The Effect of Torque Reaction on the Tractive Performance of a Quarter Scale Model Four-Wheel-Drive Tractor with Locked and Unlocked Differentials

by

James Thomas Dunn

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presented to the University of Manitoba
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THE EFFECT OF TORQUE REACTION ON THE TRACTIVE PERFORMANCE OF A QUARTER SCALE MODEL FOUR-WHEEL-DRIVE TRACTOR WITH LOCKED AND UNLOCKED DIFFERENTIALS

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ABSTRACT

A Taurus-One data acquisition system, controlled by a Corona microcomputer, was used to measure torque on the four axles and the front and rear drive shafts and also to measure drawbar pull on a quarter scale model four-wheel-drive (4WD) tractor. The model was used to test the hypothesis that the shift in axle load caused by the drive shaft torque does not affect the tractive efficiency of the vehicle because the wheels with least load have a higher slip which allow them to pull as much as the other wheels.

Three series of tests of the model were carried out in the Agricultural Engineering soil bin. The first tests included three wheel slip conditions (10 percent, 15 percent and 20 percent), three static weight distributions (51:49, 56:44 and 62:38) and two differential conditions (locked and unlocked). The second series of tests included two wheel slip conditions (10 percent and 15 percent), three static weight distributions and two differential conditions. The third and final series of tests involved two wheel slips, two static weight distributions (60:40 and 70:30) and two differential conditions.

Results of the first two series of tests were considered unacceptable since the torques indicated on the two axle shafts for the same unlocked differential were different. This lead to modifications before the final series of tests. Results of the final series of tests indicate that during testing of the model, there was no difference in torque applied to each wheel when the differentials were locked or unlocked.

It was concluded that the Taurus-One data acquisition system and Corona microcomputer were adequate for measurement of the six torques and the draft load while the tractor underwent testing. It was also concluded that the tests of the hypothesis being considered were inconclusive.

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INTRODUCTION

Four-wheel-drive (4WD) tractors have become a common machine on many farms throughout the world. As with all farm machinery today, the efficiency of these tractors has been the subject of considerable engineering research. The operating costs for any tractor are influenced not only by engine efficiency but by tractive efficiency as well. Tractive efficiency can be defined as the ratio of the input power to a tractive device to the output power of that device. Thus the tractive efficiency indicates the ability of a tractor to convert axle power to drawbar power.

An interesting phenomenon peculiar to the 4WD tractor is the torque reaction effect. This effect is the result of the rear axle assembly being able to oscillate within the frame of the tractor. The drive shaft which delivers power from the engine to the rear axles, transmits a torque to the assembly housing inducing a shift in weight between the two wheels on the assembly. This shift in weight which adds load to one wheel and decreases the load on the other is the torque reaction to the driving shaft.

<u>A conceptual hypothesis that is being considered is that the shift in axle loading caused by the drive shaft torque does not reduce the tractive efficiency of the vehicle because the wheels with the least load have a greater slip which enables them to pull as much as the other wheels</u>.

There has been substantial work done on the subject of tractive efficiency and the effect of slippage on performance in both two-wheel-drive (2WD) and 4WD tractors. Some of the research which is pertinent to this project is discussed in the Review of Literature section of this chapter.

1.1 REVIEW OF LITERATURE

1.1.1 Computer simulation models

The use of computer simulation models to determine the effects of changing variables on traction characteristics of 4WD tractors has gained popularity in recent years. This type of analysis is particularly appealing because the model can be modified with little difficulty to simulate different conditions.

In the model developed by Macnab, Wensink and Booster (1977), the equations presented by Wismer and Luth (1974) are used to predict the effects of tractive performance and soil strength on the fuel economy of agricultural tractors. The equations used were (Wismer and Luth, 1974):

$$TF/W = 1.2/Cn + 0.04 \quad \text{for a towed wheel} \qquad [1]$$

where:

TF = towed force of wheel, kN
W = dynamic wheel load, kN
Cn = wheel numeric, CIbd/W
CI = cone index as obtained by ASAE standard S313.1, kPa
b = unloaded tire section width, m
d = unloaded overall tire diameter, m

The equation for a driving wheel is:

$$P/W = 0.75(1-\exp(-0.3CnS)) -(1.2/Cn + 0.04) \qquad [2]$$

where:

P = net wheel pull, kN
S = wheel slip, decimal form
W,Cn = same as equation 1

This equation is valid for cohesive-frictional soils of moderate compactability and pneumatic tires with a b/d ratio of approximately 0.3 and a radius to diameter ratio of approximately 0.475. A plot of the slip-pull relationship using this equation is shown in Figure 1.1.

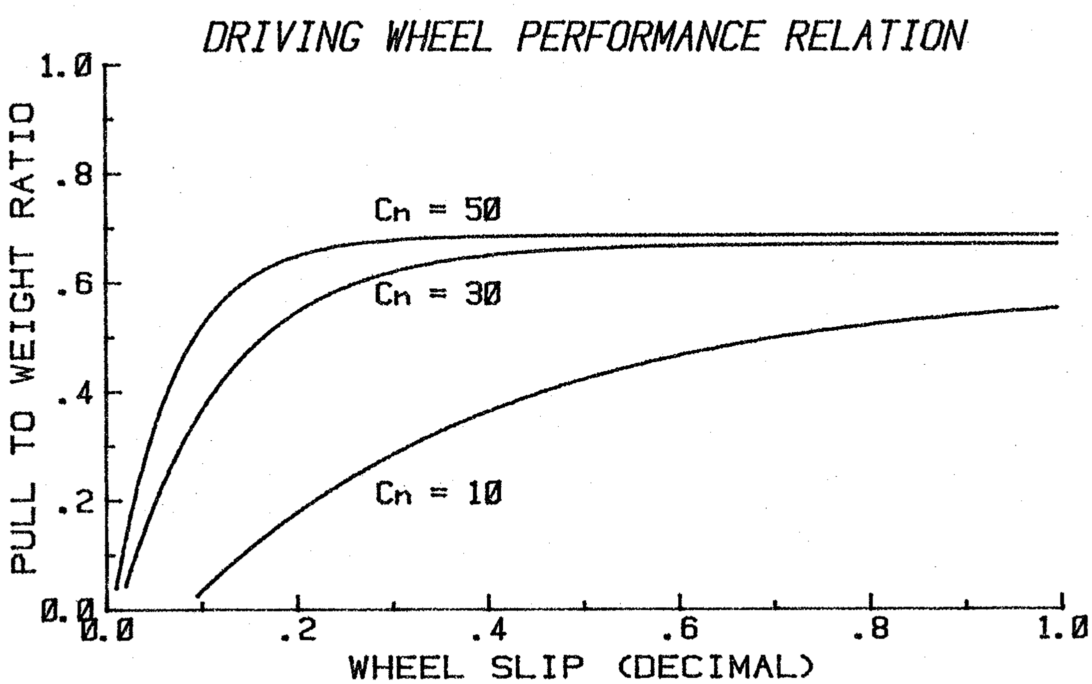

Figure 1.1: Slip pull relationship described by Wismer and Luth (1974)

The equation used for tractive efficiency (Wismer and Luth, 1974) of a wheel is:

$$TE = \left[1 - \left[\frac{1.2/Cn + 0.04}{0.75(1 - \exp(-0.3CnS))} \right] \right] (1-S) \qquad [\ 3\ ]$$

where:
TE = tractive efficiency
Cn,S = same as equation 2

Macnab et al. (1977) combined the above equations to obtain:

TTE4 = (DBP4)/((GPF/(1-FSLIP))+(GPR/(1-RSLIP))) [4] where:

TTE4 = tractor tractive efficiency 4WD
DBP4 = drawbar pull 4WD, kN
GPF = gross front axle pull, kN
GPR = gross rear axle pull, kN
FSLIP = front axle slip, decimal
RSLIP = rear axle slip, decimal

The drawbar power is converted to equivalent axle power:

$$AP4 = (DBP4/TTE4) * V \qquad [\ 5\ ]$$

where:

AP4 = axle power 4WD, kW
DBP4 = drawbar pull 4WD, kN
V = tractor speed, m/s

This computer model was verified using five 2WD tractors and one 4WD tractor with dual tires. The results indicated that the model predicted the tractive performance of the tractor reasonably accurately. Experimental results did not agree with predicted values on test plots containing vegetative cover because of the slick surface caused by the vegetation.

Khalid and Smith (1981a) used the equations developed by Wismer and Luth (1974) with some of the terms empirically modified to reflect the change in the cone index of the soil due to the passage of the front wheels. Two scale models were utilized to determine the empirical coefficients used in the modified equations. The equations developed for 4WD tractors were:

Torque ratio:

$$TF/TR = f(Vf/Vr) \qquad [\ 6\ ]$$

$$= a\left[\frac{WF - (V*X/B + H*Y/B)}{WR + (V*X/B + H*Y/B) + V}\right] \qquad [\ 7\ ]$$

where:

TF = torque on front axle
TR = torque on rear axle
Vf = dynamic weight on front axle
Vr = dynamic weight on rear axle
WF = static weight on front axle
WR = static weight on rear axle
H = horizontal component of drawbar load
V = vertical component of drawbar load
X, Y = coordinates of hitch position with the origin at the intersection of the rear axle center line and the ground surface
B = wheel base
α = constant to be calculated from experimental data

Values of α obtained from experimental data were 0.74 for the 1/5.7 scale model and 0.79 for the 1/10.94 scale model. The difference was attributed to different types of tire tread and to scaling.

Coefficient of rolling resistance:

$$RR/W = \beta Cn + \gamma \qquad [\ 8\ ]$$

where:

RR = one quarter of the tractor rolling resistance
W = one quarter of the tractor dynamic weight
Cn = wheel numeric
β, γ = constants evaluated from experimental data

Values obtained from experimental data were:

$$RR/W = 0.28 - 0.0029Cn \quad \text{for the 1/5.7 model} \qquad [\ 9\ ]$$

$$RR/W = 0.10 - 0.0008Cn \quad \text{for the 1/10.9 model} \qquad [\ 10]$$

It was concluded that the soil was not scaled properly for the 1/10.9 scale model and that the 1/5.7 scale model provided data that was comparable to full size tractors.

The equation developed for the relationship between slip and pull was:

$$P/W = \Theta(1-\exp(-S(l+uCn))) - (\beta Cn+\gamma) \qquad [11]$$

where:

P = one quarter of the net tractor pull, kN
W = one quarter of the tractor dynamic weight, kN
S = slip, decimal form
Cn = wheel numeric
Θ,l,u = constants evaluated from experimental data
β,γ = same as equation 8

The following two expressions describe the slip - pull relationship for the two models:

For the 1/5.7 scale model:

$$P/W = 0.84(1-\exp(-11.4S))-(0.28-0.0029Cn) \qquad [12]$$

For the 1/10.9 scale model:

$$P/W = 0.73(1-\exp(-8.2S))-(0.10-0.0008Cn) \qquad [13]$$

Khalid and Smith (1981a) determined that:

1. In compactable soils, the front wheels leave a firmly packed tractive surface for the rear wheels. The strength of the soil surface that the rear wheels encounter may not be proportional to that of the front wheels because the soil can only be compacted to a certain level. Thus even though the front tires may encounter variations in the soil surface, the rear wheels would not experience such a severe variation.

2. The contact area of the front tires increases as soil strength decreases and therefore the gross pull of the front axle in firm soil would be similar to that developed in soil with a lower strength. Hence the gross pull of a 4WD tractor may not be affected greatly by slight variations in soil strength.

The tractive efficiency equations developed for the experimental scale models were:

$$TE = \left[1 - \frac{0.28-0.0029Cn}{0.84(1-\exp(-11.4S))}\right](1-S) \quad \text{for } 1/5.7 \text{ model} \qquad [14]$$

$$TE = \left[1 - \frac{0.10-0.0008Cn}{0.73(1-\exp(-8.2S))}\right](1-S) \quad \text{for the } 1/10.9 \text{ model} \qquad [15]$$

Khalid and Smith (1981a) concluded that the equations developed for the 1/5.7 scale model were useful in estimating available drawbar pull, slip, distribution of power between the axles (front and rear) and the tractive efficiency of a full scale 4WD tractor.

Peters (1983) used equations based on summing the moments about the rear axle for use in a computer model to predict traction parameters for 4WD tractors. He concluded that this method is a useful method of analysis. The number of different inputs to the computer program and the different formats of outputs produced make it a versatile tool in weight transfer and tractive efficiency analysis.

In the development of a computer model using differential equations to describe the performance of agricultural tractors, Summers, Ekstrom and Von Bargen (1983) made several simplifying assumptions about torque and load distribution on a 4WD tractor. The assumptions were:

1. The force supported by the front axle is evenly distributed between the front wheels.
2. The force supported by the rear axle is evenly distributed between the rear wheels.

3. The angular displacements, velocities and accelerations are equivalent for drive wheels mounted on the same axle
4. The drive wheels on each axle develop equivalent tractive efforts.

The above assumptions may be true for a 2WD tractor but are not necessarily applicable to 4WD tractors.

The computer model was validated by testing only a 2WD tractor simulating the lugging ability test of the Nebraska Tractor Tests, and comparing the experimental results to the predicted results. Errors in this comparison were 24.5 percent for forward velocity, 7.3 percent for wheel slippage and 20.2 percent for engine speed.

Summers and Von Bargen (1983) used modified differential equations to predict the performance of farm tractors and found that the results obtained by simulating the lugging ability test of the Nebraska Tractor Test Number 1313 were close to the actual experimental values. The accuracy for the 4WD tractor was not as good as for the 2WD but was acceptable.

Clark (1984a) proposed a modified Wismer and Luth (1974) model for traction modeling:

For a towed wheel:

$$TF/W = C1/Cn + C2 \qquad [16]$$

For a driving wheel:

$$P/W = C3(1 - \exp(-C4CnS)) - (C1/Cn + C2) \qquad [17]$$

where C1 through C4 are constants related to the specific soil types and ground cover conditions. The constants are determined experimentally. Data required for determining C1, C2, C3, and C4 include tractor specifications, soil data and tractor performance data.

1.1.2 Scale model studies

Murillo-Soto and Smith (1976) used statics to obtain equations to describe the performance of a 4WD tractor. To evaluate the validity of these equations a 1/10.94 scale model of a 7020 John Deere tractor with two 480 W DC electric motors - one for each axle was used. The torque and vertical and horizontal forces acting on each axle were measured with the use of extended ring dynamometers. Angular velocity of the axles and sinkage of the front and rear wheels were also measured. Drawbar load was applied through a series of pulleys, cables and weights. Tests were done on dry sand so that repeatable soil conditions could be obtained. Three drawbar heights and four different ratios of front axle angular velocity to rear axle angular velocity were tested. Three replicates of each test were conducted.

Murillo-Soto and Smith (1976) observed a "push-pull" effect at all times during the testing of this model. They noted that "torques and vertical and horizontal forces varied between positive and negative values continuously". This effect was thought to have been caused by relative slips between front and rear wheels, to the angular acceleration and to the desychronization of the lugs on the wheels. They conclude that the conditions of static equilibrium do not account for the values of weight transfer observed and that an acceleration term must be included in the analysis.

Using the 1/10.94 scale model of Murillo-Soto and Smith (1976), Murillo-Soto and Smith (1977) conducted more testing on sand and additional testing on a clay loam soil. The same combinations of static weight distribution, drawbar positions and ratios of front to rear axle angular velocity were used. With a modified prediction model they found experimental values differed by an average of eight percent from predicted values of weight transfer. It was concluded that tractive efficiency was affected by static weight distribution, total drawbar load, drawbar height, ratio of angular velocities of the axles and total static weight. Changing the ratio of axle angular velocities to values different than unity increased the push-pull effect.

Murillo-Soto and Smith (1978) investigated the push-pull effect further using the 1/10.94 scale model on dry sand and clay loam. A computer simulation model of this effect was also included in the analysis. In this simulation the difference in soil compaction experienced by the front and rear wheels was included. Tests were conducted using lugged tires and smooth tires. An increase in tractive efficiency of three to five percent was observed with the smooth tires. The push-pull effect did not disappear and the pattern did not change noticeably when the smooth tires were tested. The simulation model produced tractive efficiency values which were in error with experimental results by an average of nine percent. They concluded that the push-pull effect in 4WD tractors is caused by normally distributed instantaneous relative slips of front and rear wheels.

Khalid, Smith and Smith (1980) constructed a 1/5.7 scale model to examine the effects of rolling radius, dynamic weight distribution and drawbar load on the torque split between the axles of a scale model 4WD tractor. Tests were conducted on dry sand, clay loam and an asphalt surface. They concluded that rolling radii of the tires and dynamic vertical load on the axle affect the pull developed by that axle.

More work was conducted on the 1/5.7 scale model (Khalid and Smith, 1981b) and it was determined that altering the distribution of axle torques did not have a significant effect on tractive efficiency. They also commented that reduced drive train wear would result if the torque on both axles could be equalized.

1.1.3 Full scale studies

Domier, Friesen and Townsend (1971) conducted field evaluations of a 2WD, 4WD and a crawler tractor. The evaluation consisted of measuring drawbar pull, travel reduction (slip) and forward speed. To measure drawbar pull, a hydraulic cylinder attached to a pressure recorder was used. Event markers on the same chart recorder were used to record wheel or track revolutions. Tests were made on three fields with different surface conditions.

In comparing traction characteristics of 2WD and 4WD tractors, they noted that as the traction conditions improve, the difference between 2WD and 4WD tractors decreases. Tractive efficiencies for the 2WD tractor ranged between 55.2 to 68.9 percent and between 68.3 and 74.5 percent for the 4WD tractor.

Dwyer and Pearson (1976) compared the tractive performance of a 2WD tractor, a 4WD tractor with unequal sized tires front to rear and a 4WD tractor with equal sized wheels. Tests were conducted in 13 different fields while ploughing. Drawbar pull was measured using a three-point linkage dynamometer. Slip was calculated by measuring no slip travel distance per revolution and by measuring travel distance per revolution while under load. Measurements under load were made with the tractors "ploughing in the normal way" and the differential lock engaged. All three tractors had the same 63 PTO kW engine. They concluded that the 4WD tractor with equal sized wheels was capable of 14 percent more drawbar power than the 2WD tractor. Similarly, the 4WD with unequal sized wheels was capable of 7 percent more drawbar power than a 2WD. They also stated that 4WD tractors should be designed to operate with a drawbar pull equal to 40 percent of the combined weight of the ballasted tractor and mounted implement. The 4WD tractor should run at 10 percent slip and operate in the highest gear possible without engine stall to obtain maximum rate of work.

Clark and Adsit (?) developed an instrumentation system to measure engine speed, ground speed, fuel flow rate, drawbar pull and torque, load and speed for each of the four wheels on a low powered tractor with front wheel assist. The tractor used was a Kubota L245DT 4WD diesel. Axle torque was measured using strain gage torque transducers and slip ring collectors. Axle loading was measured using strain gages mounted on the axle housings. Drawbar pull was measured using a three point linkage strain gage dynamometer. Measurements were taken using a data acquisition system controlled by a microcomputer mounted on the tractor. Calibration of the transducers involved three replicated applications of known levels of each physical variable over the expected range of the transducer. A correlation coefficient of at least 0.99 resulted for each regression of voltage output versus the real physical variable.

In a presentation of raw data collected with this system a difference in torque of 4.1 percent between wheels on the front axle and a difference of 10.1 percent between wheels on the rear axle was apparent. No mention of the differentials being locked was given nor was there an explanation of why the difference existed.

A field study was undertaken by Erickson, Larsen and Rust (1982) to evaluate 4WD tractors in a typical Montana summerfallow environment.

Performance was tested under high, low and normal draft conditions. Drawbar pull, front and rear wheel rotation, travel distance, axle torques and elapsed time were measured during each test. High speed movies were employed to investigate instantaneous slip levels of the individual tires.

It was noted that severe harmonic vibrations were induced in the tractor-implement system. These vibrations seemed to be related to the bite-slip characteristics of the tires and uneven pulling by front and rear tractor axles. Variations in soil properties may also have been involved in these vibrations.

Musonda, Bigsby and Zoerb (1983) developed instrumentation involving FM radio telemetry to transmit signals representing torque on the drive shafts of a Stieger Bearcat 220. The torque was sensed using strain gages mounted at 45° from the axis of the shaft. Axle and ground speeds were also recorded using eddy current metal detectors as angular position encoders. Draft was measured using a force transducer mounted at the drawbar.

They concluded that the torque measuring techniques using radio telemetry was very accurate, reliable and overcame any noise problems associated with slip rings. Also, eddy current transducers work ideally for field conditions because they are not contaminated by dust and can withstand shocks.

Clark (1984b) used a Kubota L245DT 4WD tractor which was instrumented to measure drawbar pull, ground speed, fuel consumption, engine crankshaft speed, front and rear wheel torque and front and rear wheel weight to evaluate the field performance of a 16.7 PTO kW tractor in two and 4WD modes. Tests were conducted on three soil types.

He found that maximum drawbar power developed by the 4WD tractor was between 45 percent to 124 percent greater than that developed by the 2WD tractor depending on soil characteristics. Maximum field speed without excessive slip increased from 45 to 106 percent using the same implement.

Clark (1984c) again used the Kubota tractor which had been modified to measure torque and speed of each individual wheel to determine factors required to create a reliable traction model. Tests were done on a flat asphalt surface and in an apple orchard. A computer program was used to calculate power inputs to wheels, drawbar power, tractive efficiency, slip for each wheel, pull for each wheel, drawbar pull, pull to dynamic load ratio for each wheel and drawbar pull to driving wheel load ratio from the measured quantities. It was found that in all cases there was not a significant difference between the pull and dynamic load for each wheel of a set (front or rear). Also, there was not a significant difference in slip between the driving wheels.

In the review of the current literature dealing with tractive efficiency of 4WD tractors, no information was found dealing with the effect of drive shaft torque on the net pull and tractive efficiencies of each of the wheels on one axle.

1.2 THEORY OF TORQUE REACTION

The pull developed by a tractive device is a function of the weight on the device, soil parameters and wheel slip (Wismer and Luth, 1974). For a 4WD tractor with four equal sized wheels, the weight on the wheels is affected by the torque on the drive shaft, the static weight on the wheel and the load transfer due to the draft load. The drive shaft torque causes a shift in loading of two wheels on an axle assembly which is equal to the torque on the drive shaft divided by the distance between the two wheel centers. If the equation for pull to weight ratio presented by Wismer and Luth (1974) is examined (Figure 1.1), it can be seen that as slip and/or dynamic load increases, the pull to weight ratio also increases. A tractive device with zero slip will therefore have a pull to weight ratio of nearly zero. Therefore, the load transfer created by the drive shaft torque causes two things to happen. First, the wheel with the extra load applied can produce a larger tractive effort due to the increased load. Second, the wheel with load removed from it tends to slip more because of the loss of load. Within certain limits this wheel also tends to develop more tractive force. A differential located in the axle assembly is theoretically a divider of torque and transmits an amount of torque to each of the wheels which is equal to the resisting torque of the wheel with the least traction. To calculate the change in pull and/or tractive efficiency of each of the wheels due to the drive shaft torque is very difficult because the individual wheel slips are not known or readily calculated.

The objective of this project was to develop a data acquisition system to monitor axle and drive shaft torques to determine whether the shift in loading caused by the drive shaft torque affects the tractive performance of a 4WD tractor. The hypothesis was that the tractive performance would not be affected because the wheels with least load have a greater slip and this allows them to pull as much as the other wheels. This is an interesting hypothesis on 4WD tractor traction performance.

The shift in load on an axle assembly decreases with gear ratio within the differential. The effect is greater for example on a truck with a gear ratio of 4:1 compared to a tractor with a gear ratio of 10:1 or 25:1. In a typical 4WD tractor with a 25.79:1 final drive reduction, the change in wheel load due to the drive shaft torque when the tractor is operating at 85 percent of its rated 106 kW drawbar power (available drawbar power is 75 percent of engine power) can be calculated as 675 N. This means that two diagonally opposite wheels would have 675 N added to the weight on each wheel and the other two wheels would have 675 N removed from each weight on the wheel. This 675 N represents approximately 1.6 percent of the weight on the wheel under normal operating conditions.

The method used to test the hypothesis was to first conduct tests with locked differentials in the model and then conduct the same series of tests with unlocked differentials. By comparing individual wheel torques between these two differential conditions, it should be evident whether there was a torque reaction effect. If there was a torque reaction effect, then one wheel on an axle assembly should carry more torque if the differential was locked than it would when the differential was unlocked. Similarly, the other wheel on the axle assembly should have less torque when the differential was locked than it would if the differential was unlocked.

Chapter II

DESIGN AND INSTRUMENTATION

The scale model 4WD tractor constructed by Dunn (1983) was the foundation for the scale model to be used in this project. This model was an approximate quarter scale model of a typical 4WD tractor. A 1.5 kW electric motor provided the power which was delivered to the axles through a belt and chain reduction of approximately 5.47:1. The belt drive consisted of two "B" V-belts, driving a jackshaft from the motor. The front and rear axle assemblies were driven by the jackshaft through a chain drive. Unloaded mass of the tractor was 326.5 kg. The forward speed of the model under no load conditions was 0.667 m/s (2.4 km/h). Specifications of the model are given in Table A.1 in Appendix A.

2.1 INITIAL MODIFICATIONS

Before useful data could be obtained from the original model, major modifications had to be completed. These initial modifications included:

1. Replacing worm gear final drives with differentials.
2. Incorporating a draft measurement device.
3. Installing load cells to measure weight change on both the front and rear axles.
4. Installing load racks above the front and rear axles to vary the weight distribution.

5. Developing a motor speed measurement device.
6. Allowing the hitch position to be varied in the vertical direction.
7. Replacing the Hewlett Packard data acquisition system with a Taurus-One data acquisition system controlled by a Corona microcomputer.

2.1.1 Differentials versus worm drives

To measure the effect of torque reaction on the tractive performance of the model a comparison between locked and unlocked differentials was required. Since the worm drives that were initially used as final drives could only act as locked drives, the worm drives were replaced with differentials. The differentials used were designed for golf carts and had a gear ratio of approximately 12.3:1.

The differential assemblies had to be modified to be used in the model. One of the axles and the axle housing on each of the assemblies were shortened so that both axle ends were the same distance from the center line of the input shaft to the differential. Special customized mounting brackets were designed to support the assemblies in the frame. A 127 mm inside diameter roller bearing and a 19.05 mm pillow block were used to mount the rear assembly in the frame in such a way that it could oscillate about the drive shaft. This allowed the torque on the drive shaft to be transmitted to the entire axle assembly independently of the frame. The front axle assembly was mounted solidly to the frame.

In order to lock the differential mechanism an insert was constructed for each differential. This insert fitted inside the carrier of each differential and jammed the spider gears to prevent turning. The insert was held in place using a set screw tightened against the ring gear. This effectively created a continuous axle assembly.

The original torque transducers for the wheels were retained and the wheel hub and transducer assemblies were modified so that they could be bolted directly to the axle hub of the differential.

2.1.2 Draft measurement

Measurement of the draft force developed by the model was achieved through the use of an Interface SM500 load transducer. This transducer was designed for a maximum load of 2230 N. It was considered that at times the draft might exceed this value so a draft doubling mechanism to double the maximum load that could be measured by the system was constructed. The transducer assembly was constructed in such a way that it could easily be mounted on the tool bar of the soil bin and the tractor drawbar could be connected to the assembly.

2.1.3 Axle vertical load transfer measurement

Vertical load change sensing for the front and rear axle assemblies was achieved using four support members between the axle assembly and the tractor frame. These support members acted as four beams fixed on both ends with strain gages mounted on the members in positions of maximum strain. Eight gages were used for both the front and the rear axles. These eight gages were connected into a full Wheatstone bridge circuit with two gages per arm of the Wheatstone bridge in such a way that only vertical load would be sensed.

2.1.4 Additional load racks

Angle iron framing was used to construct weight racks to enable additional weights to be added directly above both front and rear axle assemblies. These racks were built so that they could each hold a maximum of six 20 kg suitcase weights.

2.1.5 Motor speed measurement

Motor angular speed was measured using a magnet attached to the jackshaft driven by the motor. The magnet activated a reed switch each revolution. The signal from the reed switch was then converted to a voltage output that was linearly related to the rev/min of the shaft. The voltage signal was read using one of the Taurus-One channels configured as a full bridge circuit. The 10 volt supply voltage for this device was supplied by the same Taurus-One channel.

2.1.6 Variable hitch position

The hitching position to attach the tractor to the draft sensing assembly was modified to enable it to be raised or lowered on the tractor. The draft load could be applied anywhere from 60 mm above the center of the rear axle to 60 mm below the axle.

2.1.7 Data acquisition system

Using the Hewlett-Packard data acquisition system it was found that the maximum scanning rate that could be reached was in the order of 10 channels/second. It was considered that in the 10 second time span that a typical test would take, 10 or 12 samples of each channel would not be sufficient to give good accuracy of the measured variables. To obtain faster scanning of several channels, a Taurus-One data acquisition unit and a Corona microcomputer were selected. With the Taurus-One system a maximum scanning rate of about 1000 channels per second could be achieved. This means that 10 channels could be scanned 100 times in one second which would result in sufficient accuracy.

2.2 CALIBRATION OF TRANSDUCERS ON THE MODIFIED MODEL

After the necessary modifications were completed the transducers were calibrated in the lab using the new data acquisition system. The Taurus-One system used a fraction of the input voltage as the output signal indicating change in resistance of the strain gage on the transducer. For a gain of 100 (signal is amplified 100 times), the maximum voltage output of 0.1 volts is represented by the number 2047. Similarly, a voltage of -0.1 volts is represented by the number -2048. Thus the voltage output across the Wheatstone bridge can be calculated by multiplying the Taurus-One output number by 0.1/2047.

2.2.1 Calibration procedure

Since the Taurus-One and Corona were used for calibration as well as data for acquisition, it was not necessary to convert the readings from the Taurus-One into voltages and then into strains. Rather, calibration of the transducers was done as a function of the output of the Taurus-One and this output was used to produce a calibration curve. To do this an unstrained or zero reference reading for each channel was taken and then the difference between this value and the value at an incremented load was taken to produce data points to be used in producing a calibration curve.

For all calibrations of the drive shaft transducers the same general procedure was followed. The jackshaft which drove the drive shafts was held from turning. A small torque arm (length varied depending on front or rear drive shaft) was attached to the shaft on the differential side of the transducer. Weights were added to a pan at the end of the torque arm and a reading from the Taurus-One unit was taken for each increment of torque applied using the CALIBRAT program. Increments of approximately 5 Nm (depending upon torque arm length) were used up to a maximum torque of 40 Nm. This procedure was repeated for three replications to provide enough data points to obtain a calibration curve for each drive shaft.

Calibration of the axle transducers for test series #1 was done with the transducers on the tractor. A torque arm was constructed which would bolt directly on to the wheel hub using the stud bolts for the wheel. The wheel was lifted off the ground and the axle was held from turning. Weights were added to the pan at the end of the 1019 mm torque arm and a reading was taken from the Taurus-One for each increment of torque. Increments of 10 Nm up to a maximum of 140 Nm were used to obtain data for a calibration curve.

For test series #2 and #3 the axle torque transducers were calibrated with the axles removed from the model. The axle, transducer and wheel hub assembly were supported between lathe centers in a lathe (Figure 2.1). The tool carrier of the lathe was positioned under the wheel hub in such a way that the wheel hub could not rotate. The torque was applied to the axle by a torque arm assembly consisting of a spare spider gear from the differential with a 509 mm torque arm welded to it. Weights were then added to a pan at the end of this torque arm to apply torque to the axle in the same way that torque would be applied when the axle was in the differential on the tractor. To obtain data for the calibration curves three loadings were conducted using increments of 25 Nm up to a maximum of 210 Nm. Readings were taken for each torque increment using the CALIBRAT program.

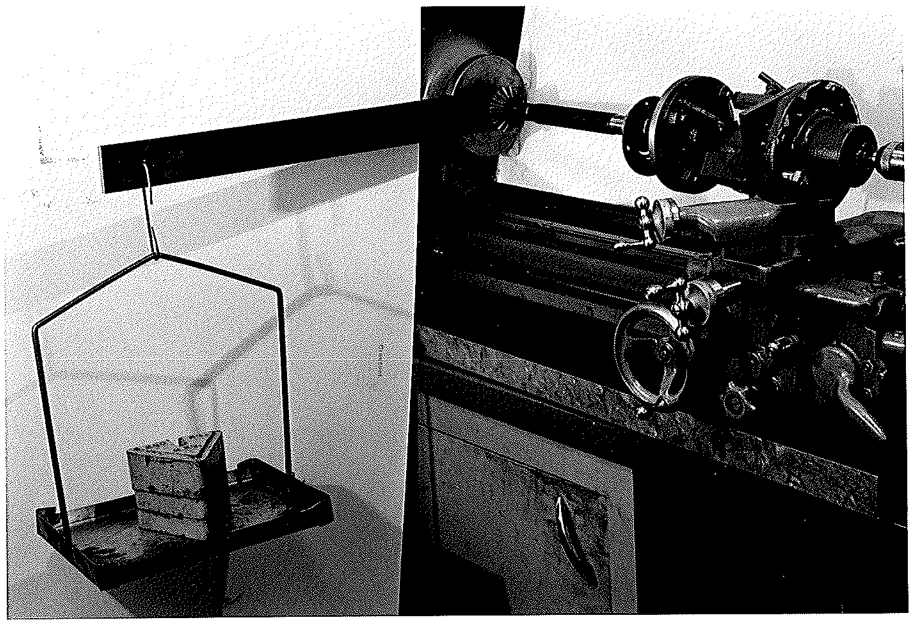

Figure 2.1: Calibration set up for axle transducers

The data obtained through these calibrations were used in the University of Waterloo Statistical Analysis System (SAS) package on the University of Manitoba main frame computer to obtain calibration curves. A linear regression was applied to the data points to obtain a slope and intercept to describe the variables as a function of the output of the

Taurus-One unit. A correlation coefficient of at least 0.999 was obtained in the linear regression for each transducer. Results for the final calibration of the torque transducers and the draft transducer are shown in Table B.1 in Appendix B. Calibration curves for the seven transducers are also shown in Appendix B.

The load sensing transducers for the front and rear axles and the motor speed transducer were not calibrated because it was felt that these variables were not required.

2.3 PROBLEMS AND MODIFICATIONS

Some preliminary tests were conducted as described in "TESTING PROCEDURE AND COMPUTER PROGRAMS". In analyzing the results obtained from these tests, it was discovered that the indicated torques on the two axles on the same unlocked differential were not equal. A difference of upwards of 30 percent was observed between the two rear wheels and also between the two front wheels. Since the theory of a differential states that these torques must be equal the task of determining the cause of this difference was undertaken.

2.3.1 Modifications for test series #2

Several recalibrations of the torque transducers on the wheels and drive shafts under various conditions led to several obviously different calibration curves. Calibrations were conducted both with the axles in place on the tractor and also when supported in a lathe. Since it was found that the calibration curves were not repeatable it was assumed that there was some mechanical or electrical problem with the transducers. After carefully checking the strain gages, slip rings and wiring, the loading of the transducer was examined while a torque was applied to the wheel. It was observed that the irregularity of the reading could have been caused by binding of the transducer pin in the drive hole on the wheel hub. The reason the pin was binding in the hole was because of the deflection of the transducer while it was loaded. In order to eliminate this binding, the hole was elongated into a sloted configuration with a flat side for the pin to slide on (Figure 2.2). All four axle transducers were modified in this way and then they were recalibrated. To calibrate the modified transducers the axle assembly was removed from the tractor and was supported between lathe centers.

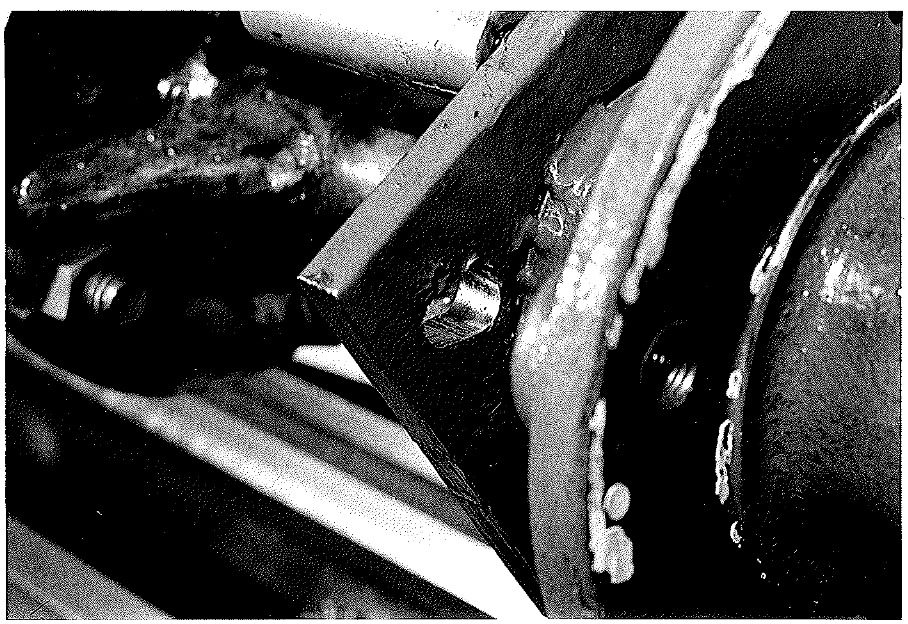

Figure 2.2: Slotted hole in drive plate on the wheel hub

In addition, the drive shaft transducers were examined and it was found that binding could have been occurring between the sprocket and the drive shaft as well. To eliminate this the sprockets were bored out and needle bearings were inserted. This effectively eliminated the binding of the sprockets on the drive shaft. The drive shaft transducers were then recalibrated to obtain new calibration curves for the drive shafts.

In order to simulate a larger torque on the drive shafts of the model torque arms were attached directly to the two differentials (Figure 2.3). By placing weights on these torque arms a torque was applied to the differential in the same way that the drive shaft would apply torque to the differential assembly. In this way an additional 200 Nm torque on the drive shafts was simulated by putting 20 kg at the end of the 1019 mm torque arms (Figure 2.4).

The tractor was then put through a series of tests with the modified transducers including the 200 Nm additional simulated torque. During these tests the rear drive shaft transducer failed and therefore had to be replaced. A larger, less sensitive transducer was constructed to replace the failed transducer and this transducer was calibrated to obtain the new calibration curve.

After several tests had been completed for test series #2, the results were analysed to see if there was a difference between the results obtained from an unlocked differential and a locked differential. It was again found that the torques on the two wheels on an unlocked differential were not equal. However, it was also found that this difference was larger when the differential was locked. This is what was expected with the additional 200 Nm torque applied to the differential assemblies.

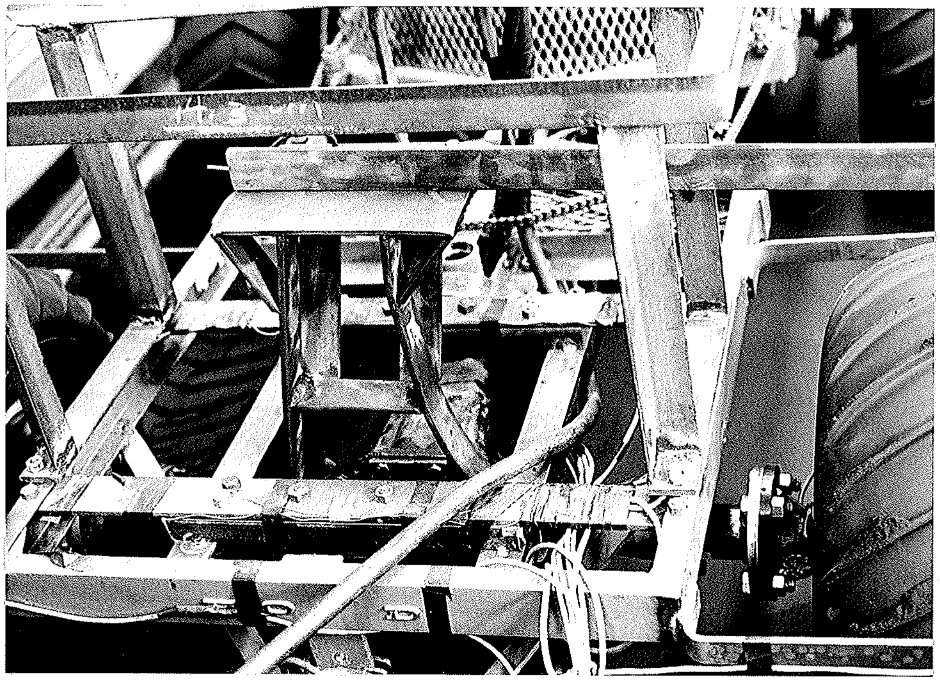

Figure 2.3: Additional torque arm attachment

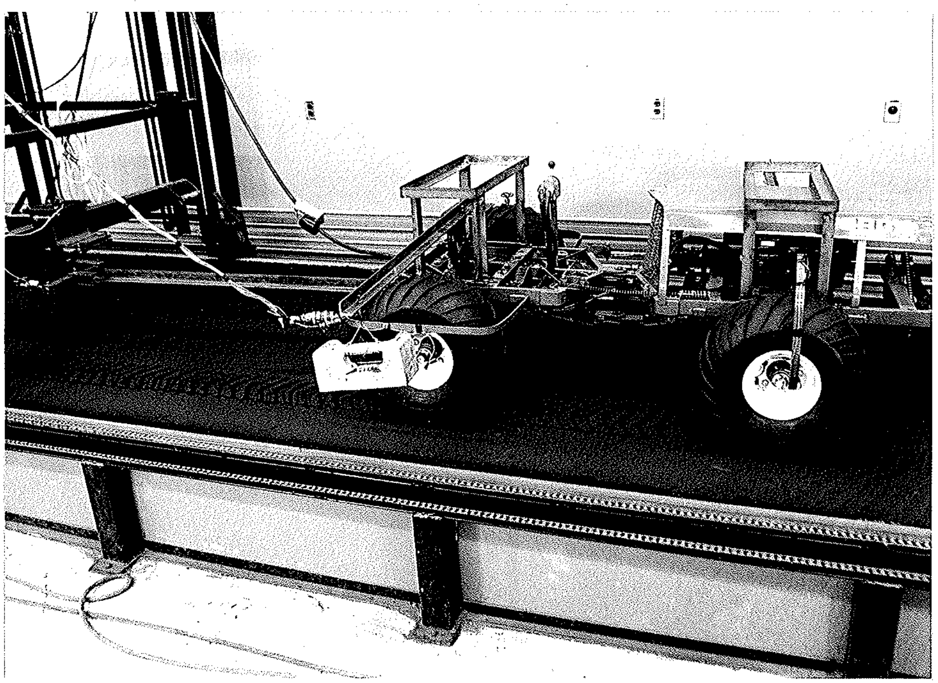

Figure 2.4: Additional torque applied to differential assemblies

Again, after extensive checking, the transducers were assumed to be the cause of the problem so a closer look at them was taken. One thing that was noticed was that the drive pin on each transducer was forming an indentation in the flat surface of the sloted hole. It was thought that this could have caused a binding effect on the transducer assembly. Further experimentation with the transducers comfirmed that there was binding at this point.

2.3.2 Modifications for test series #3

Since there was still binding occuring in the transducer pin - hole interface it was decided that a different method of applying the load to the transducer should be considered.

The original method used to measure the torque on the axle involved a transducer on the axle which drove the "free wheeling" wheel hub through a drive pin inserted into a hole in the hub (Figures 2.5 and 2.6). Using this method the load applied to the transducer was applied at the edge of the transducer. This off-center load caused deflection and rotation which was not desired. In order to eliminate the rotation component of deflection a different technique which applied the load through the center line of the transducer was required.

The alternate method which was adopted involved the use of a sealed ball bearing mounted on the transducer. A 9 mm slot was cut out of the tubing on the transducer where the drive pin was held. A 12 mm inside diameter, 28 mm outside diameter ball bearing was then positioned in this slot and the drive pin was inserted through the tubing and through the bearing. The drive pin extended through the transducer and into an enlarged hole in the wheel hub. A support bracket was welded to the

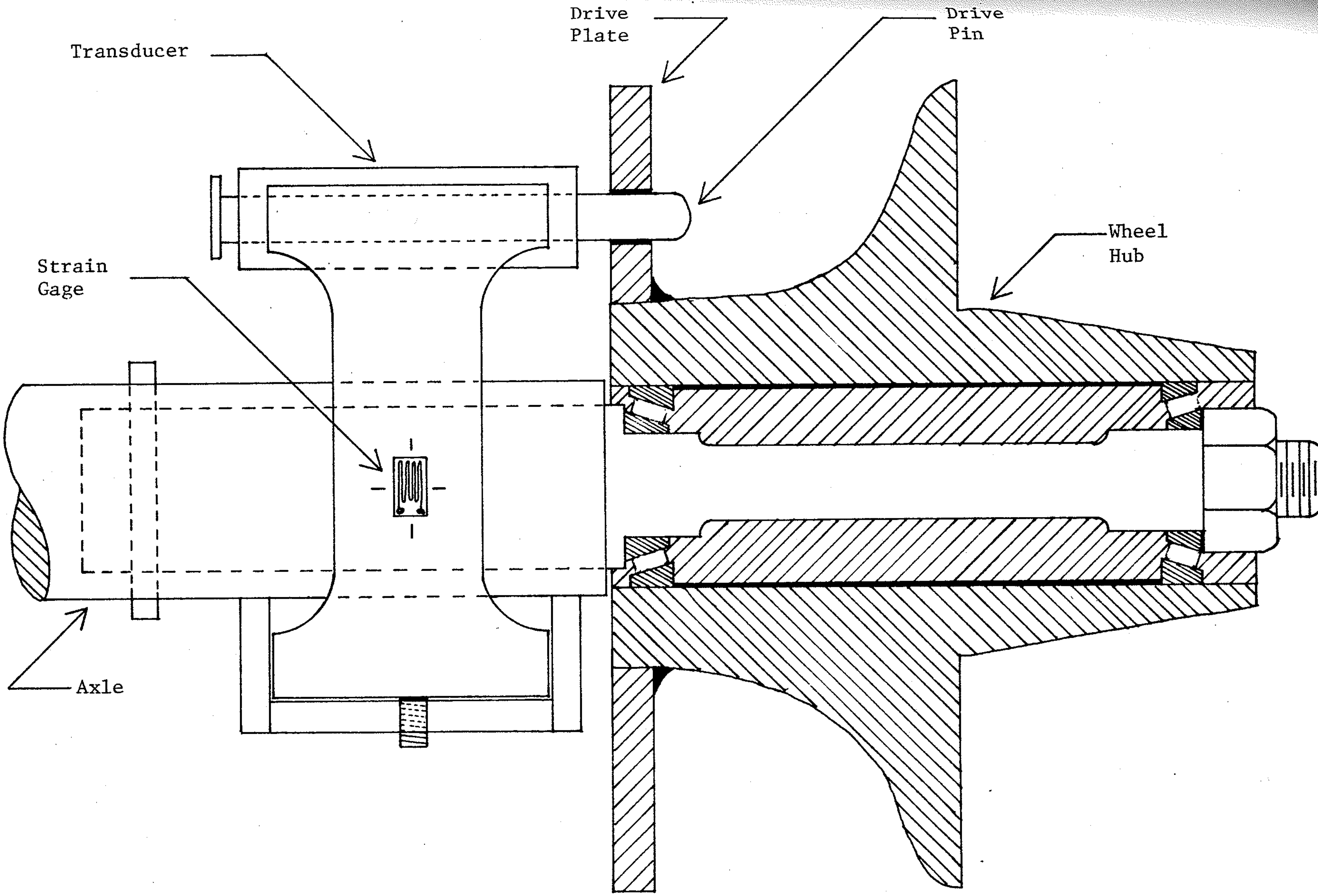

Figure 2.5: Original transducer drive mechanism

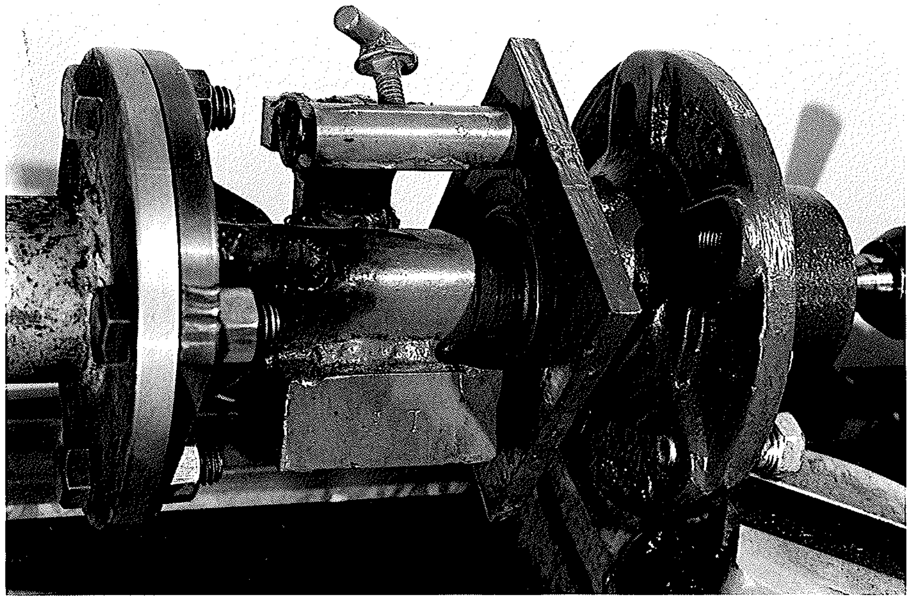

Figure 2.6: Original transducer drive mechanism (photo)

wheel hub and a piece of hardened steel was welded to this bracket in such a way that the bearing on the transducer would drive on the hardened steel. Using this method the transducer could apply torque from the axle to the wheel hub through the bearing-hardened steel interface (Figure 2.7). Since the bearing surface was also hardened no unacceptable deformation of the bearing or drive surface should be encountered. In reverse, the drive pin in the wheel hub applied the torque from the axle to the wheel. This seemed to be an acceptable solution to the binding problem of the axle transducers.

Test series #3 was then carried out with the modified transducers to see if the problem had been eliminated. One test was done with the additional torque of 200 Nm applied to the differential. When the

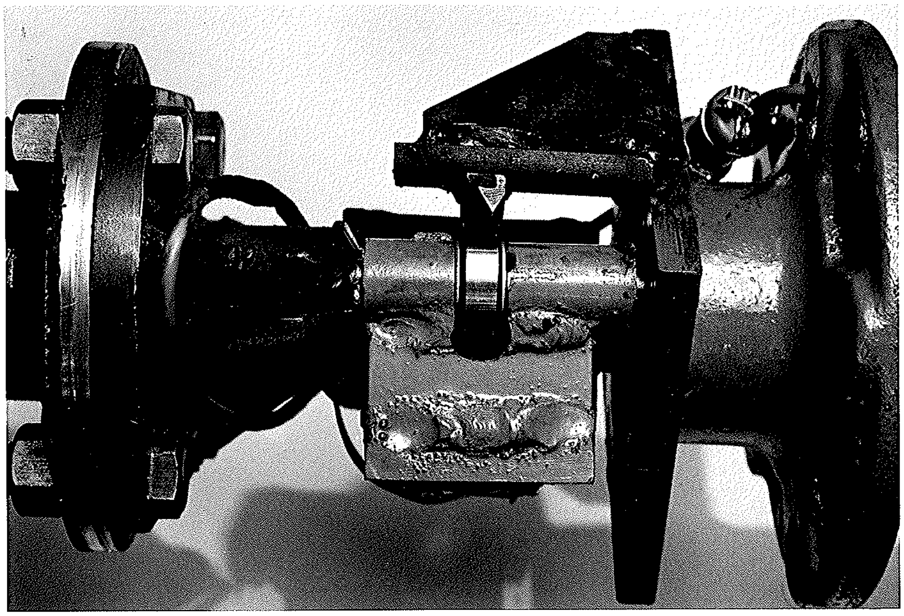

Figure 2.7: Modified transducer drive mechanism

results from this test showed a marked difference in torque between two wheels on the same unlocked differential, it was deduced that the extra load on the one wheel and bearing, caused by the added torque, was causing binding of the bearings and/or the differential itself. The subsequent tests were conducted without the additional torque applied. For the test series #3 a complete set of tests was conducted with two static weight distributions (60:40 and 70:30, fore:aft), two slip conditions (10 percent and 15 percent), and with both locked and unlocked differentials. Five replicates of each test were conducted.

Chapter III

TESTING PROCEDURE AND COMPUTER PROGRAMS

Testing of the model 4WD tractor was conducted in the 1.8 m by 15.2 m soil bin located in Agricultural Engineering at the University of Manitoba. This soil bin contains a 230 mm layer of Elm Creek sandy loam soil with another 230 mm layer of Red River clay located beneath. Soil moisture in the soil bin was maintained at between 9 percent and 12.5 percent dry basis during each of the test series. A carriage supported by tracks on either side of the bin, was chain drawn by a 7.5 kW three phase electric gear motor. A variable speed belt drive was used for speed control of the carriage. An electric clutch - brake unit was used to control the movement of the carriage. Speed of the carriage was measured using an electronic revolution counter to indicate angular velicity of the drive shaft which was then converted to linear speed of the carriage using the calibration equation:

$$V = 0.001577 * RPM + 0.0041$$

Where RPM was the speed of the drive shaft as indicated on the counter (rev/min) and V was the speed of the carriage (m/s)

3.1 TESTING PROCEDURE

Before each test, the soil was worked up with a rotary tiller to a depth of approximately 30 - 40 mm (Figures 3.1 and 3.2). The rotary tiller rotated at about 300 rev/min and operated at a forward speed of 0.278 m/s (0.99 km/h). This speed was the slowest speed setting on the soil bin carriage. The soil was then leveled off by dragging a board or a 76 mm I - beam along the soil with the carriage moving at 0.397 m/s (Figure 3.3). After two passes with this system the 300 mm diameter smooth roller was attached to the carriage. Any adhering soil was cleaned from the roller. An oily rag was then used to wipe the roller to leave a thin oil layer on the roller. This oil film kept the moist soil from sticking to the roller during the soil compaction operation. The mass of the roller was 138 kg when filled with water. For test series #3 eight cycles (16 passes) of the roller were made at 0.553 m/s (2 km/h) to compact the soil to simulate conditions of a stubble field (Figure 3.4). Ten cycles of the roller were made for test series #1 and #2. After the soil had been fully conditioned, the cone index of the first 100 mm of soil was in the range of 2.0 to 4.0 kg/cm^2 (Figure 3.5). When the soil was compacted to this level it provided a favorable tractive surface for the model.

The tractor was then placed in the soil bin and the drawbar and cable connections were connected (Figure 3.6). The pressure in the tires of the tractor was maintained at 26.49 kPa for tests series #1 and #2 and was maintained at 39.24 kPa for test series #3. The proper weight distribution was obtained by putting weights on the front weight rack or on both the front and rear weight racks. The wheels of the tractor were then adjusted so that there was no load on the torque transducers or on the draft transducer. The drawbar was attached at a height so that it was directly in line with the rear axle.

The three wheel slips that were used for the testing of the model were induced by running the soil bin carriage appropriately slower than the speed of the tractor. Since the forward speed of the tractor under no slip conditions was 0.667 m/s, the speed of the carriage was 0.600 m/s, 0.567 m/s and 0.533 m/s for wheel slips of 10 percent, 15 percent and 20 percent respectively. The setup of the instrumentation system is shown in Figure 3.7.

When everything was ready the data collection program, TRACTOR, was started. Once a pre - test check indicating any errors was accepted by the operator, the unstrained or zero reference readings were taken. To prevent impact loading on the transducers upon startup, slack was taken up in the entire drive system. The tractor was then started by a remote magnetic starter and the soil bin carriage drive was engaged immediately after. Data collection was initiated by an assistant when the front of the tractor passed a reference line. The 400 strained or loaded readings of each channel were taken over the test period. Once the data collection was complete the soil bin carriage drive was disengaged and the tractor was stopped. Data collection took approximately 10 seconds or apprximately 6 m of travel. The data collected from the test were then stored on disk and plotted out on the screen of the Corona for checking. This process took several minutes.

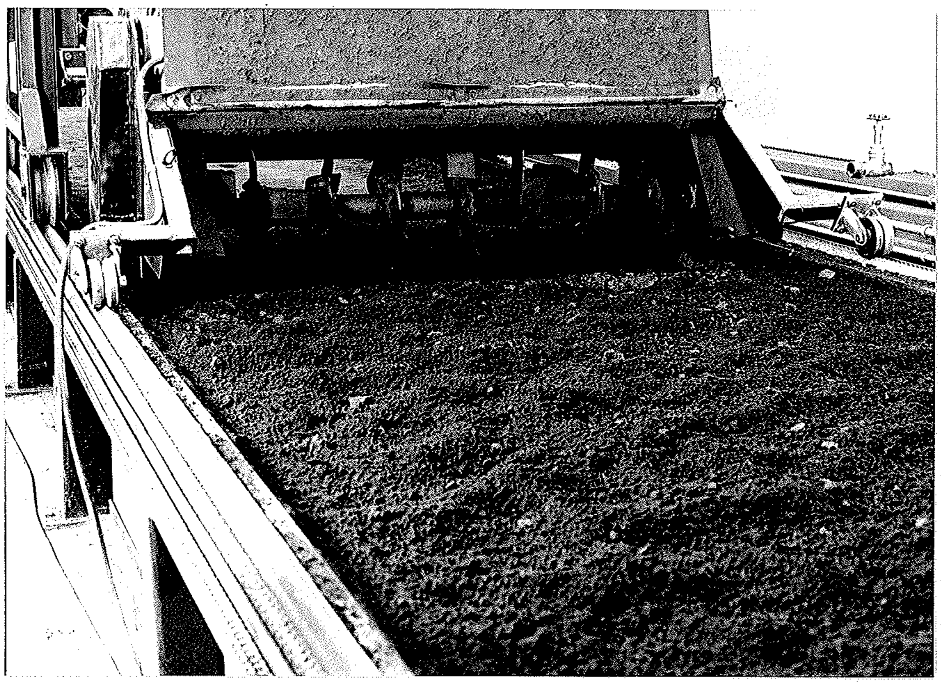

Figure 3.1: Rotary tiller used for soil conditioning

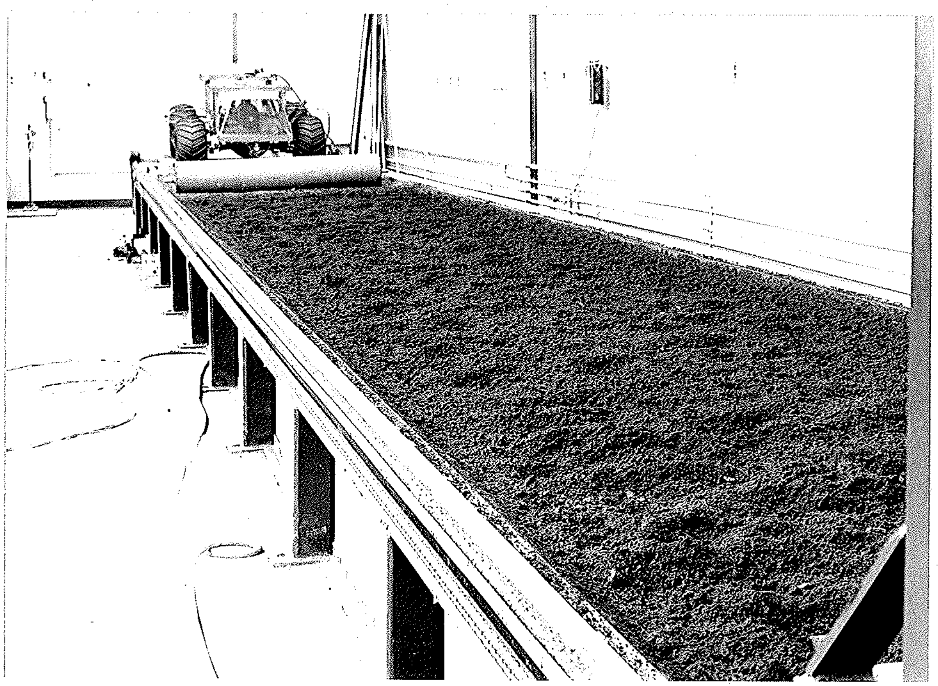

Figure 3.2: Soil bin after soil has been worked

Figure 3.3: Soil after leveling with board

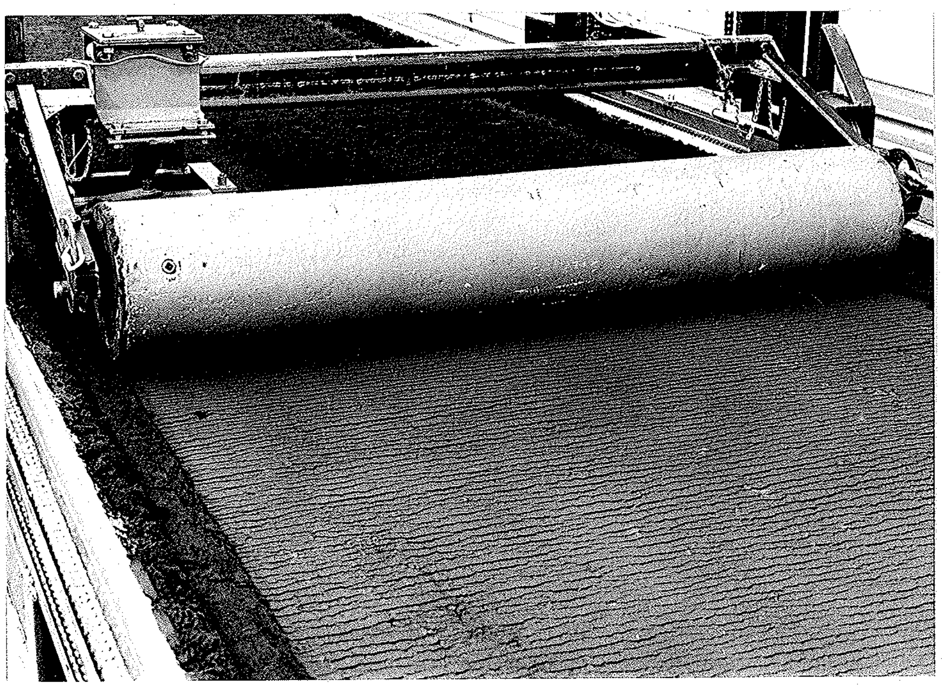

Figure 3.4: Soil compaction operation

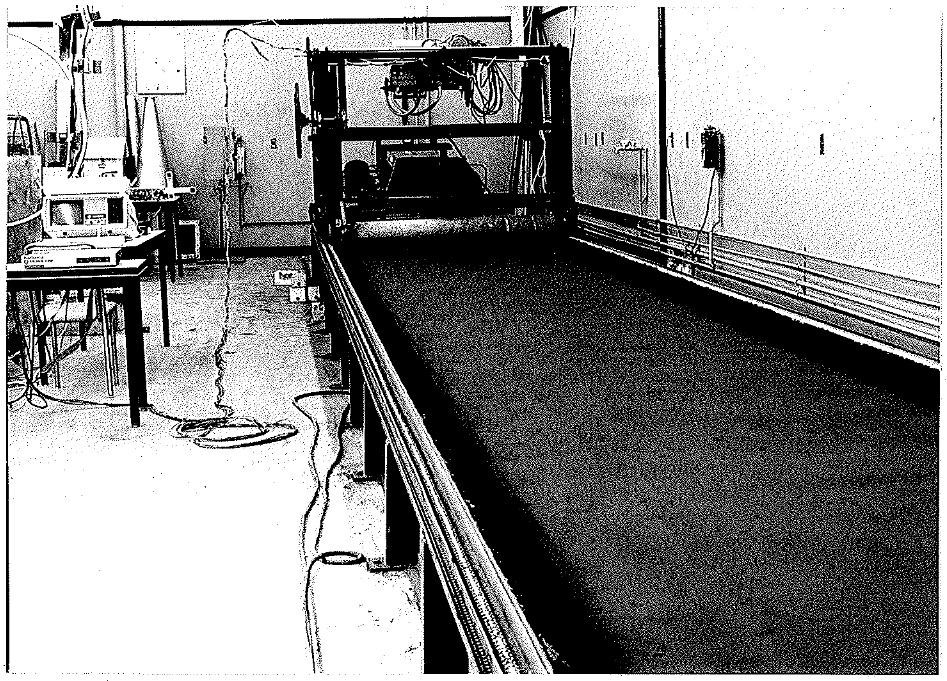

Figure 3.5: Soil surface after soil conditioning operations

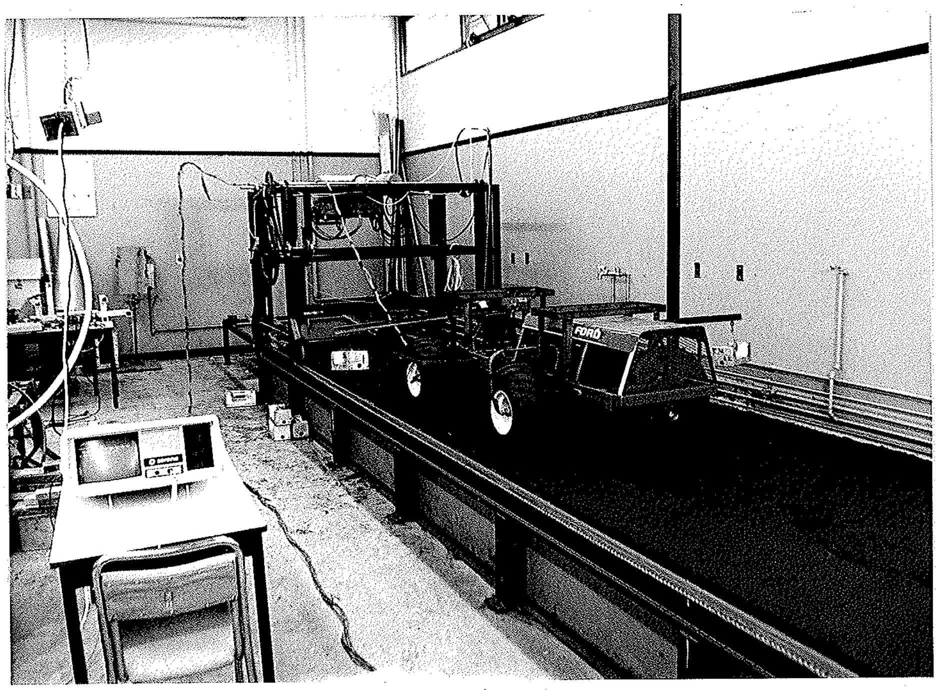

Figure 3.6: Tractor setup prior to running a test

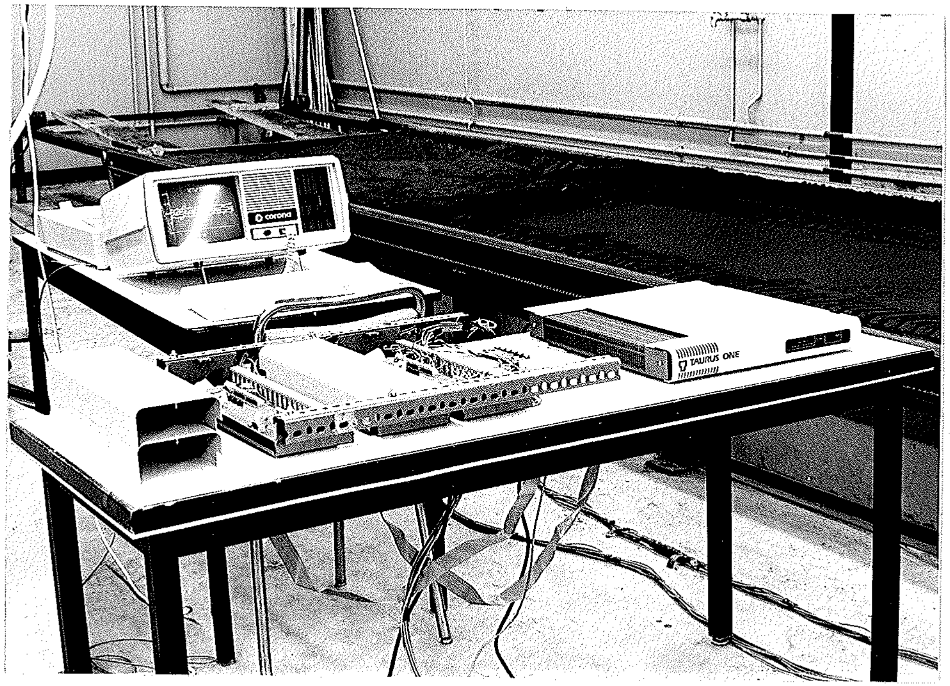

Figure 3.7: Instrumentation system set up

3.2 DATA ACQUISITION AND ANALYSIS PROGRAMS

Several computer programs were developed for the Corona microcomputer to collect and analyze data. The GWBASIC basic language was used with MS-DOS as the disk controller system. The main programs used were:

3.2.1 CHECK

This program was used to monitor the output of one of the nine channels to make sure there were no shorts or faulty connections in the circuit. A continuous display of one preselected channel was shown on the screen using the "analog read" of a single channel on the Taurus-One. This program proved quite useful in trouble-shooting the hardware system during setup for a test or calibration.

3.2.2 CALIBRAT

This program was used to calibrate the transducers for the tractor. A "scan table" was set up to read one individual channel selected by the user and then 50 scans of this channel were taken with a 25 ms delay between scans. This is the same delay used in the actual data acquisition during a test. The 50 readings were printed on the screen, followed by the average of the 50 readings. The average was then recorded to be used in the linear regression to determine the calibration curve.

3.2.3 TRACTOR

The program TRACTOR was used to collect the data during a test. The program opened communication between the Taurus-One and the Corona as output port #1 on the Corona. A scan table to scan nine channels starting at 129 on bus zero of the Taurus-One, is set up. Channel number 128 represents channel zero with a gain of 100 and therefore channels 129 through 137 represent channels one through nine with a gain of 100 each. The measured variable for each of the nine channels is shown below:

```
CHANNEL 1 --- RIGHT REAR AXLE TORQUE
CHANNEL 2 --- LEFT REAR AXLE TORQUE
CHANNEL 3 --- RIGHT FRONT AXLE TORQUE
CHANNEL 4 --- LEFT FRONT AXLE TORQUE
CHANNEL 5 --- REAR DRIVE SHAFT TORQUE
CHANNEL 6 --- FRONT DRIVE SHAFT TORQUE
CHANNEL 7 --- REAR LOAD SENSING
CHANNEL 8 --- FRONT LOAD SENSING
CHANNEL 9 --- DRAFT SENSING
```

After the communication set up message was sent the return message from the Taurus-One was checked to ensure proper communication was present. An analog acquisition was conducted for one scan of the nine channels and the result of this scan was presented on the screen so the operator could check the output of each channel to see if all connections were intact. If the operator felt that all channels were being read correctly, a file name for the data to be stored under was typed into the computer by the operator. The file name for data storage consisted of eight characters derived from the conditions used for the test. A sample file name would be: "U60-10.1". The "U" signifies that this test was done with an unlocked differential ("L" for locked differential). The "60" indicated that 60 percent of the static weight was on the front axle and 40 percent was on the rear axle. The "10" indicated that the test was done with 10 percent wheel slip. The "1" indicated that this was the first replicate under these test conditions.

The formatted data disk was in drive "B" of the Corona and the write-protect tab had to be removed. After the file name had been entered and the RETURN key had been pressed the unstrained or zero reference readings were taken automatically. To obtain unstrained readings 50 scans of the scan table at a delay of 25 ms between scans were taken and the average for each channel was stored on disk. The data file name was the same as the one entered but with an appended "U". A zero reading of the tractor speed monitor on the motor was also taken at this time.

After the Corona generated an audible beep the tractor was started and the soil bin carriage drive was immediately engaged. When the tractor passed the reference line, the "RETURN" key was pressed. This initialized 400 scans of the nine channels with a 25 ms delay. After all readings were taken, the data were manipulated and placed in the random access data file which was input before the test. Each record in the random access file represented all the readings from one channel.

Therefore, to retrieve channel three data one only had to retrieve the data stored in record number three of the random access data file. The program then ran the plotting program called OVERLAY.ATO to plot the results on the screen. A listing of this program is given in Appendix E.

3.2.4 OVERLAY.ATO

Once the data had been collected from the transducers over the course of a test, this program was run automatically to plot the indicated torque of each of the four axles versus time. This plot was displayed on the screen and by examining this plot it could be decided whether any problems were encountered during the data acquisition.

3.2.5 OVERLAY.BAS

This program was used after data collection to plot the data for one or more of the nine channels. The maximum and minimum values were calculated for the combination of channels and the plot could be auto-scaled or the user could input, via the keyboard, the maximum value of the variables being plotted. A listing of this program is also given in Appendix E.

3.2.6 MEANS

This program calculated the statistical means over an entire test for channels one through six and channel nine. Means were calculated for combined locked and unlocked differential data and then printed out on the dot matrix printer.

3.2.7 UMEANS

This program calculated statistical means for unlocked differential condition data for all combinations of tests. Averages for five replicates combined were also printed. Axle torques, drive shaft torques and draft means were given.

3.2.8 LMEANS

This program functioned the same as UMEANS except that the means were calculated and printed for the locked differential condition data.

3.2.9 STATS

This program produced an ANOVA table for all the tests combined. A statistical F value was produced to compare locked and unlocked diffferential data and to compare all replicates of the data obtained through one wheel slip, static weight distribution combination. Results were printed on the line printer for one channel and one test condition at a time.

3.2.10 USTATS

This program produced an ANOVA table for the tests conducted with an unlocked differential. A statistical F value was generated to compare the five replicates of one test condition.

3.2.11 LSTATS

This program was the same as USTATS but for the locked differential tests rather than the unlocked differential tests.

Chapter IV

RESULTS AND DISCUSSION

4.1 CALIBRATION RESULTS

The results of the final calibration of the four axle torque transducers, two drive shaft torque transducers and the draft transducer are given in Table B.1 in Appendix B. Plots of the calibration curves are also shown in Appendix B. The corresponding correlation coefficients (R^2) are all at least 0.999 which indicates that torque can accurately be measured with this measurement system.

The slopes of the calibration curves, as established by the linear regression analysis for the four axle torque transducers, show that that the sensitivity for these transducers is approximately 0.75 Nm/unit change in output from the Taurus-One. Linearity of the axle torque transducers ranged from 1.43 percent to 1.79 percent. In cases where it was statistically sound to do so ($\alpha = 0.05$), the intercept generated for the calibration curve was taken to be zero. This was done for all axle torque transducers except the right front axle where the intercept was significant at -1.16 Nm.

Calibration of the drive shaft torque transducers resulted in sensitivities of 0.2132 Nm/unit output from the Taurus-One for the rear drive shaft and 0.0889 Nm/unit output for the front drive shaft. The rear drive shaft torque transducer failed during initial testing and was replaced with a larger, less sensitive transducer. Linearities of 0.89

percent and 0.72 percent were obtained for the rear and front drive shafts, respectively. Again, both intercepts were checked and it was found that they could statistically be interpreted as zero.

The draft transducer had a sensitivity of 7.45 N/unit output from the Taurus-One using the 2:1 reduction mechanism. Linearity of this device was 0.38 percent. The intercept for this transducer could not be taken as zero and was left at 12.26 N.

4.2 RESULTS FROM TEST SERIES #1

A total of 26 valid tests were conducted for test series #1. For this series, three static weight distributions (62:38, 56:44 and 51:49 - Front:Rear) and three wheel slip conditions (10 percent, 15 percent and 20 percent) were tested. Of the 26 tests that were conducted, 20 were run with unlocked differentials and six were run with locked differentials. When the results of the unlocked differential tests were examined the large difference between the torque on the two wheels on the same unlocked differential was considered unacceptable. The difference between the torques of the two wheels on the same unlocked differential was much larger than the torque difference seen between locked and unlocked differentials.

4.3 RESULTS FROM TEST SERIES #2

In the second series of tests 18 unlocked differential and 18 locked differential tests were conducted. Three static weight distributions (60:40, 56:44 and 52:48) and two slip conditions (10 percent and 15 percent) were tested. Three replicates of each combination were run for this series.

In this series of tests an additional 200 Nm torque was applied to the differential assembly. The axle torque transducers had also been modified by making a slotted hole for the transducer drive pin to slide on. Results of these tests are recorded as statistical means of the measured variables in Tables C.1 and C.2 in Appendix C. From an examination of the means of the three replicates for any one slip - static weight distribution combination the following observations can be made comparing locked to unlocked differentials:

1. Under locked differential conditions, the right rear axle had more torque than it did when the differential was unlocked.
2. Under locked differential conditions, the left front axle nearly always had more torque than it did when the differential was unlocked.
3. Under locked differential conditions, the left rear and right front axles had less torque than when the differentials were unlocked.
4. On the average, the draft developed by the model was larger when the differentials were locked.

The above results are normally what would be expected from the tests that were conducted due to a torque reaction effect. The sense of these reactions assumes that the drive shaft applies torque in the clockwise direction (viewed from the rear) in addition to the 200 Nm torque being applied in the clockwise direction to the rear axles and in the counter clockwise direction to the front axles. However, the fact that there was such a large difference between torques on the two wheels on the same unlocked differential indicated that there were problems with the transducers and/or the differentials. One possible explanation for this difference was considered to be a binding in the support bearings near the wheels and in the wheel hub assemblies. The more load that was applied to the wheel assembly the larger the binding effect. Therefore, when the torque arms and weights to apply additional torque to the differential assemblies were employed more load was put on one wheel of the assembly which would cause more binding in this wheel than the wheel with less load. This would mean that the torques on the two axles adjacent to the differential would be equal but at the wheel itself the torques may be different.

4.4 RESULTS FROM TEST SERIES #3

The third series of tests included 20 tests with unlocked differentials followed by 20 tests with locked differentials. Two static weight distributions (60:40 and 70:30) and two wheel slip conditions (10 percent and 15 percent) were tested with five replications of each combination.

Results of this series of tests are tabulated as means of the measured variables in Tables C.3, C.4 and C.5. Statistics were applied to the data from all tests combined and then again to the data for locked and unlocked differentials separately. For the combined data, two hypotheses were tested. The first was that the statistical means for one channel and one test condition were the same for locked and unlocked differentials. The second hypothesis tested was that the replicates for one channel and one combination of slip, static weight distribution and differential condition were all the same.

4.4.1 Hypothesis I: Differential condition has no effect

An evaluation of the statistical F values calculated as the mean sum of squares for replicates divided by the mean sum of squares for error, established that for all conditions and all axles the F value was not significant at the 0.05 level (Table 4.1). This indicated that the null hypothesis of no difference could not be rejected and it was concluded that there was no difference between locked and unlocked differential for this series of tests.

4.4.2 Hypothesis II: No difference between replicates of the same test

The F values calculated for testing the null hypothesis of no difference between replicates of the same test are shown in Tables 4.2 and 4.3. This F value has 4 and 1995 degrees of freedom. In all cases, the calculated value was significant at the 0.05 level. This indicated that there was a difference between replicates of the same test.

The fact that the replicates were statistically different could be attributed to several factors:

1. Change in soil moisture between tests.
2. Change in soil compaction between tests.
3. Variation in soil compaction and moisture content along the soil bin.
4. Speed variation of soil bin carriage.
5. Path of the tractor along the soil bin.

The combination of all or some of these factors could cause a large variation between tests which could be characteristic of any testing dependent on soil related properties.

TABLE 4.1

Summarized Statistics for Combined Tests - Series #3

Hypothesis I

Statistics for Tests : 60-10

LOCATION	MS REPLICATES	$F_{1,8}$
Right rear axle	7703.80	0.01
Left rear axle	6385.52	0.22
Right front axle	769.19	2.96
Left front axle	13153.54	1.54

Statistics for Tests : 60-15

LOCATION	MS REPLICATES	$F_{1,8}$
Right rear axle	1823.63	0.48
Left rear axle	2586.56	1.04
Right front axle	3100.76	0.08
Left front axle	20419.71	1.23

Statistics for Tests : 70-10

LOCATION	MS REPLICATES	$F_{1,8}$
Right rear axle	1937.09	0.17
Left rear axle	4318.88	1.94
Right front axle	2256.84	3.82
Left front axle	20868.08	0.86

Statistics for Tests : 70-15

LOCATION	MS REPLICATES	$F_{1,8}$
Right rear axle	2686.43	0.82
Left rear axle	1376.71	2.06
Right front axle	2205.04	0.18
Left front axle	15407.71	0.10

NOTE: 60-10 indicates all tests done with 60 percent of static weight on the front axle and at 10 percent slip. Tabulated $F_{1,8,0.05}$ was 5.32

TABLE 4.2

Summarized Statistics for Unlocked Differential Tests - Series #3

Hypothesis II

Statistics for Tests : 60-10

LOCATION	MSE	$F_{4,1995}$
Right rear axle	43.40	105.58
Left rear axle	37.99	210.91
Right front axle	21.09	54.91
Left front axle	25.53	967.01

Statistics for Tests : 60-15

LOCATION	MSE	$F_{4,1995}$
Right rear axle	29.28	83.69
Left rear axle	26.25	132.54
Right front axle	28.19	83.00
Left front axle	28.47	1360.32

Statistics for Tests : 70-10

LOCATION	MSE	$F_{4,1995}$
Right rear axle	38.20	50.13
Left rear axle	26.03	283.64
Right front axle	24.69	161.43
Left front axle	20.86	1864.62

Statistics for Tests : 70-15

LOCATION	MSE	$F_{4,1995}$
Right rear axle	21.47	24.30
Left rear axle	20.86	95.86
Right front axle	26.96	153.33
Left front axle	27.44	1051.91

NOTE: 60-10 indicates all unlocked differential tests done with 60 percent of static weight on the front axle and at 10 percent slip. Tabulated $F_{4,1995,0.05}$ was 2.37

TABLE 4.3

Summarized Statistics for Locked Differential Tests - Series #3

Hypothesis II

Statistics for Tests : 60-10

LOCATION	MSE	$F_{4,1995}$
Right rear axle	64.00	169.11
Left rear axle	46.59	102.08
Right front axle	25.53	14.88
Left front axle	24.20	66.60

Statistics for Tests : 60-15

LOCATION	MSE	$F_{4,1995}$
Right rear axle	28.57	41.88
Left rear axle	25.26	66.99
Right front axle	35.15	109.83
Left front axle	79.44	26.48

Statistics for Tests : 70-10

LOCATION	MSE	$F_{4,1995}$
Right rear axle	32.84	59.60
Left rear axle	33.22	37.70
Right front axle	21.10	24.88
Left front axle	18.88	149.94

Statistics for Tests : 70-15

LOCATION	MSE	$F_{4,1995}$
Right rear axle	29.41	164.88
Left rear axle	24.71	30.52
Right front axle	34.36	8.00
Left front axle	29.53	65.77

NOTE: 60-10 indicates all locked differential tests done with 60 percent of static weight on the front axle and at 10 percent slip. Tabulated $F_{4,1995,0.05}$ was 2.37

Chapter V

CONCLUSIONS

1. Since the R^2 values in Table B.1 are all 0.999 or greater it was concluded that the torque at any time on all four axles could be determined with a sensitivity of approximately 0.75 Nm. Similarly, the drive shaft torques were determined with sensitivities of 0.21 Nm and 0.09 Nm for the rear and front drive shafts respectively. The draft load was determined with a sensitivity of approximately 7 N.
2. The summarized statistics in Tables 4.2 and 4.3 indicate that variations between tests were statistically significant. This variation was thought to have been caused by soil variation and soil bin carriage speed variation.
3. The summarized statistics in Table 4.1 indicate that the torque on a wheel was the same whether the wheel was on a locked or an unlocked differential. This result indicated that the hypothesis that the shift in ballast caused by the drive shaft torque does not cause a decrease in tractive efficiency, may in fact be true. The reason why the tractive efficiency is not affected may be because the wheels with least load have a higher slip which allows them to pull as much as the other wheels.
4. Since the tests were done on a favorable tractive surface, the performance of a 4WD tractor on a poor tractive surface cannot be predicted from these results. Phenomena such as push-pull and galloping were not encountered during testing.

Chapter VI

RECOMMENDATIONS

1. More testing of the model including accurate slip measurement and more repeatable soil conditions must be undertaken. The soil variation was a major contributor to variation between tests and this variation must be eliminated to obtain acceptable results.
2. Tests done on a concrete surface may be helpful to eliminate the soil component of the replicate variation. Tests done on concrete however may generate uncharacteristic results for the performance of a tractor in the field.
3. When additional testing of the model has been completed, the results should be confirmed by doing field tests on a full size 4WD tractor to see if the results obtained from the model apply to a full size tractor.

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Appendix A

MODEL DIMENSIONS

TABLE A.1

Specifications of the Model

ENGINE : 1.5 kW, 230 Volt Electric Motor

TIRES : ATV type - Radius = 265 mm

- Contact width - Approximately 210 mm

DIMENSIONS : Wheel base = 1.100 m

Overall Length = 1.800 m

Distance between wheel centers = 1.000 m

Mass : Front 201.0 kg

Rear 125.5 kg

No load speed = 0.667 m/s

Appendix B

CALIBRATION RESULTS

TABLE B.1

Final Calibration Results

Axle Torques

LOCATION	SLOPE	INTERCEPT		R^2
Right rear	0.7771	-0.9577	*	0.9995
Left rear	0.7525	-0.2319	*	0.9996
Right front	0.7740	-1.1587		0.9997
Left front	0.7338	-0.7038	*	0.9996

Drive Shaft Torques

LOCATION	SLOPE	INTERCEPT		R^2
Rear	0.2132	0.0514	*	0.9999
Front	0.0889	-0.0826	*	0.9998
Draft Force	7.4517	12.2732		0.9999

NOTE: * Indicates that the intercept can statistically be interpreted as zero ($\alpha = 0.05$).
Torque slopes have units of Nm/unit output from the Taurus-One.
Torque intercepts have units of Nm.
Draft slope has units of N/ unit output from the Taurus-One.
Draft intercept has units of N.

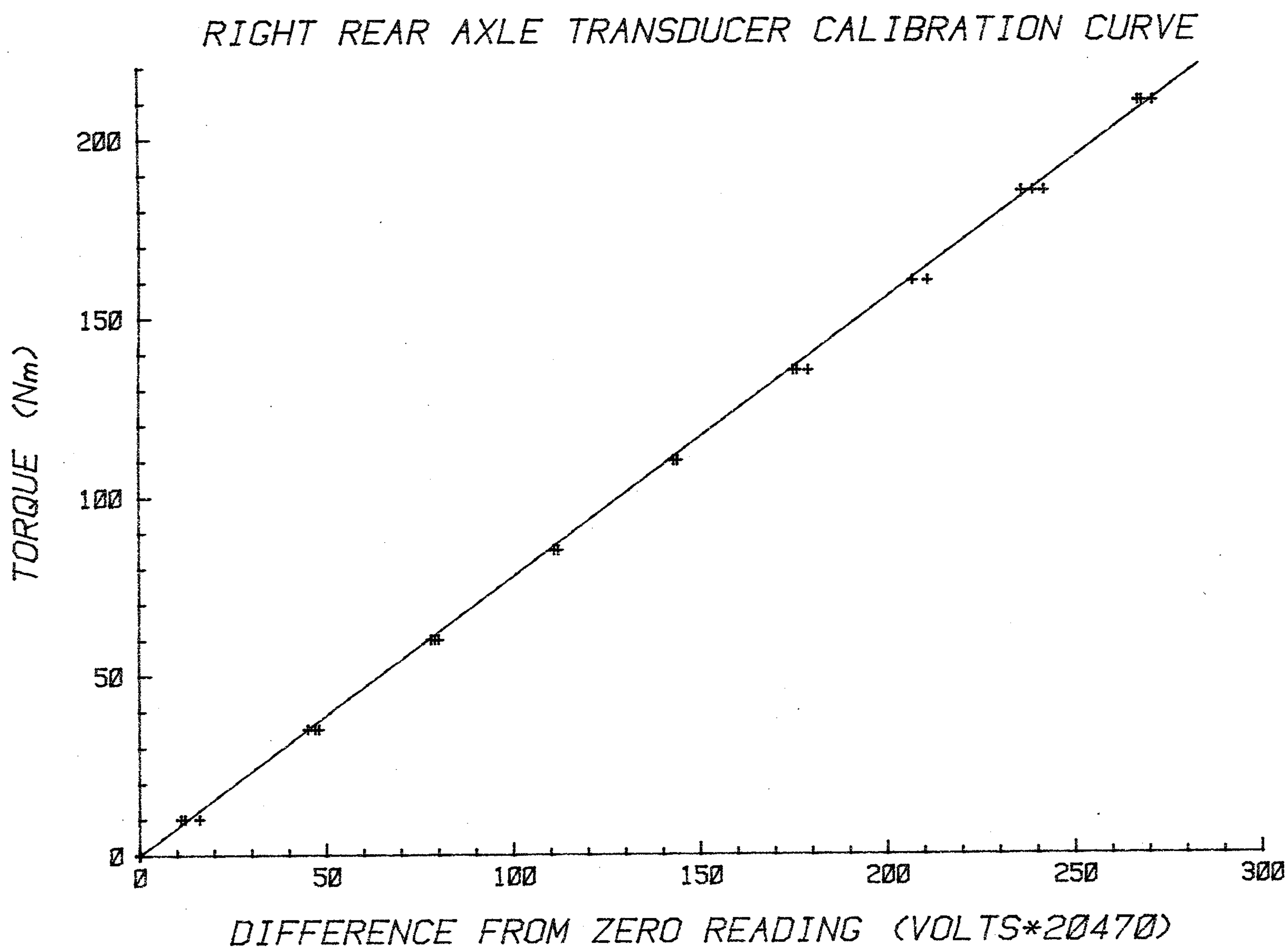

Figure B.1: Calibration curve for right rear axle torque transducer

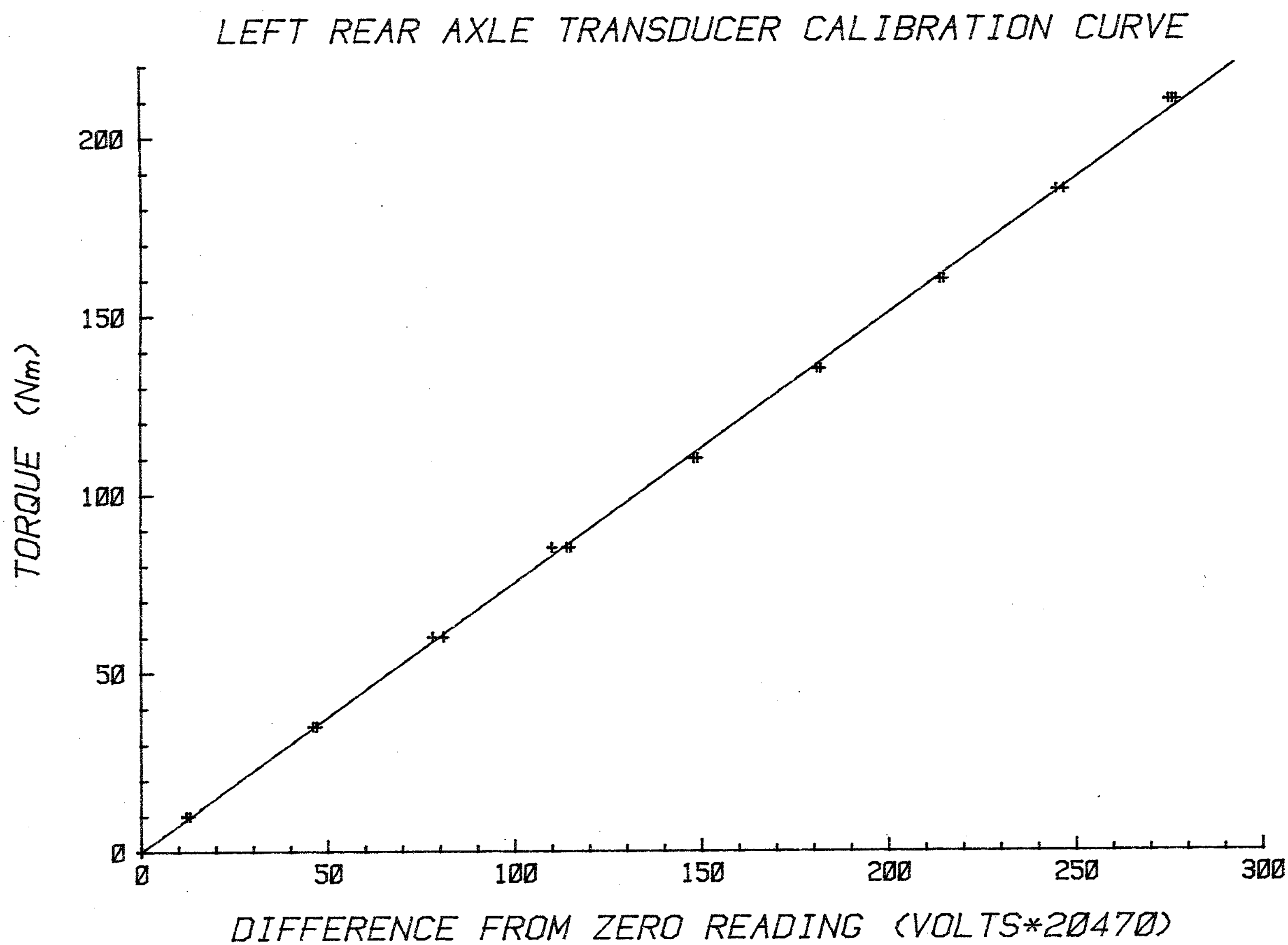

Figure B.2: Calibration curve for left rear axle torque transducer

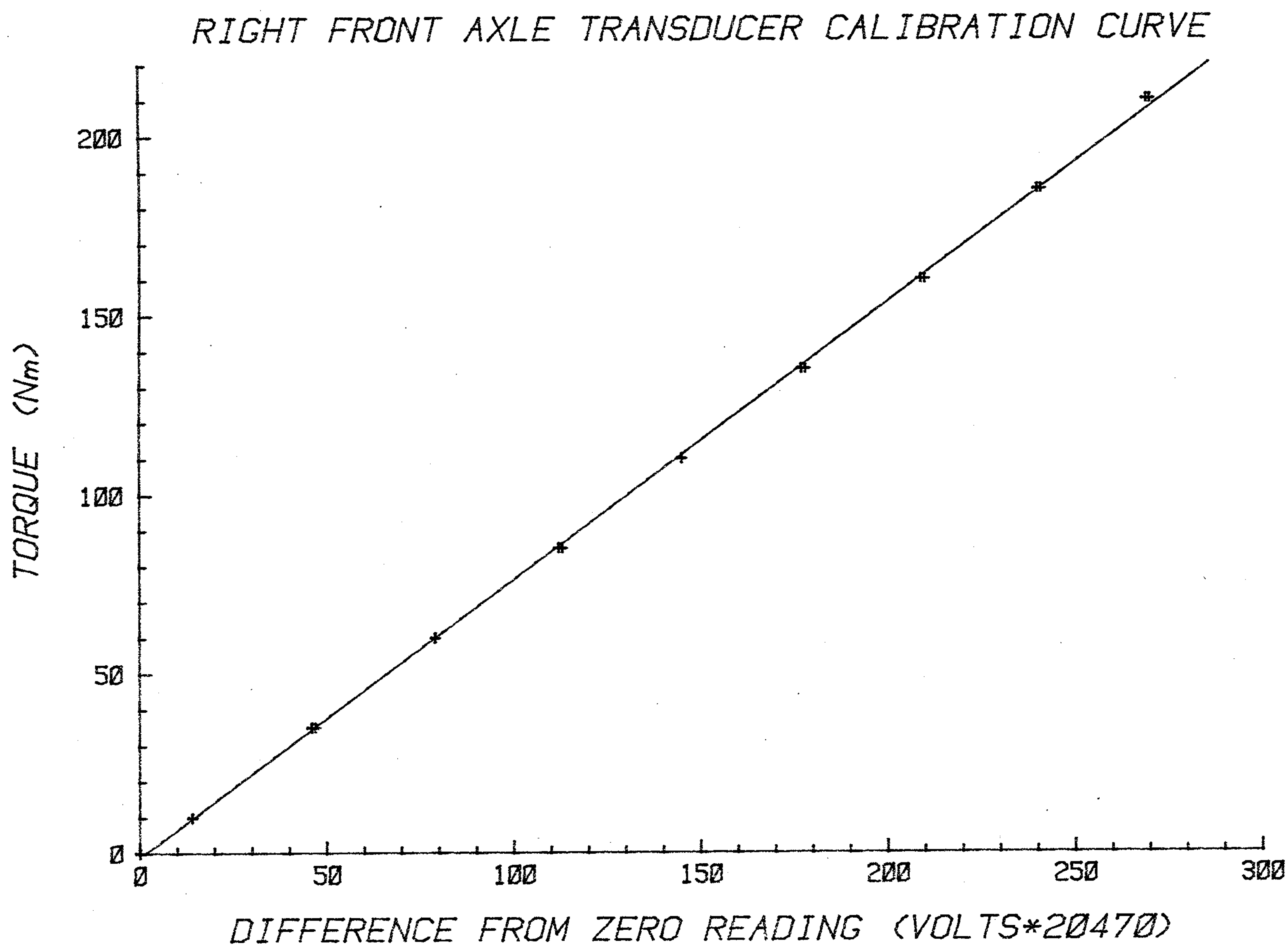

Figure B.3: Calibration curve for right front axle torque transducer

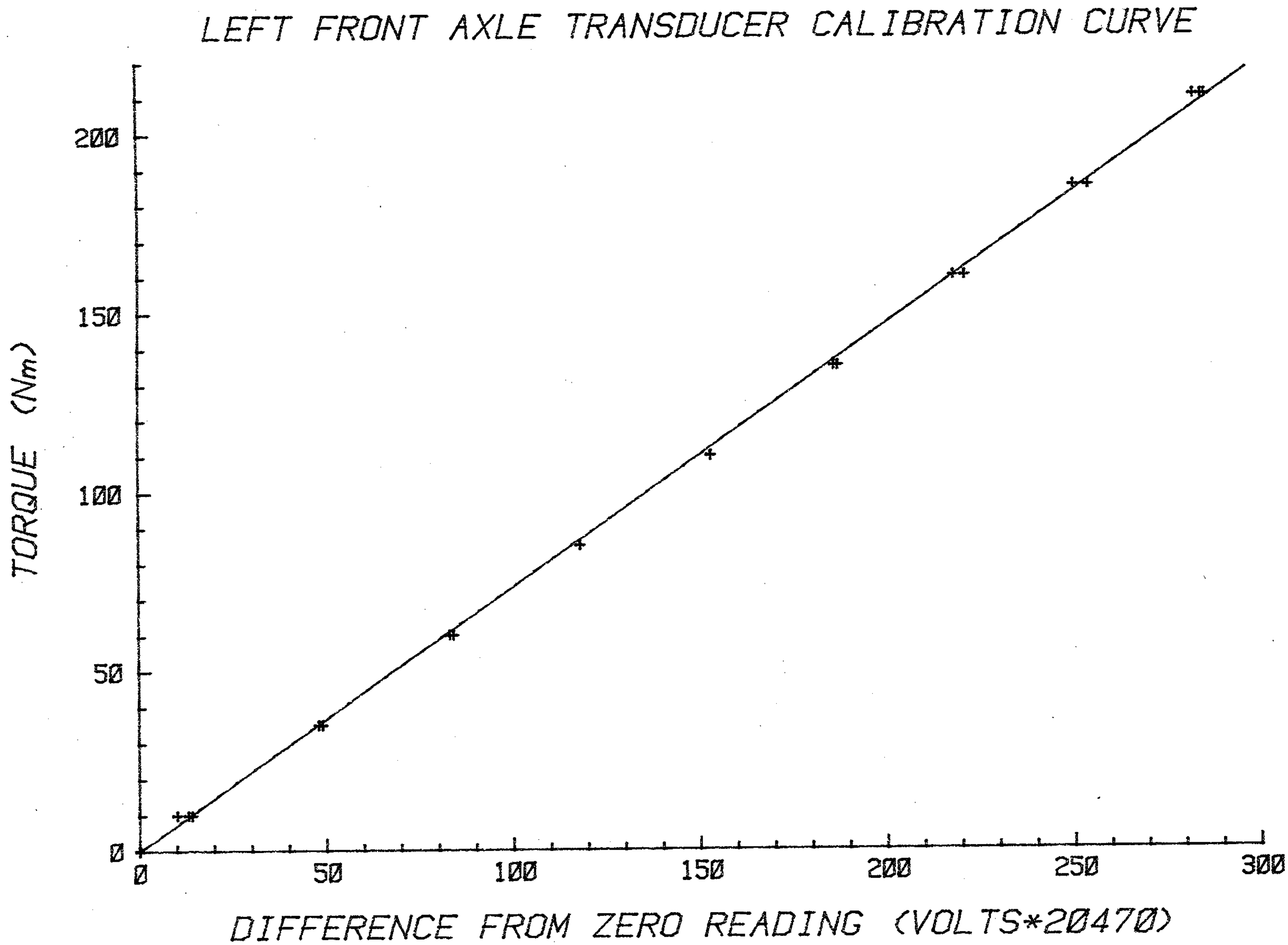

Figure B.4: Calibration curve for left front axle torque transducer

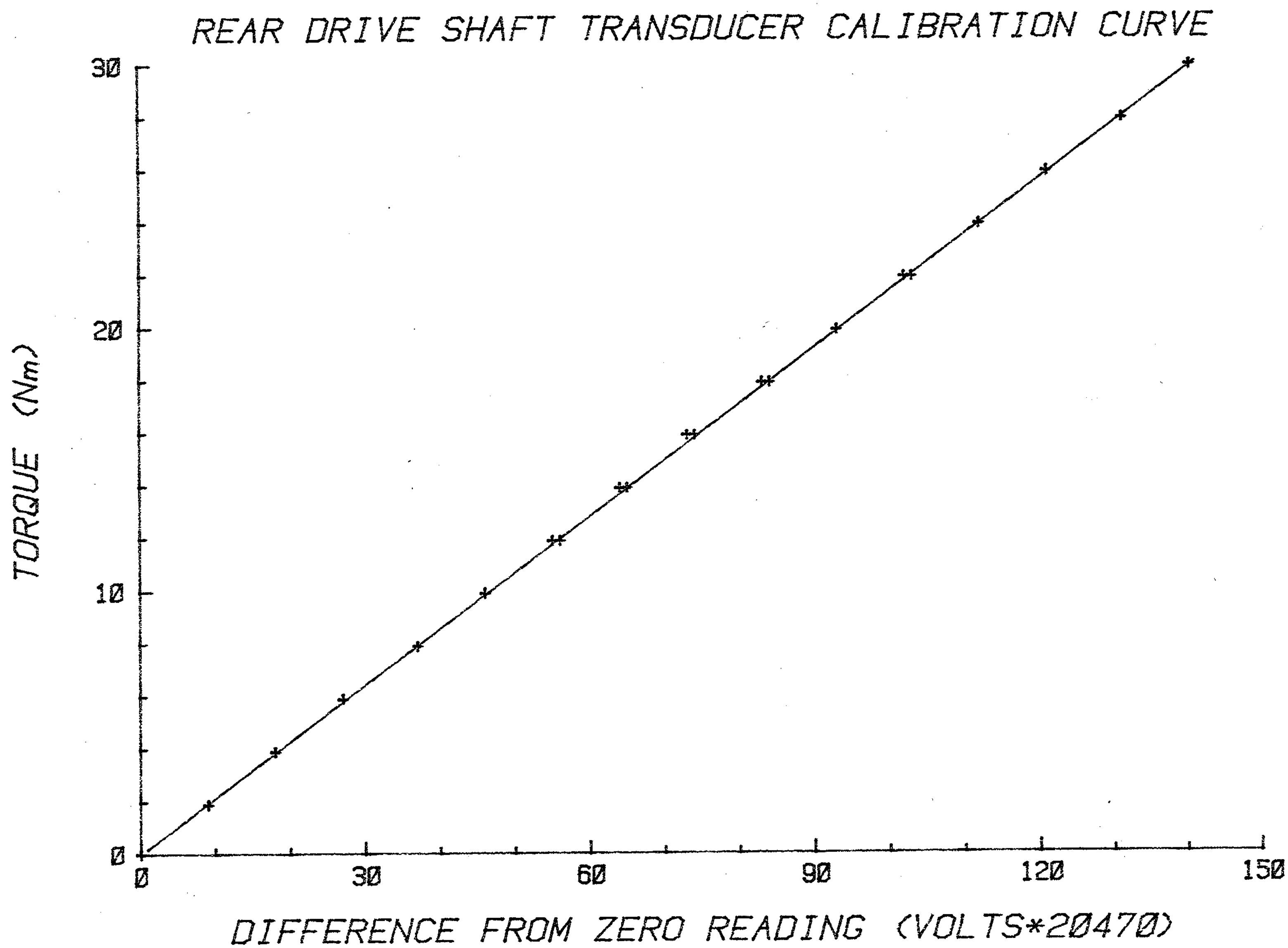

Figure B.5: Calibration curve for rear drive shaft torque transducer

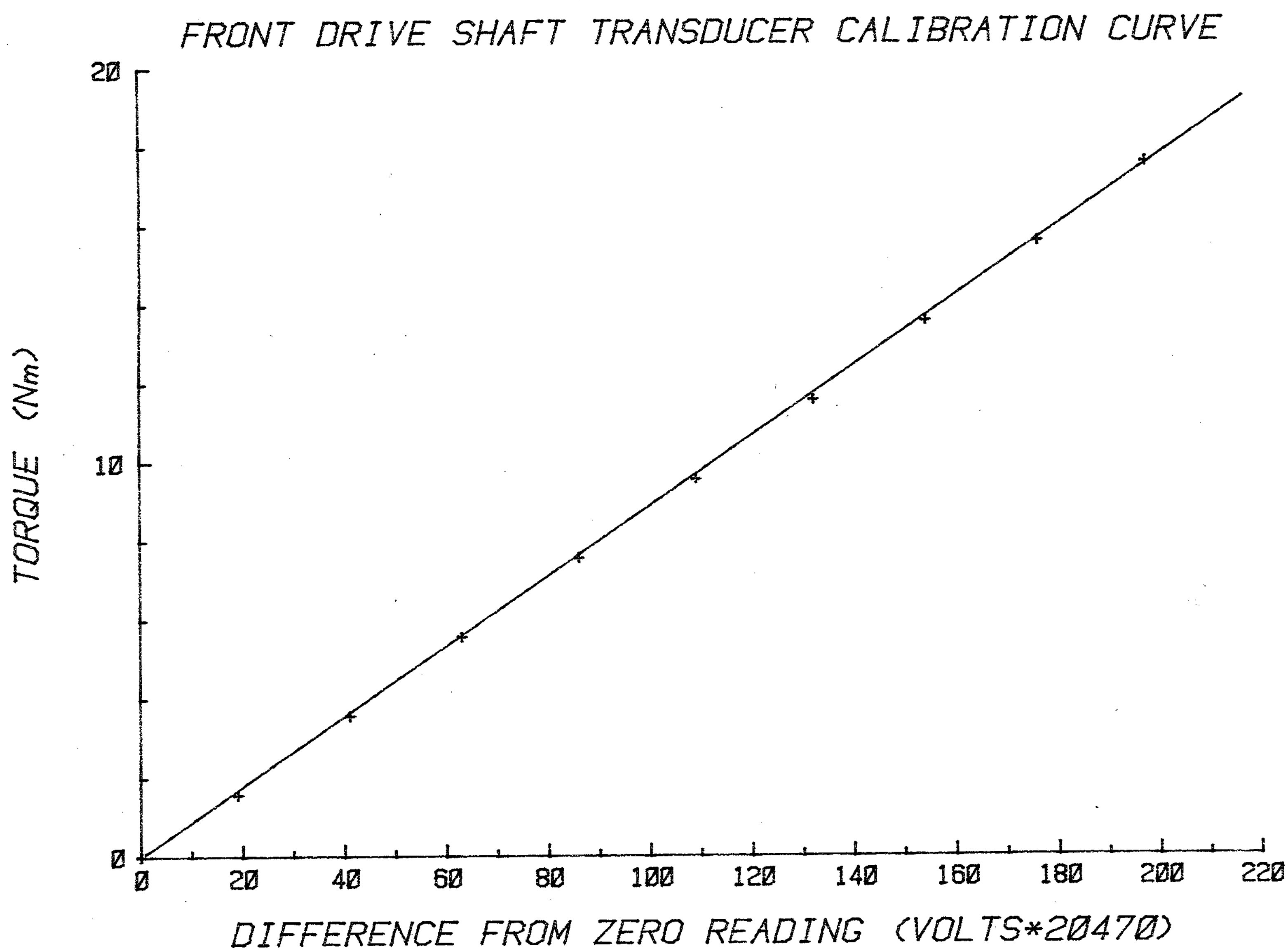

Figure B.6: Calibration curve for front drive shaft torque transducer

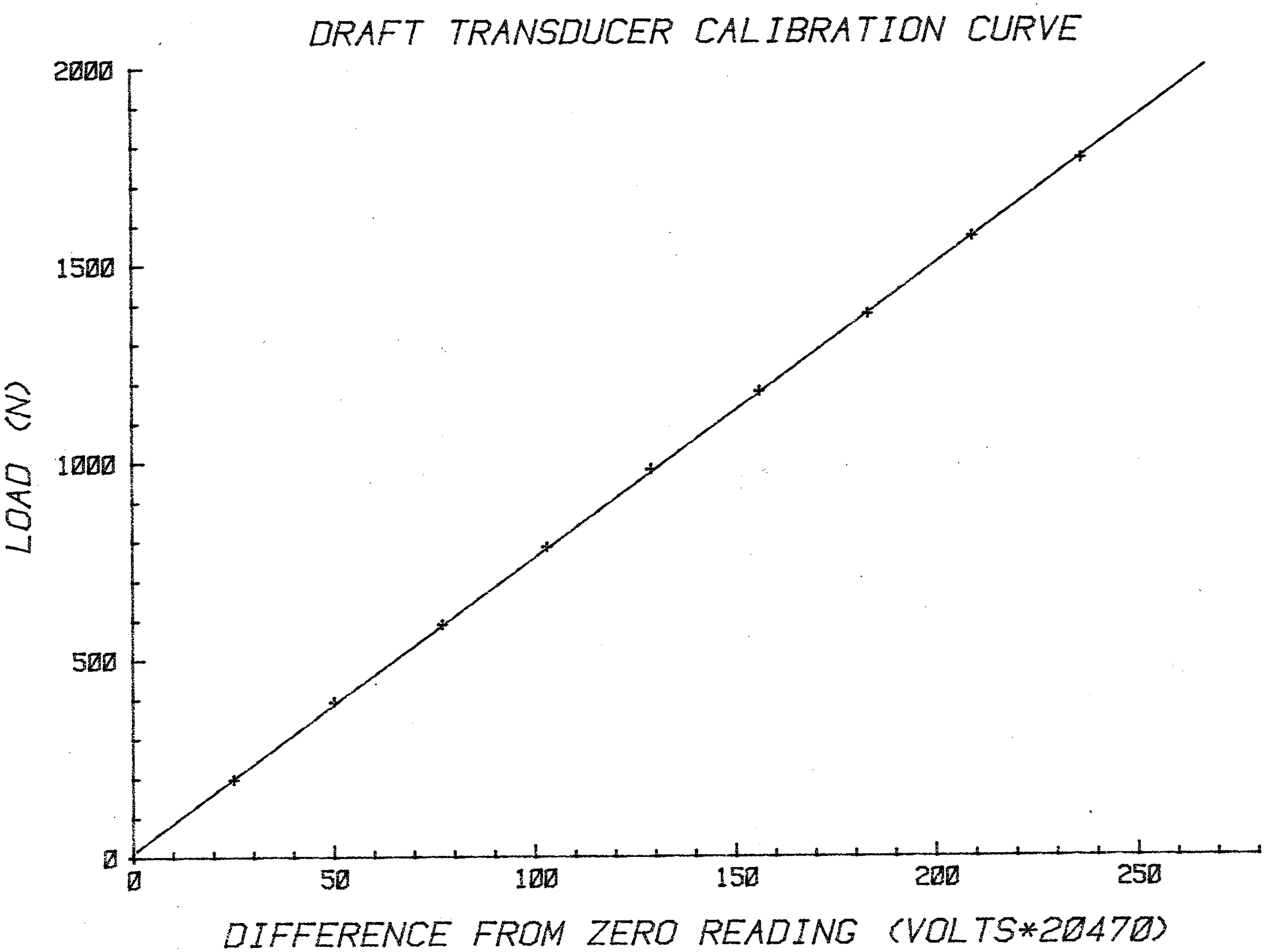

Figure B.7: Calibration curve for drawbar pull transducer

Appendix C

TEST RESULTS

TABLE C.1

Unlocked Differential Test Data for Test Series #2

TEST	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
U52-10.1	136.2	115.3	75.7	101.8	25.5	17.8	1508.2
U52-10.2	131.8	111.0	74.9	98.3	23.0	18.1	1481.0
U52-10.3	131.2	118.9	74.2	98.0	23.5	17.7	1456.6
MEANS	133.1	115.1	74.9	99.4	24.0	17.9	1481.9
U52-15.1	189.3	160.3	78.7	106.5	34.0	18.4	1926.6
U52-15.2	189.1	151.4	78.4	112.0	33.3	18.3	1930.4
U52-15.3	187.3	157.8	78.5	113.7	33.4	18.4	1941.9
MEANS	188.6	156.5	78.5	110.7	33.6	18.4	1933.0
U56-10.1	125.1	100.7	77.6	106.5	21.0	18.9	1410.8
U56-10.2	129.0	101.2	78.7	104.7	22.2	19.6	1480.9
U56-10.3	129.6	103.4	80.4	107.0	22.6	18.9	1471.2
MEANS	127.9	101.8	78.9	106.1	21.9	19.1	1454.3
U56-15.1	157.5	129.5	84.2	117.3	27.1	21.2	1753.2
U56-15.2	155.0	123.6	88.0	124.0	26.8	22.1	1756.6
U56-15.3	158.9	126.6	82.4	120.1	28.2	20.8	1782.7
MEANS	157.1	126.6	85.5	120.5	27.4	21.4	1766.8
U60-10.1	116.4	91.9	81.6	116.9	19.9	20.5	1414.5
U60-10.2	118.5	92.7	79.6	110.2	20.3	20.9	1401.3
U60-10.3	115.0	92.6	79.2	106.5	20.4	20.9	1397.2
MEANS	116.6	92.4	80.1	111.2	20.2	20.7	1404.3
U60-15.1	134.1	109.5	87.8	134.9	23.7	23.3	1687.6
U60-15.2	139.5	112.8	82.3	123.0	23.6	21.1	1597.2
U60-15.3	142.9	111.9	87.3	120.1	25.2	21.1	1655.5
MEANS	138.8	111.4	85.8	126.0	24.2	21.8	1646.8

NOTE: RR = Torque on right rear axle; LR = Torque on left rear axle
RF = Torque on right front axle; LF = Torque on left front axle
RD = Torque on rear drive shaft; FD = Torque on front drive shaft
DRAFT = Draft load on drawbar

TABLE C.2

Locked Differential Test Data for Test Series #2

TEST	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
L52-10.1	146.7	119.0	72.8	107.2	25.3	18.4	1499.8
L52-10.2	139.6	115.9	65.5	107.9	24.5	17.1	1508.7
L52-10.3	139.5	113.3	69.0	109.0	25.7	17.6	1408.4
MEANS	141.9	116.1	69.1	108.0	25.2	17.7	1472.3
L52-15.1	196.2	154.1	72.0	145.0	45.2	21.9	2107.6
L52-15.2	194.0	155.5	76.5	155.7	38.8	30.4	2084.4
L52-15.3	209.9	150.8	69.9	159.4	35.4	22.7	2077.9
MEANS	200.0	153.5	72.8	153.4	39.8	25.0	2090.0
L56-10.1	131.1	85.5	70.4	112.8	22.4	21.9	1416.9
L56-10.2	140.6	87.0	73.6	111.2	25.7	19.1	1424.9
L56-10.3	139.5	99.8	72.8	118.5	24.1	19.3	1518.5
MEANS	137.1	90.8	72.3	114.2	24.1	20.1	1453.4
L56-15.1	186.1	127.5	79.4	159.7	32.3	23.7	1960.8
L56-15.2	189.8	121.5	74.3	159.0	32.8	22.1	2077.6
L56-15.3	186.9	120.1	76.8	162.3	32.3	24.4	1975.2
MEANS	187.6	123.0	76.8	160.3	32.5	23.4	2004.5
L60-10.1	136.3	76.5	75.1	101.0	22.9	19.8	1424.2
L60-10.2	134.8	92.3	73.8	113.5	23.0	19.1	1442.3
L60-10.3	133.1	91.5	74.0	126.5	ND	19.9	1460.4
MEANS	134.7	86.8	74.3	113.7	23.0	19.6	1442.3
L60-15.1	171.1	103.8	78.7	156.1	29.9	25.8	1908.2
L60-15.2	169.6	104.2	77.3	158.0	27.9	23.5	1878.1
L60-15.3	173.4	111.2	76.0	160.7	29.2	23.0	1851.5
MEANS	171.4	106.4	77.3	158.3	29.0	24.1	1879.3

NOTE: RR = Torque on right rear axle; LR = Torque on left rear axle
RF = Torque on right front axle; LF = Torque on left front axle
RD = Torque on rear drive shaft; FD = Torque on front drive shaft
DRAFT = Draft load on drawbar
ND = No data

TABLE C.3

Unlocked Differential Test Data for Test Series #3

TEST	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
U60.10.1	143.5	141.1	119.6	106.6	26.3	27.2	1801.1
U60-10.2	157.7	141.2	115.4	121.8	27.1	26.8	1830.6
U60-10.3	150.8	137.9	119.6	122.2	27.6	25.6	1949.6
U60-10.4	147.5	138.1	118.1	127.3	27.2	27.5	1764.0
U60-10.5	150.7	148.9	118.6	122.3	27.1	26.1	1936.4
MEANS	148.8	141.4	118.3	120.1	27.1	26.7	1856.3

TEST	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
U60-15.1	165.0	158.9	130.9	118.6	28.3	29.8	2142.1
U60-15.2	168.2	157.9	128.3	136.9	30.3	28.4	2084.0
U60-15.3	170.8	161.3	133.8	142.2	30.0	29.5	2099.1
U60-15.4	170.3	165.5	127.9	141.4	30.7	30.1	2089.3
U60-15.5	170.7	162.0	131.6	140.3	30.2	29.3	2079.9
MEANS	169.0	161.1	130.5	135.9	29.9	29.4	2098.9

TEST	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
U70-10.1	119.8	112.3	137.1	123.3	21.2	32.3	1735.7
U70-10.2	120.5	123.8	138.9	137.6	22.3	30.3	1778.8
U70-10.3	121.8	119.9	142.9	143.9	21.6	33.5	1784.7
U70-10.4	125.4	118.2	144.4	148.1	22.2	38.8	1811.6
U70-10.5	121.2	115.9	143.5	144.9	22.1	34.1	1825.8
MEANS	121.7	118.0	141.4	139.6	21.9	33.8	1787.3

TEST	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
U70-15.1	140.3	130.5	159.8	167.6	24.7	37.4	2110.4
U70-15.2	140.5	132.7	157.4	163.6	24.9	36.2	2043.2
U70-15.3	140.5	135.5	161.3	164.0	25.4	37.0	2111.6
U70-15.4	141.4	131.7	165.6	167.1	25.9	39.8	2067.3
U70-15.5	143.1	129.7	163.7	184.2	24.9	40.5	2073.5
MEANS	141.2	132.0	161.5	169.3	25.2	38.2	2081.2

NOTE: RR = Torque on right rear axle LR = Torque on left rear axle
RF = Torque on right front axle LF = Torque on left front axle
RD = Torque on rear drive shaft FD = Torque on front drive shaft
DRAFT = Draft load on drawbar
ND = No data

TABLE C.4

Locked Differential Test Data for Test Series #3

TEST	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
L60-10.1	142.2	138.6	118.7	123.5	25.5	25.0	1824.1
L60-10.2	146.9	141.4	120.3	124.5	26.3	25.2	1808.1
L60-10.3	147.9	144.8	118.9	122.5	27.4	25.1	1816.5
L60-10.4	154.1	140.8	120.9	124.5	25.8	25.7	1915.8
L60-10.5	154.6	135.5	120.1	127.8	27.5	26.3	1903.9
MEANS	149.1	140.2	119.8	124.6	26.5	25.5	1853.7
TEST	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
L60-15.1	170.5	156.9	134.4	140.6	29.7	29.5	2117.1
L60-15.2	170.2	162.3	133.0	141.4	30.9	28.4	2073.3
L60-15.3	167.2	159.0	126.8	137.2	30.4	27.9	2023.5
L60-15.4	169.9	158.5	128.8	141.7	30.5	28.6	2059.3
L60-15.5	171.9	160.7	132.0	143.5	30.8	28.0	2247.5
MEANS	169.9	159.5	131.0	140.9	30.5	28.5	2104.1
TEST	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
L70-10.1	121.2	121.0	143.2	143.7	21.7	32.7	1870.0
L70-10.2	120.0	118.6	143.2	144.2	21.1	32.1	1823.0
L70-10.3	124.0	120.1	145.6	144.7	22.5	35.2	1878.8
L70-10.4	121.0	123.4	145.4	146.8	22.2	33.4	1904.7
L70-10.5	125.3	121.6	144.0	139.5	22.9	32.2	1826.5
MEANS	122.3	120.9	144.3	143.8	22.1	33.1	1860.6
TEST	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
L70-15.1	134.9	128.6	161.2	173.9	24.1	38.1	2062.8
L70-15.2	137.2	131.4	162.3	169.3	24.0	39.0	2085.8
L70-15.3	142.6	131.9	161.9	168.7	24.9	38.4	2100.4
L70-15.4	142.7	129.3	163.5	169.3	24.0	34.5	ND
L70-15.5	141.0	130.4	162.0	171.7	24.1	38.3	2133.7
MEANS	139.7	130.3	162.2	170.6	24.2	37.7	2095.2

NOTE: RR = Torque on right rear axle; LR = Torque on left rear axle
RF = Torque on right front axle; LF = Torque on left front axle
RD = Torque on rear drive shaft; FD = Torque on front drive shaft
DRAFT = Draft load on drawbar
ND = No data

TABLE C.5

Combined Locked and Unlocked Differential Test Data - Test Series #3

Means for five replicates and two differential conditions

TESTS	RR(Nm)	LR(Nm)	RF(Nm)	LF(Nm)	RD(Nm)	FD(Nm)	DRAFT(N)
60-10	149.0	140.8	119.0	122.3	26.8	26.1	1855.0
60-15	169.5	160.3	130.7	138.4	30.2	29.0	2101.5
70-10	122.0	119.5	142.8	141.7	22.0	33.5	1824.0
70-15	140.4	131.2	161.9	169.9	24.7	37.9	2088.2

NOTE: RR = Torque on right rear axle
LR = Torque on left rear axle
RF = Torque on right front axle
LF = Torque on left front axle
RD = Torque on rear drive shaft
FD = Torque on front drive shaft
DRAFT = Draft load on drawbar

Appendix D

TYPICAL PLOTS OF RESULTS

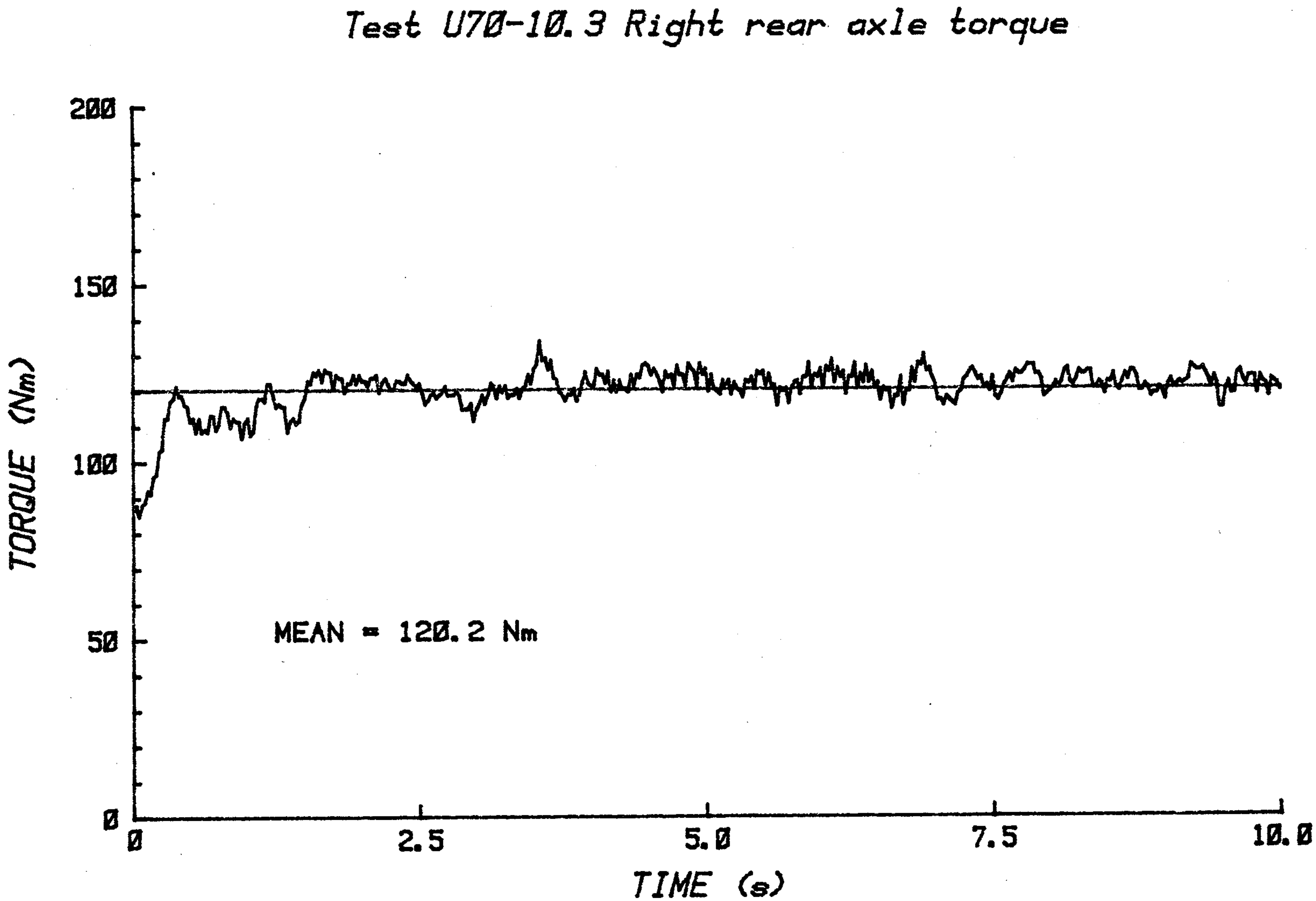

Figure D.1: Typical results for right rear axle

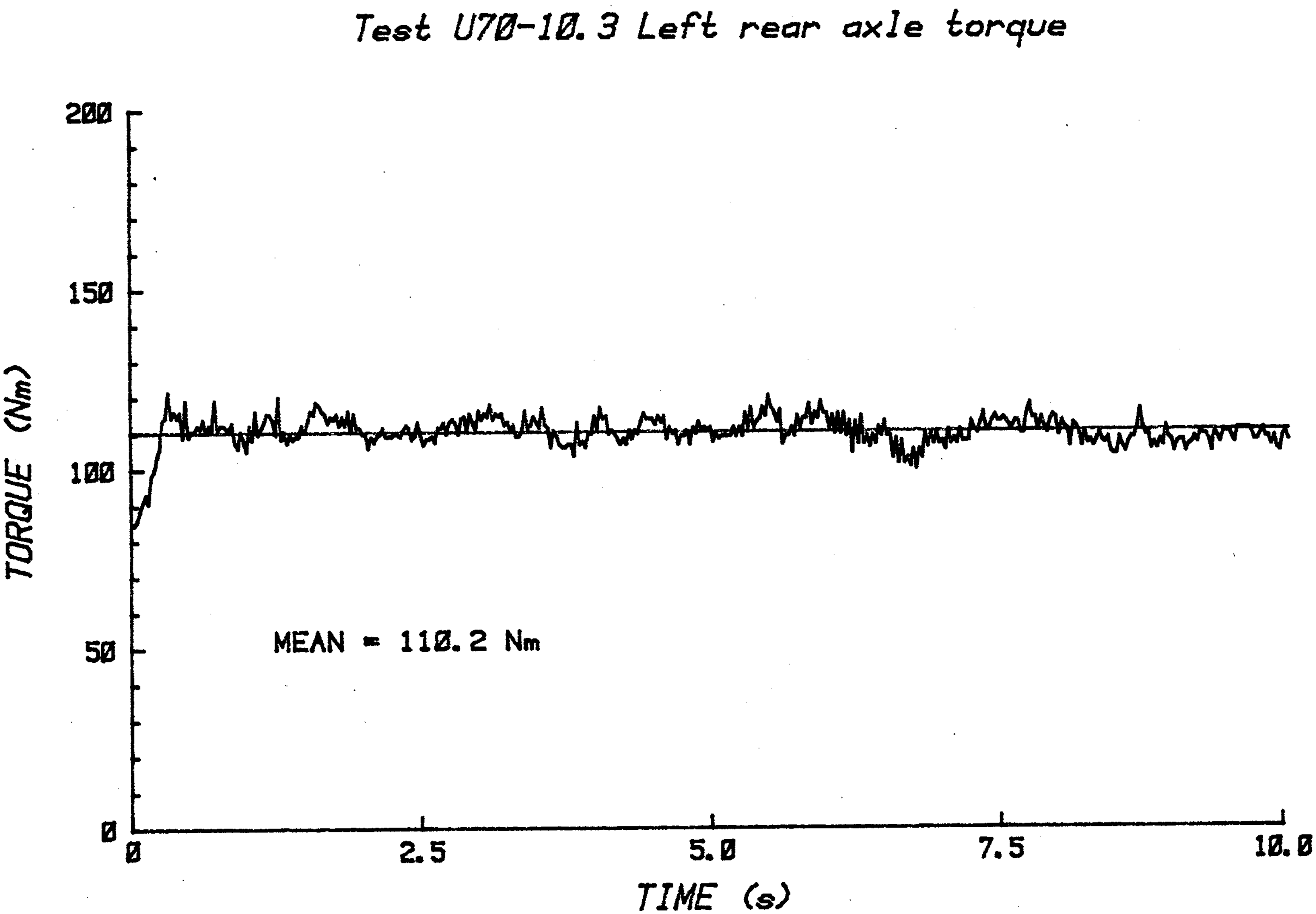

Figure D.2: Typical results for left rear axle

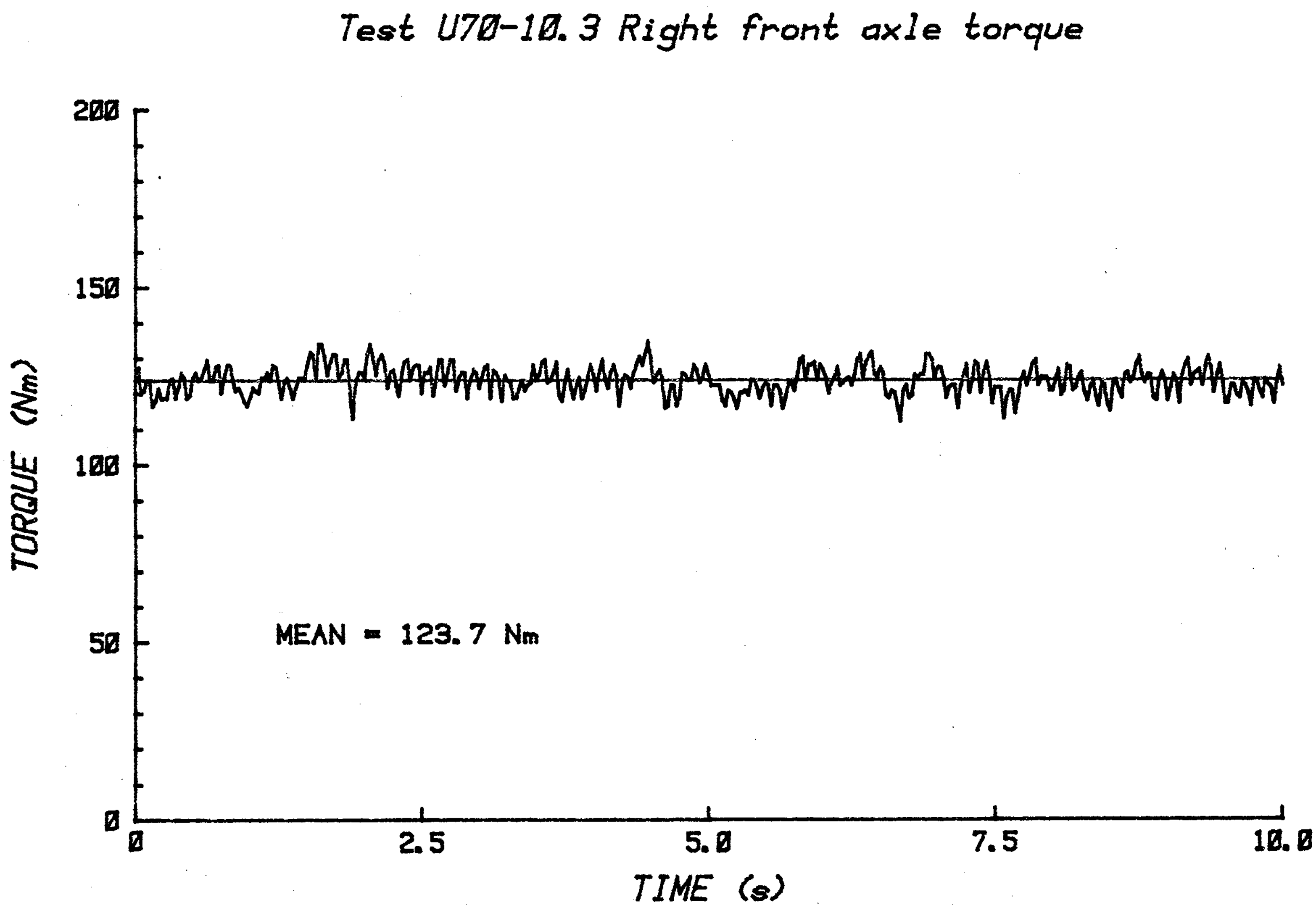

Figure D.3: Typical results for right front axle

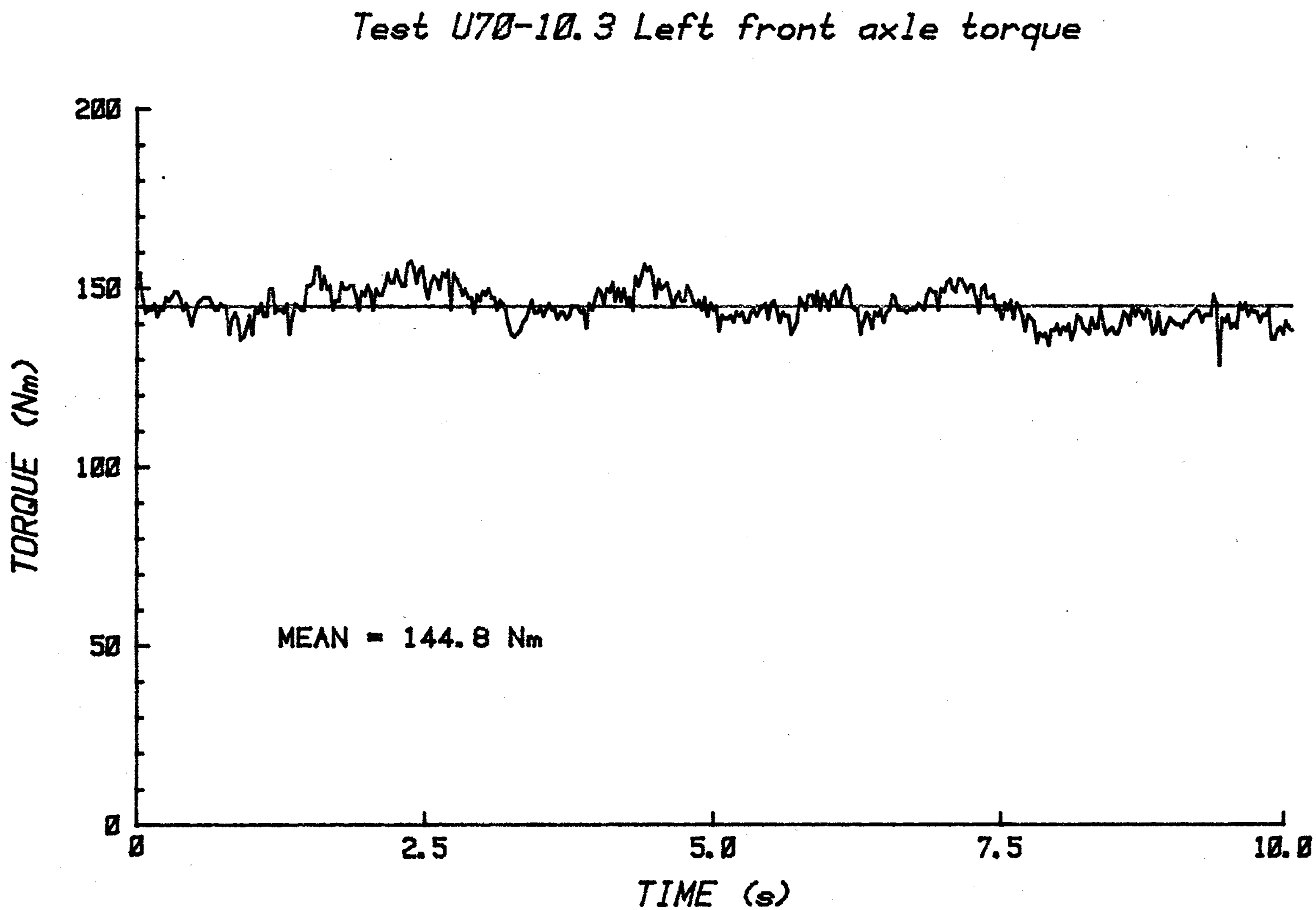

Figure D.4: Typical results for left front axle

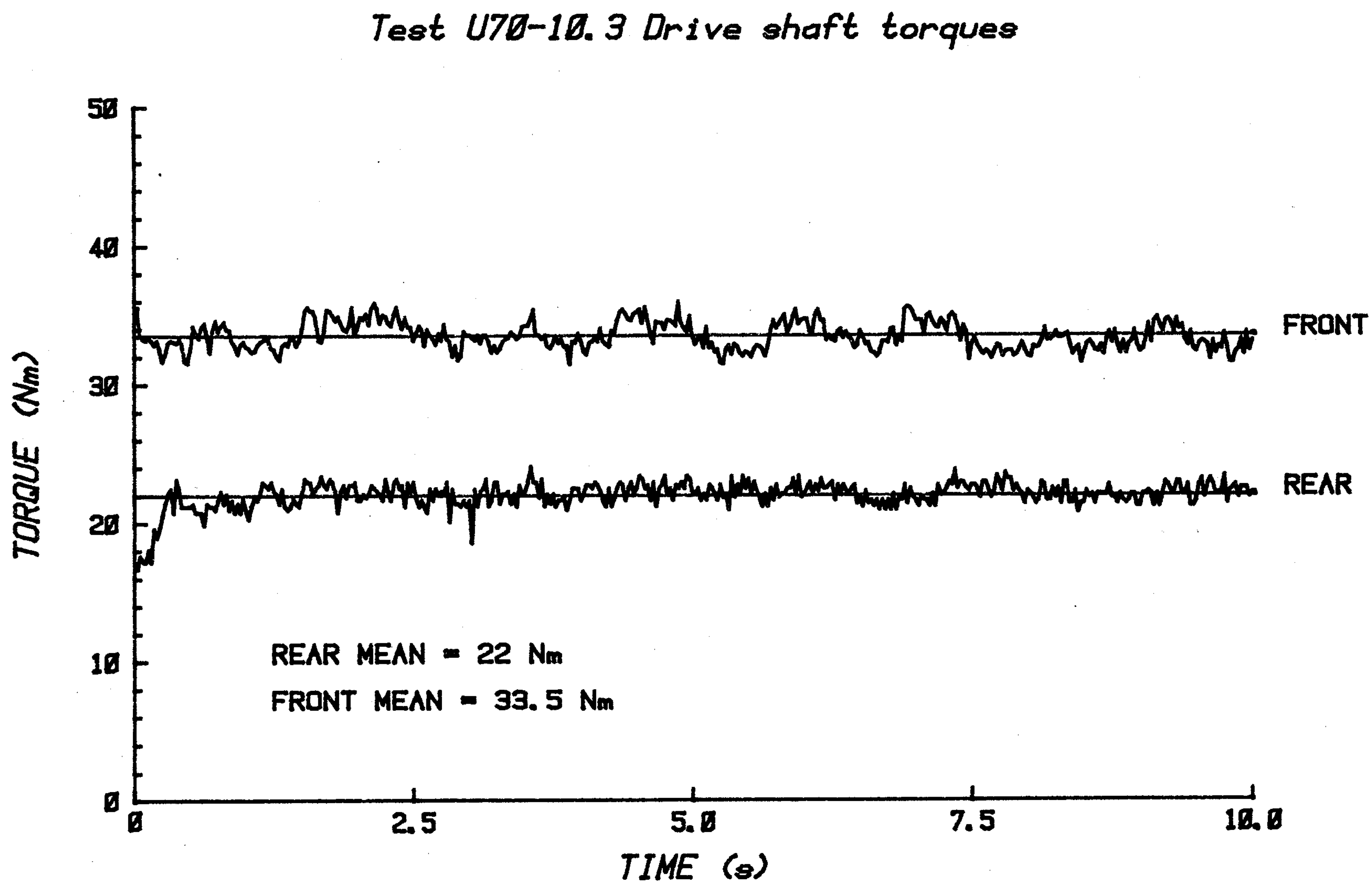

Figure D.5: Typical results for drive shafts

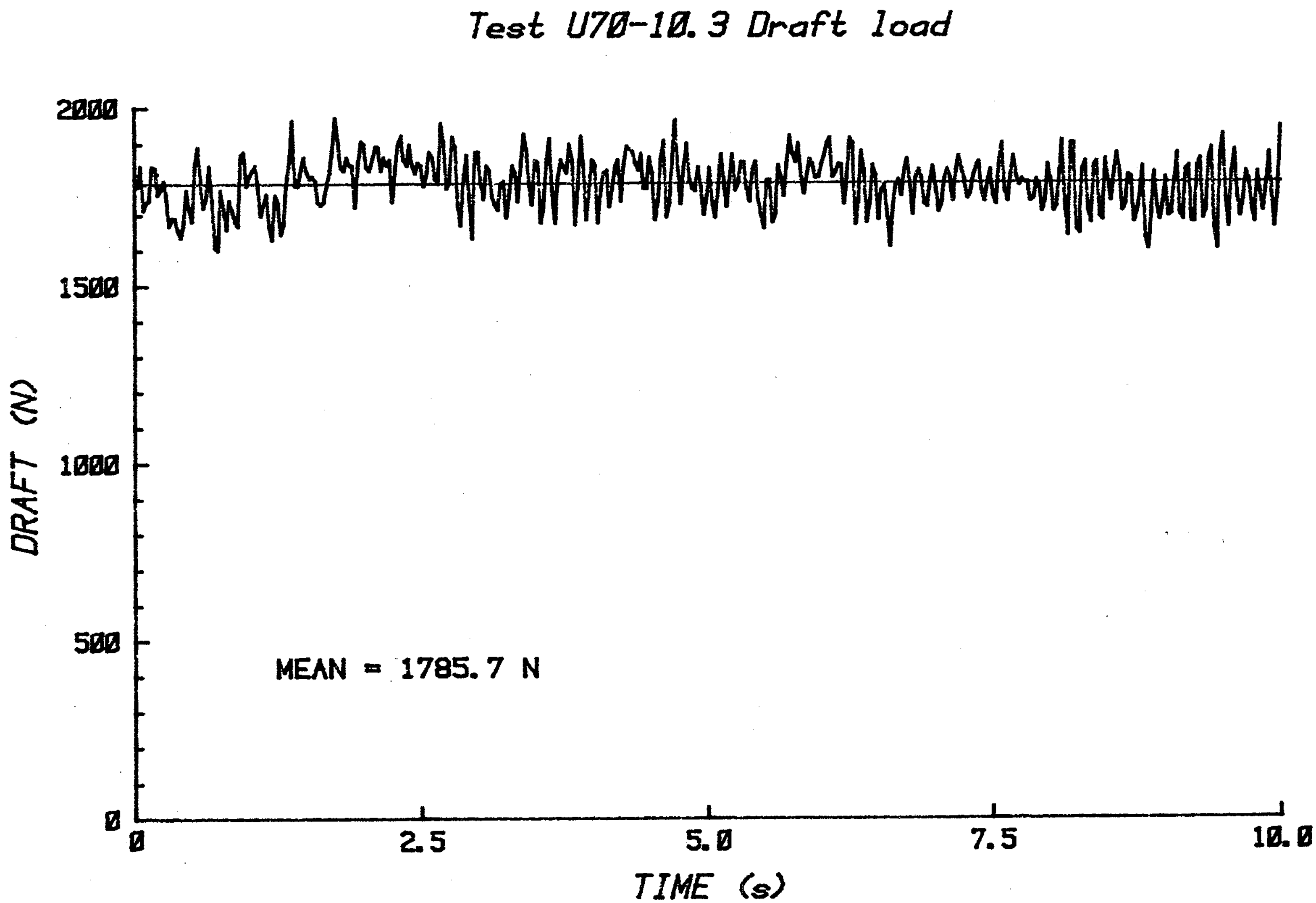

Figure D.6: Typical results for draft

Appendix E

PROGRAM LISTINGS

```
10 REM ***************************************************************************
20 REM ** ---------------------------TRACTOR---------------------------------**
30 REM ***************************************************************************
40 REM
50 REM ***************************************************************************
60 REM ** PROGRAM FOR DATA COLLECTION FROM 4WD TRACTOR USING TAURUS UNIT     ***
70 REM ** JIM DUNN #5207342  JULY 1984                                       ***
80 REM ***************************************************************************
90 REM
100 REM    CHANNEL          READS
110 REM  ------------------------------------
120 REM      0         SPEED MONITOR
130 REM      1         RIGHT REAR AXLE TORQUE
140 REM      2         LEFT REAR AXLE TORQUE
150 REM      3         RIGHT FRONT AXLE TORQUE
160 REM      4         LEFT FRONT AXLE TORQUE
170 REM      5         REAR DRIVE SHAFT TORUQE
180 REM      6         FRONT DRIVE SHAFT TORQUE
190 REM      7         REAR LOAD TRANSDUCER
200 REM      8         FRONT LOAD TRANSDUCER
210 REM      9         DRAFT TRANSDUCER
220 REM
230 COMMON F$
240 OPTION BASE 1
250 A=0:B=0:C=0:D=0:COUNT=0
260 DIM D$(4000)
270 DIM D(4000)
280 CLS: OPEN "COM1:9600,E,7,1,RS,CS,DS" AS #1:REM Opens communication
290 PRINT #1,"$a0 0 uc ca (18 10)"
300 LINE INPUT #1, B$
310 PRINT B$
320 PRINT #1,"$A0 1 AS CL (0,129,9)":REM  Sets up SCAN table
330 REM *************************************************************************
340 REM ** SETS UP SCAN TABLE, BUS ADDRESS=0, START CHANNEL=1 NUMBER OF CHAN=9*
350 REM *************************************************************************
360 INPUT #1,B$
370 INPUT #1,E$
380 IF E$="E" THEN INPUT #1,B$: PRINT "ERROR ";B$:END
390 REM *************************************************************************
400 REM ** CHECKS FOR ERROR IN TAURUS RETURN MESSAGE                          **
410 REM *************************************************************************
420 PRINT #1,"$A0 1 AA (1,0)":REM  Performs one scan of SCAN table
430 LINE INPUT #1,B$
440 LINE INPUT #1,B$
450 PRINT B$
460 PRINT
470 PRINT "SAMPLE OF READINGS FROM ALL CHANNELS"
480 PRINT
490 PRINT "   CHAN 1  CHAN 2  CHAN 3  CHAN 4  CHAN 5  CHAN 6  CHAN 7  CHAN 8  CH
AN 9"
500 FOR CHAN = 1 TO 9
510 PRINT #1,"$A0 1 AR (1)":REM  Gets information from Taurus
520 INPUT #1,B$
530 INPUT #1,R$
540 INPUT #1,E$
550 IF E$="E" THEN PRINT "ERROR FOUND ";R$:END
560 DA=VAL(R$)
570 PRINT USING "########";DA;
```

```
580 NEXT CHAN
590 PRINT:PRINT
600 REM ***********************************************************************
610 REM ** TAKES ONE SCAN OF ALL CHANNELS AND PRINTS THEM OUT FOR ERROR CHECK *
620 REM ***********************************************************************
630 INPUT "TEST DESIGNATION = FILENAME FOR DATA STORAGE ";F$:F$="B:"+F$
640 PRINT #1,"$A0 1 AA (50,25)":REM  Performs 50 scans with 25 ms delay between
650 LINE INPUT #1,B$
660 LINE INPUT #1,B$
670 PRINT B$
680 REM ***********************************************************************
690 REM ** GETS UNSTRAINED DATA INTO TAURUS UNIT AND PRINTS RETURN MESSAGE  ***
700 REM ***********************************************************************
710 UNSTRAIN$ = F$ + "U"
720 OPEN "R",#2,UNSTRAIN$,2
730 FIELD #2,2 AS DA$
740 FOR CHAN = 1 TO 50
750 PRINT #1,"$A0 1 AR (9)"
760 INPUT #1,B$
770 FOR NUM = 1 TO 9
780 INPUT #1,R$
790 IF E$="E" THEN PRINT "ERROR FOUND ";R$:END
800 DA(NUM)=VAL(R$)+DA(NUM)
810 NEXT NUM
820 INPUT #1,E$
830 NEXT CHAN
840 FOR CHAN= 1 TO 9
850 DA=DA(CHAN)/50
860 LSET DA$=MKI$(DA)
870 PUT #2,CHAN
880 NEXT CHAN
890 REM
900 REM ***********************************************************************
910 REM ** GETS ONE READING OF SPEED MONITOR (UNSTRAINED)                     **
920 REM ***********************************************************************
930 REM
940 PRINT #1,"$A0 1 RD AN (0,000)"
950 INPUT #1,B$
960 INPUT #1,E$
970 INPUT #1,SPEED$
980 LSET DA$=MKI$(VAL(SPEED$))
990 PUT #2,10
1000 CLOSE #2
1010 REM ***********************************************************************
1020 REM ** PUTS UNSTRAINED DATA ON DISK AS FILE CALLED "UNSTRAIN$"            ***
1030 REM ** UNSTRAIN$ IS THE TEST DESIGNATION FOLLOWED BY "U"                  ***
1040 REM ***********************************************************************
1050 PRINT #1,"$A0 1 AS CL (0,129,9)"
1060 LINE INPUT #1,B$
1070 PRINT B$
1080 PLAY "G2A"
1090 PRINT "PRESS ANY KEY TO START DATA COLLECTION (STRAINED)"
1100 A$ = INKEY$:IF A$ = "" THEN GOTO 1100
1110 IF A$<>CHR$(13) THEN GOTO 1100
1120 PRINT #1,"$A0 1 RD AN (0,00)"
1130 INPUT #1,B$,E$,SPEED$
1140 REM
1150 REM ***********************************************************************
```

```
1160 REM ** TELLS TAURUS TO READ SPEED MONITOR ONLY ONCE AT BEGINNING OF TEST **
1170 REM ***********************************************************************
1180 REM
1190 PRINT #1,"$A0 1 AA (400,25)"
1200 LINE INPUT #1,B$
1210 LINE INPUT #1,B$
1220 PRINT B$
1230 REM ***********************************************************************
1240 REM ** SENDS MESSAGE TO TAURUS TO TAKE 400 READINGS OF EACH CHANNEL WITH **
1250 REM ** A DELAY OF THE SECOND NUMBER IN THE BRACKETS                      **
1260 REM ***********************************************************************
1270 OPEN "R",#2,F$,800
1280 FOR I= 1 TO 400
1290 FIELD #2,A AS DUMMYA$,B AS DUMMYB$,C AS DUMMYC$,D AS DUMMYD$,2 AS D$(I)
1300 IF A<250 THEN A=A+2:GOTO 1340
1310 IF A =250 AND B<250 THEN B=B+2:GOTO 1340
1320 IF A =250 AND B=250 AND C<250 THEN C=C+2:GOTO 1340
1330 IF A =250 AND B=250 AND C=250 THEN D=D+2:GOTO 1340
1340 NEXT I
1350 REM ***********************************************************************
1360 REM ** FIELDS THE FILE WITH  800 BYTE RECORD.  READINGS ARE STORED AS    **
1370 REM ** NINE BLOCKS OF 400 READINGS EACH.  THESE BLOCKS ARE BLOCKS        **
1380 REM ** FOR EACH CHANNEL (400 READINGS FOR EACH CHANNEL)                  **
1390 REM ***********************************************************************
1400 PRINT "START TIME IS ";TIME$:PRINT
1410 PRINT "PRESS ANY KEY FOR STATUS OF DATA TRANSFER (COUNT = 1 TO 3600)"
1420 COUNT = 1
1430 FOR LOOP1 = 1 TO 225
1440 A$ = INKEY$:IF A$<>"" THEN PRINT "COUNT IS ";COUNT
1450 PRINT #1,"$A0 1 AR (16)"
1460 INPUT #1,B$
1470 FOR I = 1 TO 16
1480 INPUT #1,R$
1490 D(COUNT) = VAL(R$)
1500 COUNT = COUNT + 1
1510 NEXT I
1520 INPUT #1,E$
1530 IF E$="E" THEN PRINT  "ERROR ";R$:END
1540 NEXT LOOP1
1550 PRINT "FINISH TIME IS ";TIME$
1560 FOR CHAN = 1 TO 9
1570 PRINT CHAN;",";
1580 COUNT = CHAN
1590 FOR READNG = 1 TO 400
1600 LSET D$(READNG)=MKI$(D(COUNT))
1610 COUNT = COUNT + 9
1620 NEXT READNG
1630 PUT #2 ,CHAN
1640 NEXT CHAN
1650 PRINT
1660 LSET D$(1)=MKI$(VAL(SPEED$)):PUT #2,10
1670 REM ***********************************************************************
1680 REM ** READS STRAINED DATA FROM TAURUS ONE BYTE AT A TIME AND STORES IT  **
1690 REM ** ON DISK IN A RANDOM ACCESS FILE CALLED "F$"                       **
1700 REM ***********************************************************************
1710 CLOSE
1720 CHAIN"OVERLAY.ATO": REM  Runs the plotting program
```

```
10 REM -------------------------- OVERLAY ------------------------------------
20 REM
30 REM ************************************************************************
40 REM ** PROGRAM FOR PLOTTING RESULTS FROM SEVERAL CHANNELS ONE TEST        **
50 REM ** JIM DUNN JULY 1984                                                 **
60 REM ************************************************************************
70 DIM D$(400)
80 DIM D1(9,400)
90 A=0:B=0:C=0:D=0:MIN=12047:MAX=-12048
100 SCREEN 100
110 LOCATE 1,1
120 INPUT "TEST DESIGNATION TO PLOT ";F$:F$="B:"+F$
130 OPEN "R",#2,F$,800
140 FOR I = 1 TO 400
150     FIELD #2,A AS DUMA$,B AS DUMB$,C AS DUMC$,D AS DUMD$,2 AS D$(I)
160     IF A<250 THEN A=A+2:GOTO 200
170     IF A=>250 AND B<250 THEN B=B+2:GOTO 200
180     IF A=>250 AND B=>250 AND C<250 THEN C=C+2:GOTO 200
190     IF A=>250 AND B=>250 AND C=>250 THEN D=D+2:GOTO 200
200 NEXT I
210  FU$=F$+"U"
220  OPEN "R",#1,FU$,2
230  FIELD #1,2 AS UN$
240 PRINT "HOW MANY PLOTS TO OVERLAY ?";
242 N$=INKEY$:IF N$=""THEN 242
243 N=VAL(N$):PRINT N
250 FOR NUM = 1 TO N:PRINT "CHANNEL # FOR PLOT #";NUM;"?";
252 PN$=INKEY$:IF PN$="" THEN 252
253 P(NUM)=VAL(PN$):PRINT P(NUM)
254 NEXT NUM
260 NUM = 1
270 FOR TRAC = 1 TO N
280 CHAN = P(NUM):PRINT CHAN
290  GET #1,CHAN
300  UNSTRAIN =CVI(UN$)
310 IF CHAN = 1 THEN GOSUB 1110
320 IF CHAN = 2 THEN GOSUB 1150
330 IF CHAN = 3 THEN GOSUB 1190
340 IF CHAN = 4 THEN GOSUB 1230
350 IF CHAN = 5 THEN GOSUB 1030
360 IF CHAN = 6 THEN GOSUB 1070
390 IF CHAN = 9 THEN GOSUB 1330
400 GET #2,CHAN
405 DUMSUM=0
510     FOR READNG = 1 TO 400
520             PDATA=CVI(D$(READNG))-UNSTRAIN
530             TNUMB =((PDATA)^2)*SLOPE1 + PDATA*SLOPE2 + INTER
540             SUM=SUM+TNUMB:DUMSUM=DUMSUM+TNUMB
550             IF TNUMB>MAX THEN MAX=TNUMB:GOTO 570
560             IF TNUMB<MIN THEN MIN=TNUMB
570             D1(CHAN,READNG)=TNUMB
580     NEXT READNG
585 SSUM(CHAN)=DUMSUM
590 MEAN(CHAN)=SSUM(CHAN)/400
595 NUM = NUM + 1
600 NEXT TRAC
602 PRINT "ACTUAL MINIMUM = ";MIN
604  MIN = 0
```

```
606 PRINT "IS MAX = ";MAX;" OK";:INPUT ANSWER$:IF ANSWER$<>"Y" THEN INPUT "INPUT
 MAX ";MAX
610 VAR=(MAX-MIN)
620 MAGNIFY=250/VAR
630 'MAGNIFY=1
640 SUM=0
650 CLS
660 X=64
670 SCREEN 105
680 CLS
690 PSET (64,0),1
700 DRAW "D25R5L5D62R5L5D63R5L5D62R5L5D63R5L5D45U45R140D5U5R140D5U5R140D5U5R140D
5"
710 MID = VAR/2
720 PRINT "                                      PLOT FOR TEST ";F$
730 PRINT "                                      MAX  =";MAX;"   MIN =";MIN
735 NUM=1
740 FOR TRAC= 1 TO N
745 CHAN = P(NUM)
750 READNG=1
760 PSET (X,150+(MAX-MID-(D1(CHAN,READNG)))*MAGNIFY),1
770 FOR READNG = 2 TO 400
780 X=X+1.4
790 Y = 150+(MAX-MID-(D1(CHAN,READNG)))*MAGNIFY
800 LINE -(X,Y),1
810 NEXT READNG
820 LOCATE Y*25/324,X*81/639:PRINT T$(CHAN)
825 PSET (64,150+(MAX-MID-(MEAN(CHAN)))*MAGNIFY),1
826 LINE -(624,150+(MAX-MID-(MEAN(CHAN)))*MAGNIFY),1
830 X=64
835 NUM = NUM +1
840 NEXT TRAC
850 LOCATE 2,3:PRINT USING"###.##";MAX-MID+VAR/2
860 LOCATE 7,3:PRINT USING "###.##"; MAX-MID+VAR/4
870 LOCATE 12,3:PRINT USING "###.##";MAX-MID
880 LOCATE 17,3:PRINT USING "###.##"; MAX-MID-VAR/4
890 LOCATE 22,3:PRINT  USING "###.##"; MAX-MID-VAR/2
900 LOCATE 25,40:PRINT "TIME"
910 LOCATE 7,1:PRINT "T"
920 LOCATE 8,1:PRINT "O"
930 LOCATE 9,1:PRINT "R"
940 LOCATE 10,1:PRINT "Q"
950 LOCATE 11,1:PRINT "U"
960 LOCATE 12,1:PRINT "E"
970 LOCATE 12,3:PRINT USING "###.##";MAX-MID
972 LOCATE 18,15
980 PRINT (MEAN(1)-MEAN(2))/((MEAN(1)+MEAN(2))/2)*100;"% REAR DIFFERENCE"
985 LOCATE 19,15
990 PRINT (MEAN(3)-MEAN(4))/((MEAN(3)+MEAN(4))/2)*100;"% FRONT DIFFERENCE"
1000 'PRINT M$;
1010 'IF M$="N"
1020 END
1030 SLOPE1=-2.26521E-05
1035 SLOPE2=.21634851#
1040 INTER=0
1050 T$(CHAN) = "RD"
1060 RETURN
1070 SLOPE1=1.222736E-05
```

```
1075 SLOPE2=8.651142E-02
1080 INTER=.014718
1090 T$(CHAN) = "FD"
1100 RETURN
1110 SLOPE1= 0
1115 SLOPE2 = .77707457#
1120 INTER = 0
1130 T$(CHAN) = "RR"
1140 RETURN
1150 SLOPE1= 0
1155 SLOPE2 = .75251657#
1160 INTER =0
1170 T$(CHAN) = "LR"
1180 RETURN
1190 SLOPE1=0
1195 SLOPE2=.77402379#
1200 INTER=-1.15867
1210 T$(CHAN) = "RF"
1220 RETURN
1230 SLOPE1=0
1235 SLOPE2=.73383555#
1240 INTER=0
1250 T$(CHAN) = "LF"
1260 RETURN
1330 SLOPE1=0!
1335 SLOPE2=-.75960656#*9.810001
1340 INTER = 1.251147*9.810001
1345 T$(CHAN)="DT"
1350 RETURN
```