Vehicle Weights and Dimensions Study

Volume 12

Vehicle Rollover Threshold Evaluation

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Abstract

The feasibility of quickly evaluating the vehicle rollover threshold at a road side control station is investigated. This report presents the process which has been retained starting with the selection of a static rollover computer model suitable for personal type computer. The most significant parameters controling heavy trucks rollover are identified and a method of measuring, or estimating them for the vehicle under investigation is presented. The errors on the vehicle rollover threshold resulting from the imprecision in the determination of each parameter are evaluated. A preliminary design of a special readside tilt deck is included.

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Supplementary Information

DISCLAIMER

This publication is produced under the auspices of the Technical Steering Committee of the Vehicle Weights and Dimensions Study. The points of view expressed herein are exclusively those of the authors and do not necessarily reflect the opinions of the Technical Steering Committee, Canroad Transportation Research Corporation or its supporting agencies.

This report has been published for the convenience of individuals or agencies with interests in the subject area. Readers are cautioned that the use and interpretation of the data, material and findings contained herein is done at their own risk. Conclusions drawn from this research, particularly as applied to regulation, should include consideration of the broader context of Vehicle Weights and Dimension issues, some of which have been examined in other elements of the research program and are reported on in other volumes in this series.

The Technical Steering Committee will be considering the findings of these research investigations in preparing its "Final Technical Report" (Volume 1 & 2), scheduled for completion in December 1986.

PREFACE

The report which follows constitutes one volume in a series of sixteen which have been produced by contract researchers involved in the Vehicle Weights and Dimensions Study. The research procedures and findings contained herein address one or more specific technical objectives in the context of the development of a consistent knowledge base necessary to achieve the overall goal of the study; improved uniformity in interprovincial weight and dimension regulations.

The Centre de Recherche Industrielle du Quebec undertook a program of testing on the newly constructed tilt table to examine the static roll stability characteristics of a range of tractor semitrailer configurations. Canroad Transportation Research Corporation gratefully acknowledges the contributions of Transport Canada in providing the tilt table and financial support for the program. In addition, the contributions of the following companies who provided equipment and components for testing purposes are gratefully acknowledged:

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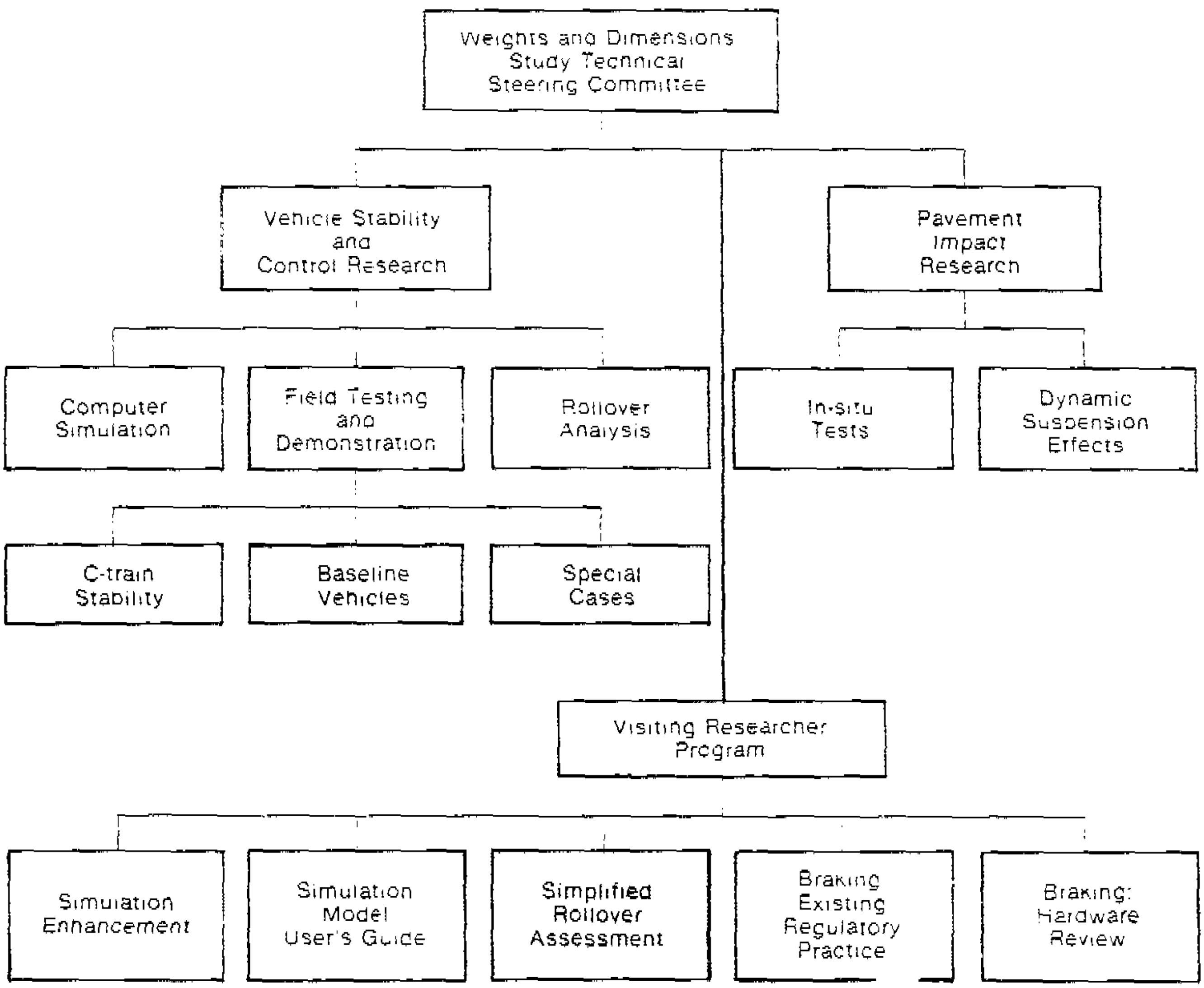
TECHNICAL WORK ELEMENTS OVERVIEW



Volume 12

VEHICLE ROLLOVER THRESHOLD EVALUATION

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July, 1986

SUMMARY

The objective of this study is to examine the feasability of evaluating the rollover threshold of heavy vehicles at road-side control stations. The Australian Road Research Board (ARRB) and the University of Michigan Transportation Research Institute (UMTRI) static rollover models are both detailed mathematical models well capable of predicting vehicle rollover threshold as long as vehicle parameters are precisely known.

The most important parameters to measure on the vehicle for which we want to estimate the rollover threshold are identified. A method of measuring, or estimating, these parameters is also presented.

The net effect of not being able to determine precisely the characteristics of the vehicle controlling its rollover is a large imprecision on the computed rollover threshold.

It is pointed out that more experimental work is needed to establish how the measurement of the height of the center of gravity can be made with a good accuracy. The quick determination of suspension characteristics is also difficult and this will need to be looked at in more detail.

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LIST OF SYMBOLS

A1:	Dual tire spacing on front axle
A2:	Dual tire spacing on tractor rear axle
A3:	Dual tire spacing on trailer axle
COULFR:	Coulomb friction in tractor frame
FWR:	5th wheel radius
H:	Load supported by the high side tires
Ho:	Load supported by the high side tires at zero tilt
HR1:	Height of tractor front axle roll center
HR2:	Height of tractor rear axle roll center
HR3:	Height of trailer axle roll center
KFR:	Tortional stiffness of tractor frame
KOVT1:	Overturning stiffness of one tire on front axle
KOVT2:	Overturning stiffness of one tire on tractor rear axle
KOVT3:	Overturning stiffness of one tire on trailer axle
KRS1:	Auxiliary roll stiffness of front suspension
KRS2:	Auxiliary roll stiffness of tractor rear suspension
KRS3:	Auxiliary roll stiffness of trailer suspension
KT11:	Vertical stiffness of one tire on front axle
KT21:	Vertical stiffness of one tire on tractor rear axle
KT31:	Vertical stiffness of one tire on trailer axle
KYT1:	Lateral stiffness of one tire on front axle
KYT2:	Lateral stiffness of one tire on tractor rear axle
KYT3:	Lateral stiffness of one tire on trailer axle
L:	Load supported by the low side tires
Lo:	Load supported by the low side tires at zero tilt
LASH5:	Angular lash of the 5th wheel
M5:	Roll stiffness of the 5th wheel assembly
R1:	Tractor front axle C.G. height
R2:	Tractor rear axle C.G. height
R3:	Trailer axle C.G. height
S1:	Half front spring lateral spacing
S2:	Half tractor rear axle lateral spring spacing

LIST OF SYMBOLS

S3:	Half trailer axle lateral spring spacing
T:	Track width of an axle
T1:	Half distance between front axle tires
T2:	Half distance between tires on tractor rear axle
T3:	Half distance between tires on trailer axle
W:	Total weight supported by an axle
WAXL1:	Tractor front axle load
WAXL1:	Tractor rear axle load
WAXL1:	Trailer axle load
WS1:	Tractor front sprung mass
WS2:	Tractor rear sprung mass
WS3:	Trailer sprung mass
WU1:	Tractor front axle unsprung mass
WU2:	Tractor rear axle unsprung mass
WU3:	Trailer axle unsprung mass
Z:	Height of the C.G. of a solid body
ZFR:	Height of the tractor frame above ground
ZS1:	Tractor front sprung mass C.G. height
ZS2:	Tractor rear sprung mass C.G. height
ZS3:	Trailer sprung mass C.G. height
Z5:	Height of 5th wheel above ground
θ:	Tilt angle

1.0 PROJECT OBJECTIVES

This project was undertaken under the Vehicle Weights and Dimensions Study - Visiting Researcher Program.

The main objective of this project can be summarized as follows:

To determine a simple procedure to quickly estimate the rollover threshold of heavy vehicles at roadside control stations. This procedure must require a minimum of parameters to be measured on the vehicle itself and it must not need the tilting of the vehicle more than a few degrees in order to eliminate the risks of damaging the vehicle or its load.

Three major steps were foreseen at the beginning of the project:

1- The development of a simple mathematical model based on the Australian Road Research Board (ARRB) and the University of Michigan Transportation Research Institute (UMTRI) rollover mathematical models.

2- The validation of the new simplified model by comparing its rollover predictions with the original models and with the result of the Weights and Dimensions Study tilt table test.

3- The preliminary design of the roadside control station special equipment needed and the establishment of a preliminary test procedure.

For reasons which will become evident later on, the study deviated slightly from the initial work plan but essentially, the practical feasibility of such equipment has been fully investigated and its inherent limitations pointed out.

2.0 THE MATHEMATICAL MODELS

2.1 The UMTRI static roll model

The static roll model developed by UMTRI is a very detailed mathematical analysis of a semi-trailer truck rolling over on a flat surface under the influence of a lateral acceleration as when going around a steady level curve at constant speed. The model has few simplifying hypotheses:

- No dynamics effects are considered.

- All the masses are rigid and connected by flexible elements. This means the masses are and stay concentrated at their original C.G.

- The ground is horizontal.

- The vehicle has only three axles; one at the front one at the rear of the tractor and one at the rear of the trailer. In case of vehicles having more axles, each axle group is replaced by an equivalent axle located at the center of the axle group and whose properties represent the whole group.

- The idealized roll centers are fixed with respect to the sprung masses.

- The reactions at ground act through the center of each tire.

- The spring forces are always perpendicular to the axles and all the horizontal forces acting actually on the springs are assumed to be transmitted through the roll center. In other words, there are no transverse forces on the springs.

- The lateral translation of the normal load is neglected.

- The chassis friction is represented by idealized coulomb friction.

- The articulation angle between tractor and trailer is negligable.

- The initial loading is centered laterally.

Figure 1 shows the modelled truck.

The model solves the equilibrium only in the roll plane for increasing values of trailer sprung mass roll angle. This implies finding the solution of some 15 simultaneous equations describing the equilibrium of the truck and trailer combination under a constant lateral acceleration.

When running this model in its actual PC version, the outputs indicate the sprung and unsprung masses roll and the net roll moment at each axle for increasing trailer roll angles. It clearly indicates the conditions at which the first wheel lifts and it keeps on increasing the roll angle until a second wheel lifts. At this point, the vehicle is considered totally unstable and the program is stopped. A list of the inputs and a sample output sheet is given in appendix B.

As expected, the execution time was found inversely proportional to the trailer roll angle increment and the precision of the results was also influenced by the size of this increment especially when it was made large. In fact we never had experimental results of a fully described vehicle to compare with but what we did to determine a practical roll angle increment was to assume that smaller increments give more precise solutions and to increase this increment until the results of first and second wheel lift changed significantly.

A study with typical input data indicated that the increment should be kept smaller than 0.1 deg. As shown in figure 2, the model predictions for first and second wheel lifts were quite constant for small roll angle increments and they started fluctuating for roll angle increments larger than 0.1 deg. This roll angle increment yielded an execution time of 5 minutes including 30 sec. for specifying inputs from an already prepared file. Tests were done using the compiled version of the program on a COMPAQ micro computer (IBM-PC compatible) equipped with two floppy disks. The removal from the program of some features like the storage of data on disk for future plotting of roll moments and the printing of intermediate results combined with the addition of a mathematical co-processor can improve the computing time by a factor of 2 or 3. This means the total execution time could be reduced to approximately 2 minutes for our application. We felt this time was very short in comparison with the whole process and no effort was made to further reduce it by simplifying the model.

A brief sensitivity analysis has also been done with this model by simply varying two sets of typical inputs by +10% and -10%. The most significant factors influencing the first wheel lift lateral acceleration were found as indicated in table 1:

TABLE 1

UMTRI roll model - the effect of varying the most significant parameters by ±10% on the rollover threshold (first wheel lift)

Parameters	Variation of lateral acceleration at first wheel lift	
	-10%	+10%
1- Trailer sprung mass C.G. height	+12.8%	-10.5%
2- Trailer sprung mass	+ 7.9%	- 3.9%
3- Trailer track width	- 6.0%	+ 4.9%
4- Trailer axle load	- 5.8%	+ 5.2%
5- Tractor rear spring spacing	- 3.9%	+ 4.3%
6- Height of tractor rear suspension roll center	- 2.7%	+ 2.5%
7- Tractor rear axle track width	- 2.3%	+ 1.8%
8- Trailer axle dual tire spacing	- 2.0%	+ 1.8%

The others factors have an effect of less than 2% for a variation of ± 10%. The typical truck data were two truck/semi-trailers having total GVW of 23 200 and 37 700 kg. Table B2 of appendix B lists the effects of more parameters for both tests.

Appendix B also gives a listing of the original UMTRI program in BASIC language.

2.2 The Australian Road Research Board Static Roll Model

The static roll model developed by ARRB is also a very detailed mathematical analysis of a semi-trailer truck rolling over on a flat surface under the influence of a lateral acceleration.

This model has simplifying hypotheses very similar to the UMTRI model; the most important are:

- The vehicle is represented by 7 interconnected masses. Here, it differs from UMTRI in the sense that it divides the trailer sprung mass in two parts, one supported by the trailer wheels and one by the fifth wheel. For our application, we believe this has no noticeable effects.

- No dynamics effects.

- All the masses are concentrated at the C.G. (solid masses).

- The ground is horizontal.

- The vehicle has only 3 axles, 1 at front, 1 at the rear of the tractor and 1 at the rear of the trailer. Each of these axles are located at the center of the axle group and their properties represent the whole group.

- The ground reactions act through the center of the tire for single tire axle and through the center of the two tires for axle with dual tires.

- The reactions are fixed with respect to ground and lateral displacement are calculated.

- The masses rotate around idealized roll centers.

- The initial loading is centered laterally.

- The articulation angle between tractor and trailer is zero.

The ARRB model solves the equilibrium only in the roll place for increasing value of lateral acceleration up to first wheel lift. The numerical method used is quite complex and as the UMTRI model, each step is the solution of a series of simultaneous equations describing the equilibrium of the truck/semi-trailer combination under a constant lateral acceleration.

Typical results include the roll angles of trailer, tractor rear and tractor front, axles, suspensions and bodies for increasing lateral accelerations. They also include the percent of load transferred at each axle, the fifth wheel moment and sprung mass positions.

This model takes care of suspension roll characteristics by defining functions which represent the whole suspension reaction to a roll moment. The vertical and lateral stiffness of tire are also represented by similar relations.

The listings we have got have not permitted us to run this program; there was always something going wrong in the mathematical solution and this at the very first iterative step.

The inputs required to run this program are listed in appendix C.

2.3 Selection of a computer program

As we have just seen, both mathematical models are a comprehensive analysis of the rollover process of a heavy vehicle. The equations of both models are based on a quite detailed representation of the vehicle and we believe that both would be more than suitable for our application. The UMTRI model has been retained for the following reasons:

- It is, as the ARRB one, a rollover analysis going into details beyond our needs.

- The execution time is relatively short with respect to the time required for the whole process.

- It is already in a PC compatible version which means it will run on many inexpensive MS-DOS micro computers.

- The source version is written in basic so it is very easy to modify to meet any particular needs in terms of inputs or outputs.

The listing of the source program is presented in appendix B.

We have not made any attempt to simplify this model because it became evident that the time which can be saved would be meaningless as compared with the total time of the whole process. The precision with which the vehicle parameters can be measured appeared to be a much more determining factor in the application of this technique at roadside control stations. If needed the program could always be easily simplified later on.

2.4 Estimation of the error on the vehicle rollover threshold

Based on the sensitivity analysis done on the UMTRI model, the effect of each significant parameter on the vehicle rollover threshold has been analyzed taking into account the precision at which each variable could be best determined at a roadside station.

Table 2 lists all these interesting vehicle parameters, their best estimated precision and the resulting errors on the rollover threshold of two typical vehicles.

The table also shows that when we combine all the errors, the total error on the calculated vehicle rollover threshold runs as high as 22%, half of this coming from the big 10% error on the height of the center of gravity which is explained in appendix A.

TABLE 2

Errors on the vehicle rollover threshold resulting from the best estimated precision on the most important vehicule parameters

Vehicle parameters	Variable name	Best estimated precision	Typical vehicle no 1, error on lat. acc. at first wheel lift (+ or −)	Typical vehicle no 2, error on lat acc. at first wheel lift (+ or −)
Trailer sprung mass C.G. height	ZS3	10%	12.35	12.86
Tractor rear axle lateral spring spacing	S2	5%	2.16	1.97
Tractor front sprung mass. C.G. Height	ZS1	10%	1.85	1.05
Height of tractor rear axle roll center	HR2	5%	1.34	0.92
Tractor rear spring table	-	5%	0.93	0.79
Trailer rear spring table	-	10%	0.62	1.31
Dual tire spacing on trailer axle	A3	4%	0.82	0.42
Lateral distance between tires on trailer axle	T3	1%	0.60	0.50
Height of trailer axle roll center	HR3	5%	0.72	0.53
Trailer sprung mass	WS3	1%	0.39	0.79
Height of tractor front axle roll center	HR1	5%	0.62	0.26
Tractor rear sprung mass C.G. height	ZS2	10%	0.62	0.26
Tractor front spring lateral spacing	S1	5%	0.62	0.26
Trailer rear spring lateral spacing	S3	5%	0.31	0.66
Tractor front spring table	-	10%	0.62	0.26
Dual tire spacing on tractor rear axle	A2	4%	0.25	0.21
Tire spacing on tractor rear axle	T2	1%	0.23	0.21
Trailer axle load	WAXL3	0.5%	0.11	0.29
Vertical stiffness of one tire on tractor rear axle	KT21	1%	0.10	0.13
Tractor front axle load	WAXL1	0.5%	0.08	0.03
Tractor rear axle load	WAXL2	0.5%	0.04	0.05
All parameters combined to give the worst case			21%	22%

3.0 DATA ACQUISITION

As seen in the preceding section, many parameters control the rollover of a heavy vehicle. Theoretically all these parameters would have to be measured precisely in order to get a precise rollover estimation. This is acceptable with a research vehicle but simply impossible at a roadside control station.

Fortunately, the sensitivity analyses of both models indicate that many parameters have a lesser importance in the rollover threshold so one can hope to bring down the data acquisition problem to some acceptable level.

Among the most important vehicle characteristics are the height of the center of gravity, the tractor and trailer track width, the spring spacings, the spring force curves, the tire stiffness, etc. The next paragraphs dicuss how these important parameters could be measured and/or estimated at a roadside control station and what could be the error.

3.1 Measurement of the height of the center of gravity

The simplest, and probably the only possible way to determine the height of the center of gravity at roadside station, is to tilt the whole vehicle for a few degrees and to observe the lateral weight transfer. The tilting must be small enough so there is little suspension and tire deformation thus allowing the vehicle to be considered as a solid body. On the other hand, tilting must be large enough to induce a measurable weight transfer or rate of weight transfer.

Appendix A presents different approches which can be used to evaluate the height of the center of gravity of a solid body from tilt deck data. The first method is based on the difference in the high side load readings at zero tilt and at a small tilt angle. The next three methods presented use the rate of load transfer and finally, the last one uses the slope of the curve of [Ho/W - H/W/cos θ] vs tan θ. Which is theoretically a straight line for a solid body.

Each tilt table test data of the Vehicle Weight and Dimensions Study (ref. 3) have been analyzed using the five methods for tilt angles from 0 to 10 degrees. The first method, based on weight measurements at two small tilt angles, gives very fluctuating estimations of the center of gravity; the four other methods, using the rate of weight transfer, or a straight line fitted through a series of points, gives center of gravity heights quite constant and very close to each other for each particular test. See appendix A for more details.

However, when we look at the heights of the center of gravity calculated for the very same trailer and load tilted four consecutive times with different but very similar tractors, we find a variation of $\pm$ 10%. This is best illustrated by figures 4 and 5 where the same trailer and load have been used for tests 8, 9, 10 & 11, a second one for tests 16, 17, 18 & 19 and a third one for tests 24, 25, 26 & 27.

This large unexpected variation is difficult to explain because when we look at each particular test in detail, everything is very normal. This aspect of CG height measurement will need more experimental investigation but for the time being, the only logical conclusion is that we can expect an error of $\pm$ 10% in the measurement of the height of the CG with a tilt deck.

3.2 Measurement of axle group loads

The axle group loads can be simply calculated by adding up the high side and low side load readings at zero tilt angle during the measurement of the height of the CG. This could be done automatically by a computer controlled data acquisition system. The precision can be ± 0,5% or even better.

3.3 Evaluation of the trailer sprung mass

The trailer sprung mass is a quite important parameter which can be calculated from axle group weight readings, estimated axle unsprung masses and tractor rear sprung mass.

For most of the tractors and trailers, the tractor rear and trailer unsprung masses can be simply estimated by the weight of a typical axle times the number of axles. For more precision, the weight of the typical tractor and trailer axles can be varied according with the size of the tires.

The weight of the tractor rear sprung mass is not very significant and it can be assumed constant for all tractors; if needed two values can be used for small and large tractors.

These approximations should give a precision close to ± 1% on the trailer sprung mass.

3.4 Measurement of track width, dual tire spacing and number of axles

A series of narrow switches can be mounted across the tilt deck just before the scale section. These switches, activated by the contact of each tire, inform the computer where each tire of each axle touches the ground. From this information, it is easy to compute the number of axles in each group, the number of tires on each axle, the distance between the inside tires and the dual tire spacings. If each switch covers 1.2 cm in width, the precision on track width will be approximately ± 1% and the one on dual tire spacing, ± 4%. Narrower switches will give more precision but this means more switches to read in a quite short time and we do not think it is needed.

3.5 Evaluation of the spring spacings

The sensitivity analysis shows little effect of the tractor front spring spacing and a typical constant value (around 88 cm) can be taken without introducing any significant error on the rollover threshold evaluation.

The tractor rear spring spacing has a much larger effect on the vehicle stability; it can be measured with a tape for more precision but because of the very small difference in tractor frame width, a constant value around 1.02 m can be taken for spring suspensions and around 85 cm for air suspensions. We estimate these constant values to be within ± 5% of actual spring spacings; a survey on many truck should confirm this.

The trailer rear spring spacing has a much smaller effect and choosing a constant typical value around 1 m should be quite a good approximation for the wide track trailer; 85 cm would be best for the 8 foot trailers. In case of air suspension, each value should be reduced to 90 and 75 cm. This should yield an error not larger than 5%. A survey on many trailers should confirm these values.

3.6 Evaluation of the suspension roll center height

The suspension roll center heights do not have any large effect on the vehicle rollover threshold and they can be estimated from the tire size. The front axle is generally a drop axle and in this case an estimate of 50% of the diameter of the tire is very adequate. For the tractor rear and trailer axles, 75% of the diameter of the tire will be a good estimate. These estimations should have an error less than 5%.

3.7 Tires properties

The sensitivity analysis has shown that only the vertical stiffness of the tractor rear tires has a noticeable effect on the rollover threshold. However, as it is very easy to identify tires, all the tires on the vehicle can be checked and their coded size given to the computer. All the properties for these tires will be read from already stored files. If it is needed to save time; only the drive axle tires can be checked, all the others being considered identical. The precision on tire properties should then be better than ± 1%

3.8 Suspension stiffness curves or tables

The front axle spring stiffness has little effect on the vehicle rollover and a straight line stiffness curve can be defined using the front axle spring capacity and a typical spring deflexion at axle rated capacity of some 10 cm.

The tractor rear spring stiffness is a much more important parameter. A series of tables will have to be stored in the computer memory and referred to with information taken from the vehicle gross axle weight rating and suspension identification. In these cases, we can expect a precision of ± 5% or better.

When this information is not available, the operator will have to figure out spring stiffness from spring dimensions (length, thickness, width, number, ...); it is going to be a long and difficult job and the precision will suffer very much.

The trailer spring stiffness is not as important but it can't be neglected. As for the tractor rear springs, it will be best to have tables stored in the computer memory to which the operator will refer to, with information taken from the trailer identification plate and suspension type. A precision of ± 5% should be possible in these cases.

A review of the stiffness curves of all the tractor and trailor suspensions in use today is indicated; this analysis will indicate if it is possible to simplify the problem by regrouping all the suspension characteristics into a limited number of typical suspensions. Also this study should point out ways to correctly identify suspensions.

3.9 Other factors

All the other factors were found to have a very little effect on the vehicle rollover threshold and it is suggested to simply give them a constant typical value. For more precision, there might be two or three groups of constant values for different category of heavy vehicles.

4.0 SPECIAL ROAD SIDE TEST EQUIPMENT

The special roadside test equipment which will be required to perform heavy vehicle rollover evaluation consists of a low angle tilting deck coupled with a data acquisition system and a micro computer capable to control the data acquisition system and to run the rollover mathematical program. A standard line printer can be used to provide results on a hard copy.

The preliminary design of this special tilting deck is presented in Figures 6, 7 and 8. It consists of three separate pivoted platforms which, when installed, form a long tilting deck with a center weighing section. Screw jack actuators, driven by a single centered motor,are used to get a perfectly synchronized smooth tilting.

The center weighing section has two long rigid pads mounted on 4 load cells to measure the high side and low side loads of each axle group. Longitudinal and transversal reaction rods take all the shearing forces so the load cells see only the load perpendicular to the top of the platform.

At the end of the first platform, close to the center scale section, there is a track width detector mounted transversely across the tilting deck. This detector is basically a series of narrow switches which are actuated when the tires contact them. The status of these switches is automatically read by the data acquisition system while the vehicle is driven to the scale section. The computer knows the position of each switch and it quickly computes track width and dual tire spacing as each axle goes over this track width detector; it also counts the number of axles in each group.

The data acquisition system and the micro computer are installed in a control room located close to the tilt deck. There is a variety of models to choose from; both will have to be dedicated to this particular job.

A permanent tilt deck installed at ground level has been retained because it does not need access ramps which makes the whole installation shorter and it is easier for the trucks to drive on. During winter, snow clearing is also much easier. However, if for other reasons an installation over the ground is preferred, it is possible to mount similar tilting platforms on a subframe which will simply be put on the ground. The design of either type does not present any particular problem.

5.0 TEST PROCEDURES

We will now examine what a typical vehicle rollover estimation will imply.

First, the vehicle will have to be identified by the operator and this information given to the computer; this might be the registration plate numbers, the permit number or any convenient identification. This identification will start the whole process.

The vehicle will then be driven on the tilt deck and stopped with its front axle on the scale section; the front axle width will have been measured when going over the track width detector and the operator will command the weighing of the front axle with the vehicle completely stopped on the scale section.

The next step will be to bring the tractor rear axle group on the scale section. As for the front axles, the track widths, dual tire spacings and number of axles will be measured when going over the track width detector. This time, the operator will start the tilting of the vehicle; automatically, the data acquisition system will measure high side and low side loads while the deck is tilting. The first measurements will give the axle load and the analysis of all the data will yield the height of the CG as seen by this axle group. The preferred method for calculating the height of the center of gravity is to mathematically fit a straight line through the curve of:

$$\left[\frac{Ho}{W} - \frac{H}{W \cos\theta}\right] \text{ vs } \tan\theta$$

and to determine the height of the CG by:

Z = slope x track width

These calculations will take place during the lowering of the vehicle.

The vehicle will then go forward again until the trailer axles are on the scale section. The same process will be repeated to get trailer axle data and height of the CG as seen by the rear axle.

Finally the operator will have to get some additionnal information from the vehicle and to input them to the computer. He will need:

- tire identification,
- tractor rear and trailer spring spacings,
- front axle suspension capacity,
- tractor rear axle suspension identification or its spring stiffness curve,
- trailer axle suspension identification or its spring stiffness curve.

The tractor rear and trailer suspension characteristics will always be more or less reliable because it will be almost impossible to make sure the springs on the vehicle have been correctly identified.

After all this information are entered into the computer, the program will generate all the other inputs it needs and it will run for about 2 minutes; the vehicle first wheel lift lateral acceleration will be printed along with all the other useful data. There could be an indication if the vehicle meets or does not meet the predetermined minimum safe rollover threshold.

6.0 CONCLUSION AND RECOMMENDATIONS

The rollover mathematical models developed by UMTRI and ARRB are both detailed analysis of the rollover of heavy vehicles submitted to lateral acceleration as when the vehicle is going around a level curve at constant speed. The UMTRI model already exists in a version suitable for IBM-PC and compatible micro computers and it has been retained for our application.

A sensitivity analysis has indicated the dominant factors controlling the rollover threshold; the height of the center of gravity of the trailer sprung mass comes first with as much as 12.8% variation in lateral acceleration at first wheel lift for 10% variation in the height of CG. The tractor rear spring spacing and track width have about half this effect but they are easy to measure accurately. The tractor rear and trailer spring characteristics also play an important role and it appears they might be the most difficult factors to get accurately especially with vehicles no longer equipped with their original springs or with defective or worn out springs.

Theoretically, it should be possible to accurately measure the height of the center of gravity of a vehicle with a tilt deck capable of inclining the vehicle up to 5 or 7.5 degrees. However, the analysis of the Vehicle Weights and Dimensions Study tilt test data (ref. 3) from 0 to 10 deg. has given estimation of the height of the CG varying by as much ± 10% for the very same trailer coupled to almost identical trucks. This large variation stays unexplained and more testing is indicated to clarify this point.

The estimated precision in the roadside determination of the vehicle rollover threshold appears to be not much better than ± 22%, more than half of this coming from the imprecision in the determination of the height of the center of gravity. This is a big error and as long as this can't be improved by at least a factor of 2, there would not be much interest in this application.

The special equipment needed for roadside vehicle threshold evaluation appears to be quite simple to build, install and operate. There would not be any danger to damage the vehicle or its load because the maximum tilting would represent small efforts as compared to what the vehicle is submitted to when it goes around curves on the roads.

Is is recommended to conduct more tests with the tilt table to find out why the height of the center of gravity could not be measured with more precision.

The problem of how the truck and trailer suspension characteristic curves can be quickly determined should also be looked at by reviewing all the suspensions in use today. An ideal solution would be to oblige the truck and trailer manufacturers to supply all the pertinent information on the vehicle identification plates or even on a magnetic card.

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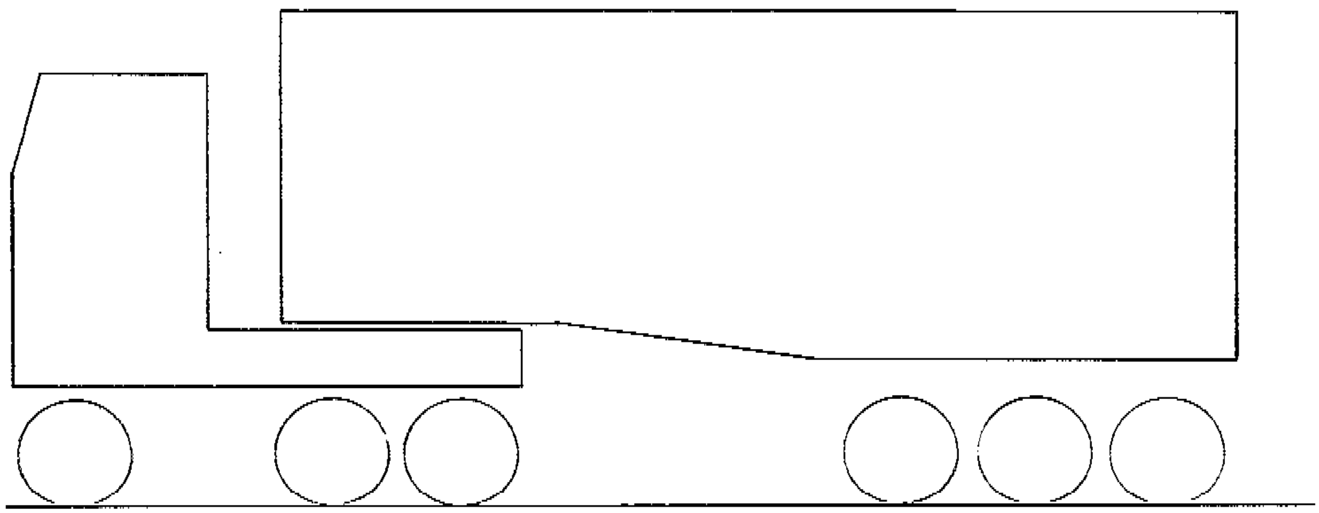
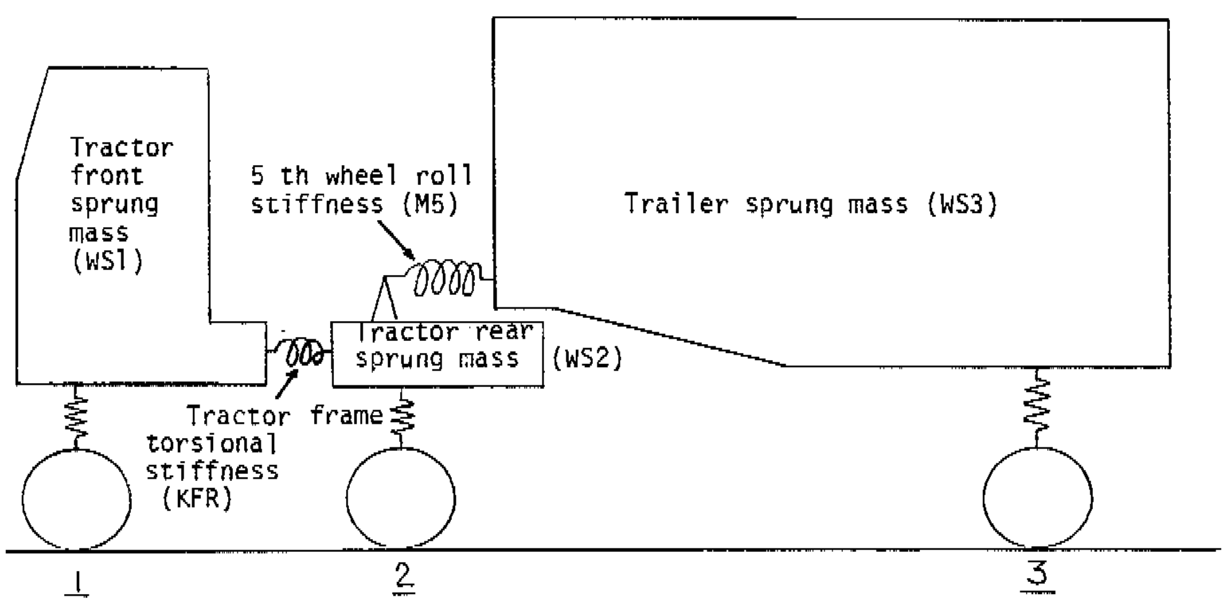
2. L. Mai and P. Sweatman, Articulated vehicle stability - Phase II Tilt tests and Computer model, Australian Road Research Board, Internal report AIR 323-2, 1984

3. G. Delisle, Investigating Articulated Vehicle Roll Stability Using a tilt table, Centre de recherche industrielle du Québec, Report no. 645-19168, june 1986



a) Actual



b) Representation in model

Figure 1: The University of Michigan Transportation Research Institute static roll model.

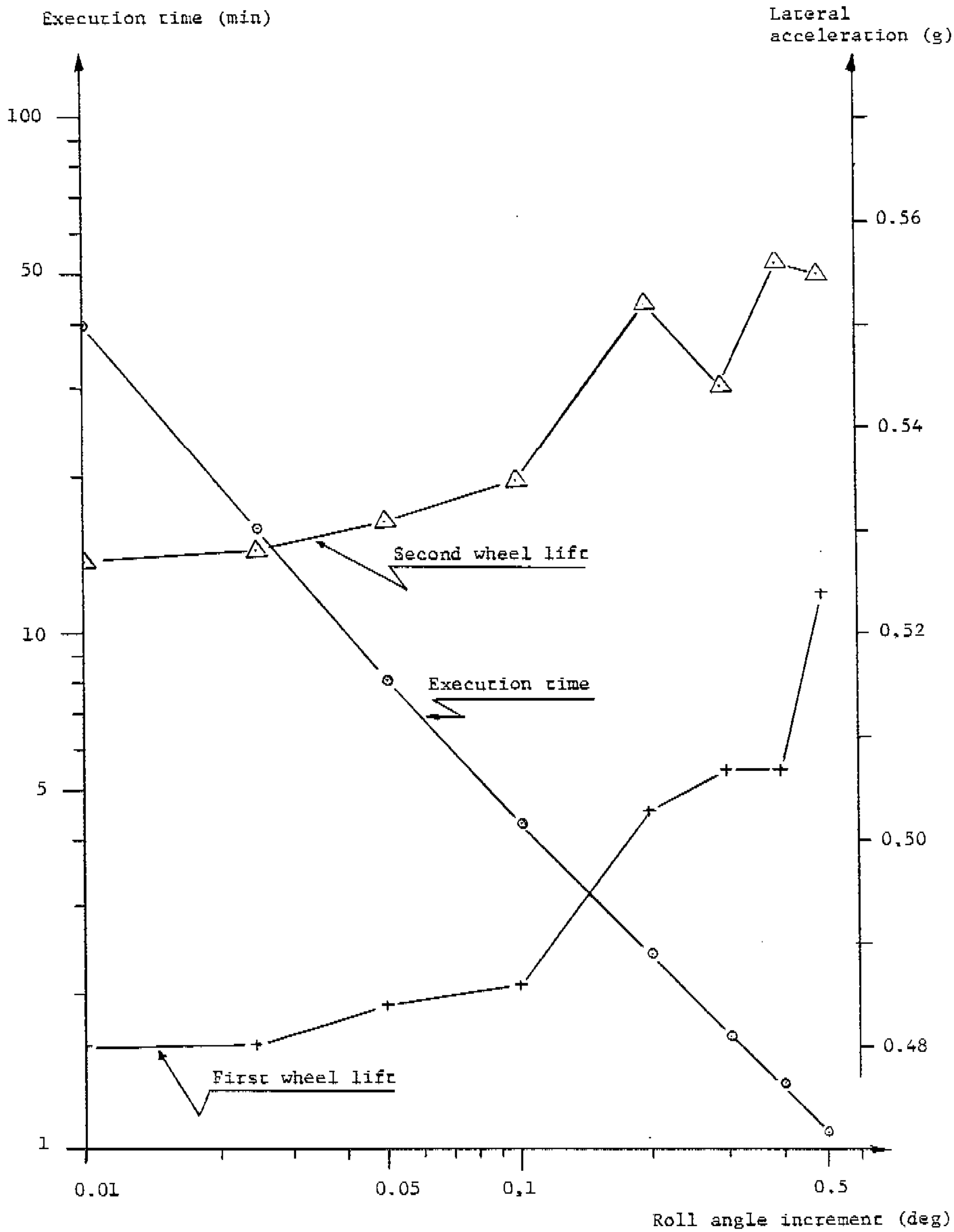
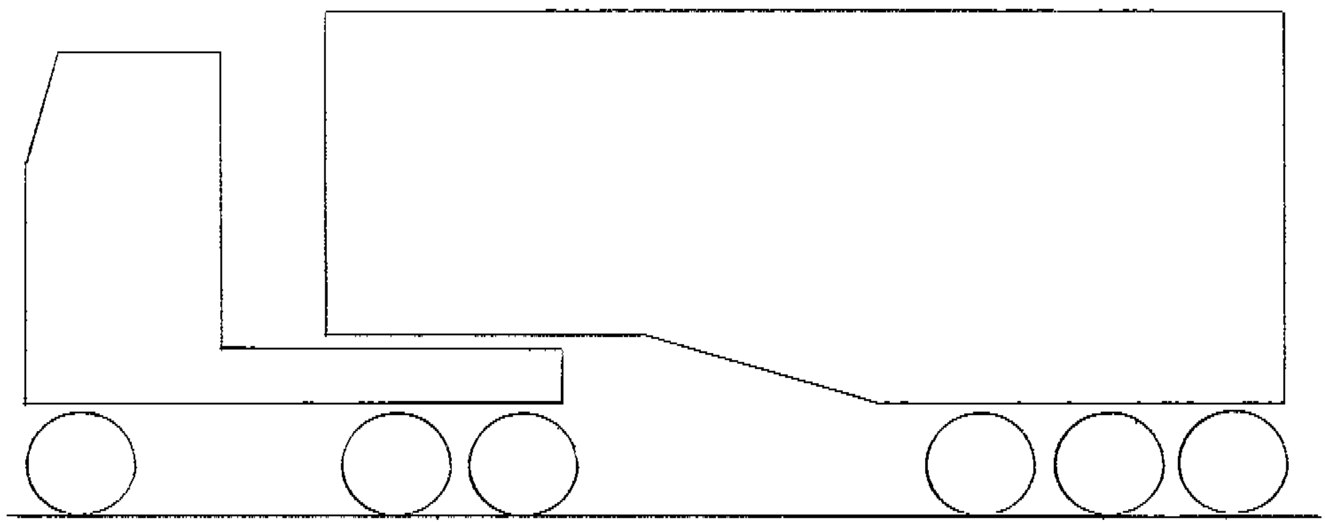
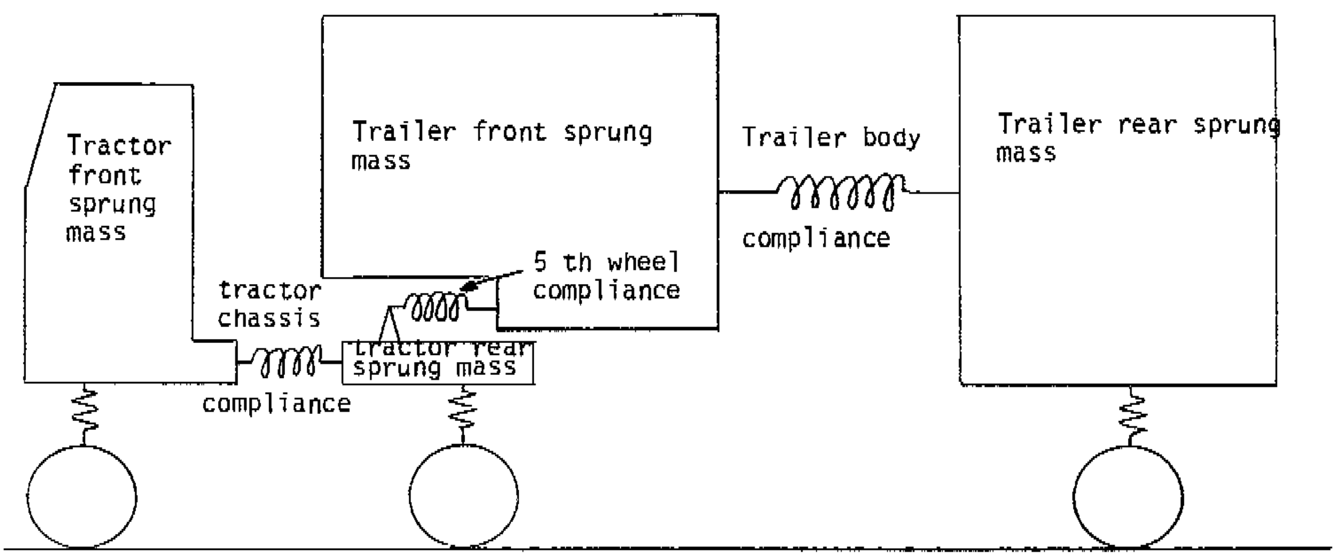


FIGURE 2: Typical effects of trailer roll angle increment on execution time and first and second wheel lift predictions.



a) Actual



b) Représentation in model

Figure 3: The Australian Road Research Board static roll model

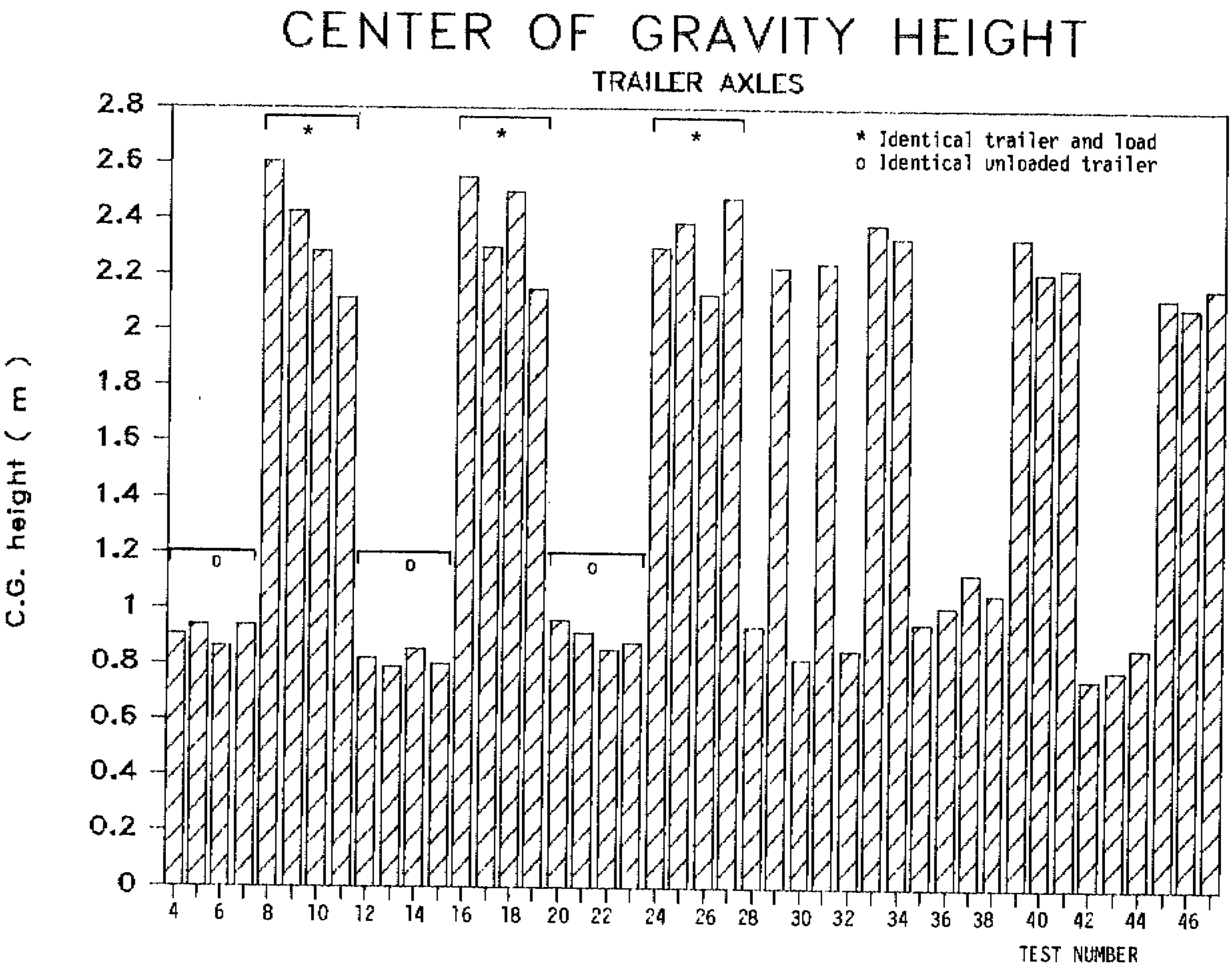


Figure 4: Center of gravity heights calculated from tilt table test data of ref 3 as seen by trailer axles.

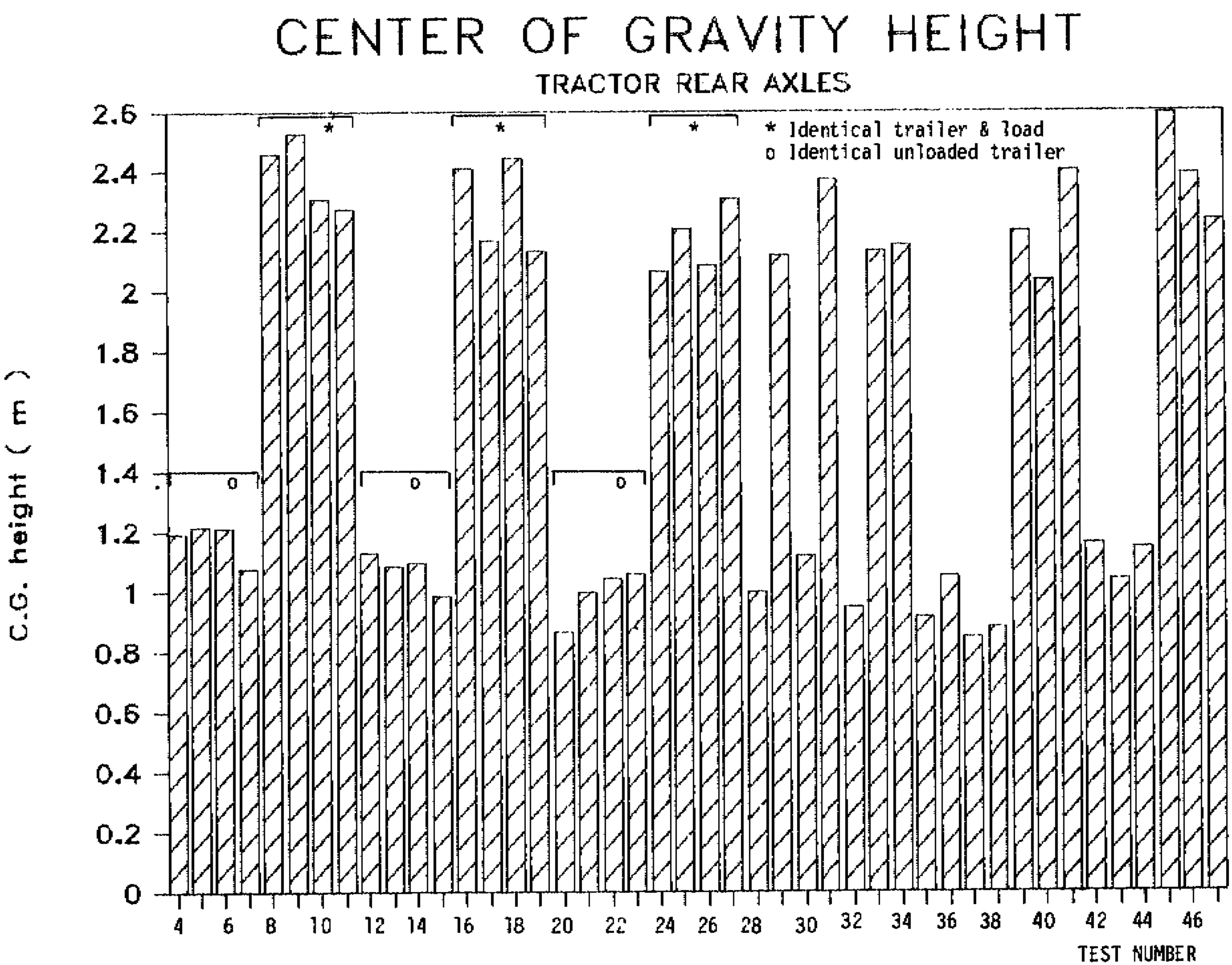


Figure 5: Center of gravity heights calculated from tilt table tests data of ref. 3 as seen by tractor rear axles.

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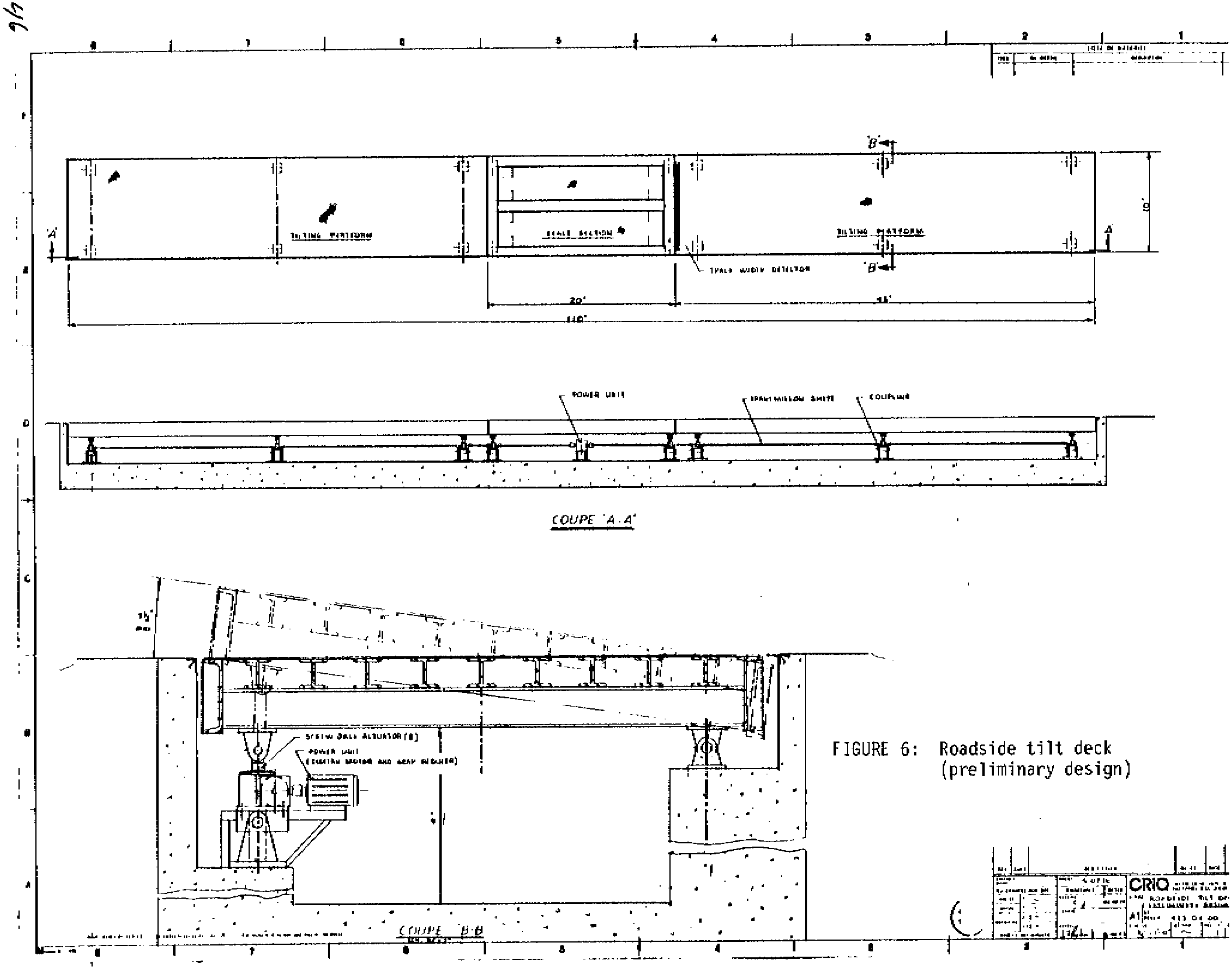


FIGURE 6: Roadside tilt deck (preliminary design)

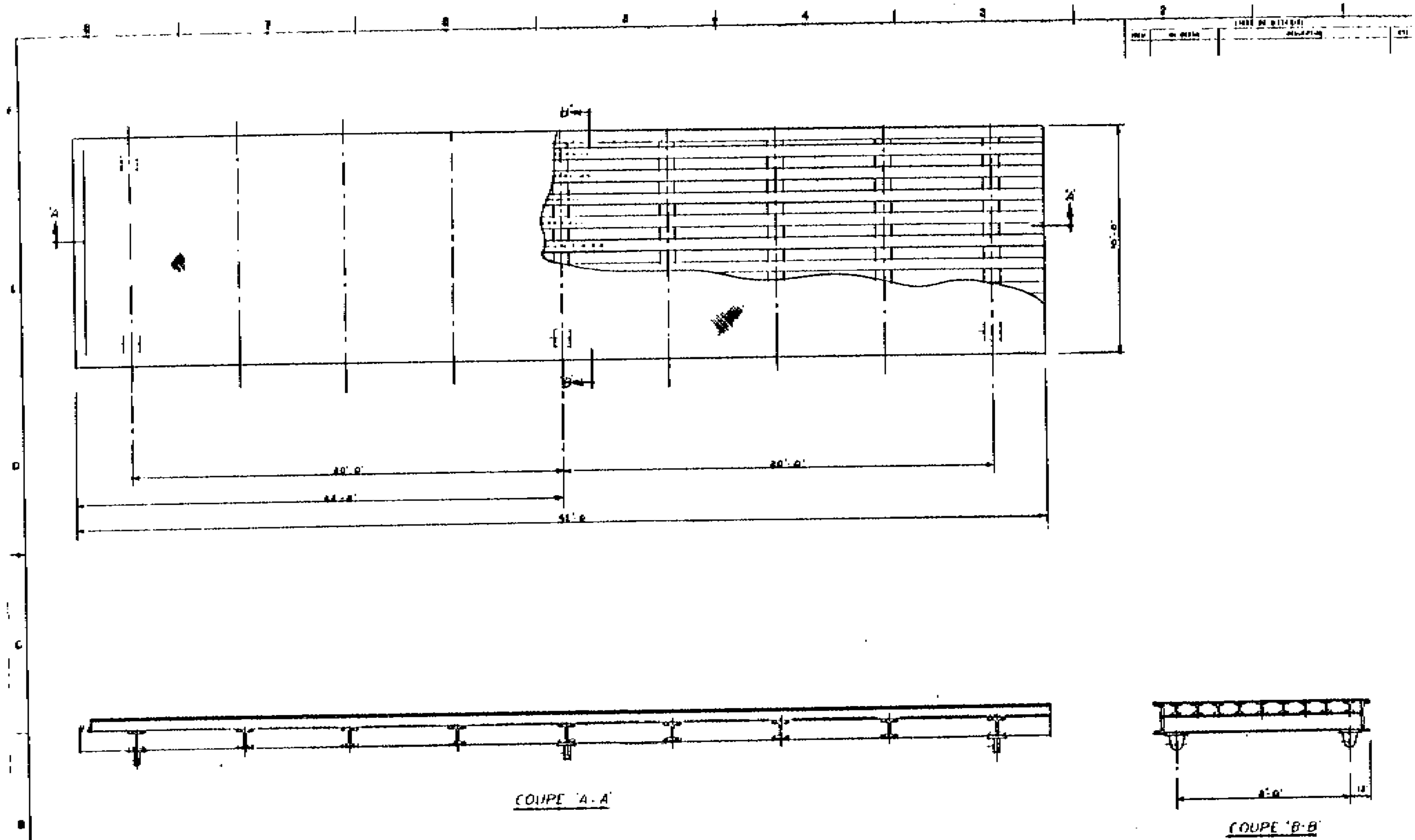


FIGURE 7: Tilting platform ass'y
(preliminary design)

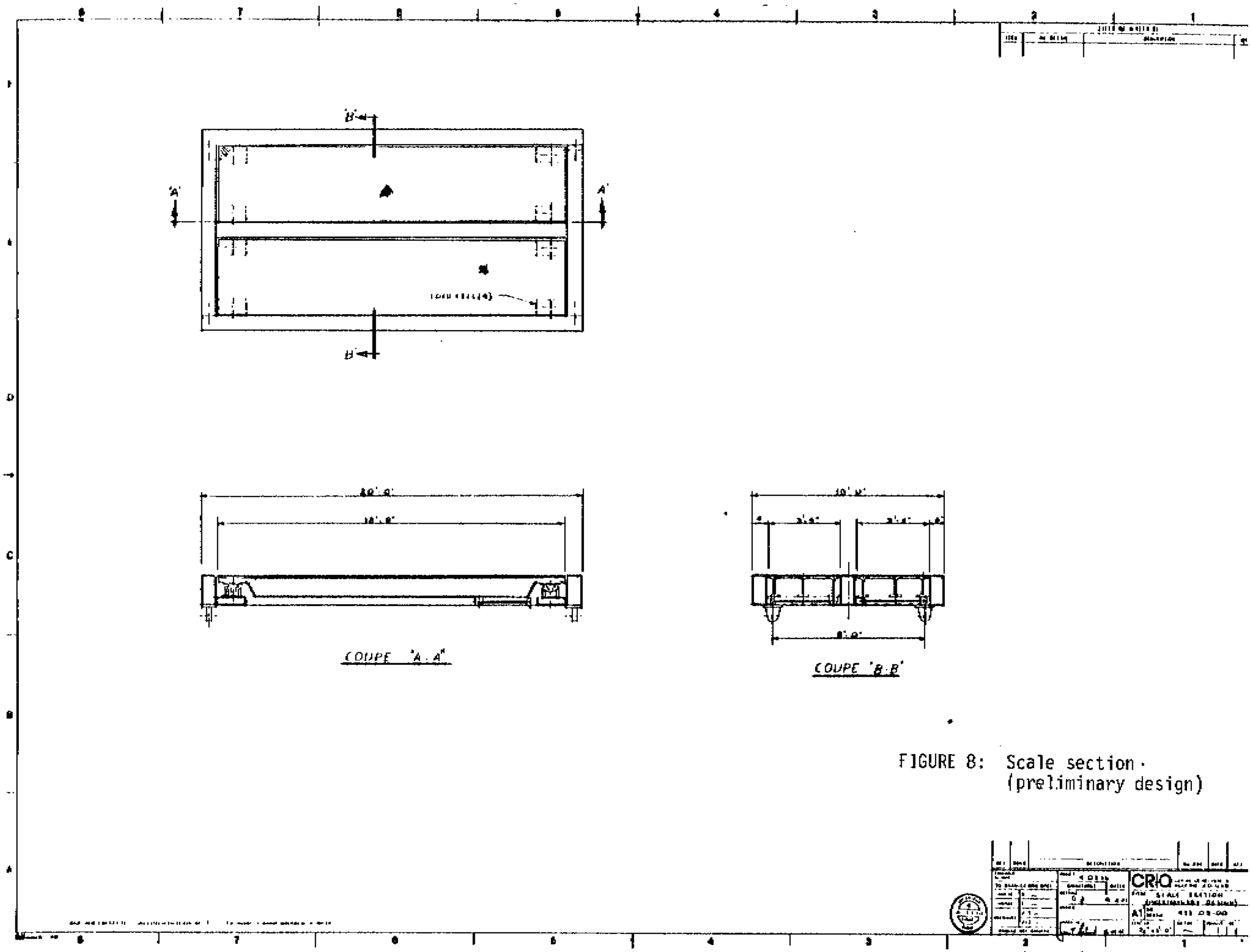


FIGURE 8: Scale section (preliminary design)

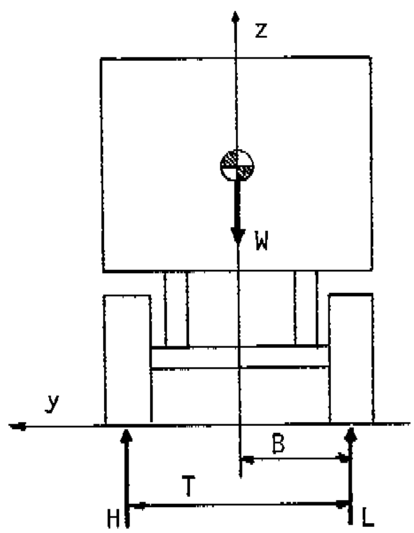
APPENDIX A

Evaluation of the height of the center of gravity

EVALUATION OF THE HEIGHT OF THE CENTER OF GRAVITY

1- THEORY

Let consider an axle on a level ground supporting a total load W; the resultant tire to ground contact forces H and L are separated by a distance T, the effective thrack width. With no other forces acting on this body, the following equations can be written:



vertical forces.

$$Ho + Lo = W \qquad (1)$$

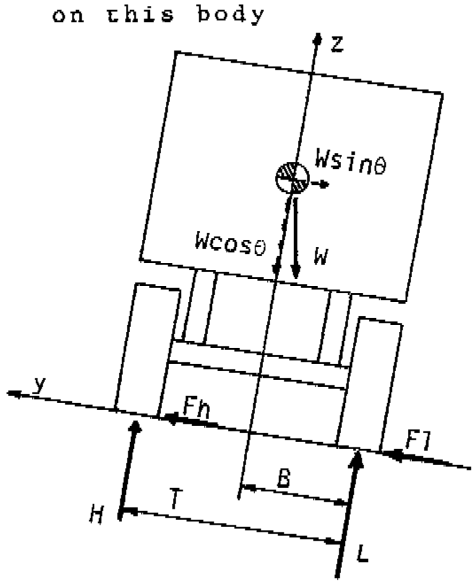
moment about Lo.

$$W \times B - H \times T = \emptyset \qquad (2)$$

Equation 2 gives the lateral position of the CG with respect to the low side ground reaction L.

$$B = \frac{Ho \times Y}{W} \qquad (3)$$

When this body is inclined by an angle θ, the followings relations hold true if there in no other outside force, except the gravity and the ground reaction forces, acting on this body



y direction forces.

$$Fh + Fl = W \sin\theta \qquad (4)$$

z direction forces.

$$H + L = W \cos\theta \qquad (5)$$

Moments about L

$$WxB \cos\theta - WxZ \sin\theta - HxT = \emptyset \qquad (6)$$

If the body is considered rigid and if the ground reactions do not shift position, the distance B from the low side vertical ground reaction L and the position of the CG does not change. The height of the CG can then be derived by introducing the value of B from eq. 3 into eq. 6.

$$Z = \frac{T}{W.\sin\theta}\left[Ho.\cos\theta - H\right] \qquad (7)$$

where Ho represents the high side load at $\theta = \emptyset$

In a non-dimensional form this reads:

$$Z/T = (1/\sin\theta)\ [(Ho/W).\cos\theta - (H/W)] \qquad (8)$$

Equations 7 and 8 are very simple expressions which calculate the height of the center of gravity of a vehicle considered as a rigid body from measurements of the axle load (W), the track width (T), the initial high side load (Ho) and the high side load (H) at an angle .

However, when applying it to a real vehicle, the assumption of a rigid body is true only for small tilt angles where suspension and tire deformations can be neglected. At these small angles, the expression in brackets and $\sin\theta$ both tend towards zero and the calculated height of the center of gravity can be very erroneous even if all variables are measured accurately.

In order to solve this difficulty, an expression based on the rate of weight transfer can be derived.

Substituting eq. 3 into 6, yields:

$$Ho.T.\cos\theta - W.Z.\sin\theta - H.T = \emptyset \qquad (9)$$

Differentiating this expression with respect to θ, keeping in mind that, for a rigid body, Ho, T and Z are constant, we get this relation:

$$Z = -\frac{T}{W}\left[Ho.\tan\theta + \frac{1}{\cos\theta}.\frac{dH}{d\theta}\right] \qquad (10)$$

In a non-dimensional form, this reads:

$$Z/T = \frac{Ho}{W} \cdot \tan\theta - \frac{1}{\cos\theta} \cdot \frac{\delta(H/W)}{\delta\theta} \tag{11}$$

These expressions are still only valid for small tilt angles because of our hypothesis of rigid body, but the rate of weight transfer is more accuratly determined during a tilt test because it averages through many readings at low angles.

For $\theta = \emptyset$, this expression simplifies to:

$$Z = -\frac{T}{W} \cdot \left.\frac{\delta H}{\delta\theta}\right|_{\theta = 0} \tag{12}$$

or:

$$Z/T = -\left.\frac{\delta(H/W)}{\delta\theta}\right|_{\theta = 0} \tag{13}$$

The previous equations calculate the center of gravity height from measurements of the high side force H or its variation with respect to the tilt angle. In order to possibly get more consistent results from experimental data, an expression using both high side and low side ground reactions can be derived.

Looking at the preceding diagram showing the body inclined at an angle θ, the moment equation about the origin is:

$$L \cdot B - H\,(T - B) - W.Z \cdot \sin\theta = 0 \tag{14}$$

Differenciating this expression with respect to θ and re-arranging gives:

$$Z = \frac{T}{W.\cos\theta}\left[\frac{Ho}{W} \cdot \frac{\delta L}{\delta\theta} - \left(1 - \frac{Ho}{W}\right)\frac{\delta H}{\delta\theta}\right] \tag{15}$$

or, in a non-dimensional form:

$$\frac{Z}{T} = \frac{1}{\cos\theta}\left[\frac{Ho}{W} \times \frac{\delta\,(L/W)}{\delta\theta} - \left(1 - \frac{Ho}{W}\right)\frac{\delta\,(H/W)}{\delta\theta}\right] \tag{16}$$

Finally, another method of calculating the height of the center of gravity from experimental tilt table data can be derived starting from eq. 8.

$$\frac{Z}{T} = \frac{1}{\sin\theta}\left[\frac{Ho}{W} \cdot \cos\theta - \frac{H}{W}\right] \tag{8}$$

This last equation can be re-written as:

$$\left[\frac{Ho}{W} - \frac{H}{W\cos\theta}\right] = (Z/T) \cdot \tan\theta \tag{17}$$

This expression shows that the graph of $[Ho/W - H/W\cos\theta]$ vs $\tan\theta$ is a straight line passing through the origin with a slope Z/T. This is another way to calculate the center of gravity height which has the advantage to average for many measurements taken at low tilt angles and to check if the assumption of a rigid body holds true.

2- ANALYSIS OF THE TILT TABLE TEST DATA

The tilt table test data of ref. 3 have been used to determine how precisely the tilting of a vehicle by few degrees can be used to determine the height of its center of gravity. The various equations developped previously have been programmed and all the test data have been analysed for tilt angles up to 10 degrees.

The equations used were:

Method i

$$Z/T = (1/\sin\theta)\,[(Ho/W) \cdot \cos\theta - (H/W)]$$

Method ii

$$Z/T = -(Ho/W)\tan\theta - (1/\cos\theta) \cdot \frac{\delta(H/W)}{\delta\theta}$$

Method iii

$$Z/T = -\delta(H/W)/\delta\theta\,\Big|_{\theta = 0}$$

Method v

$$Z/T = \frac{1}{\cos\theta}\left[\frac{Ho}{W} \cdot \frac{\delta(L/W)}{\delta\theta} - \left(1 - \frac{Ho}{W}\right)\frac{\delta(H/W)}{\delta\theta}\right]$$

Method vi

Z/T = slope of the straight line fitted through the graph of $[(Ho/W) - (H/W) \cdot 1/\cos\theta]$ vs $\tan\theta$

The trailer and tractor rear axle groups have been analyzed individually.

First, the measured loads have been corrected to take into account the tilting of the supported weight of the weighing pads. Graphs of high side and low side perpendicular loads vs tilt angle were made for trailer and tractor rear for each test in order to check that the variation of these loads were, as expected, on a straight line for small tilt angle. These graphs all showed a very normal variation of the loads as a function of the tilt angle except at the very beginning of the test where there is very often a small delay in load variation. This can be the result of hysteresis or imprecision in the tilt sensors. Figures A1, A2, A3 and A4 show typical high side and low side curves for tests TT09 and TT11 of ref. 3.

A graph of $[(Ho/W) - (H/W \cdot \cos\theta)]$ vs $\tan\theta$ has also be made for each test. Figures A5 and A6 present these curves for the same tests TT09 and TT11. As expected the data points were all quite well on a straight line and still there was, in most cases, a small shifting of the tilt angle as observed with the load curves. All the curves were fitted with a straight line using the least square curve fitting technique for tilt angles from 0,5 to 10 degres. The non-dimensional center of gravity heights were computed using the various method and presented on graphs in order to appreciate the difference between each analysis. Figures A7, A8, A9 and A10 show the varioux Z/L computed for tests TT09 and TT11 of ref. 3.

The first conclusion to be drawn from this study on the adequacy of a tilting deck to evaluate the height of the center of gravity of a vehicle is that the method 1 is not a good approach. As explained before, the calculated height is the result of the division of two very small quantities and a small error in the reading of loads can produce a quite large error in the estimation of the center of gravity.

The second observation is that for most of the tests, the four others methods, based on all the data points between a tilt angle of 0.5 and 10 degres, give quite close answers for each particular test. For most tests, these various ways of estimating Z/T are within a range of ± 2%.

To complete this analysis, the Z/T calculated with method vi were retained as one of the good methods and the heights of the center of gravity were calculated taking into account the various track widths. These were calculated as the distance between centers of dual tires and between centers of super singles. Table A1 shows the calculated center of gravity heights for most of the tests of ref. 3; Figures 4 an 5 illustrate these results.

In order to estimate the accuracy of a tilt deck to evaluate the height of the center of gravity as seen by the different axle groups, Table A2 and has been prepared. During tilt table tests of ref. 3, the very same trailer unloaded and loaded was used with four different tractors. Each trailer was left on the table with the very same load and only the tractors were changed; the tractors were all of the same model fitted with different rear suspensions. If we except the slight difference in fifth wheel height, the height of the center of gravity should have been identical for the same trailer and load used in each group of tests.

Table A2 shows a range of variation in the height of CG from 8,1 to 11,6% of the average value for the unloaded trailers and a range of 15.0 to 20.7% for the loaded trailers. For the tractor rear, the corresponding ranges are 11.8% to 19.5% for the unloaded tests and 10.7 to 13.5% for the loaded tests.

The analysis of the tilt test data of ref. 3 shows that the determination of the height of the CG with a tilt deck would yield answers with a little more than 20% variation ($\pm$ 10%). This is a much higher imprecision than one could expect and a closer look at what is happenning is indicated.

TABLE A1

Center of gravity heights calculated from tilt test data of ref. 3

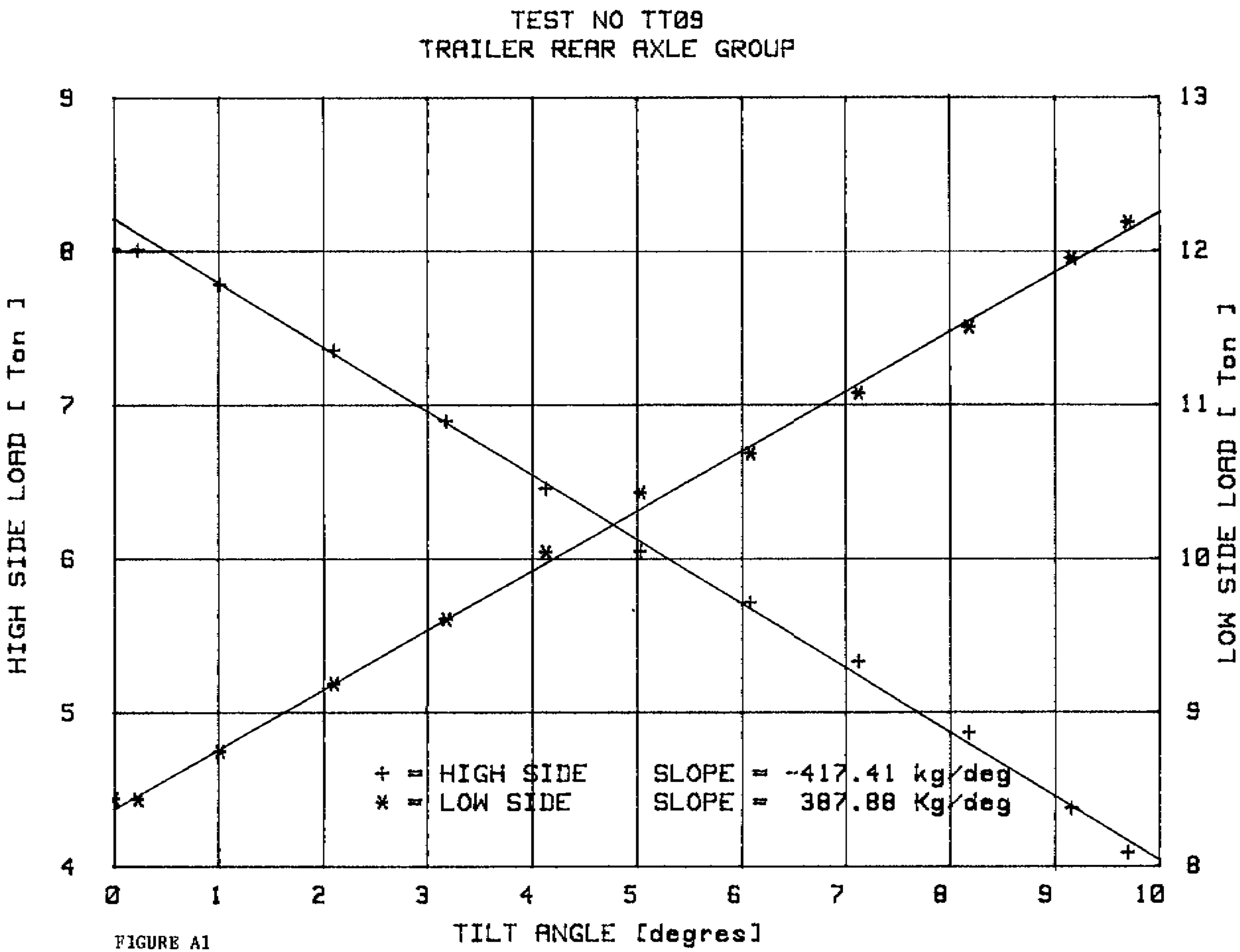
Ref. 3 test number	Tractor axle width (m)	Trailer axle width (m)	Tractor tires identif.	Trailer tires identif.	Tractor tires width (po)	Trailer tires width (po)	Tractor track width (m)	Trailer track width (m)	Calculated 7/1 Trailer	Calculated 7/1 Tractor	C.G. Height Trailer (m)	C.G. Height Tractor (m)
11 04	2.40	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.750	1.700	0.52	0.70	0.987	1.191
11 05	2.40	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.750	1.700	0.54	0.71	0.941	1.217
11 06	2.36	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.710	1.700	0.58	0.71	0.864	1.212
11 07	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.720	1.700	0.54	0.63	0.940	1.078
11 08	2.40	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.750	1.700	1.40	1.44	2.607	2.460
11 09	2.36	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.710	1.700	1.41	1.40	2.473	2.520
11 10	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.720	1.700	1.37	1.35	2.281	2.306
11 11	2.36	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.710	1.700	1.23	1.33	2.114	2.272
11 12	2.36	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.716	1.700	0.48	0.66	0.873	1.131
11 13	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.720	1.709	0.46	0.63	0.789	1.003
11 14	2.40	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.750	1.710	0.49	0.64	0.855	1.096
11 15	2.36	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.710	1.700	0.47	0.58	0.801	0.985
11 16	2.41	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.750	1.700	1.45	1.41	2.558	2.409
11 17	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.770	1.700	1.33	1.27	2.299	2.170
11 18	2.41	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.750	1.700	1.42	1.43	2.497	2.443
11 19	2.36	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.710	1.700	1.25	1.25	2.140	2.135
11 20	2.36	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.710	1.700	0.56	0.51	0.960	0.866
11 21	2.36	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.710	1.706	0.53	0.58	0.915	0.998
11 22	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.720	1.706	0.49	0.61	0.855	1.043
11 23	2.40	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.750	1.700	0.50	0.67	0.878	1.059
11 24	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.770	1.700	1.33	1.21	2.299	2.067
11 25	2.36	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.710	1.700	1.39	1.29	2.389	2.204
11 26	2.36	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.710	1.706	1.24	1.22	2.131	2.094
11 27	2.41	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.750	1.700	1.41	1.35	2.479	2.306
11 28	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.770	1.700	0.54	0.58	0.941	0.998
11 29	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.770	1.700	1.29	1.24	2.230	2.118
11 30	2.37	2.51	11 R 22.5	11 R 22.5	11.00	11.00	1.770	1.650	0.47	0.60	0.821	1.119
11 31	2.37	2.51	11 R 22.5	11 R 22.5	11.00	11.00	1.770	1.860	1.30	1.27	2.247	2.373
11 32	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.770	1.700	0.49	0.55	0.855	0.947
11 33	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.770	1.700	1.30	1.25	2.385	2.135
11 34	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.770	1.700	1.35	1.76	2.333	2.153
11 35	2.37	2.35	11 R 22.5	11 R 22.5	11.00	11.00	1.776	1.700	0.55	0.53	0.954	0.917
11 36	2.37	2.35	11 R 22.5	SS 16.5 R	11.00	16.50	1.726	1.911	0.59	0.54	1.017	1.050
11 37	2.37	2.34	11 R 22.5	1000-20	11.00	11.94	1.770	1.615	0.65	0.50	1.132	0.846
11 38	2.37	2.34	11 R 22.5	275/80R22.5	11.00	10.70	1.726	1.750	0.61	0.50	1.059	0.880
11 39	2.37	2.34	11 R 22.5	275/80R22.5	11.00	10.70	1.720	1.750	1.35	1.25	2.333	2.198
11 40	2.37	2.34	11 R 22.5	1000-20	11.00	11.91	1.770	1.615	1.20	1.20	2.212	2.034
11 41	2.37	2.34	11 R 22.5	SS 16.5 R	11.00	16.50	1.720	1.971	1.29	1.25	2.230	2.401
11 42	2.37	2.51	11 R 22.5	275/80R22.5	11.00	10.70	1.720	1.970	0.43	0.60	0.751	1.161
11 43	2.37	2.51	11 R 22.5	1000-20	11.00	11.94	1.770	1.815	0.46	0.56	0.787	1.048
11 44	2.37	2.51	11 R 22.5	SS 16.5 R	11.00	16.50	1.770	2.051	0.50	0.55	0.866	1.145
11 45	2.37	2.51	11 R 22.5	SS 16.5 R	11.00	16.50	1.770	2.091	1.23	1.24	2.176	2.593
11 46	2.37	2.51	11 R 22.5	275/80R22.5	11.00	10.70	1.770	1.970	1.21	1.24	2.091	2.391
11 47	2.37	2.51	11 R 22.5	1000-20	11.00	11.94	1.770	1.815	1.25	1.20	2.160	2.238

TABLE A2

Summary of Center of gravity heights calculated from tilt tests data of ref. 3

TEST NO	TRAILER SUSPENSION	CENTER OF GRAVITY HEIGHT (m)	(m)	(m)	(m)	Average (m)	Variation (m)	Varia./ Avg (%)
a) CG as seen from trailer rear axles								
TT04-TT07	Chalmers M 7000	0.907	0.941	0.864	0.940	0.913	0.077	8.4
TT12-TT15	4 springs	0.855	0.801	0.823	0.789	0.817	0.066	8.1
TT20-TT23	Air suspension	0.878	0.960	0.915	0.855	0.902	0.105	11.6
TT08-TT11	Chalmers M 7000	2.602	2.423	2.114	2.281	2.355	0.488	20.7
TT16-TT19	4 springs	2.497	2.550	2.148	2.299	2.373	0.402	16.9
TT24-TT27	Air suspension	2.479	2.389	2.131	2.299	2.324	0.348	15.0
b) CG as seen from tractor rear axles								
TT04-TT07	Chalmers M 7000	1.194	1.217	1.212	1.078	1.175	0.139	11.8
TT12-TT15	4 springs	1.096	0.985	1.131	1.083	1.074	0.146	13.6
TT20-TT23	Air suspension	1.059	0.866	0.998	1.043	0.991	0.193	19.5
TT08-TT11	Chalmers M 7000	2.460	2.528	2.272	2.306	2.391	0.256	10.7
TT16-TT19	4 springs	2.443	2.409	2.135	2.170	2.289	0.308	13.5
TT24-TT27	Air suspension	2.306	2.204	2.084	2.067	2.165	0.239	11.0

Tractor rear suspension (INTER AIR) (NEWAY AIR) (HENDRICKSON) (INTER 4-SPRING)


TEST NO TT09
TRAILER REAR AXLE GROUP
HIGH SIDE LOAD [Ton]
LOW SIDE LOAD [Ton]
TILT ANGLE [degres]
+ = HIGH SIDE
* = LOW SIDE
SLOPE = -417.41 kg/deg
SLOPE = 387.88 Kg/deg
9
8
7
6
5
4
13
12
11
10
9
8
0
1
2
3
4
5
6
7
8
9
10
FIGURE A1

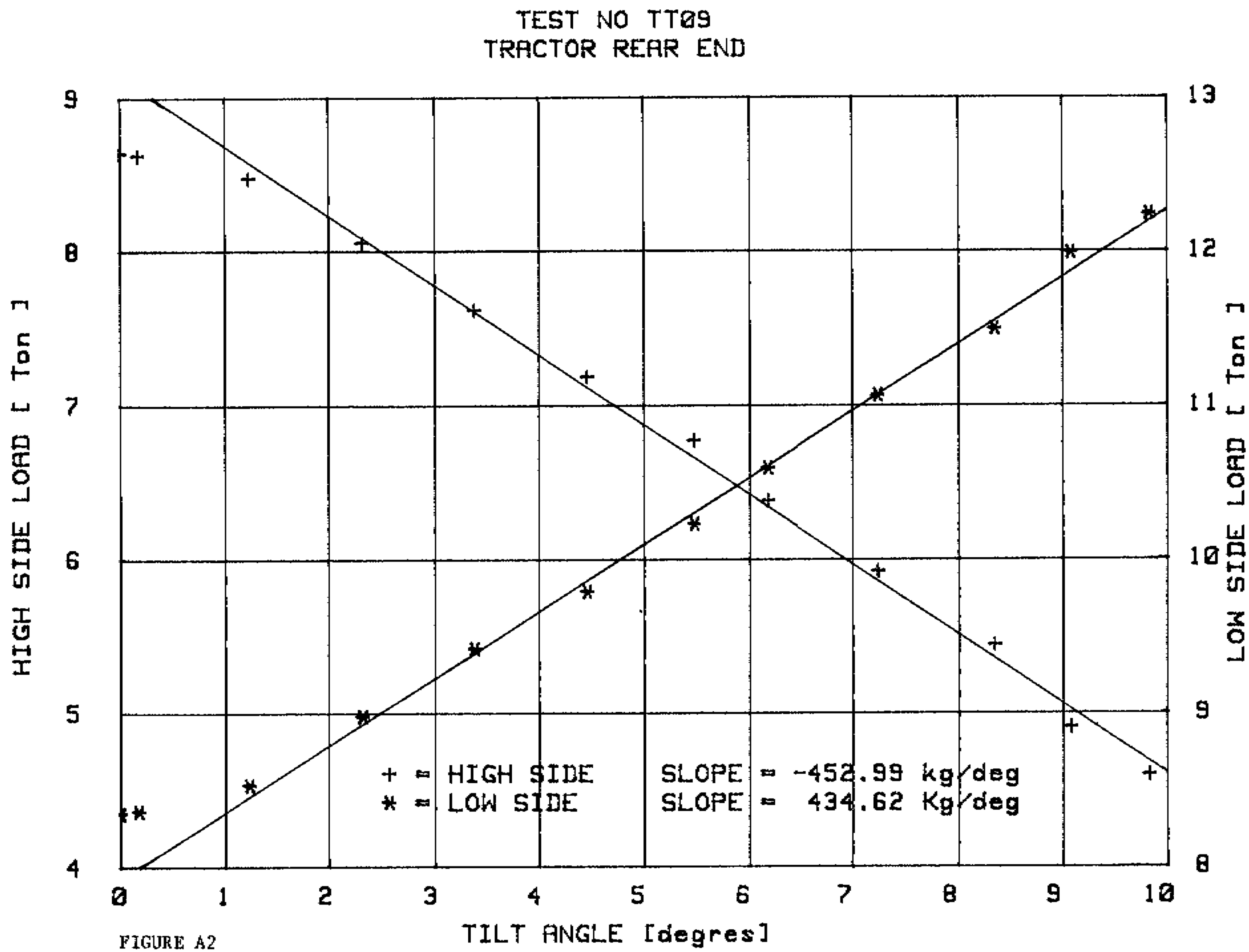

TEST NO TT09
TRACTOR REAR END
HIGH SIDE LOAD [Ton]
LOW SIDE LOAD [Ton]
TILT ANGLE [degres]
+ = HIGH SIDE
* = LOW SIDE
SLOPE = -452.99 kg/deg
SLOPE = 434.62 Kg/deg
9
8
7
6
5
4
13
12
11
10
9
8
0
1
2
3
4
5
6
7
8
9
10

FIGURE A2

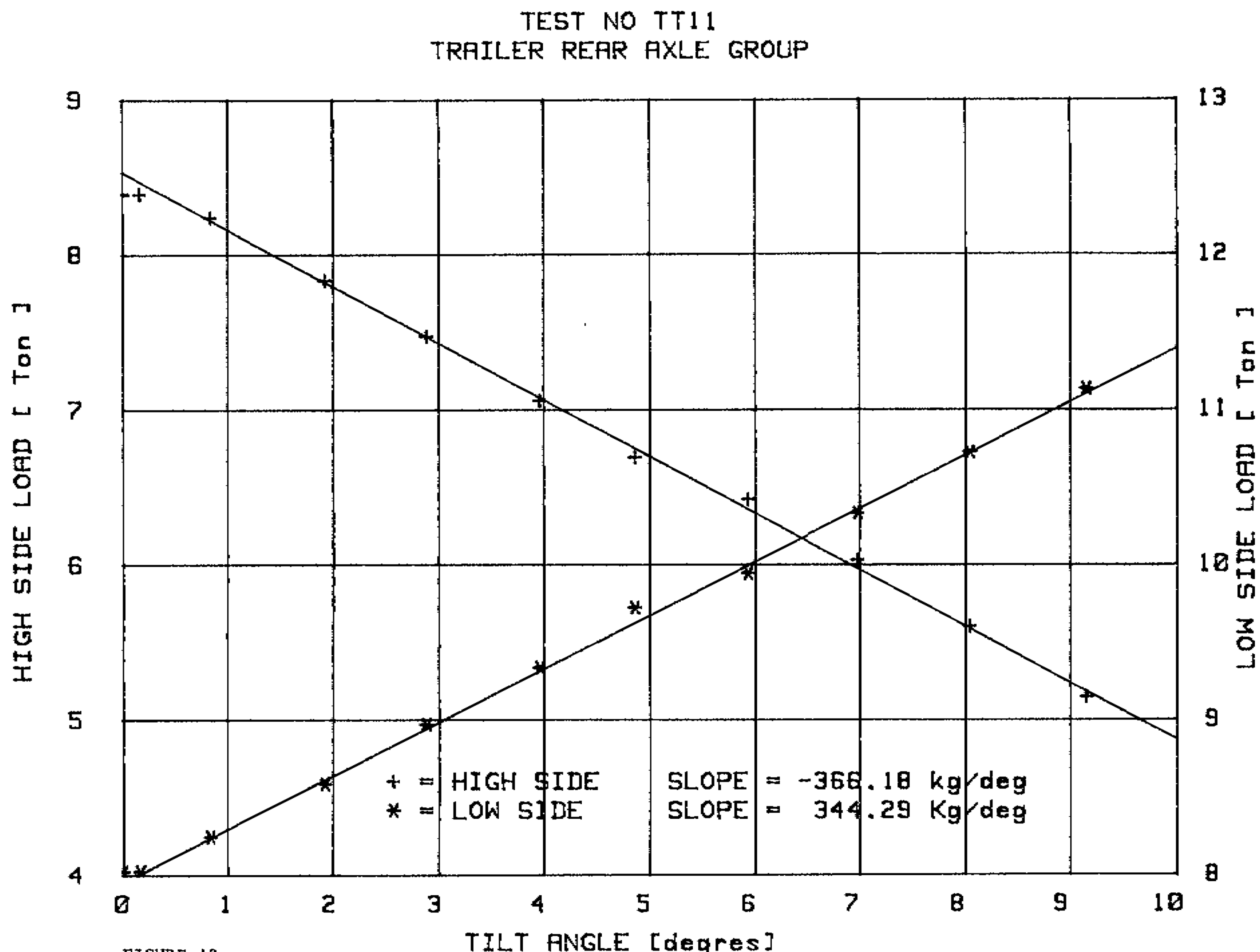
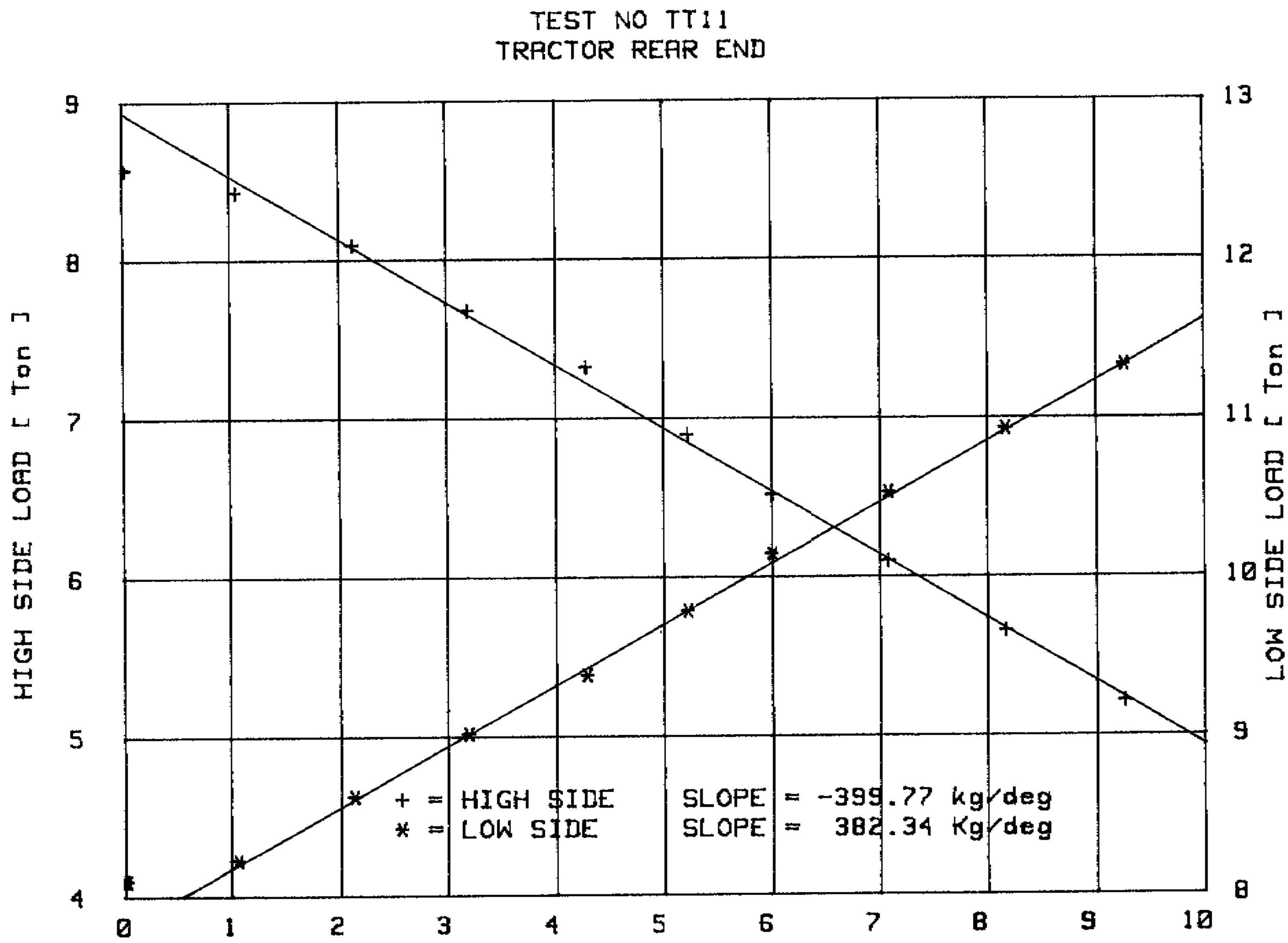

TEST NO TT11
TRAILER REAR AXLE GROUP
HIGH SIDE LOAD [Ton]
LOW SIDE LOAD [Ton]
TILT ANGLE [degres]
+ = HIGH SIDE
* = LOW SIDE
SLOPE = -366.18 kg/deg
SLOPE = 344.29 Kg/deg
9
8
7
6
5
4
13
12
11
10
9
8
0
1
2
3
4
5
6
7
8
9
10

FIGURE A3



TEST NO TT11
TRACTOR REAR END
HIGH SIDE LOAD [Ton]
LOW SIDE LOAD [Ton]
TILT ANGLE [degres]
+ = HIGH SIDE
* = LOW SIDE
SLOPE = -399.77 kg/deg
SLOPE = 382.34 Kg/deg
0
1
2
3
4
5
6
7
8
9
10
4
5
6
7
8
9
10
11
12
13

FIGURE A4

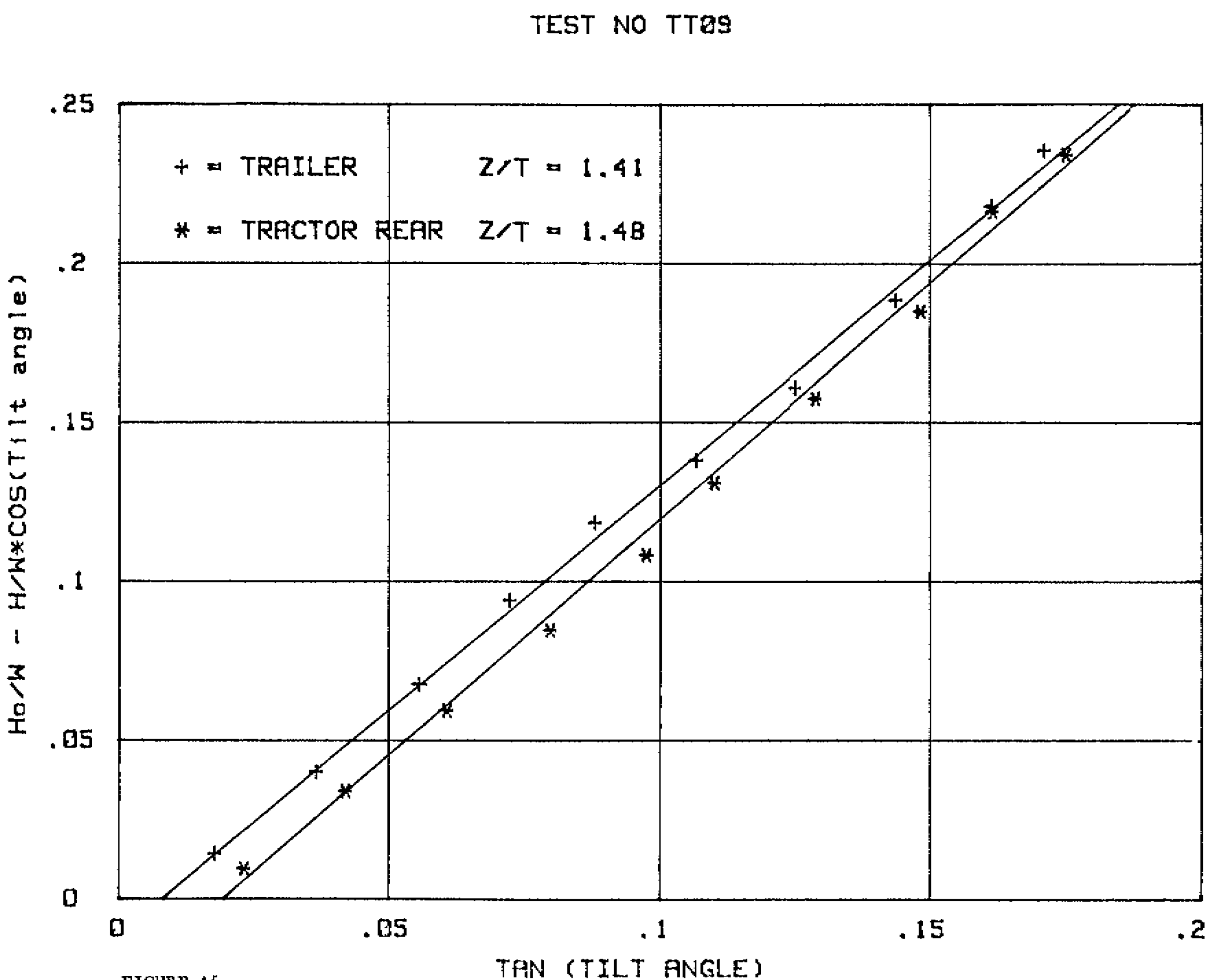

TEST NO TT09
+ = TRAILER Z/T = 1.41
* = TRACTOR REAR Z/T = 1.48
.25
.2
.15
.1
.05
0
Ho/W - H/W*COS(Tilt angle)
0
.05
.1
.15
.2
TAN (TILT ANGLE)

FIGURE A5

TEST NO TT11

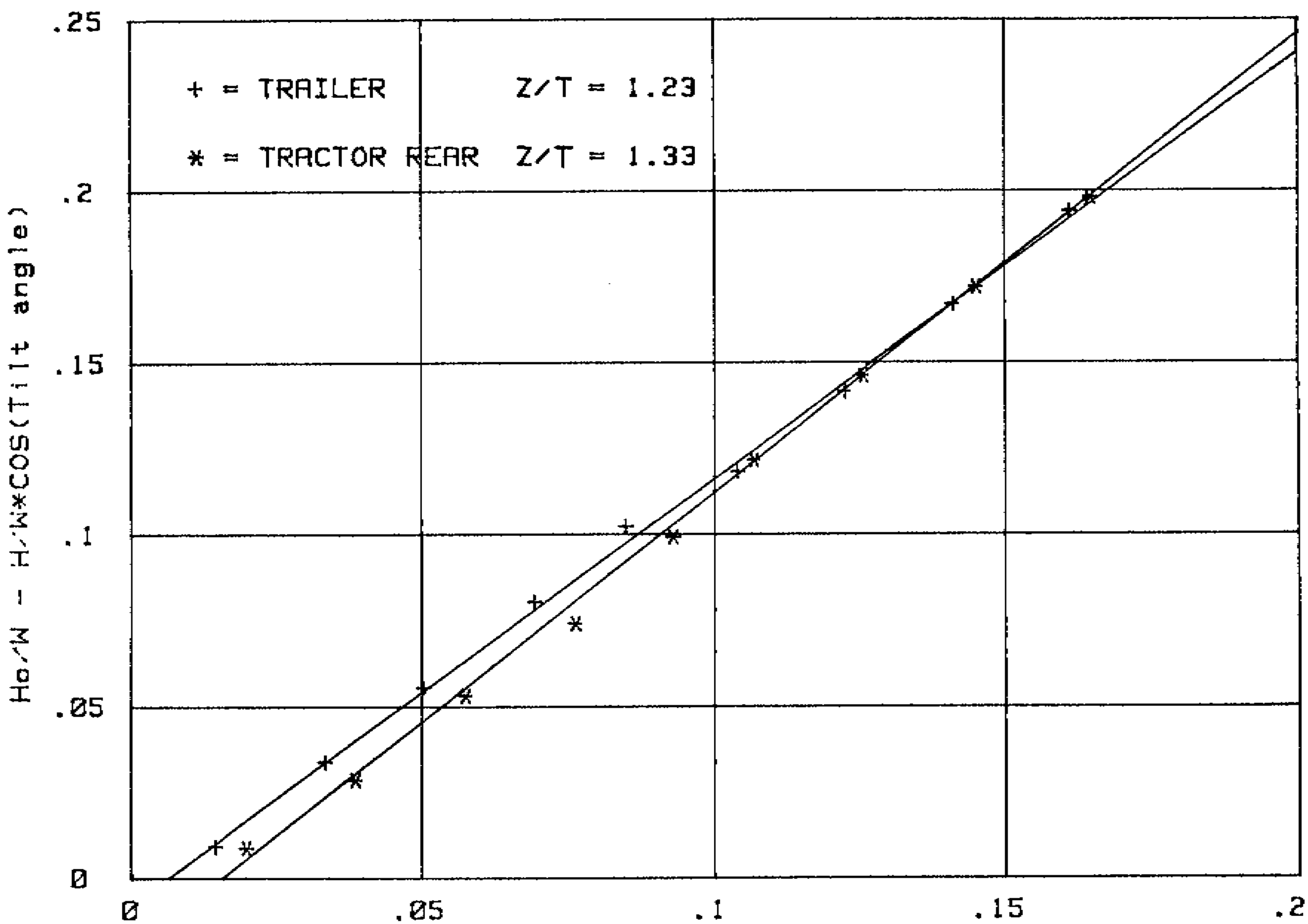


FIGURE A6

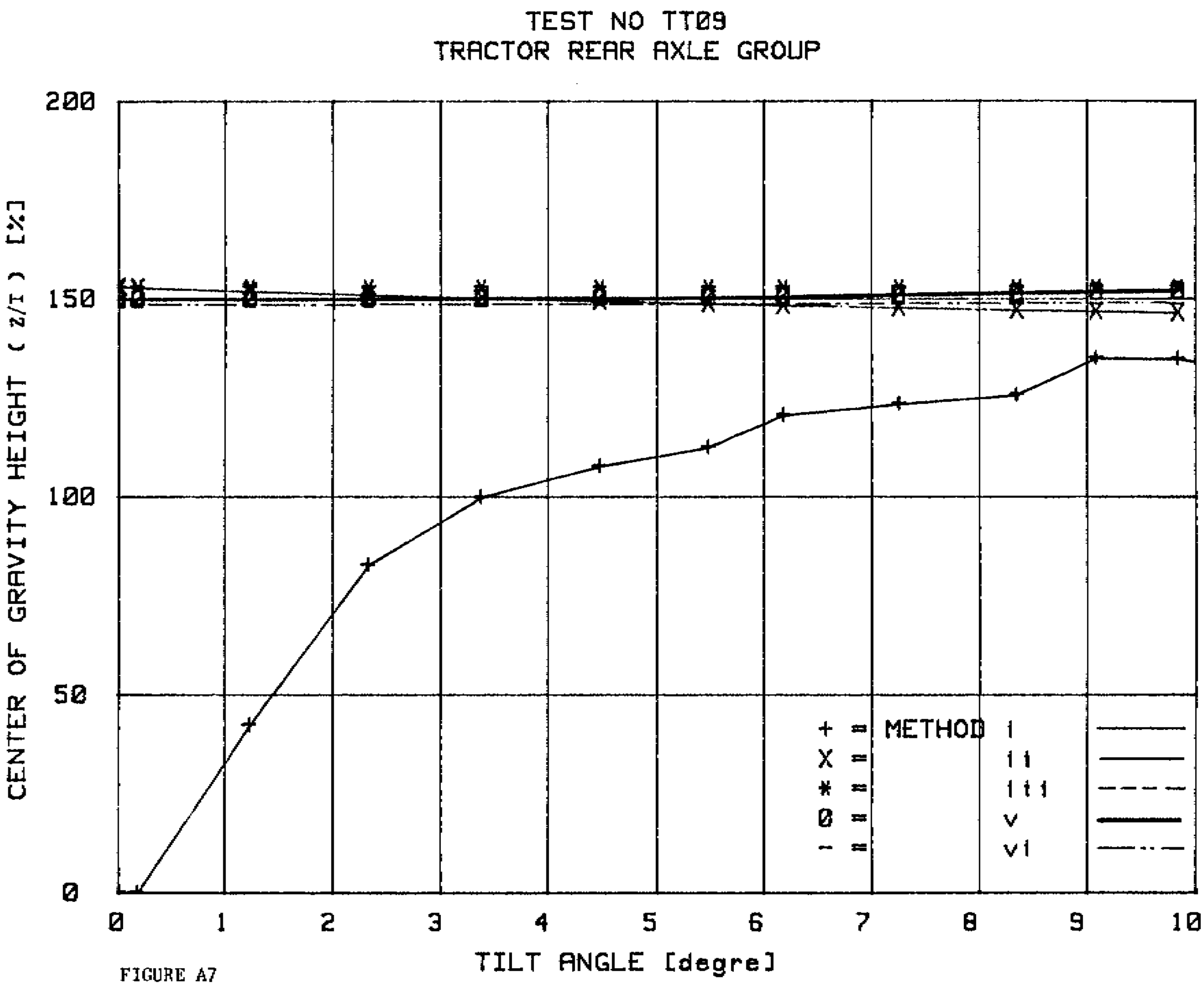

TEST NO TT09
TRACTOR REAR AXLE GROUP
CENTER OF GRAVITY HEIGHT (z/I) [%]
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
TILT ANGLE [degre]
+ = METHOD I
X = II
* = III
0 = V
- = VI

FIGURE A7

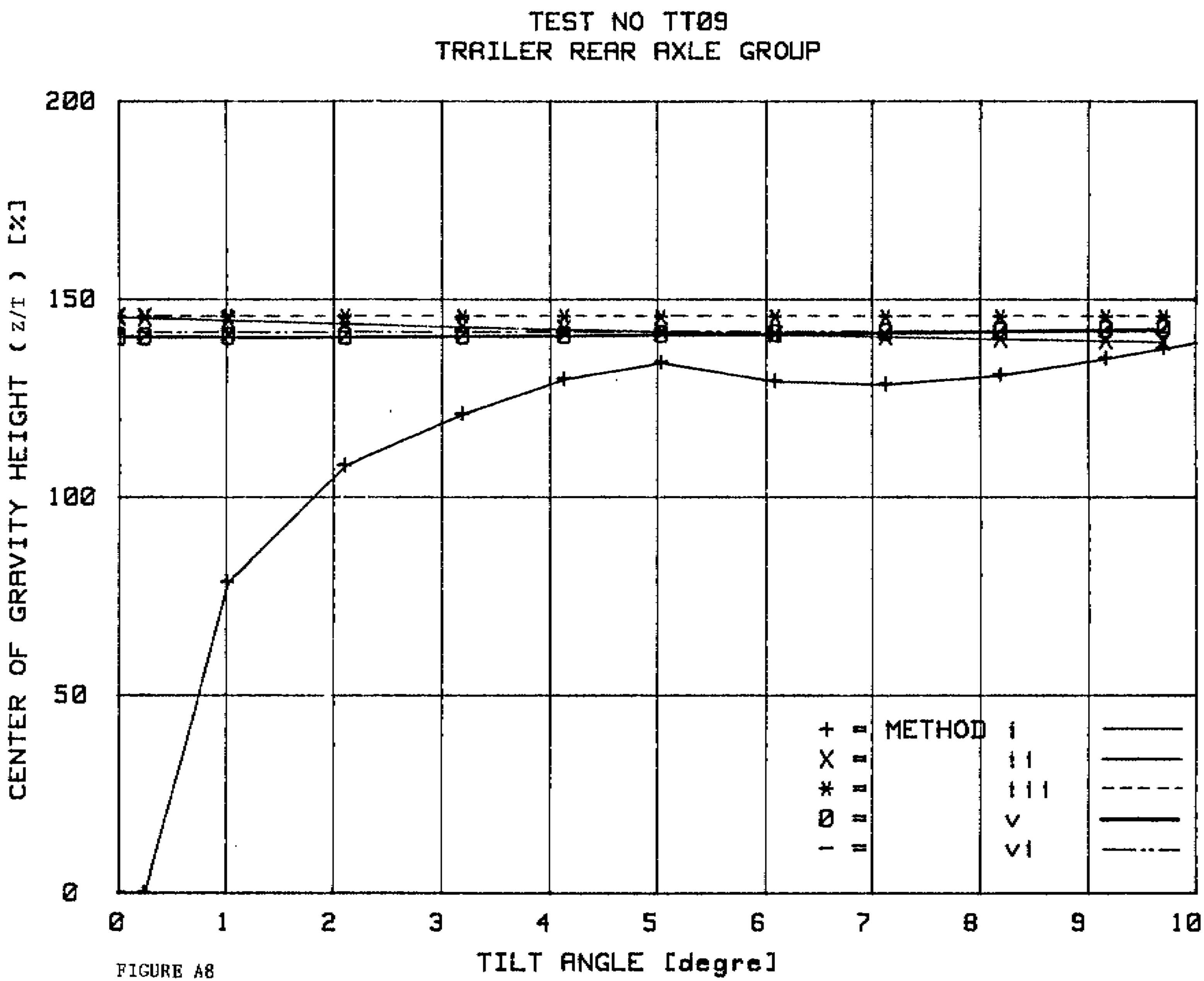

TEST NO TT09
TRAILER REAR AXLE GROUP
CENTER OF GRAVITY HEIGHT (Z/T) [%]
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
TILT ANGLE [degre]
+ = METHOD i
X = ii
* = iii
0 = v
- = vi

FIGURE A8

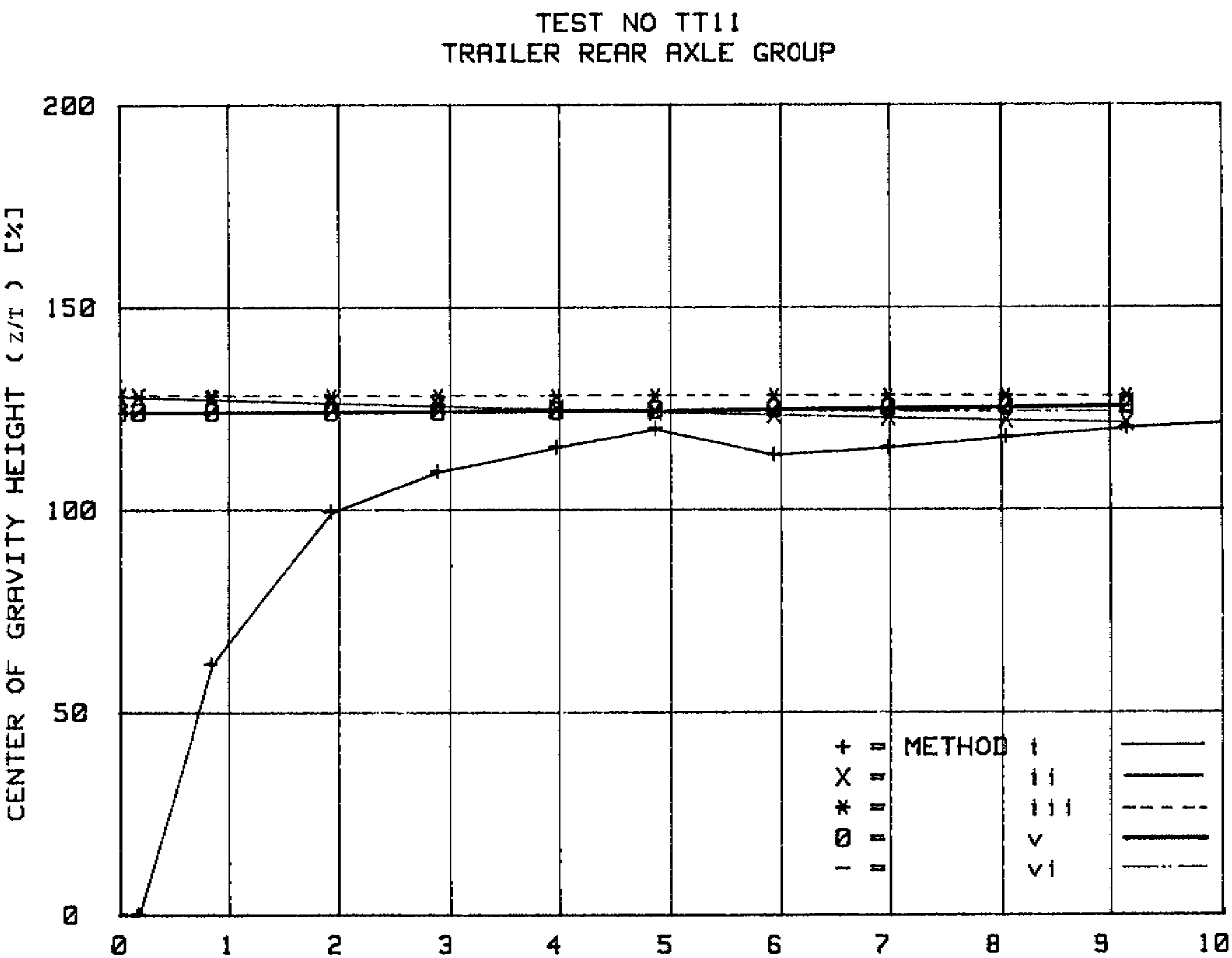

TEST NO TT11
TRAILER REAR AXLE GROUP
CENTER OF GRAVITY HEIGHT (Z/T) [%]
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
TILT ANGLE [degre]
+ = METHOD i
X = ii
* = iii
0 = v
- = vi

FIGURE A9

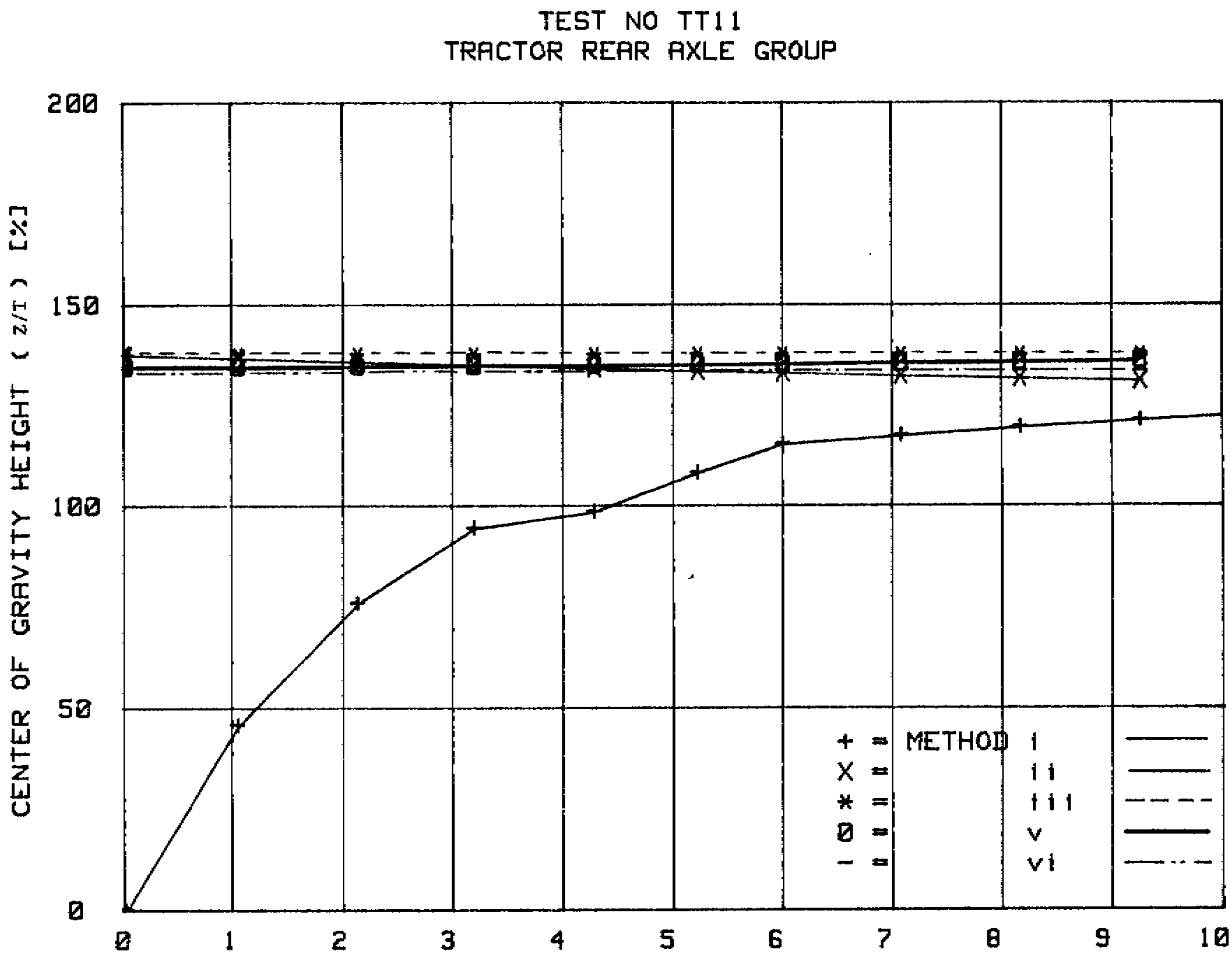

TEST NO TT11
TRACTOR REAR AXLE GROUP
CENTER OF GRAVITY HEIGHT (Z/T) [%]
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10
TILT ANGLE [degre]
+ = METHOD i
X = ii
* = iii
0 = v
- = vi

FIGURE A10

APPENDIX B

The University of Michigan Transportation Research Institute Rollover Mathematical Model

TABLE B1

UMTRI COMPUTER PROGRAM INPUTS

	Variable name
1- Title	
2- Tractor rear sprung mass	WS2
3- Trailer sprung mass	WS3
4- Tractor front axle load	WAXL1
5- Tractor rear axle load	WAXL2
6- Trailer axle load	WAXL3
7- Front axle unsprung weight	WU1
8- Tractor rear axle unsprung weight	WU2
9- Trailer axle unsprung weight	WU3
10- Half distance between front axle tires	T1
11- Dual tire spacing on front axle	A1
12- Half distance between tires on tractor rear axle	T2
13- Dual tire spacing on tractor rear axle	A2
14- Half lateral distance between tires on trailer axle	T3
15- Dual tire spacing on trailer axle	A3
16- Half front spring lateral spacing	S1
17- Half tractor rear axle lateral spring spacing	S2
18- Half trailer lateral spring spacing	S3
19- Tractor front sprung mass C.G. height	ZS1
20- Tractor rear sprung mass C.G. height	ZS2
21- Trailer sprung mass C.G. height	ZS3
22- Tractor front axle C.G. height	R1
23- Tractor rear axle C.G. height	R2
24- Trailer axle C.G. height	R3
25- Height of tractor front axle roll center	HR1
26- Height of tractor rear axle roll center	HR2
27- Height of trailer axle roll center	HR3
28- Height of 5th wheel above ground	Z5
29- Height of tractor frame above ground	ZFR

TABLE B1

UMTRI COMPUTER PROGRAM INPUTS

	Variable name
1- Title	
2- Tractor rear sprung mass	WS2
3- Trailer sprung mass	WS3
4- Tractor front axle load	WAXL1
5- Tractor rear axle load	WAXL2
6- Trailer axle load	WAXL3
7- Front axle unsprung weight	WU1
8- Tractor rear axle unsprung weight	WU2
9- Trailer axle unsprung weight	WU3
10- Half distance between front axle tires	T1
11- Dual tire spacing on front axle	A1
12- Half distance between tires on tractor rear axle	T2
13- Dual tire spacing on tractor rear axle	A2
14- Half lateral distance between tires on trailer axle	T3
15- Dual tire spacing on trailer axle	A3
16- Half front spring lateral spacing	S1
17- Half tractor rear axle lateral spring spacing	S2
18- Half tractor lateral spring spacing	S3
19- Tractor front sprung mass C.G. height	ZS1
20- Tractor rear sprung mass C.G. height	ZS2
21- Trailer sprung mass C.G. height	ZS3
22- Tractor front axle C.G. height	R1
23- Tractor rear axle C.G. height	R2
24- Trailer axle C.G. height	R3
25- Height of tractor front axle roll center	HR1
26- Height of tractor rear axle roll center	HR2
27- Height of trailer axle roll center	HR3
28- Height of 5th wheel above ground	Z5
29- Height of tractor frame above ground	ZFR

	Variable name
30- Vertical stiffness of one tire on front axle	KT11
31- Vertical stiffness of one tire on tractor rear axle	KT21
32- Number of tractor rear axles	
33- Vertical stiffness of one tire on trailer axle	KT31
34- Number of trailer axle	
35- Lateral stiffness of one tire on front axle	KYT1
36- Lateral stiffness of one tire on tractor rear axle	KYT2
37- Lateral stiffness of one tire on trailer axle	KYT3
38- Overturning stiffness of one tire on front axle	KOVT1
39- Overturning stiffness of one tire on tractor rear axle	KOVT2
40- Overturning stiffness of one tire on trailer axle	KOVT3
41- Auxiliary roll stiffness of front suspension	KRS1
42- Auxiliary roll stiffness of tractor rear suspension	KRS2
43- Auxiliary roll stiffness of trailer suspension	KRS3
44- Torsional stiffness of tractor frame	KFR
45- Coulomb friction in tractor frame	COU

TABLE B2

Summary of the sensitivity analysis of the UMTRI Model

VARIABLE NUMBER (Y)	VARIABLE NAME (Y)	TEST #1 NOMINAL VALUE OF VARIABLE (Ynom.)	TEST #1 % VARIATION OF "a" WITH (Y=0.9Ynom.)	TEST #1 % VARIATION OF "a" WITH (Y=1.1Ynom.)	TEST #2 NOMINAL VALUE OF VARIABLE (Ynom.)	TEST #2 % VARIATION OF "a" WITH (Y=0.9Ynom.)	TEST #2 % VARIATION OF "a" WITH (Y=1.1Ynom.)
2	WS2	2000 lb	0.00	0.00	2500 lb	-	-
3	WS3	36700 lb	3.91	-3.70	61300 lb	7.87	-3.94
4	WAXL1	11000 lb	1.44	-1.65	11000 lb	0.52	-0.52
5	WAXL2	20000 lb	0.41	-0.82	36000 lb	0.79	-1.05
6	WAXL3	20000 lb	-2.26	1.85	36000 lb	-5.77	5.25
7	WU1	1190 lb	-0.21	0.00	1300 lb	-	-
8	WU2	2340 lb	-0.21	0.21	5000 lb	-	-
9	WU3	1500 lb	-0.21	0.00	3200 lb	-	-
10	T1	30.5 in.	-0.41	0.21	40.0 in.	-	-
11	A1	0.0 in.	-	-	0.0 in.	-	-
12	T2	29.0 in.	-2.26	1.85	27.15 in.	-2.10	1.57
13	A2	13.0 in.	-0.62	0.62	13.4 in.	-0.52	0.26
14	T3	29.0 in.	-5.97	4.94	27.0 in.	-4.99	3.41
15	A3	13.0 in.	-2.06	1.85	13.4 in.	-1.05	1.05
16	S1	17.0 in.	-1.23	1.03	18.0 in.	-0.52	0.52
17	S2	20.0 in.	-3.09	4.32	20.0 in.	-3.94	3.67
18	S3	19.0 in.	-0.62	0.00	20.0 in.	-1.31	1.05
19	ZS1	43.7 in.	1.65	-1.85	45.0 in.	1.05	-1.05
20	ZS2	43.7 in.	0.41	-0.62	45.0 in.	0.26	-0.26
21	ZS3	66.4 in.	12.35	-10.03	90.0 in.	12.86	-10.50
22	R1	19.5 in.	0.00	0.00	20.0 in.	-	-
23	R2	19.5 in.	0.00	-0.21	20.0 in.	-	-
24	R3	19.5 in.	0.00	-0.21	20.0 in.	-	-
25	HR1	21.0 in.	-1.23	1.03	21.0 in.	-0.52	0.52
26	HR2	31.0 in.	-2.67	2.47	30.0 in.	-1.64	1.57
27	HR3	29.0 in.	1.44	-0.41	30.0 in.	1.05	-1.05
28	ZS	46.8 in.	-0.41	0.21	46.0 in.	-	-
29	ZFR	35.0 in.	0.00	0.00	35.0 in.	-	-
30	KT11	5000 lb/in.	-0.21	0.00	5000 lb/in.	-	-
31	KT21	5000 lb/in.	-1.03	0.32	5000 lb/in.	-1.31	0.79
32	Actual tractor rear axles	1	-	-	2	-	-
33	KT31	5000 lb/in.	0.21	-0.62	5000 lb/in.	-	-
34	Actual trailer axles	1	-	-	2	-	-
35	KYT1	3000 lb/in.	0.00	0.00	3000 lb/in.	-	-
36	KYT2	3000 lb/in.	-0.21	0.00	3000 lb/in.	-	-
37	KYT3	3000 lb/in.	-0.21	0.00	3000 lb/in.	-	-
38	KOVT1	1000 lb in./deg.	0.00	0.00	1000 lb in./deg.	-	-
39	KOVT2	1000 lb in./deg.	0.00	0.00	1000 lb in./deg.	-	-
40	KOVT3	1000 lb in./deg.	0.00	0.00	1000 lb in./deg.	-	-
41	KRS1	0 lb in./deg.	-	-	0 lb in./deg.	-	-
42	KRS2	0 lb in./deg.	-	-	0 lb in./deg.	-	-
43	KRS3	0 lb in./deg.	-	-	0 lb in./deg.	-	-
44	KFR	9000 lb in./deg.	0.00	0.00	10000 lb in./deg.	-	-
45	COULFR	11000 lb in./deg.	0.00	0.00	11000 lb in./deg.	-	-
46	MS	1000000 lb in./deg.	-0.21	0.00	1000000 lb in./deg.	-	-
47	FWR	18.0 in.	0.00	0.00	12.0 in.	-	-
48	LASH5	2.0 deg.	0.00	0.00	1.5 deg.	-	-

CRIQ

TABLE B2 (cont'd)

Summary of the sensitivity analysis of the UMTRI Model

VARIABLE NAME (Y)	TEST #1 NOMINAL VALUE OF VARIABLE (Ynom.) (lb)	TEST #1 NOMINAL VALUE OF VARIABLE (Ynom.) (in.)	TEST #1 % VARIATION OF "a" WITH (Y=0.9Ynom.)	TEST #1 % VARIATION OF "a" WITH (Y=1.1Ynom.)	TEST #2 NOMINAL VALUE OF VARIABLE (Ynom.) (lb)	TEST #2 NOMINAL VALUE OF VARIABLE (Ynom.) (in.)	TEST #2 % VARIATION OF "a" WITH (Y=0.9Ynom.)	TEST #2 % VARIATION OF "a" WITH (Y=1.1Ynom.)
SPRING #1	F(1,1)=-5000 F(1,2)= 0.0 F(1,3)= 5000	DEL(1,1)=-3.0 DEL(1,2)= 0.0 DEL(1,3)= 3.0	-0.62	0.62	F(1,1)=-5000 F(1,2)= 0.0 F(1,3)= 5000	DEL(1,1)=-3.0 DEL(1,2)= 0.0 DEL(1,3)= 3.0	-0.26	0.26
SPRING #2	F(2,1)= -5000 F(2,2)= 0.0 F(2,3)= 0.0 F(2,4)= 2000 F(2,5)= 3500 F(2,6)= 7000 F(2,7)= 12000 F(2,8)= 20000	DEL(2,1)=-4.0 DEL(2,2)=-2.0 DEL(2,3)= 0.0 DEL(2,4)= 0.6 DEL(2,5)= 1.0 DEL(2,6)= 1.5 DEL(2,7)= 1.9 DEL(2,8)= 2.8	1.05	1.44	F(2,1)=-8200 F(2,2)= 0.0 F(2,3)= 0.0 F(2,4)= 3290 F(2,5)= 5750 F(2,6)=11500 F(2,7)=19700 F(2,8)=32850	DEL(2,1)=-4.0 DEL(2,2)=-1.0 DEL(2,3)= 0.0 DEL(2,4)= 0.6 DEL(2,5)= 1.0 DEL(2,6)= 1.5 DEL(2,7)= 1.9 DEL(2,8)= 2.8	-1.57	1.31
SPRING #3	F(3,1)=-10000 F(3,2)= -7500 F(3,3)= 0.0 F(3,4)= 0.0 F(3,5)= 3000 F(3,6)= 7000 F(3,7)= 13000 F(3,8)= 20000	DEL(3,1)=-3.15 DEL(2,2)= -2.7 DEL(3,3)= -1.0 DEL(3,4)= 0.0 DEL(2,5)= 0.55 DEL(3,6)= 1.0 DEL(3,7)= 1.4 DEL(3,8)= 1.8	-0.62	0.21	F(3,1)=-20000 F(3,2)=-15000 F(3,3)= 0.0 F(3,4)= 0.0 F(3,5)= 6000 F(3,6)= 14000 F(3,7)= 26000 F(3,8)= 40000	DEL(3,1)=-3.15 DEL(2,2)= -2.7 DEL(3,3)= -1.0 DEL(3,4)= 0.0 DEL(2,5)= 0.55 DEL(3,6)= 1.0 DEL(3,7)= 1.4 DEL(3,8)= 1.8	-1.31	-0.26

UMTRI COMPUTER MODEL - SAMPLE SOLUTION

Solution of typical vehicle 3

AYOUT g	USPM1 deg	USPM2 deg	USPM3 deg	SPMAS1 deg	SPMAS2 deg	SPMAS3 deg	NRM1 ftlb	NRM2 ftlb	NRM3 ftlb
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.	0.	0.
0.049	0.071	0.173	0.232	0.453	0.446	0.500	1558.	11726.	15646.
0.098	0.142	0.347	0.449	0.906	0.893	1.000	3107.	23393.	30112.
0.142	0.210	0.494	0.651	1.372	1.353	1.500	4592.	33179.	43534.
0.200	0.292	0.669	0.883	1.845	1.818	2.000	6332.	44664.	58738.
0.257	0.374	0.844	1.116	2.318	2.282	2.500	8058.	56054.	73828.
0.312	0.454	1.016	1.368	2.792	2.748	3.000	9750.	67129.	87757.
0.370	0.578	1.189	1.708	3.271	3.218	3.500	11485.	78120.	99255.

The inside tires on axle 3 have left the ground at the following conditions:

0.381	0.555	1.224	1.776	3.367	3.312	3.600	11830.	80310.	100901.
0.420	0.617	1.373	2.278	3.747	3.687	4.000	13094.	87541.	101154.
0.466	0.691	1.629	2.898	4.231	4.166	4.500	14624.	96175.	101484.

The vehicle is now unstable as the inside tires on axles 2 and 3
have left the ground at the following conditions:

0.489	0.732	1.772	3.262	4.519	4.451	4.800	15465.	100520.	101704.

LISTING OF THE UMTRI ROLLOVER MATHEMATICAL MODEL

PC VERSION

```
10 DOT = 0
20 CLEAR ,,2000
30 DIM B(15),A(225),F(3,15),DEL(3,15),NUM(3),DUST(15)
40 KEY OFF:CLS:LOCATE 12
50 'ON ERROR GOTO 5501
60 '*************************************************************************
70 '
80 '          Existing file is opened and data read from it
90 '
100 INPUT "Please enter name of file that contains the truck data";F$
110 OPEN F$ FOR INPUT AS 1
120 INPUT #1,BT$
130 INPUT #1,WS2,WS3,WAXL1,WAXL2,WAXL3,WU1,WU2,WU3,T1,A1,T2,A2,T3,A3,S1,S2,S3,ZS
1,ZS2,ZS3,R1,R2,R3,HR1,HR2,HR3,Z5,ZFR,KT11,KT21,NA2,KT31,NA3,KYT1,KYT2,KYT3,KOVT
1,KOVT2,KOVT3,KRS1,KRS2,KRS3,KFR,COULFR,H5,FWR,LASH5,DELPH,XPRINT,MUD
140 INPUT #1,NUM(1),NUM(2),NUM(3),DUST(1)
150 FOR J = 1 TO NUM(1)
160 INPUT #1,F(1,J),DEL(1,J),DUST(J)
170 NEXT J
180 FOR J = 1 TO NUM(2)
190 INPUT #1,F(2,J),DEL(2,J),DUST(J)
200 NEXT J
210 FOR J = 1 TO NUM(3)
220 INPUT #1,F(3,J),DEL(3,J),DUST(J)
230 NEXT J
240 CLOSE #1
250 '
260 '          F$ is opened for output from programme
270 LOCATE 14
280 INPUT "Please enter filename for storing output";F$
290 OPEN F$ FOR OUTPUT AS #1
300 '
310 '          Adjust tire parameters if more than one axle
320 IF NA2 < 2 THEN GOTO 370
330 KT21 = KT21*NA2:KYT2 = KYT2*NA2:KOVT2 = KOVT2*NA2
340 FOR J = 1 TO NUM(2)
350 F(2,J) = F(2,J)*NA2
360 NEXT J
370 IF NA3 < 2 THEN GOTO 420
380 KT31 = KT31*NA3:KYT3 = KYT3*NA3:KOVT3 = KOVT3*NA3
390 FOR J = 1 TO NUM(3)
400 F(3,J) = F(3,J)*NA3
410 NEXT J
420 W5 = WS3 + WU3 - WAXL3'    W5 is the fifth wheel load
430 '
440 MOMSEP = W5*FWR
450 '*************************************************************************
460 '
470 '          Equation solution follows
480 '
490 '*******************************************************************
500 '
510 LOCATE 16
```

```
520 INPUT "Enter interval of trailer sprung mass roll angle DELPH";DELPH
530 PI = 4*ATN(1)
540 RAD = 180/PI
550 '
            INITIALIZATIONS
560 '
570 '           Look after dual/single tires
580 '
590 IF A1 = 0 THEN GOTO 610
600 KYT1 = 2*KYT1:KOVT1 = 2*KOVT1
610 IF A2 = 0 THEN GOTO 630
620 KYT2 = 2*KYT2:KOVT2 = 2*KOVT2
630 IF A3 = 0 THEN GOTO 660
640 KYT3 = 2*KYT3:KOVT3 = 2*KOVT3
650 '
660 HU1 = R1:HU2 = R2:HU3 = R3
670 ZU1 = HR1 - HU1:ZU2 = HR2 - HU2:ZU3 = HR3 - HU3
680 ZR1 = ZS1 - HR1:ZR2 = ZS2 - HR2:ZR3 = ZS3 - HR3
690 Z52 = Z5 - ZS2
700 Z53 = ZS3 - Z5
710 WFR = W5 + WS2 + WU2 -WAXL2
720 ZFR1 = ZS1 - ZFR
730 ZFR2 = ZS2 - ZFR
740 '            Set stiffnesses of other tires on each axle
750 KT12 = KT11:KT13 = KT11:KT14 = KT11
760 IF A1 > 0 THEN GOTO 780
770 KT12 = 0:KT13 = 0
780 KT22 = KT21:KT23 = KT21:KT24 = KT21
790 IF A2 > 0 THEN GOTO 810
800 KT22 = 0:KT23 = 0
810 KT32 = KT31:KT33 = KT31:KT34 = KT31
820 IF A3 > 0 THEN GOTO 850
830 KT32 = 0:KT33 = 0
840 '            Convert to radians
850 KRS1 = KRS1*RAD:KRS2 = KRS2*RAD:KRS3 = KRS3*RAD
860 KOVT1 = KOVT1*RAD:KOVT2 = KOVT2*RAD:KOVT3 = KOVT3*RAD
870 M5 = M5*RAD:KFR = KFR*RAD
880 DELPH1 = DELPH
890 DELPH = DELPH/RAD
900 DEF51 = NOMSEP/M5
910 DEF51 = DEF51 + LASH5
920 DEFFR = COULFR/900000!
930 PHIS1 = 0:PHIS2 = 0:PHIS3 = 0
940 PHIU1 = 0:PHIU2 = 0:PHIU3 = 0
950 USPM1 = 0:USPM2 = 0:USPM3 = 0
960 SPMAS1 = 0:SPMAS2 = 0:SPMAS3 = 0
970 Y1 = 0:Y2 = 0:Y3 = 0
980 AY = 0
990 LOOP = INT(XPRINT/DELPH1):COUNT = 0'       LOOP is number of loops between
print-out of results
1000 '
1010 '           Now calculate static spring deflection
1020 '
1030 F11 = (WAXL1 - WU1)/2:F12 = F11
1040 FOR J = 1 TO NUM(1)
1050 IF F11 < F(1,J) THEN GOTO 1090
1060 NEXT J
1070 IF J > NUM(1) THEN J = NUM(1)
1080 IF J = 1 THEN  J = J + 1
1090 K11 = (F(1,J) - F(1,J - 1))/(DEL(1,J) - DEL(1,J - 1))
```

```
1100 DELS11 = DEL(1,J - 1) + (F11 - F(1,J - 1))/K11
1110 Z1 = DELS11:DELS12 = DELS11:K12 = K11
1120 '
1130 F21 = (WAXL2 - WU2)/2:F22 = F21
1140 FOR J = 1 TO NUM(2)
1150 IF F21 < F(2,J) THEN GOTO 1190
1160 NEXT J
1170 IF J > NUM(2) THEN J = NUM(2)
1180 IF J = 1 THEN  J = J + 1
1190 K21 = (F(2,J) - F(2,J - 1))/(DEL(2,J) - DEL(2,J - 1))
1200 DELS21 = DEL(2,J - 1) + (F21 - F(2,J - 1))/K21
1210 Z2 = DELS21:DELS22 = DELS21:K22 = K21
1220 '
1230 F31 = (WAXL3 - WU3)/2:F32 = F31
1240 FOR J = 1 TO NUM(3)
1250 IF F31 < F(3,J) THEN GOTO 1290
1260 NEXT J
1270 IF J > NUM(3) THEN J = NUM(3)
1280 IF J = 1 THEN  J = J + 1
1290 K31 = (F(3,J) - F(3,J - 1))/(DEL(3,J) - DEL(3,J - 1))
1300 DELS31 = DEL(3,J - 1) + (F31 - F(3,J - 1))/K31
1310 Z3 = DELS31:DELS32 = DELS31:K32 = K31
1320 '
1330 '          Now calculate static tire deflection
1340 '
1350 WTIN1 = WAXL1/4
1360 DELT11 = WTIN1/KT11
1370 DELT12 = DELT11:DELT13 = DELT11:DELT14 = DELT11
1380 IF A1 > 0 THEN GOTO 1400
1390 DELT11 = 2*DELT11:DELT14 = DELT11:DELT12 = 0:DELT13 = 0
1400 ZT1 = DELT11
1410 '
1420 WTIN2 = WAXL2/4
1430 DELT21 = WTIN2/KT21
1440 DELT22 = DELT21:DELT23 = DELT21:DELT24 = DELT21
1450 IF A2 > 0 THEN GOTO 1470
1460 DELT21 = 2*DELT21:DELT24 = DELT21:DELT22 = 0:DELT23 = 0
1470 ZT2 = DELT21
1480 '
1490 WTIN3 = WAXL3/4
1500 DELT31 = WTIN3/KT31
1510 DELT32 = DELT31:DELT33 = DELT31:DELT34 = DELT31
1520 IF A3 > 0 THEN GOTO 1540
1530 DELT31 = 2*DELT31:DELT34 = DELT31:DELT32 = 0:DELT33 = 0
1540 ZT3 = DELT31
1550 '
1560 '          Calculate tire forces
1570 '
1580 FZ11 = KT11*DELT11:FZ12 = KT12*DELT12:FZ13 = KT13*DELT13:FZ14 = KT14*DELT14
1590 FZ21 = KT21*DELT21:FZ22 = KT22*DELT22:FZ23 = KT23*DELT23:FZ24 = KT24*DELT24
1600 FZ31 = KT31*DELT31:FZ32 = KT32*DELT32:FZ33 = KT33*DELT33:FZ34 = KT34*DELT34
1610 '
1620 '
1630 '
1640 '
1650 '          Calculate net moment on each mass as a check
1660 GOTO 1750
1670 FR1 = (WAXL1 - WU1)*(AY*COS(PHIU1) + SIN(PHIU1)):FR2 = (WAXL2 - WU2)*(AY*CO
S(PHIU2) + SIN(PHIU2)):FR3 = (WAXL3 - WU3)*(AY*COS(PHIU3) + SIN(PHIU3))
1680 MS1 = (F11 - F12)*S1 + FR1*COS(PHIS1 - PHIU1)*ZR1 + (F11 + F12)*SIN(PHIS1 -
```

```
PHIU1)*ZR1 + KFR*(PHIS2 - PHIS1) - WFR*(AY*COS(PHIS1) + SIN(PHIS1))*ZFR1 - KRS1
*(PHIS1 - PHIU1)
1690 MS2 = (F21 - F22)*S2 + FR2*COS(PHIS2 - PHIU2)*ZR2 + (F21 + F22)*SIN(PHIS2 -
 PHIU2)*ZR2 - KFR*(PHIS2 - PHIS1) + (AY*COS(PHIS2) + SIN(PHIS2))*(WFR*ZFR2 + W5*
Z52) + M5*(PHIS3 - PHIS2) - KRS2*(PHIS2 - PHIU2)
1700 MS3 = (F31 - F32)*S3 + FR3*COS(PHIS3 - PHIU3)*ZR3 + (F31 + F32)*SIN(PHIS3 -
 PHIU3)*ZR3 + W5*Z53*(AY*COS(PHIS3) + SIN(PHIS3)) - M5*(PHIS3 - PHIS2) - KRS3*(P
HIS3 - PHIU3)
1710 MU1 = -(F11 - F12)*S1 + (FZ11 - FZ14)*(T1 + A1)*COS(PHIU1) + (FZ12 - FZ13)*
T1*COS(PHIU1) + FR1*ZU1 + KYT1*Y1*COS(PHIU1)*HU1 + (FZ13 + FZ14)*Y1 - KOVT1*PHIU
1 + (FZ11 + FZ12 + FZ13 + FZ14)*R1*SIN(PHIU1) + KRS1*(PHIS1 - PHIU1)
1720 MU2 = -(F21 - F22)*S2 + (FZ21 - FZ24)*(T2 + A2)*COS(PHIU2) + (FZ22 - FZ23)*
T2*COS(PHIU2) + FR2*ZU2 + KYT2*Y2*COS(PHIU2)*HU2 + (FZ23 + FZ24)*Y2 - KOVT2*PHIU
2 + (FZ21 + FZ22 + FZ23 + FZ24)*R2*SIN(PHIU2) + KRS2*(PHIS2 - PHIU2)
1730 MU3 = -(F31 - F32)*S3 + (FZ31 - FZ34)*(T3 + A3)*COS(PHIU3) + (FZ32 - FZ33)*
T3*COS(PHIU3) + FR3*ZU3 + KYT3*Y3*COS(PHIU3)*HU3 + (FZ33 + FZ34)*Y3 - KOVT3*PHIU
3 + (FZ31 + FZ32 + FZ33 + FZ34)*R3*SIN(PHIU3) + KRS3*(PHIS3 - PHIU3)
1740 '          Calculate net roll moment at each axle
1750 NRM1 = (FZ13*(T1 - Y1) + FZ14*(T1 + A1 - Y1) - FZ12*T1 - FZ11*(T1 + A1))*CO
S(PHIU1)/12
1760 NRM2 = (FZ23*(T2 - Y2) + FZ24*(T2 + A2 - Y2) - FZ22*T2 - FZ21*(T2 + A2))*CO
S(PHIU2)/12
1770 NRM3 = (FZ33*(T3 - Y3) + FZ34*(T3 + A3 - Y3) - FZ32*T3 - FZ31*(T3 + A3))*CO
S(PHIU3)/12
1780 '
1790 '          Print out the results
1800 '
1810 WIDTH "LPT1:",132
1820 OPEN "LPT1:" FOR OUTPUT AS #2
1830 PRINT #2, "Solution of ";ST$:PRINT #2,"" :PRINT #2,""
1840 WRITE #1,ST$
1850 PRINT #2,"  AYOUT  USPM1  USPM2  USPM3 SPMAS1 SPMAS2 SPMAS3   NRM1    NRM2
   NRM3"
1860 PRINT #2,"   g     deg    deg    deg    deg    deg    deg     ftlb    ftlb
   ftlb"
1870 PRINT #2,"-----------------------------------------------------------------
-------"
1880 PRINT #2,"":PRINT #2,USING "###.###";AY,USPM1,USPM2,USPM3,SPMAS1,SPMAS2,SPM
AS3;
1890 PRINT #2,USING "#######.";NRM1,NRM2,NRM3
1900 '
1910 PRINT #1,USING "#.####^^^^,";AY,USPM1,USPM2,USPM3,SPMAS1,SPMAS2,SPMAS3,NRM1
,NRM2,NRM3
1920 '**********************************************************************
1930 '          This is where the programme returns to
1940 '          for successive increments of
1950 '          trailer sprung mass roll angle, DELPH
1960 '
1970 PHIS3 = PHIS3 + DELPH
1980 '
1990 '          Funny looking tractor frame coulomb friction calculation
2000 '
2010 IF ABS(SPMAS2 - SPMAS1) < DEFFR THEN KFR = 900000!*RAD
2020 '
2030 '          Fifth wheel characteristics
2040 '
2050 P1 = ABS(SPMAS3 - SPMAS2)
2060 IF P1 < DEFS1 THEN K5 = M5
2070 IF P1 > DEF52 THEN K5 = M5
2080 IF P1 =< DEF52 AND P1 => DEF51 THEN K5 = 0
```

```
2090 '
2100 '          Initialize the data arrays
2110 '
2120 FOR J = 1 TO 15
2130 B(J) = 0
2140 FOR I = 1 TO 15
2150 A(I +(J - 1)*15) = 0
2160 NEXT I:NEXT J
2170 '
2180 '          Put appropriate values into matrix pigeon holes
2190 '
2200 SW1 = WAXL1-WU1:SW2 = WAXL2-WU2:SW3 = WAXL3-WU3
2210 '
2220 A(1) = SW1*ZR1*(1 - PHIU1*(PHIS1 - PHIU1)) - WFR*ZFR1
2230 A(16) = -(K11 + K12)*S1*S1 + (F11 + F12)*ZR1 - KFR - WFR*ZFR1 - KRS1
2240 A(31) = KFR
2250 A(46) = (K11 + K12)*S1*S1 + SW1*ZR1*(1 - AY*(PHIS1 - PHIU1)) - (F11 + F12)*
ZR1 + KRS1
2260 A(91) = (K11 - K12)*S1
2270 '
2280 A(2) = SW2*ZR2*(1 - PHIU2*(PHIS2 - PHIU2)) + WFR*ZFR2 + W5*Z52
2290 A(17) = KFR
2300 A(32) = -(K21 + K22)*S2*S2 + (F21 + F22)*ZR2 - KFR + WFR*ZFR2 - K5 + W5*Z52
 - KRS2
2310 A(62) = (K21 + K22)*S2*S2 + SW2*ZR2*(1 - AY*(PHIS2 - PHIU2)) - (F21 + F22)*
ZR2 + KRS2
2320 A(107) = (K21 - K22)*S2
2330 '
2340 A(3) = SW3*ZR3*(1 - PHIU3*(PHIS3 - PHIU3)) + W5*Z53
2350 A(33) = K5
2360 A(78) = (K31 + K31)*S3*S3 + SW3*ZR3*(1 - AY*(PHIS3 - PHIU3)) - (F31 + F32)*
ZR3 + KRS3
2370 A(123) = (K31 - K32)*S3
2380 '
2390 A(4) = SW1*ZU1 + WAXL1*HU1
2400 A(19) = (K11 + K12)*S1*S1 + KRS1
2410 A(49) = -(K11 + K12)*S1*S1 + WAXL1*R1 + SW1*ZU1 - KT11*(T1 + A1)^2 - KT12*T
1*T1 - KT13*(T1 - Y1)^2 - KT14*(T1 + A1 - Y1)^2 - KOVT1 - KRS1
2420 A(94) = -(K11 - K12)*S1 + SW1*(AY + PHIU1)
2430 A(139) = -(KT11 - KT14)*(T1 + A1) - (KT12 - KT13)*T1 - (KT13 + KT14)*Y1 + W
AXL1*AY
2440 A(184) = (FZ13 + FZ14) + ((KT13 + KT14)*(T1 - Y1) + KT14*A1)*PHIU1
2450 '
2460 A(5) = SW2*ZU2 + WAXL2*HU2
2470 A(35) = (K21 + K22)*S2*S2 + KRS2
2480 A(65) = -(K21 + K22)*S2*S2 + WAXL2*R2 + SW2*ZU2 - KT21*(T2 + A2)^2 - KT22*T
2*T2 - KT23*(T2 - Y2)^2 - KT24*(T2 + A2 - Y2)^2 - KOVT2 - KRS2
2490 A(110) = -(K21 - K22)*S2 + SW2*(AY + PHIU2)
2500 A(155) = -(KT21 - KT24)*(T2 + A2) - (KT22 - KT23)*T2 - (KT23 + KT24)*Y2 + W
AXL2*AY
2510 A(200) = (FZ23 + FZ24) + ((KT23 + KT24)*(T2 - Y2) + KT24*A2)*PHIU2
2520 '
2530 A(6) = SW3*ZU3 + WAXL3*HU3
2540 A(81) = -(K31 + K32)*S3*S3 + WAXL3*R3 + SW3*ZU3 - KT31*(T3 + A3)^2 - KT32*T
3*T3 - KT33*(T3 - Y3)^2 - KT34*(T3 + A3 - Y3)^2 - KOVT3 - KRS3
2550 A(126) = -(K31 - K32)*S3 + SW3*(AY + PHIU3)
2560 A(171) = -(KT31 - KT34)*(T3 + A3) - (KT32 - KT33)*T3 - (KT33 + KT34)*Y3 + W
AXL3*AY
2570 A(216) = (FZ33 + FZ34) + ((KT33 + KT34)*(T3 - Y3) + KT34*A3)*PHIU3
2580 '
```

```
2590 A(7) = SW1*PHIU1
2600 A(22) = -(K11 - K12)*S1
2610 A(52) = (K11 - K12)*S1 + SW1*AY
2620 A(97) = K11 + K12
2630 '
2640 A(8) = SW2*PHIU2
2650 A(38) = -(K21 - K22)*S2
2660 A(68) = (K21 - K22)*S2 + SW2*AY
2670 A(113) = (K21 + K22)
2680 '
2690 A(9) = SW3*PHIU3
2700 A(84) = (K31 - K32)*S3 + SW3*AY
2710 A(129) = K31 + K32
2720 '
2730 A(55) = -(KT11 + KT12 - KT13 - KT14)*T1 - (KT11 - KT14)*A1 - (KT13 + KT14)*
Y1
2740 A(145) = -(KT11 + KT12 + KT13 + KT14)
2750 A(190) = -(KT13 + KT14)*PHIU1
2760 '
2770 A(71) = -(KT21 + KT22 - KT23 - KT24)*T2 - (KT21 - KT24)*A2 - (KT23 + KT24)*
Y2
2780 A(161) = -(KT21 + KT22 + KT23 + KT24)
2790 A(206) = -(KT23 + KT24)*PHIU2
2800 '
2810 A(87) = -(KT31 + KT32 - KT33 - KT34)*T3 - (KT31 - KT34)*A3 - (KT33 + KT34)*
Y3
2820 A(177) = -(KT31 + KT32 + KT33 + KT34)
2830 A(222) = -(KT33 + KT34)*PHIU3
2840 '
2850 A(13) = WAXL1
2860 A(193) = -KYT1
2870 '
2880 A(14) = WAXL2
2890 A(209) = -KYT2
2900 A(15) = WAXL3
2910 A(225) = -KYT3
2920 '
2930 '
2940 B(2) = -K5*DELPH
2950 B(3) = ((K31 + K32)*S3*S3 - (F31 + F32)*ZR3 + K5 - W5*Z53 + KRS3)*DELPH
2960 B(6) = -((K31 + K32)*S3*S3 + KRS3)*DELPH
2970 B(9) = (K31 - K32)*S3*DELPH
2980 '
2990 '***************************************************************************
3000 '
3010 '          We must now solve these 15 simultaneous equations
3020 '          The program uses IBM SSP "SIMQ"
3030 '
3040 '***************************************************************************
3050 '
3060 N = 15
3070 '
3080 '
3090 '
3100 '
3110 '
3120 '
3130 '
3140 '
3150 '
```

```
3160 '
3170 '
3180 '
3190 '
3200 TOL= 0!
3210 KS = 0
3220 JJ = -N
3230 FOR J=1 TO N
3240 JY = J+1
3250 JJ = JJ+N+1
3260 BIGA = 0!
3270 IT = JJ-J
3280 FOR I=J TO N
3290 IJ = IT+I
3300 IF ABS(BIGA)-ABS(A(IJ))<0 GOTO 3310 ELSE 3330
3310 BIGA = A(IJ)
3320 IMAX = I
3330 NEXT I
3340 IF (ABS(BIGA)-TOL) =< 0 GOTO 3350 ELSE 3360
3350 PRINT "THE EQUATIONS HAVE NO MEANINGFULL SOLUTION":GOTO 6080
3360 I1 = J+N*(J-2)
3370 IT = IMAX - J
3380 FOR K=J TO N
3390 I1 = I1+N
3400 I2 = I1+IT
3410 SAV = A(I1)
3420 A(I1) = A(I2)
3430 A(I2) = SAV
3440 A(I1) = A(I1)/BIGA
3450 NEXT K
3460 SAV = B(IMAX)
3470 B(IMAX) = B(J)
3480 B(J) = SAV/BIGA
3490 IF J-N<>0 GOTO 3500 ELSE 3610
3500 IQS = N*(J-1)
3510 FOR IX=JY TO N
3520 IXJ = IQS+IX
3530 IT = J-IX
3540 FOR JX=JY TO N
3550 IXJX = N*(JX-1)+IX
3560 JJX = IXJX + IT
3570 A(IXJX) = A(IXJX) - (A(IXJ)*A(JJX))
3580 NEXT JX
3590 B(IX) = B(IX) - (B(J)*A(IXJ))
3600 NEXT IX,J
3610 NY = N-1
3620 IT = N*N
3630 FOR J=1 TO NY
3640 IA = IT-J
3650 IB = N-J
3660 IC = N
3670 FOR K = 1 TO J
3680 B(IB) = B(IB) - A(IA)*B(IC)
3690 IA = IA-N
3700 IC = IC-1
3710 NEXT K,J
3720 '
3730 '
3740 '
3750 '
```

```
3760 '
3770 '
3780 '
3790 '
3800 '          End of simultaneous equation solution routine
3810 '
3820 '***************************************************************************
3830 '
3840 '          We must now calculate the new values
3850 '
3860 AY = AY + B(1)
3870 '
3880 PHIS1 = PHIS1 + B(2)
3890 PHIS2 = PHIS2 + B(3)
3900 PHIU1 = PHIU1 + B(4)
3910 PHIU2 = PHIU2 + B(5)
3920 PHIU3 = PHIU3 + B(6)
3930 ZU1 = ZU1 + B(7)
3940 ZU2 = ZU2 + B(8)
3950 ZU3 = ZU3 + B(9)
3960 HU1 = HU1 + B(10)
3970 HU2 = HU2 + B(11)
3980 HU3 = HU3 + B(12)
3990 Y1 = Y1 + B(13)
4000 Y2 = Y2 + B(14)
4010 Y3 = Y3 + B(15)
4020 Z1 = Z1 - B(7)'          Used in calculating new spring deflection
4030 Z2 = Z2 - B(8)
4040 Z3 = Z3 - B(9)
4050 ZT1 = ZT1 - B(10)'       Used in calculating new tire deflection
4060 ZT2 = ZT2 - B(11)
4070 ZT3 = ZT3 - B(12)
4080 '
4090 '
4100 SPMAS1 = PHIS1*RAD:SPMAS2 = PHIS2*RAD:SPMAS3 = PHIS3*RAD
4110 '
4120 USPM1 = PHIU1*RAD:USPM2 = PHIU2*RAD:USPM3 = PHIU3*RAD
4130 '
4140 '          New spring deflections
4150 '
4160 DELS11 = Z1 - S1*(PHIS1 - PHIU1)
4170 DELS12 = Z1 + S1*(PHIS1 - PHIU1)
4180 DELS21 = Z2 - S2*(PHIS2 - PHIU2)
4190 DELS22 = Z2 + S2*(PHIS2 - PHIU2)
4200 DELS31 = Z3 - S3*(PHIS3 - PHIU3)
4210 DELS32 = Z3 + S3*(PHIS3 - PHIU3)
4220 '          Given the spring deflection, calculate the
4230 '          stiffness and spring force at that point
4240 '
4250 FOR J = 1 TO NUM(1)
4260 IF DELS11 < DEL(1,J) THEN GOTO 4280
4270 NEXT J
4280 IF J = 1 THEN J = J + 1
4290 IF J > NUM(1) THEN J = NUM(1)
4300 JS11 = J
4310 K11 = (F(1,J) - F(1,J-1))/(DEL(1,J)-DEL(1,J-1))
4320 F11 = F(1,J-1) + (DELS11 - DEL(1,J-1))*K11
4330 '
4340 FOR J = 1 TO NUM(1)
4350 IF DELS12 < DEL(1,J) THEN GOTO 4370
```

```
4360 NEXT J
4370 IF J = 1 THEN J = J + 1
4380 IF J > NUM(1) THEN J = NUM(1)
4390 JS12 = J
4400 K12 = (F(1,J) - F(1,J-1))/(DEL(1,J)-DEL(1,J-1))
4410 F12 = F(1,J-1) + (DELS12 - DEL(1,J-1))*K12
4420 '
4430 FOR J = 1 TO NUM(2)
4440 IF DELS21 < DEL(2,J) THEN GOTO 4460
4450 NEXT J
4460 IF J = 1 THEN J = J + 1
4470 IF J > NUM(2) THEN J = NUM(2)
4480 JS21 = J
4490 K21 = (F(2,J) - F(2,J-1))/(DEL(2,J)-DEL(2,J-1))
4500 F21 = F(2,J-1) + (DELS21 - DEL(2,J-1))*K21
4510 '
4520 FOR J = 1 TO NUM(2)
4530 IF DELS22 < DEL(2,J) THEN GOTO 4550
4540 NEXT J
4550 IF J = 1 THEN J = J + 1
4560 IF J > NUM(2) THEN J = NUM(2)
4570 JS22 = J
4580 K22 = (F(2,J) - F(2,J-1))/(DEL(2,J)-DEL(2,J-1))
4590 F22 = F(2,J-1) + (DELS22 - DEL(2,J-1))*K22
4600 FOR J = 1 TO NUM(3)
4610 '
4620 IF DELS31 < DEL(3,J) THEN GOTO 4640
4630 NEXT J
4640 IF J = 1 THEN J = J + 1
4650 IF J > NUM(3) THEN J = NUM(3)
4660 JS31 = J
4670 K31 = (F(3,J) - F(3,J-1))/(DEL(3,J)-DEL(3,J-1))
4680 F31 = F(3,J-1) + (DELS31 - DEL(3,J-1))*K31
4690 '
4700 FOR J = 1 TO NUM(3)
4710 IF DELS32 < DEL(3,J) THEN GOTO 4730
4720 NEXT J
4730 IF J = 1 THEN J = J + 1
4740 IF J > NUM(3) THEN J = NUM(3)
4750 JS32 = J
4760 K32 = (F(3,J) - F(3,J-1))/(DEL(3,J)-DEL(3,J-1))
4770 F32 = F(3,J-1) + (DELS32 - DEL(3,J-1))*K32
4780 '
4790 '
4800 '          New tire deflections
4810 '
4820 DELT11 = ZT1 -(T1 + A1)*PHIU1
4830 DELT12 = ZT1 -T1*PHIU1
4840 DELT13 = ZT1 + (T1 - Y1)*PHIU1
4850 DELT14 = ZT1 + (T1 + A1 - Y1)*PHIU1
4860 IF A1 > 0 THEN GOTO 4880
4870 DELT12 = 0:DELT13 = 0
4880 '
4890 DELT21 = ZT2 - (T2 + A2)*PHIU2
4900 DELT22 = ZT2 - T2*PHIU2
4910 DELT23 = ZT2 + (T2 - Y2)*PHIU2
4920 DELT24 = ZT2 + (T2 + A2 - Y2)*PHIU2
4930 IF A2 > 0 THEN GOTO 4950
4940 DELT22 = 0:DELT23 = 0
4950 '
```

```
4960 DELT31 = ZT3 - (T3 + A3)*PHIU3
4970 DELT32 = ZT3 - T3*PHIU3
4980 DELT33 = ZT3 + (T3 - Y3)*PHIU3
4990 DELT34 = ZT3 + (T3 + A3 - Y3)*PHIU3
5000 IF A3 > 0 THEN GOTO 5060
5010 DELT32 = 0:DELT33 = 0
5020 '
5030 '          When the inside tires leave the ground
5040 '          then their stiffness and deflection is set to zero
5050 '
5060 IF DELT11 > 0 THEN GOTO 5080
5070 KT11 = 0:DELT11 = 0
5080 IF DELT12 > 0 THEN GOTO 5100
5090 KT12 = 0:DELT12 = 0
5100 IF DELT21 > 0 THEN GOTO 5120
5110 KT21 = 0:DELT21 = 0
5120 IF DELT22 > 0 THEN GOTO 5140
5130 KT22 = 0:DELT22 = 0
5140 IF DELT31 > 0 THEN GOTO 5160
5150 KT31 = 0:DELT31 = 0
5160 IF DELT32 > 0 THEN GOTO 5180
5170 KT32 = 0:DELT32 = 0
5180 '
5190 '          Calculate tire forces
5200 '
5210 FZ11 = KT11*DELT11:FZ12 = KT12*DELT12:FZ13 = KT13*DELT13:FZ14 = KT14*DELT14
5220 FZ21 = KT21*DELT21:FZ22 = KT22*DELT22:FZ23 = KT23*DELT23:FZ24 = KT24*DELT24
5230 FZ31 = KT31*DELT31:FZ32 = KT32*DELT32:FZ33 = KT33*DELT33:FZ34 = KT34*DELT34
5240 '
5250 '
5260 '          When the spring forces become tensile then
5270 '          auxiliary roll stiffness has no effect
5280 '  NOTE:I have removed this effect as it seems unreasonable!
5290 '
5300 GOTO 5390
5310 FR1 = (WAXL1 - WU1)*(AY*COS(PHIU1) + SIN(PHIU1)):FR2 = (WAXL2 - WU2)*(AY*CO
S(PHIU2) + SIN(PHIU2)):FR3 = (WAXL3 - WU3)*(AY*COS(PHIU3) + SIN(PHIU3))
5320 MS1 = (F11 - F12)*S1 + FR1*COS(PHIS1 - PHIU1)*ZR1 + (F11 + F12)*SIN(PHIS1 -
 PHIU1)*ZR1 + KFR*(PHIS2 - PHIS1) - WFR*(AY*COS(PHIS1) + SIN(PHIS1))*ZFR1 - KRS1
*(PHIS1 - PHIU1)
5330 MS2 = (F21 - F22)*S2 + FR2*COS(PHIS2 - PHIU2)*ZR2 + (F21 + F22)*SIN(PHIS2 -
 PHIU2)*ZR2 - KFR*(PHIS2 - PHIS1) + (AY*COS(PHIS2) + SIN(PHIS2))*(WFR*ZFR2 + W5*
Z52) + M5*(PHIS3 - PHIS2) - KRS2*(PHIS2 - PHIU2)
5340 MS3 = (F31 - F32)*S3 + FR3*COS(PHIS3 - PHIU3)*ZR3 + (F31 + F32)*SIN(PHIS3 -
 PHIU3)*ZR3 + W5*Z53*(AY*COS(PHIS3) + SIN(PHIS3)) - M5*(PHIS3 - PHIS2) - KRS3*(P
HIS3 - PHIU3)
5350 MU1 = -(F11 - F12)*S1 + (FZ11 - FZ14)*(T1 + A1)*COS(PHIU1) + (FZ12 - FZ13)*
T1*COS(PHIU1) + FR1*ZU1 + KYT1*Y1*COS(PHIU1)*HU1 + (FZ13 + FZ14)*Y1 - KOVT1*PHIU
1 + (FZ11 + FZ12 + FZ13 + FZ14)*R1*SIN(PHIU1) + KRS1*(PHIS1 - PHIU1)
5360 MU2 = -(F21 - F22)*S2 + (FZ21 - FZ24)*(T2 + A2)*COS(PHIU2) + (FZ22 - FZ23)*
T2*COS(PHIU2) + FR2*ZU2 + KYT2*Y2*COS(PHIU2)*HU2 + (FZ23 + FZ24)*Y2 - KOVT2*PHIU
2 + (FZ21 + FZ22 + FZ23 + FZ24)*R2*SIN(PHIU2) + KRS2*(PHIS2 - PHIU2)
5370 MU3 = -(F31 - F32)*S3 + (FZ31 - FZ34)*(T3 + A3)*COS(PHIU3) + (FZ32 - FZ33)*
T3*COS(PHIU3) + FR3*ZU3 + KYT3*Y3*COS(PHIU3)*HU3 + (FZ33 + FZ34)*Y3 - KOVT3*PHIU
3 + (FZ31 + FZ32 + FZ33 + FZ34)*R3*SIN(PHIU3) + KRS3*(PHIS3 - PHIU3)
5380 '
5390 NRM1 = (FZ13*(T1 - Y1) + FZ14*(T1 + A1 - Y1) - FZ12*T1 - FZ11*(T1 + A1))*CO
S(PHIU1)/12'            These moments are all ft.lb
5400 NRM2 = (FZ23*(T2 - Y2) + FZ24*(T2 + A2 - Y2) - FZ22*T2 - FZ21*(T2 + A2))*CO
S(PHIU2)/12
```

```
5410 NRM3 = (FZ33*(T3 - Y3) + FZ34*(T3 + A3 - Y3) - FZ32*T3 - FZ31*(T3 + A3))*CO
S(PHIU3)/12
5420 MOMSUM = MS1 + MS2 + MS3 + MU1 + MU2 + MU3
5430 '
5440 '
5450 '
5460 '          If the trailer and rear tractor inside tires
5470 '          have lifted off the ground, the go to completion routine
5480 '
5490 IF (KT11 + KT12 + KT21 + KT22) = 0 THEN HALT$ = "1 and 2":GOTO 5970
5500 IF (KT21 + KT22 + KT31 + KT32) = 0 THEN HALT$ = "2 and 3":GOTO 5970
5510 IF (KT11 + KT12 + KT31 + KT32) = 0 THEN HALT$ = "1 and 3":GOTO 5970
5520 '
5530 PRINT #1,USING "#.####^^^^,";AY,USPM1,USPM2,USPM3,SPMAS1,SPMAS2,SPMAS3,NRM1
,NRM2,NRM3
5540 DOT = DOT + 1'     Used to mark tire lift-off in output file
5550 '          When the trailer or rear tractor inside tires
5560 '          lift off, mark this event somehow
5570 '
5580 IF LIFTAXL > 0 THEN GOTO 5630
5590 IF (KT11 + KT12) = 0 THEN LIFTAXL = 1
5600 IF (KT21 + KT22) = 0 THEN LIFTAXL = 2
5610 IF (KT31 + KT32) = 0 THEN LIFTAXL = 3
5620 IF LIFTAXL > 0 THEN GOTO 5870
5630 '
5640 '          Check if ready to print out,
5650 '          otherwise do another increment of DELPH
5660 '
5670 IF COUNT = 0 THEN CLS:LOCATE 6:PRINT "I am busy calculating. PLEASE DO NOT
DISTURB ME"
5680 COUNT = COUNT + 1 : GOTO 5780
5690 COUNT = COUNT + 1:LOCATE 10:PRINT "MSi = ";MS1;MS2;MS3:PRINT "MUi = ";MU1;M
U2;MU3
5700 PRINT "ZUi = ";ZU1;ZU2;ZU3:PRINT "HUi = ";HU1;HU2;HU3:PRINT "yi = ";Y1;Y2;Y
3:PRINT "NRMi = ";NRM1,NRM2,NRM3:PRINT "MOMSUM = ";MOMSUM
5710 TF1 = FZ11 + FZ12 + FZ13 + FZ14 - WAXL1:TF2 = FZ21 + FZ22 + FZ23 + FZ24 - W
AXL2:TF3 = FZ31 + FZ32 + FZ33 + FZ34 - WAXL3:PRINT "TFi = ";TF1;TF2;TF3
5720 SF1 = F11 + F12 - SW1*(COS(PHIU1)-AY*SIN(PHIU1)):SF2 = F21 + F22 - SW2*(COS
(PHIU2)-AY*SIN(PHIU2)):SF3 = F31 + F32 - SW3*(COS(PHIU3)-AY*SIN(PHIU3))
5730 PRINT "SFi = ";SF1;SF2;SF3
5740 PRINT "DELSij = ";DELS11;DELS12;DELS21;DELS22;DELS31;DELS32
5750 PRINT "JSij = ";JS11;JS12;JS21;JS22;JS31;JS32
5760 PRINT "Kij = ";K11;K12;K21;K22;K31;K32
5770 PRINT "Fij = ";F11;F12;F21;F22;F31;F32
5780 IF COUNT = LOOP THEN GOTO 5810 ELSE GOTO 1970
5790 '
5800 '           Print out the results
5810 PRINT #2,"":PRINT #2,USING "###.###";AY,USPM1,USPM2,USPM3,SPMAS1,SPMAS2,SPM
AS3;
5820 PRINT #2,USING "#######.";NRM1,NRM2,NRM3
5830 '
5840 '
5850 COUNT = 0:GOTO 1970
5860 '
5870 '          Lift axle routine
5880 '
5890 PRINT #2,"-----------------------------------------------------------------
-------"
5900 PRINT #2, "The inside tires on axle ";LIFTAXL;" have left the ground at the
 following conditions:"
```

```
5910 PRINT #2,"":PRINT #2,USING "###.###";AY,USPM1,USPM2,USPM3,SPMAS1,SPMAS2,SPM
AS3;
5920 PRINT #2,USING "#######.";NRM1,NRM2,NRM3
5930 '
5940 PRINT #2,"-----------------------------------------------------------------
-------"
5950 ISTAR = DOT'       Point in data where first axle lifts off
5960 GOTO 5630
5970 PRINT #2,"-----------------------------------------------------------------
-------"
5980 PRINT #2, "The vehicle is now unstable as the inside tires on axles ";HALT$
5990 PRINT #2, "have left the ground at the following conditions:"
6000 PRINT #2,"":PRINT #2,USING "###.###";AY,USPM1,USPM2,USPM3,SPMAS1,SPMAS2,SPM
AS3;
6010 PRINT #2,USING "#######.";NRM1,NRM2,NRM3
6020 '
6030 PRINT #2,"-----------------------------------------------------------------
-------"
6040 PRINT #1,USING "#.####^^^^,";AY,USPM1,USPM2,USPM3,SPMAS1,SPMAS2,SPMAS3,NRM1
,NRM2,NRM3
6050 PRINT #1,USING "#.###^^^^,";LIFTAXL,ISTAR
6060 WRITE #1,HALT$
6070 PRINT #2,CHR$(13)+CHR$(12)+CHR$(12)
6080 CLOSE:END
```

APPENDIX C

The Australian Road Research Board
Computer Model

ARRB COMPUTER MODEL INPUTS

1- Title

2- Front axle load
3- Tractor rear axle load
4- Trailer axle load

5- Tractor front sprung mass
6- Tractor rear sprung mass
7- Trailer front sprung mass
8- Trailer rear sprung mass

9- Tractor front unsprung mass
10- Tractor rear unsprung mass
11- Trailer unsprung mass

12- Half front axle track width
13- Half tractor rear axle track width
14- Half trailer axle track width
15- Half dual tire spacing on tractor rear axle*
16- Half dual tire spacing on trailer axle*

17- Front axle height
18- Tractor rear axle height
19- Trailer axle height

20- Front suspension height
21- Tractor rear sspension height
22- Trailer suspension height

23- Tractor front sprung mass C.G. height
24- Tractor rear sprung mass C.G. height
25- Trailer front sprung mass C.G. height
26- Trailer rear sprung mass C.G. height
27- Tractor chassis height
28- Trailer body height
29- 5th wheel pivot height

30- 5th wheel pivot to skid distance
31- 5th wheel half width

32- Front axle unsprung mass roll
compliance
33- Tractor rear unsprung mass roll
compliance
34- Trailer unsprung mass roll compliance

35- Front suspension roll compliance
36- Tractor rear suspension roll compliance
37- Trailer suspension roll compliance

38- Front axle unsprung mass
lateral movement coefficient
39- Tractor rear axle unsprung mass
lateral movement coefficient
40- Trailer axle unsprung mass
lateral movement coefficient

41- Front axle unsprung mass
vertical movement coefficient
42- Tractor rear axle unsprung mass
vertical movement coefficient
43- Trailer axle unsprung mass
vertical movement coefficient

44- Tractor chassis roll compliance
45- Trailer body roll compliance

* : used only when the program is extended to calculate 2nd wheel lift but there might be no solution with the method used.