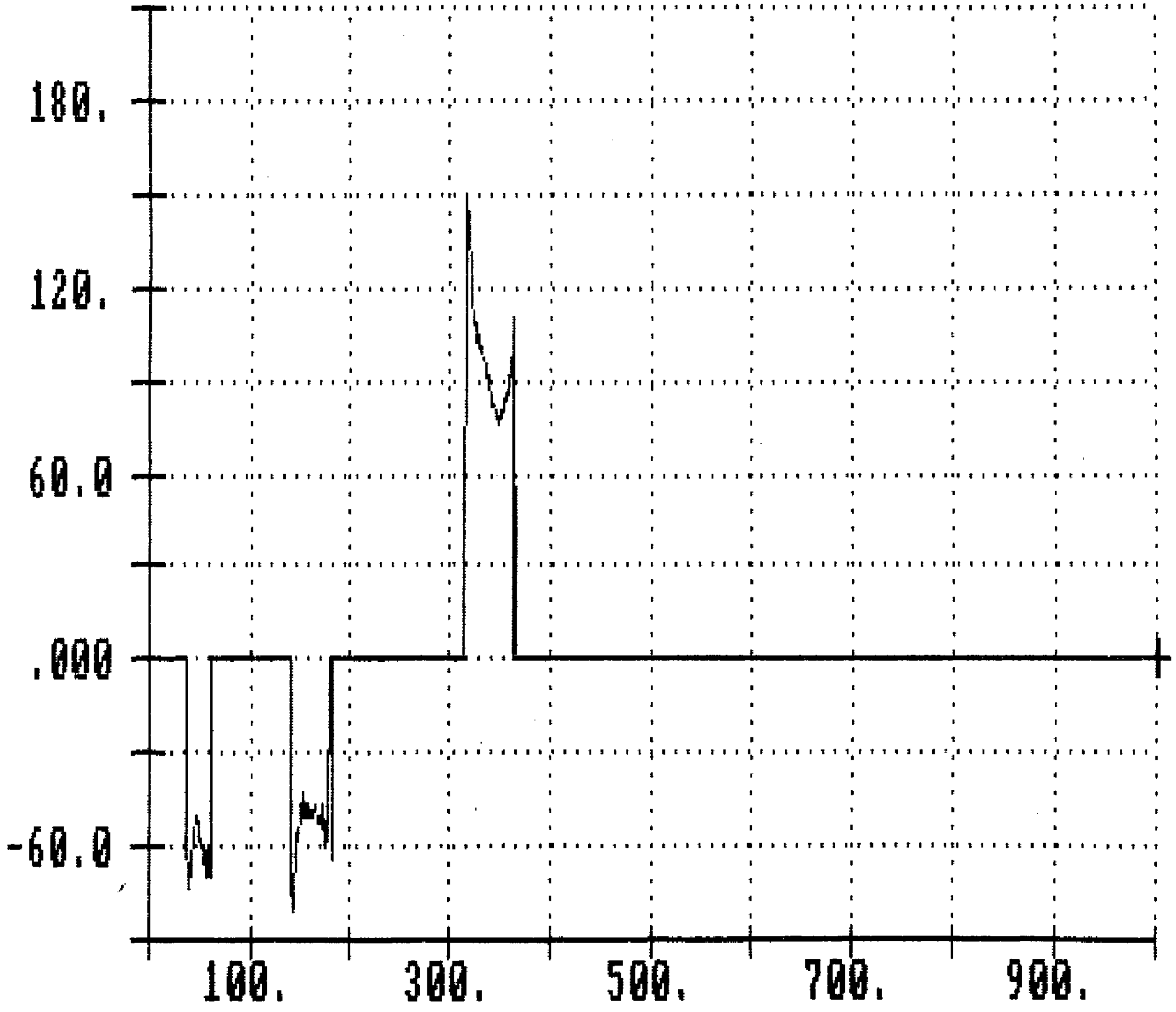

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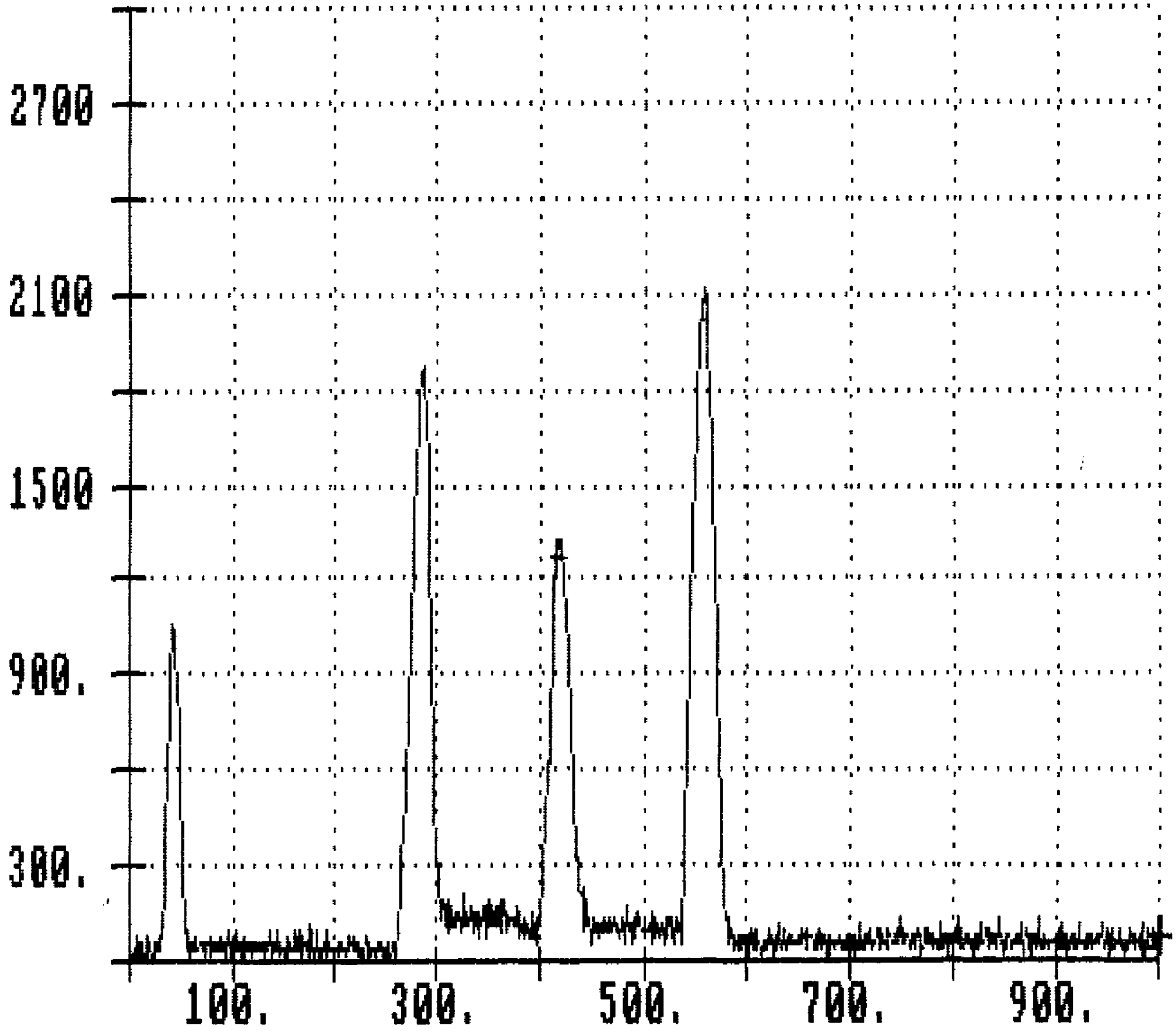

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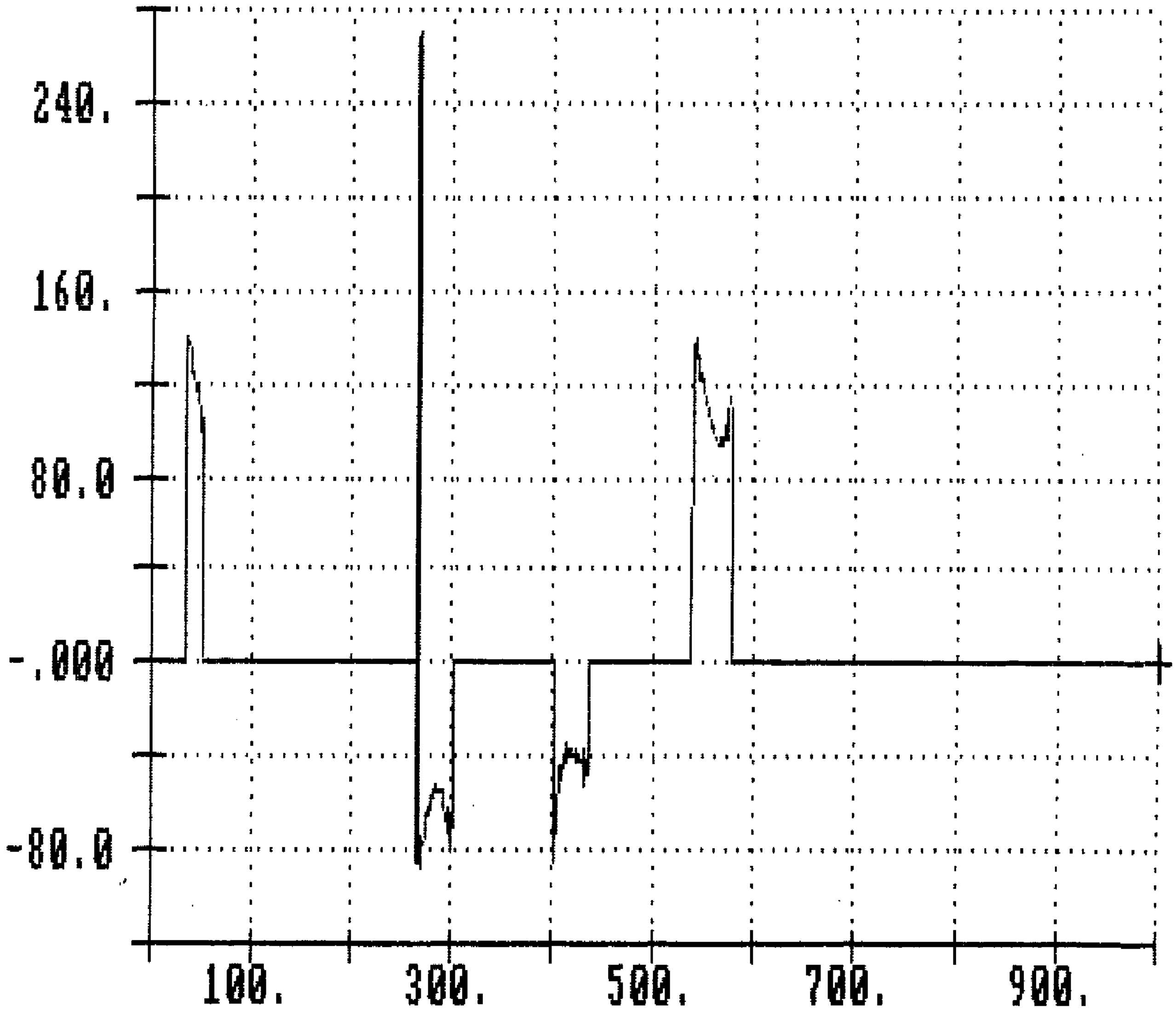

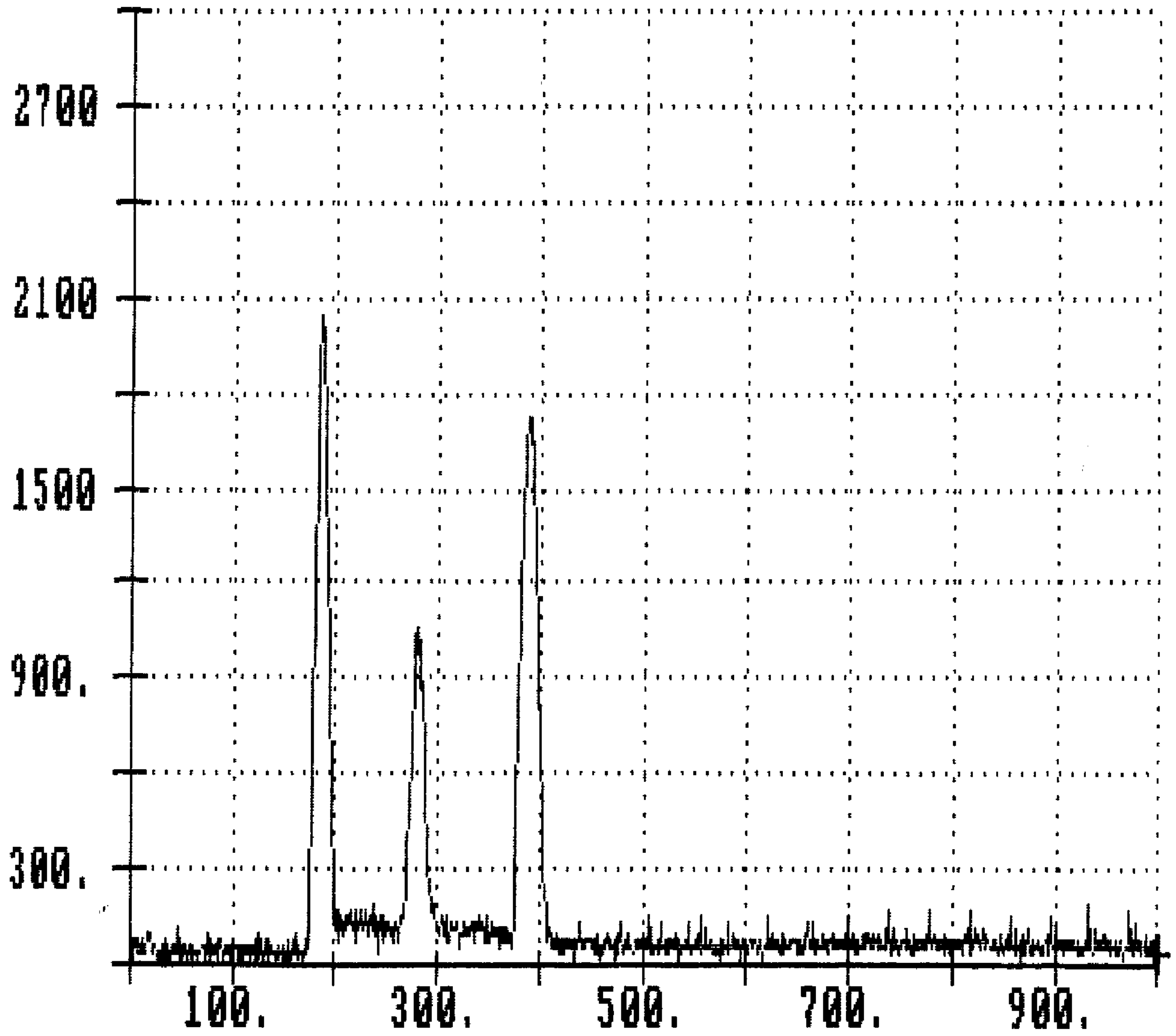

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MAGNITITUDE OF
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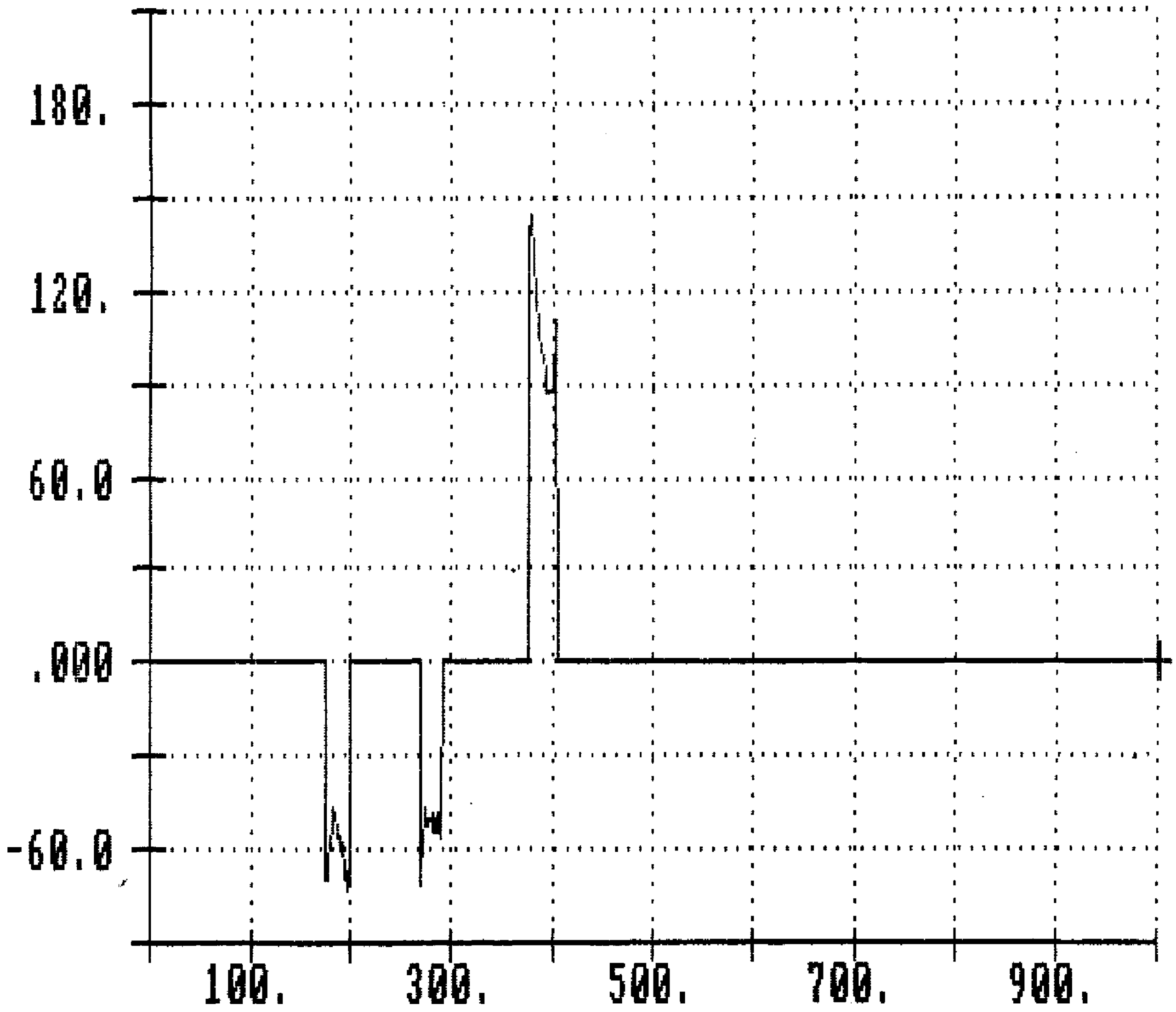
TT190.DAT

ANGLE OF FORCE



TF290.DAT

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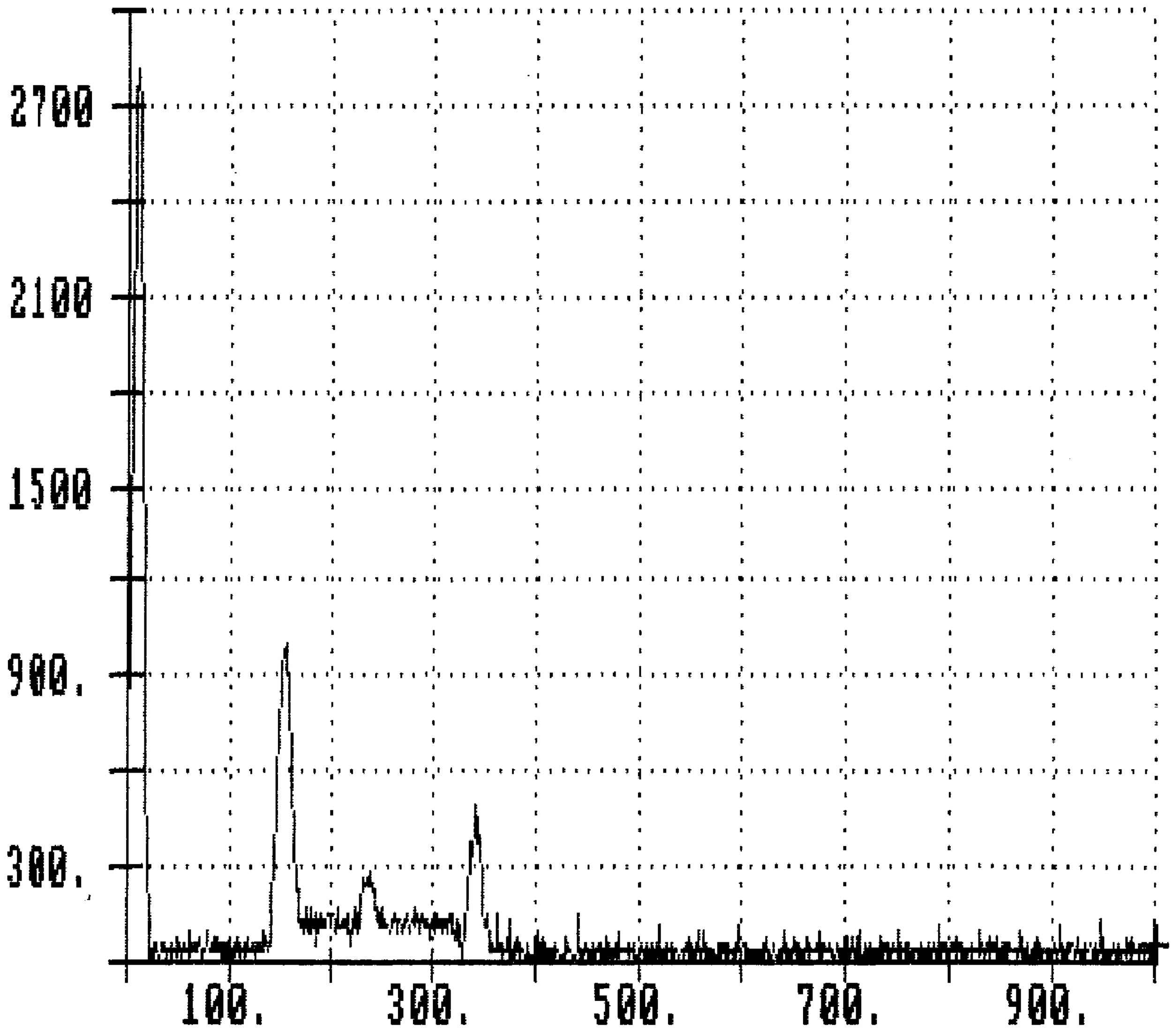

TF290.DAT

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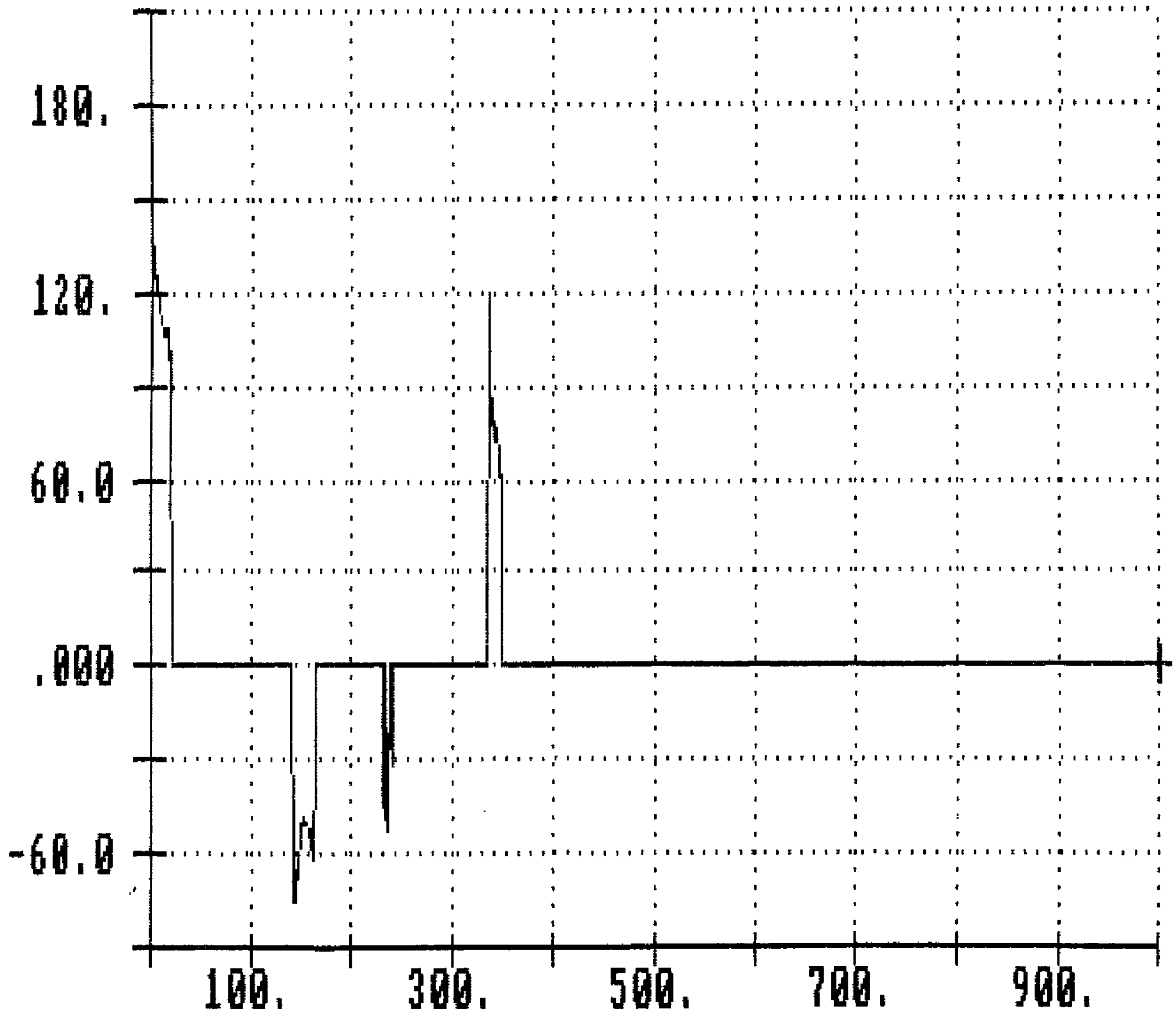

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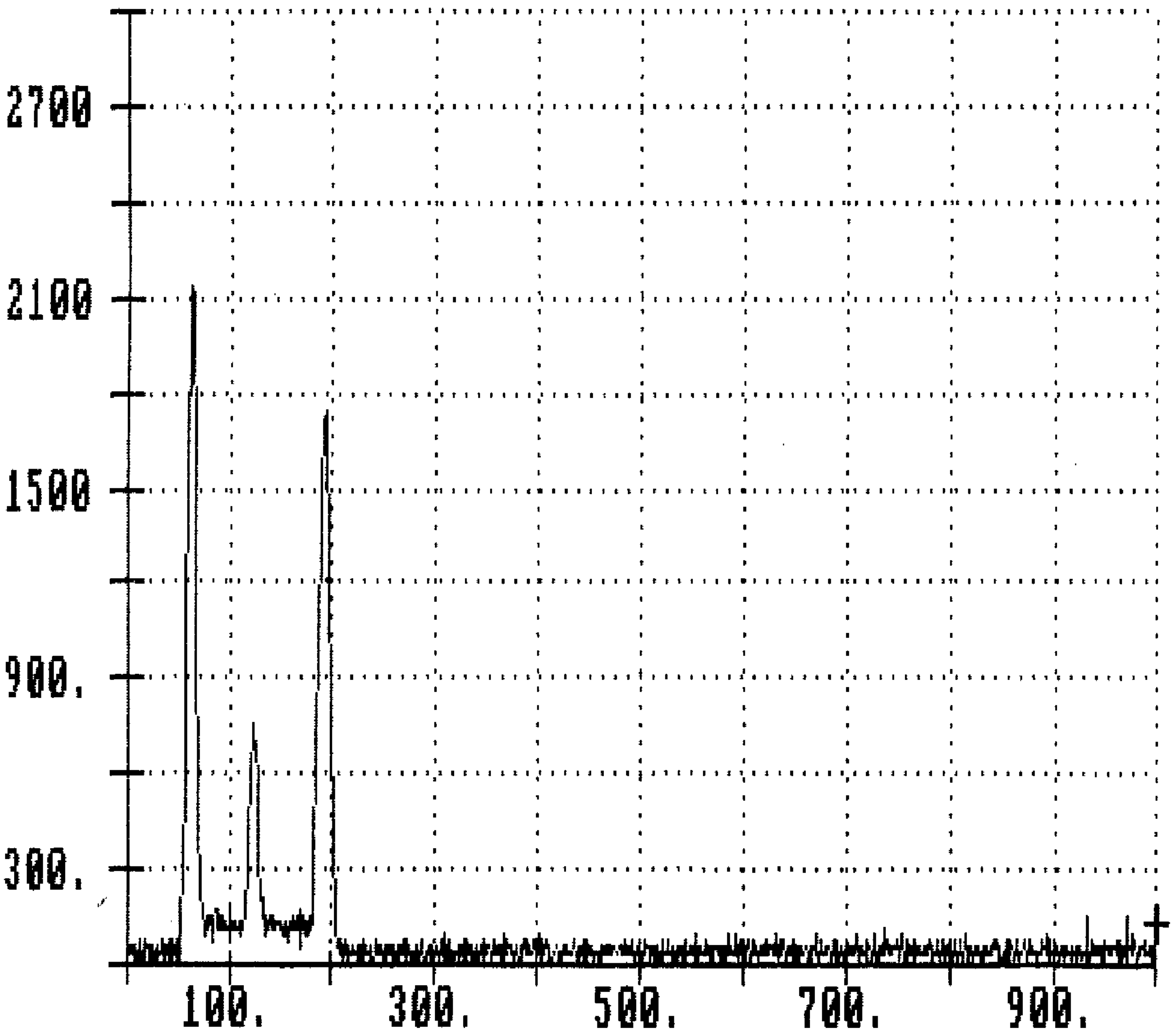

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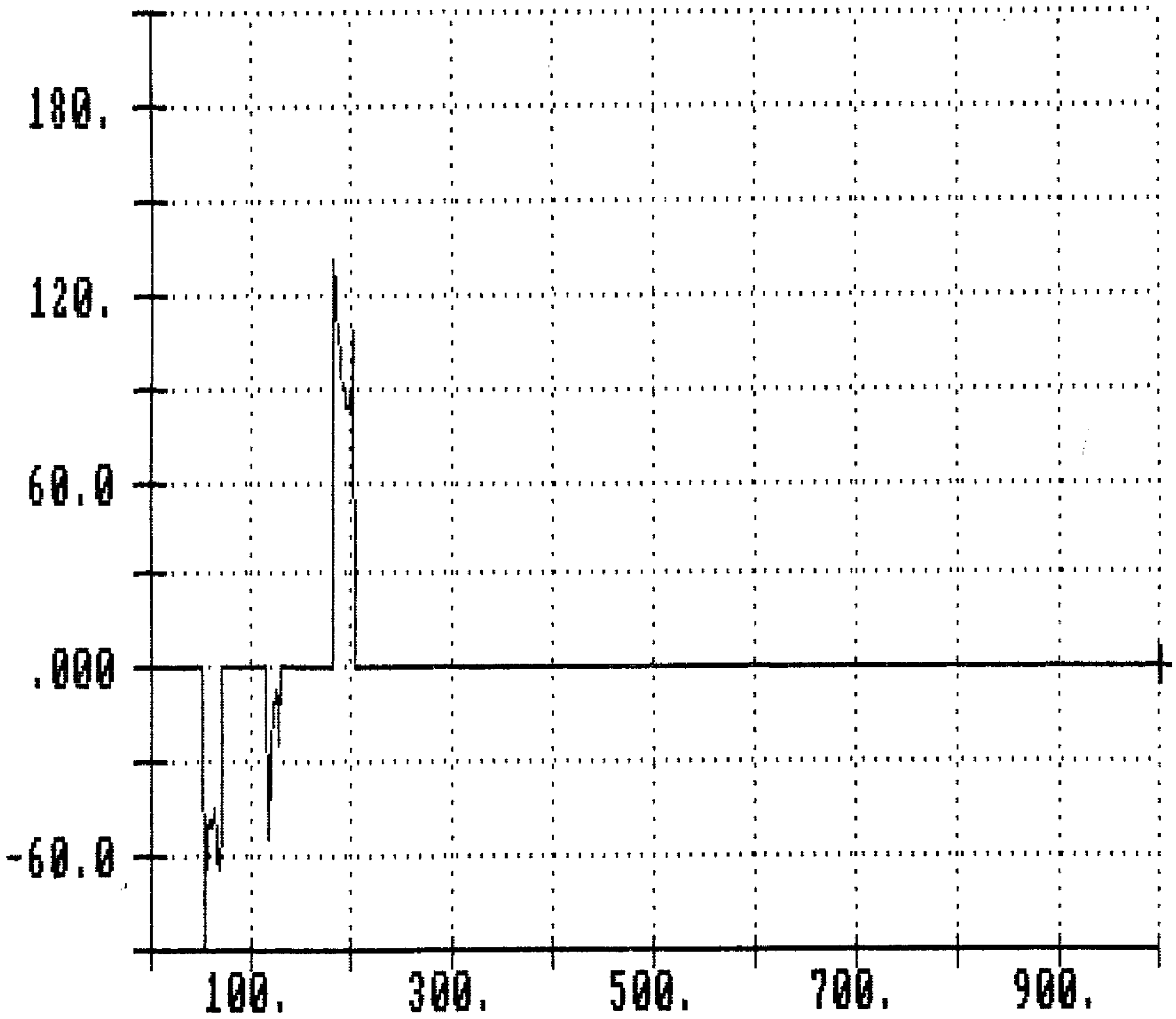

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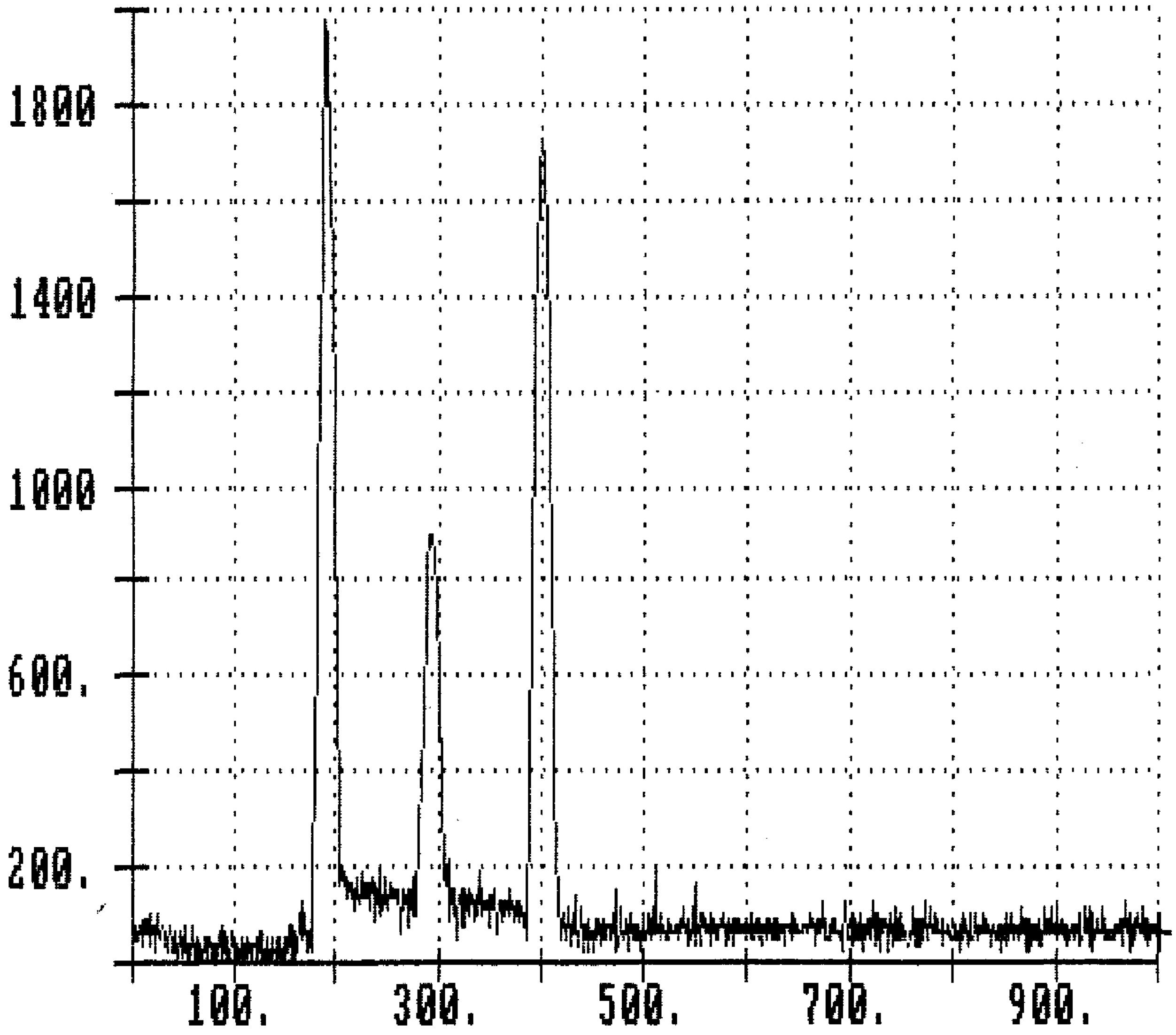

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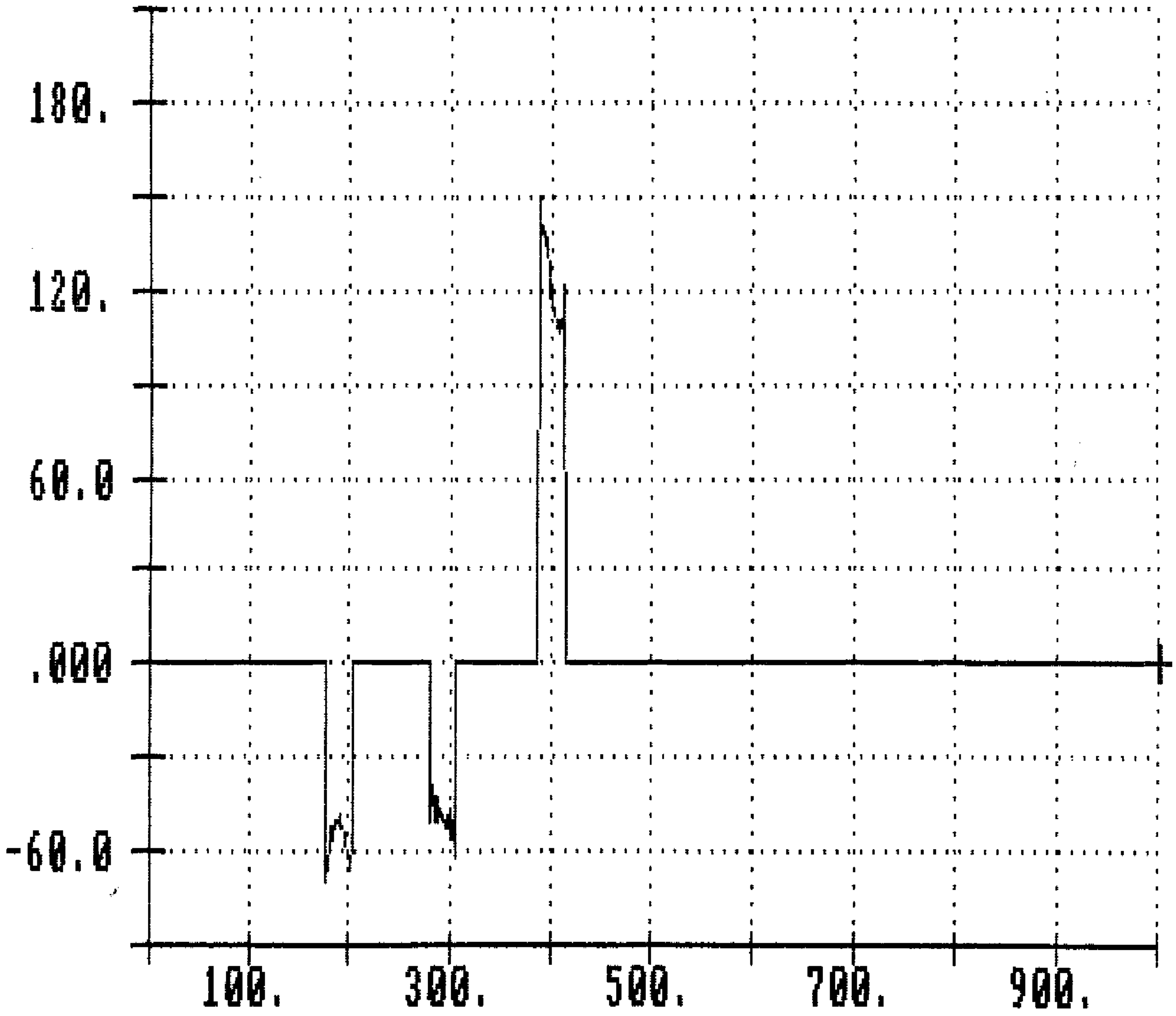

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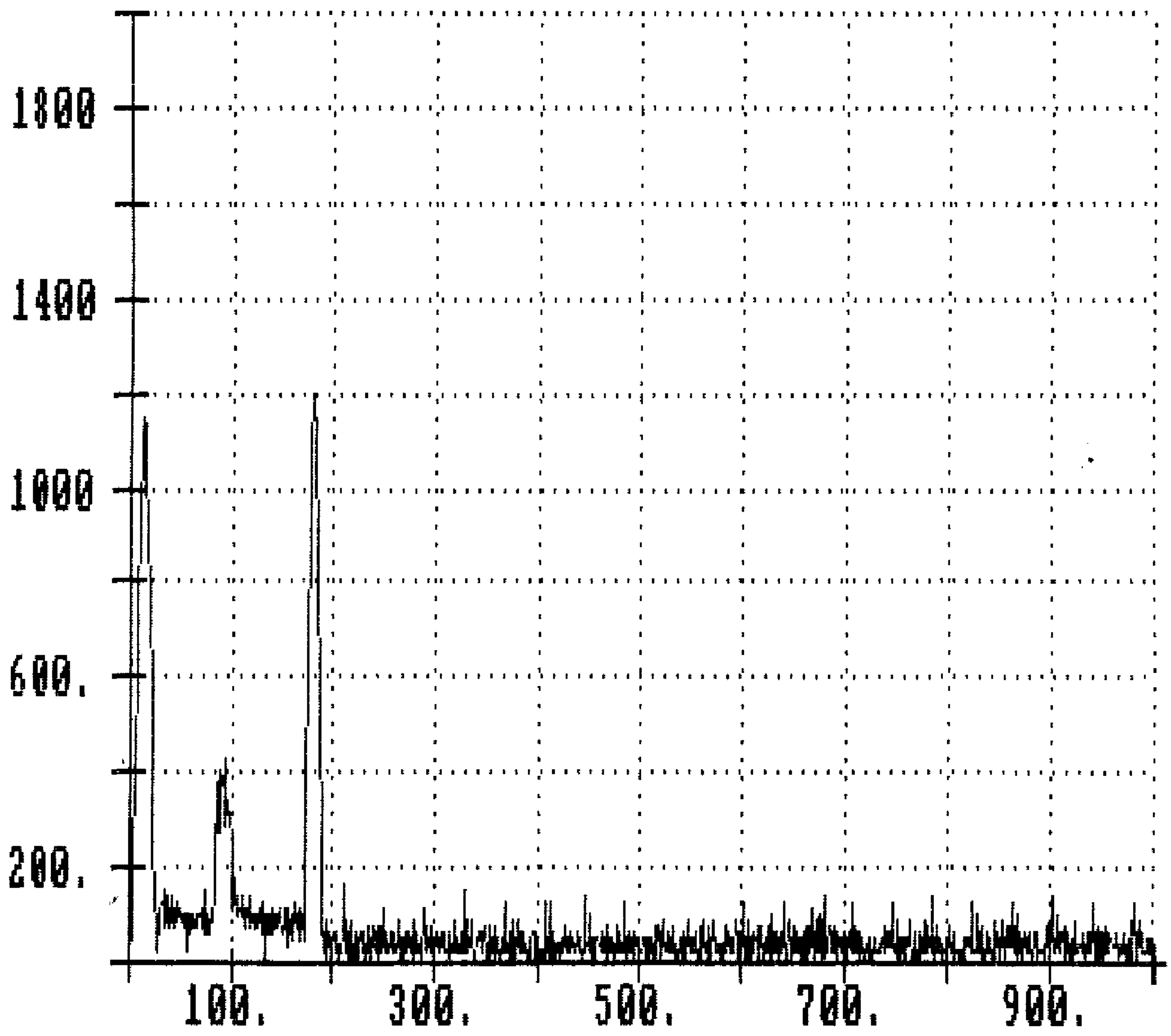

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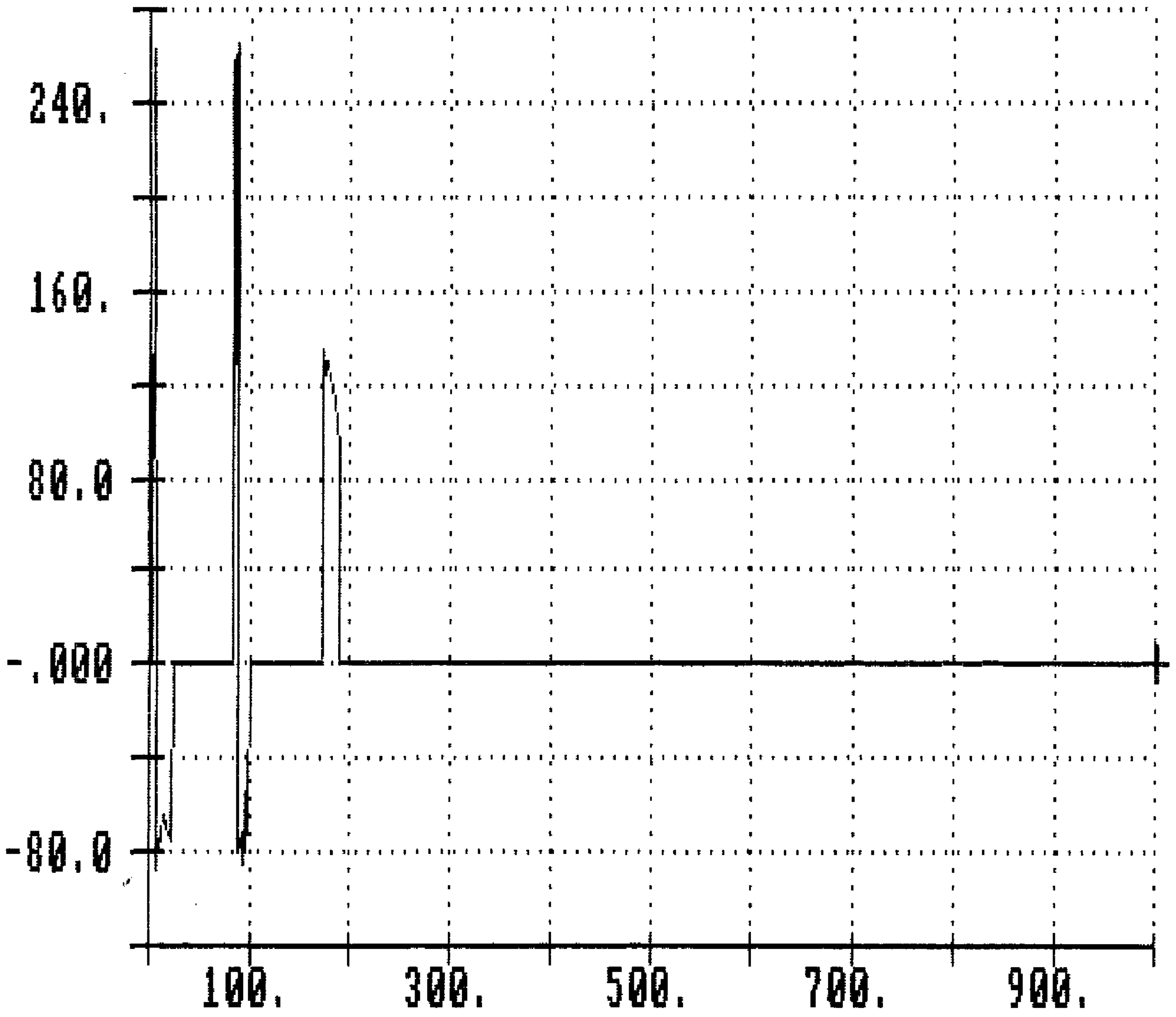

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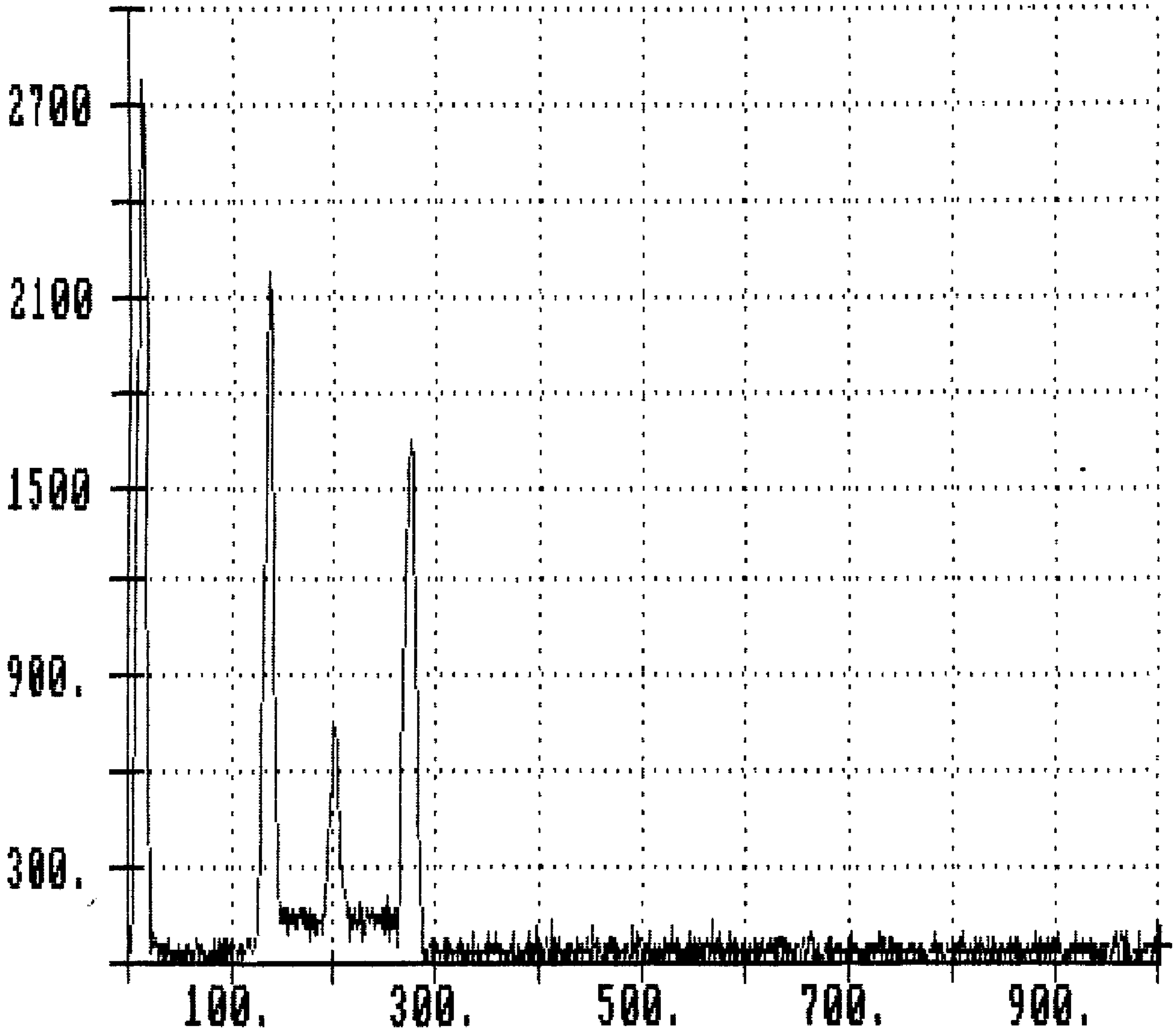

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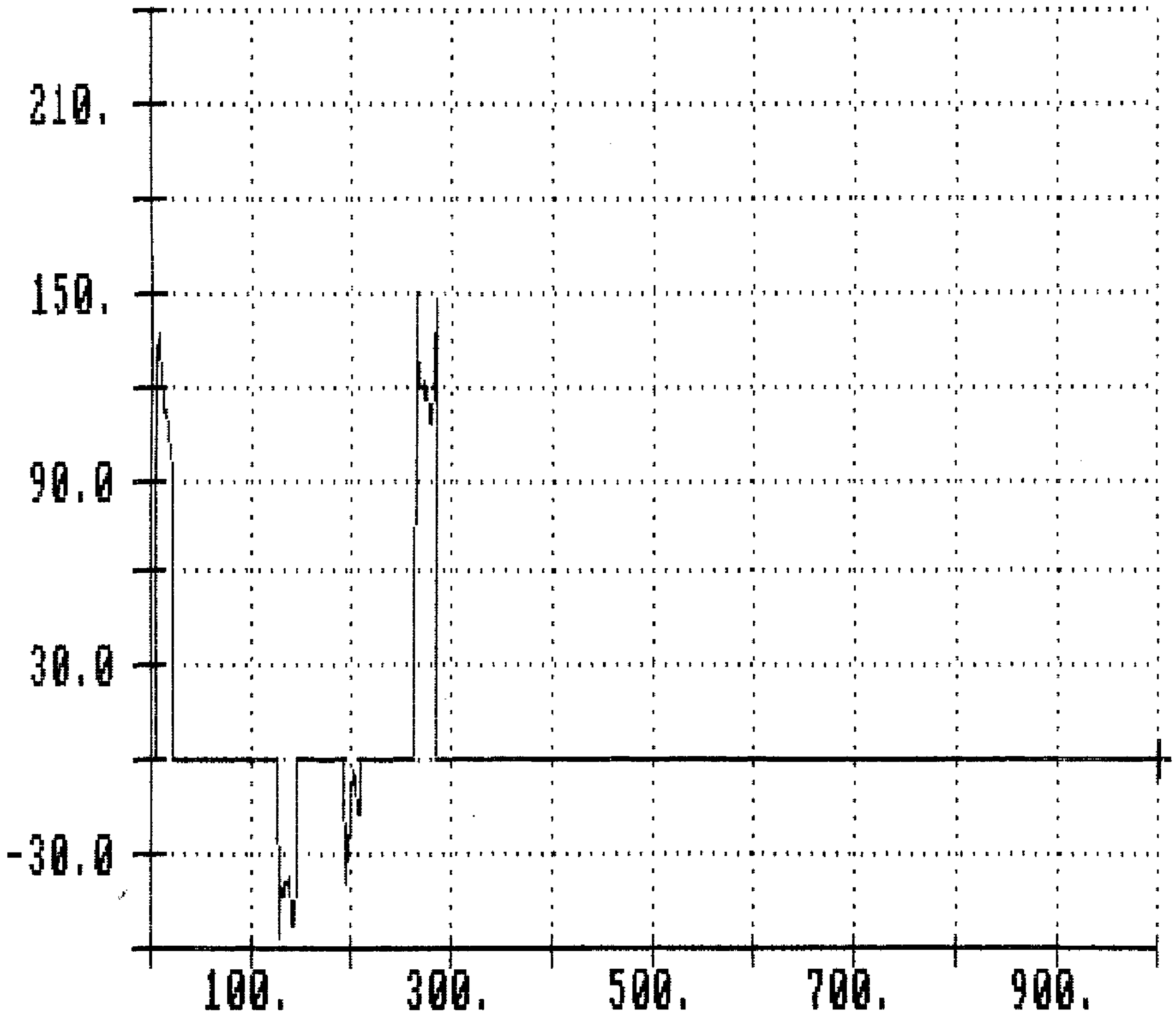

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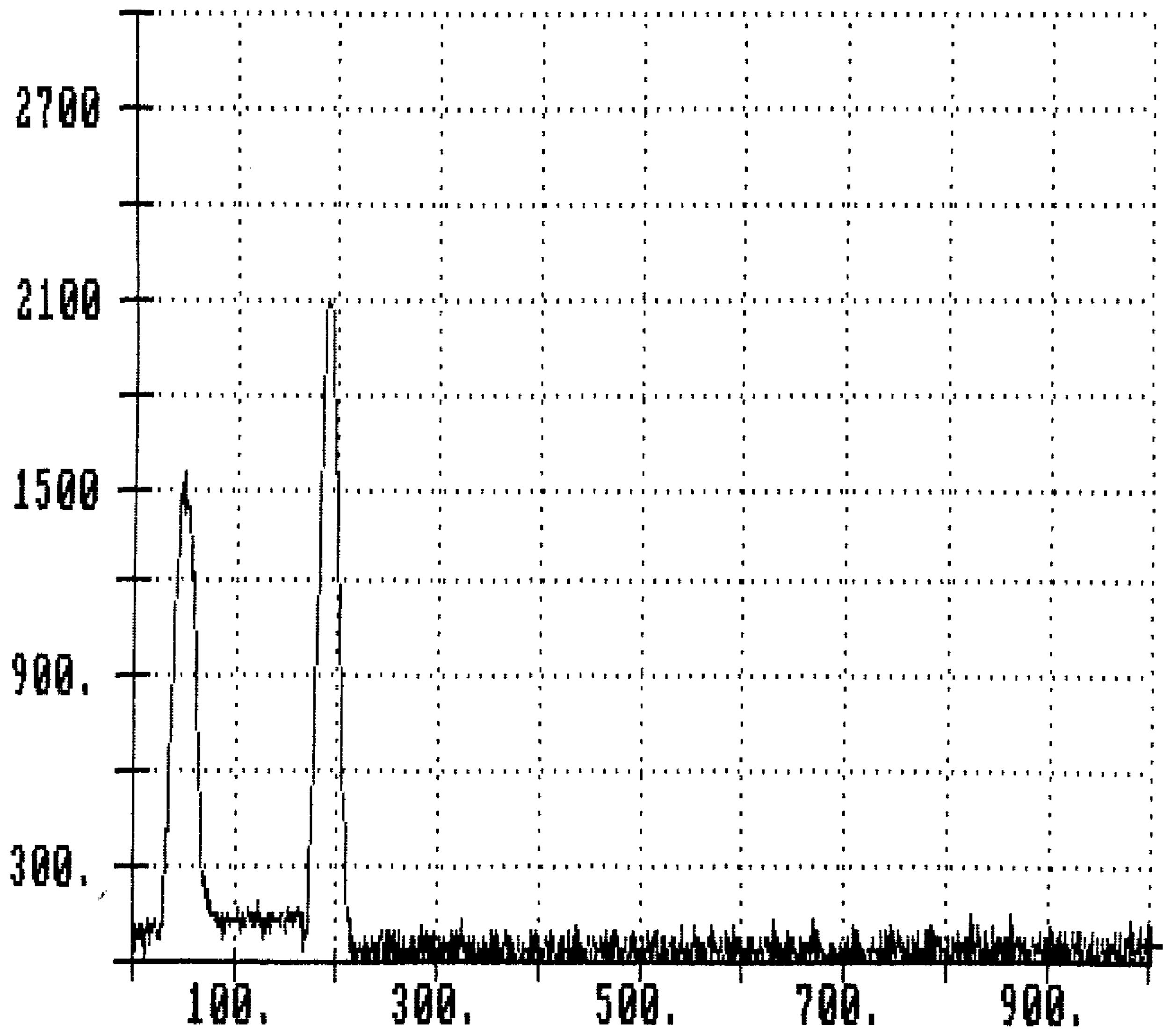

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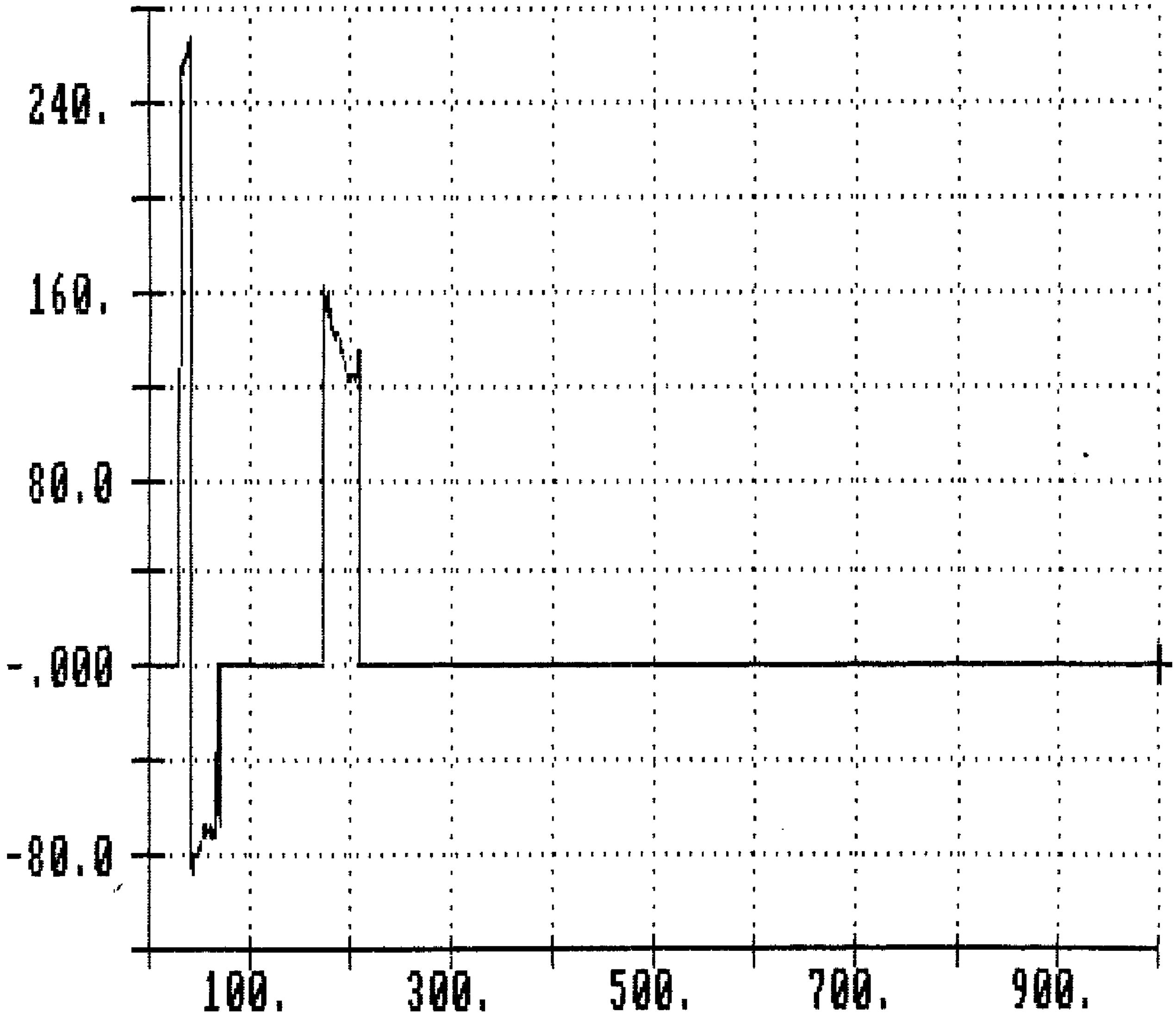

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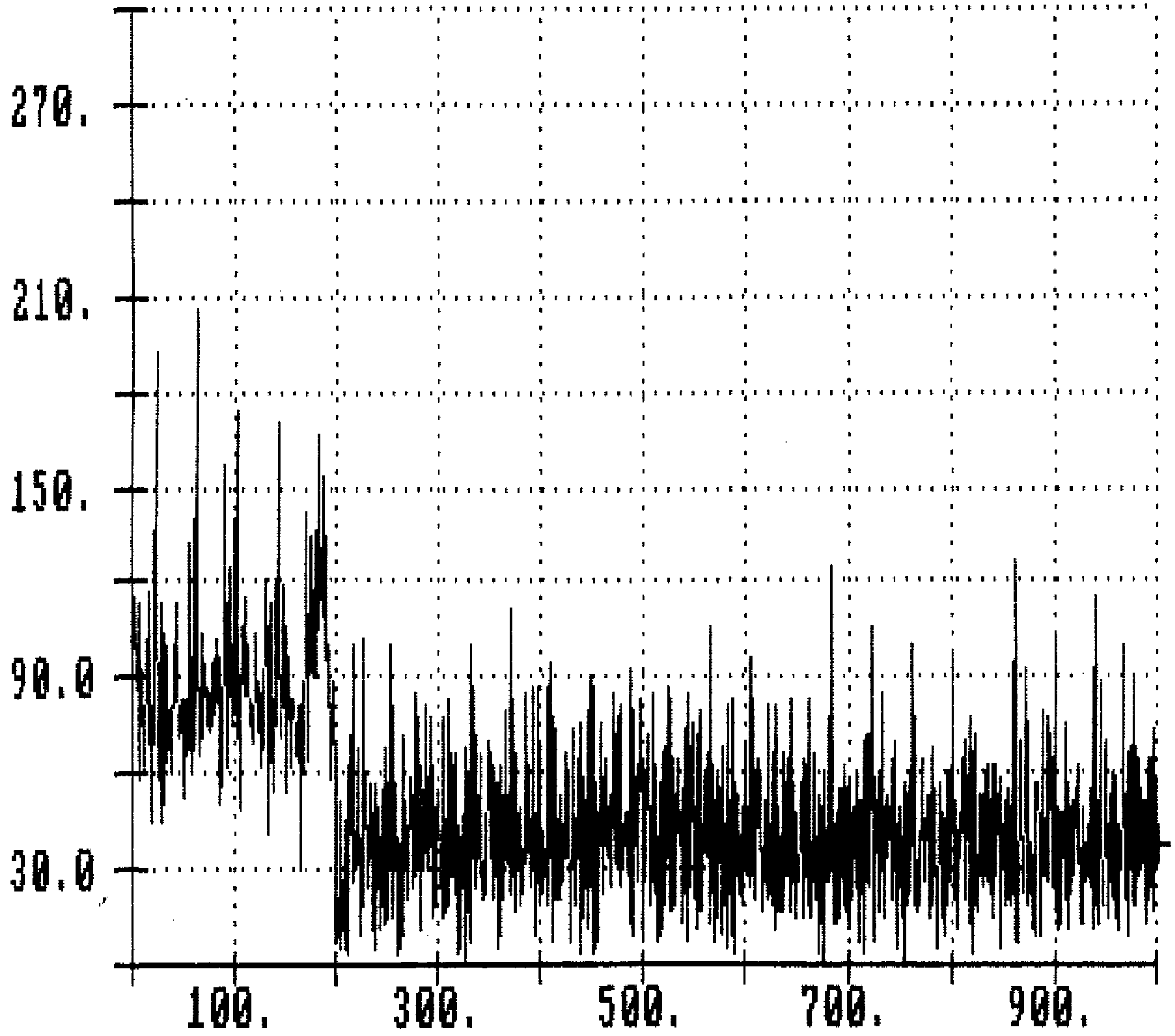

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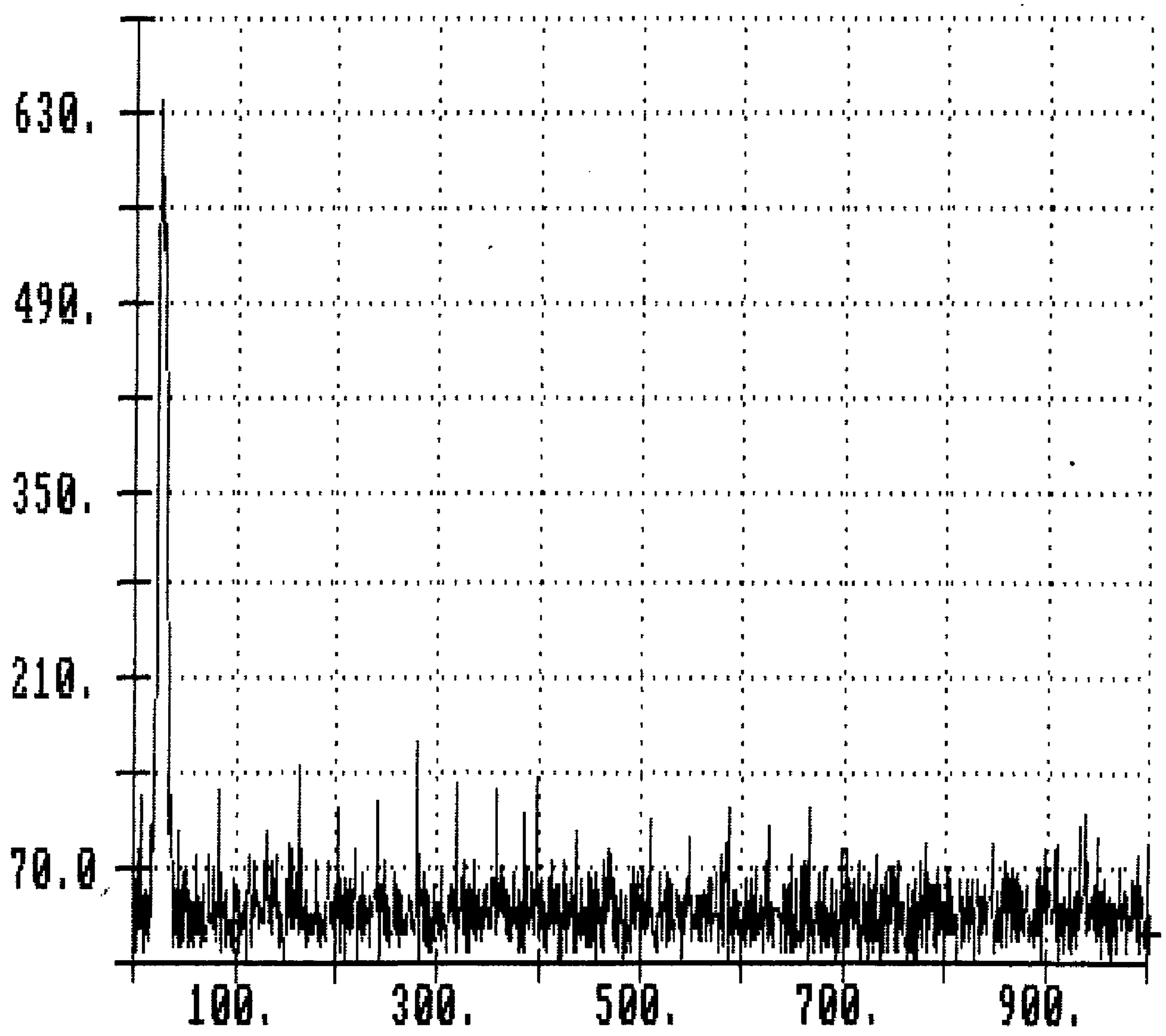

TF20.DAT

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