DYNAMIC LOAD AND WHEEL SPEED RATIO EFFECTS ON FOUR WHEEL DRIVE TRACTIVE PERFORMANCE

By

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PREFACE

This research is concerned with the tractive performance of four wheel drive tractors. The effects of wheel speed ratio, dynamic load ratio, wheel slip, forward speed and soil cone index were examined. This work was supported by the Oklahoma State University Experiment Station and Agricultural Engineering Department. I also acknowledge the contributions of F. W. Zaloudek Co., Kremlin, OK and Cessna Fluid Power Division, Hutchinson, KS, for supplying equipment used in this research.

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LIST OF SYMBOLS

A/D	Analog to Digital Reading From Computer
b	Unloaded Tire Section Width (cm)
Bn	Mobility Number
CI	Soil Cone Index (kPa)
CIa	Soil Cone Index After Traffic (kPa)
CIb	Soil Cone Index Before Traffic (kPa)
Cn	Wheel Numeric
d	Unloaded Tire Diameter (cm)
DVd	Drawbar Transducer Vertical Downward Force (N)
DVu	Drawbar Transducer Vertical Upward Force (N)
Es	Engine Speed and Hydraulic Pump Speed (RPM)
Ep	Number of Pulses from Engine Speed Sensor During Time Interval
f	Subscript Referring to the Front Axle
Fp	Number of Pulses from Front Axle Speed Sensor During Time Interval
F_PR	Input Pressure for Front Hydraulic Motor (kPa)
F_RPM	Input Rotational Speed to the Front Differential (RPM)
g	Gravitational Constant (m/s)
Gp	Number of Pulses Counted From Radar
GR	Differential and Final Drive Gear Reduction (29.25)
h	Unload Tire Section Height (cm)
K1,K2,K3	Prediction Constants

LP	Left Transducer Net Traction (N)
LV	Left Transducer Vertical Load (N)
MR	Motion Resistance (N)
P	Net Traction or Pull (N)
pos	Position of the Rear Ballast Rack
r	Subscript Referring to the Rear Axle
Rp	Number of Pulses from Rear Axle Speed Sensor During Time Interval
RP	Right Transducer Net Traction (N)
R_PR	Input Pressure for Rear Hydraulic Motor (kPa)
rr	Rolling Radius (cm)
RR	Rolling Radius Ratio of One Axle to the Other Axle
R_RPM	Input Rotational Speed to the Rear Differential (RPM)
RV	Right Transducer Vertical Load (N)
S	Wheel Slip
t	Subscript Referring to the Total Tractor
T	Axle Torque (N·m)
TD	Loaded Tire Deflection (cm)
TE	Tractive Efficiency
TF	Towed Force (N)
T1	Time Interval Corresponding to Radar (1.598152 s)
T2	Time Interval Corresponding to Front Axle Speed (1.598040 s)
T3	Time Interval Corresponding to Rear Axle Speed (1.598076 s)
T4	Time Interval Corresponding to Engine and Hydraulic Pump Speed (1.598014 s)
TQ	Self-Propelled Torque

V	Actual Forward Speed (km/h)
Vt	Theoretical Forward Speed (km/h)
ω	Rotational Speed of the Axle (RPM)
W	Dynamic Load (N)
W_r0	Rear Axle Load (N) with No Ballast Moved to the Front Ballast Rack
W_r680	Rear Axle Load (N) with 680 kg of Ballast Moved to the Front Ballast Rack
WSR	Wheel Speed Ratio of One Axle to Another

CHAPTER I

INTRODUCTION

Four wheel drive and front wheel assist agricultural tractors are popular because they increase field capacity, operating efficiency and traction under poor working conditions. On all production four wheel drive tractors, the front angular velocity (wheel speed) is constant relative to the rear wheel speed and designed to produce a ratio of front wheel speed to rear wheel speed greater than one. This is because the front tires compact a path for the rear tires; with firmer soil to operate on, the rear tires produce their share of thrust with less slip. For a range of soil conditions and dynamic load distribution, the designed ratio of wheel speeds greater than one may be correct; for a different soil condition or dynamic load distribution, the rear drive might be "pulling" or "pushing" the front. This may reduce operating efficiency resulting in increased fuel requirement, decreased field capacity, increased tire wear and increased drive train stress.

An instrumented four wheel drive tractor was used to investigate the effects of different operating parameters on tractive performance which included four wheel drive motion resistance, dynamic traction ratio and tractive efficiency.

The relationships among dynamic load distribution, forward speed, wheel slip, wheel speed ratio, soil strength and tractive performance had not been evaluated for a four wheel drive traction system. Prediction equations had not been developed for a four wheel drive system. These equations may be used to determine tractor performance under various operating conditions and provide information on traction devices operated in tandem. The equations may also be used to determine the merits of controlling wheel speed ratio, dynamic load ratio, or "borrowing" dynamic load from implements as has been suggested by some authors.

The overall objective of this research was to determine the relationship among dynamic load distribution, forward speed, wheel slip, wheel speed ratio, soil strength and tractive performance under field conditions. The research also involved evaluating possible improvements in the efficiency of a four wheel drive traction system by controlling the parameters of wheel speed ratio, dynamic load ratio or both. This was accomplished by completing the following specific objectives:

1. Determine relationships among dynamic load distribution, forward speed, wheel slip, wheel speed ratio, soil strength as measured by soil cone index and tractive performance for a four wheel drive traction system.

2. Develop equations to predict four wheel drive tractive performance and evaluate the tractive performance improvement by controlling or maintaining dynamic load

distribution, wheel speed ratio, wheel slip and forward speed for a four wheel drive traction system.

3. Determine the feasibility of an automatic control system to control wheel speed ratio or dynamic load ratio and if warranted evaluate it using a computer simulation model of tractor performance.

CHAPTER II

REVIEW OF LITERATURE

Tractor Use and Trends

Fuel efficiency is a major consideration in agricultural production. Williford and Smith (1982) examined fuel requirements of three cotton production systems. Fuel use ranged from 84 to over 120 liters per hectare. Hauck et al. (1983) conducted a tractor use study of over 130 tractors in North Dakota. Results indicated that on the average, four wheel drive tractors utilized 69 percent more fuel per hour than did two wheel drive tractors; but this was offset by a 68 percent increase in field capacity. This increased capacity partially explains the popularity of four wheel drive tractors for agricultural production along with their ability to operate under adverse soil conditions.

Bowers (1978) examined some of the advantages and presented a simple procedure for determining an adequate match between tractor and implement. According to Bower's 0.86 "rule of thumb" conversion factor, on concrete approximately 26 percent of the usable engine power is lost in the transmission and traction drive, on soft soil these losses may approach 60 percent.

Ohrmann (1979) examined how efficiently Montana farmers were utilizing four wheel drive tractors. In most cases, drawbar power utilized during an operation was less than the estimated available drawbar power. Pull to dynamic load ratio exhibited some correlation with wheel slip and roughly followed the prediction equation of Wismer and Luth (1974). According to actual axle load distributions for the tractors tested, most tractors were normally operated with dynamic front axle load slightly above 50 percent of total load, while static load distribution averaged slightly under 60 percent on the front axle.

Buckingham (1980) states that front wheel assist tractors have become very common for use in European agriculture. One reason is the higher fuel prices seen in Europe as compared to the United States. Depending on soil conditions, front wheel assist can normally be expected to show increased drawbar power, decreased fuel consumption and decreased rear axle torque when compared to a similar sized two wheel drive tractor. Buckingham (1978) states that front wheel assist tractors are normally designed to operate the front wheels 1 to 3 percent faster than the rear, because of this, tire wear and tractor operation on the highway are significant considerations in front wheel assist tractors.

Burt and Bailey (1982) examined dynamic load and inflation pressure effects on tractive efficiency and net traction. Dynamic load had significant effects while inflation pressure exhibited less of an effect on both net traction and tractive efficiency. Charles (1983) also examined the effects of load and inflation pressure on tire performance. Plots of tractive efficiency as a function of slip were parallel for all five inflation pressures used. The lowest inflation pressure exhibited the best tractive efficiency for all three ballast conditions used. The highest ballast condition exhibited the best tractive efficiency at all five inflation pressures used.

Lyne et al. (1980) and Lyne et al. (1984) studied improving tractive efficiency and optimizing engine performance. It was concluded that by controlling inflation pressure and ballast to maintain high tractive efficiency, while controlling gear ratio and engine speed to optimize engine efficiency, a high overall operating efficiency could be maintained. Engine speed and gear ratio were controlled by the operator in a feedback arrangement.

Burt et al. (1980) examined the effects of dynamic load and wheel speed ratio on a simulated four wheel drive system for two soil types. It was shown that peak tractive efficiency occurred at a wheel speed ratio of approximately 1.1. They suggested, that due to the shape of the tractive efficiency-wheel speed ratio curve, controlling wheel speed ratio may not be warranted. Front wheel slip was held constant at either 10 or 20 percent while rear wheel slip was varied, thus only the rear wheel is likely to pass through maximum tractive efficiency. Forward speeds in the soil bins at the National Soil Dynamics Laboratory are normally below 0.6 meters per second.

Brixius and Wismer (1978) studied the role of slip in traction. On the soil used, maximum tractive efficiency occurred between 10 and 15 percent slip. The ratio of pull to dynamic load increased with slip, then leveled off as slip continued to rise. They emphasized the importance of slip in traction and stated that zero pull on a hard surface was a good zero condition for comparing slips on other surfaces.

Wismer and Luth (1974) developed off-road traction prediction equations for wheeled vehicles. These equations were used extensively for predicting tractive efficiency and pull to dynamic load ratio. The equations developed were given as follows:

$$\frac{P}{W} = 0.75 \times (1 - e^{-0.3 \times Cn \times S}) - (\frac{1.2}{Cn} + 0.04) \quad (1)$$

$$\frac{TF}{W} = \frac{1.2}{Cn} + 0.04 \quad (2)$$

$$\frac{T}{rr \times W} = \frac{P}{W} + \frac{TF}{W} \quad (3)$$

$$TE = \frac{P}{W} \times \left(\frac{1-S}{\frac{T}{rr \times W}}\right) \quad (4)$$

where: $\frac{P}{W}$ = Pull to dynamic load ratio

$\frac{T}{rr \times W}$ = Ratio of axle torque to rolling radius and dynamic load

$\frac{TF}{W}$ = Towed force to dynamic load ratio

Cn = Wheel numeric, defined as $\frac{CIxbxd}{W}$

S = Slip, defined as $1-\frac{V}{Vt}$

Both equations are functions of soil cone index, dynamic load on the tire, tire width, tire diameter and slip.

Greenlee et al. (1986) developed off road traction prediction equations which included forward speed as a significant parameter. The equation developed predicted dynamic traction ratio as follows:

$$\frac{P}{W} = A \times \{1-e^{[-KxCnx(S+\log_e(\frac{A}{A+\frac{TF}{W}}))]}\} \quad (5)$$

where: $A = 0.0823 + 0.162 \times \frac{d}{b}$

$$K = 0.107 + \frac{0.0394}{\frac{Vt^2}{gxb} + 0.0345}$$

$$\frac{TF}{W} = .2292 + \frac{0.2337}{Cn} - .7038 \times \frac{b}{d}$$

Brixius (1987) presented traction prediction equations for bias ply tires. These equations were meant to be revisions of equations developed by Wismer and Luth (1974).

$$\frac{T}{rrxW} = 0.88x(1-e^{-.1xBn})x(1-e^{-7.5xS})+0.04 \quad (6)$$

$$\frac{TF}{W} = Bn^{-1} + .04 + 0.5xSxBn^{-.5} \quad (7)$$

$$\frac{P}{W} = \frac{T}{rrxW} - \frac{TF}{W} \qquad (8)$$

$$TE = \frac{P}{W} \times \frac{1-S}{\frac{T}{rrxW}} \qquad (9)$$

where: Bn = Mobility number, defined as

$$Cn \times \left(\frac{1 + 3\frac{b}{d}}{1 + 5\frac{TD}{h}}\right)$$

Burt et al. (1979) examined the combined effects of dynamic load and slip on tire performance. For constant wheel slip, tractive efficiency increased as dynamic load increased for compacted soils, and decreased as dynamic load increased for a soil with an uncompacted subsurface. This was partially the result of increased rolling resistance as the tire sank into the soil with an uncompacted subsurface.

Burt and Lyne (1983) studied the effects of forward speed on tractive performance. Within the range of 0.1 to 0.6 meters per second, there was no effect of forward speed on net traction or tractive efficiency for constant slip and dynamic load. Forward speed of 0.6 meters per second is less than one-fourth the normal operating range for modern four wheel drive tractors.

Performance of Four Wheel Drive Tractors

As the front tire passes over the soil it produces a compacted path for the rear tire. This results in a "stronger" soil condition for the rear tire and a difference in the operating point for maximum tractive efficiency. Several researchers have examined multipass behavior of pneumatic tires in terms of increases in soil cone index, soil bulk density, dynamic traction ratio and tractive efficiency.

Holm (1969) studied multipass effects of a multiple drive axle vehicle. The second pass of a tire in the same rut resulted in significant increases in drawbar pull. Drawbar pull also increased for the third and fourth pass of a tire in the same rut, but this increase was markedly reduced. Rolling resistance followed an inverse trend to that of drawbar pull.

Taylor et al. (1982) studied the effects of multiple passes of a tire in the same rut in tilled soils. Both net traction and tractive efficiency were significantly lower on the first pass of a tire compared to subsequent passes. The first pass of a tire in tilled soil caused 75 percent of the change in soil bulk density and 90 percent of the tire sinkage. Another significant result was the considerable difference in slip corresponding to maximum tractive efficiency for the first and subsequent passes of a tire.

Koger et al. (1985) studied multipass effects of skidder tires on soil compaction. The effects of tire size, dynamic load, inflation pressure and multiple passes varied significantly with soil type. The results indicated that the increase in soil bulk density as a result of tire traffic was reduced by lowering inflation pressure and increasing tire size.

Soil cone index is defined as the force required to press a 30 degree circular cone through the soil divided by the base area of the cone. Pitts and Goering (1979) developed an equation predicting soil cone index changes caused by a driven wheel. Several equations were developed to represent the test data. Slip was included in a number of the models but the model chosen to best represent the data did not include slip and was given as follows:

$$\frac{CIa}{CIb} = 1+18.09x\left(\frac{W}{CIbxbxd}\right)^{0.554} x\ e^{\left(\frac{-0.585xV^2}{gxb}\right)} \qquad (10)$$

Brixius (1987) presented a simpler equation for predicting soil cone index changes caused by a driven tire.

$$\frac{CIa}{CIb} = 1 + 1.8\ x\ e^{-.11xBn} \qquad (11)$$

Bashford et al. (1985) examined the performance of a front wheel assist tractor under two-wheel and four-wheel drive modes. Relative front wheel speed was varied by changing the size of the front tires. Gross traction from the front axle was increased by increasing wheel speed ratio or ballast. Wheel speed ratios of 1.01 to 1.05 were near optimum for maximum tractive efficiency. Dynamic load distributions with 30 to 40 percent of the total load on the front axle were shown to result in maximum tractive efficiency. Conclusions of this study are confounded by the changing of tire diameter to vary wheel speed ratio. Taylor et al. (1967) concluded that increasing tire diameter results in increased pull and increased coefficient of traction for pneumatic tires. Therefore, it cannot be determined if the increased traction and tractive efficiency are the result of wheel speed ratio or tire diameter.

Young and Schafer (1977) suggested that automatic controls could improve traction. It was concluded that the necessary measurement techniques already exist to allow an automatic control system to reduce motion resistance, improve tractive efficiency or control slip.

Clark and Vande Linde (1986) developed an automatic ballast system to reduce the difficulty of ballasting a tractor for a particular implement. A small four wheel drive tractor was modified by adding ballast tanks on the front and rear of the tractor. Liquid ballast could be shifted between the tanks to provide the desired static load distribution. No attempt was made to dynamically ballast the tractor to improve performance under field conditions.

Zhang and Chancellor (1989) developed an automatic ballasting system for a two wheel drive tractor. Rails on each side of the tractor on which a mass was moved horizontally were used to vary dynamic load distribution. The control system was designed to maintain a preset level of front dynamic load ratio. Reducing the normal front dynamic load ratio from 30 percent to a preset level of 13 percent improved tractive performance between 2 and 20 percent.

Zhang et al. (1984) examined controlling slip of a single hydrostatically driven tire under laboratory conditions. The tire drove a small test stand which loaded the tire to the desired level. Three equations in state variable form and the output equation for slip were used in the model. The system was designed to control wheel slip to the level desired and no attempt was made to correlate the slip value with tractive performance.

CHAPTER III

EXPERIMENTAL APPARATUS

Four Wheel Drive Tractor

A four wheel drive test apparatus was constructed to collect performance data not collected by previous researchers. Several unique modifications were incorporated in the four wheel drive tractor design. In previous research the contribution of the front axle to total tractor performance was not measured. The speed of the front wheels in relation to the rear wheels was fixed so that the contribution of wheel speed ratio was not measured except by changing front tire diameter (Bashford et al. 1985) or simulating a tractor by operating a single tire twice in the same track (Burt et al. 1980).

A four wheel drive tractor and instrumentation system was designed with the capability to: vary the ratio of rotational speed of the front wheels in relation to the rear wheels during operation, vary the mass distribution between the front and rear axles to obtain the desired dynamic load ratio, measure drawbar forces, measure net pull and dynamic load of each axle, and measure performance of the total tractor and each axle in terms of dynamic traction ratio and tractive efficiency.

Tractor Design

A four wheel drive tractor was designed and built to enable measurement of tractor performance. The tractor was constructed by modifying a Case 2470 four wheel drive tractor. Before modification the tractor was equipped with 23.1-30 tires, 12-speed transmission and 130 kW engine measured at the power take-off. This tractor was excellent for the purposes of this research because of its "crab" type steering allowing a very tight turning radius and it's size near the mean size of production four wheel drive tractors (Figure 1).

Figure 1. Case 2470, Four Wheel Drive Research Tractor

The original tractor was completely disassembled and then reconstructed with several significant modifications to produce the research vehicle. A cutaway drawing of the final research tractor showing the position of major components is shown in Figure 2.

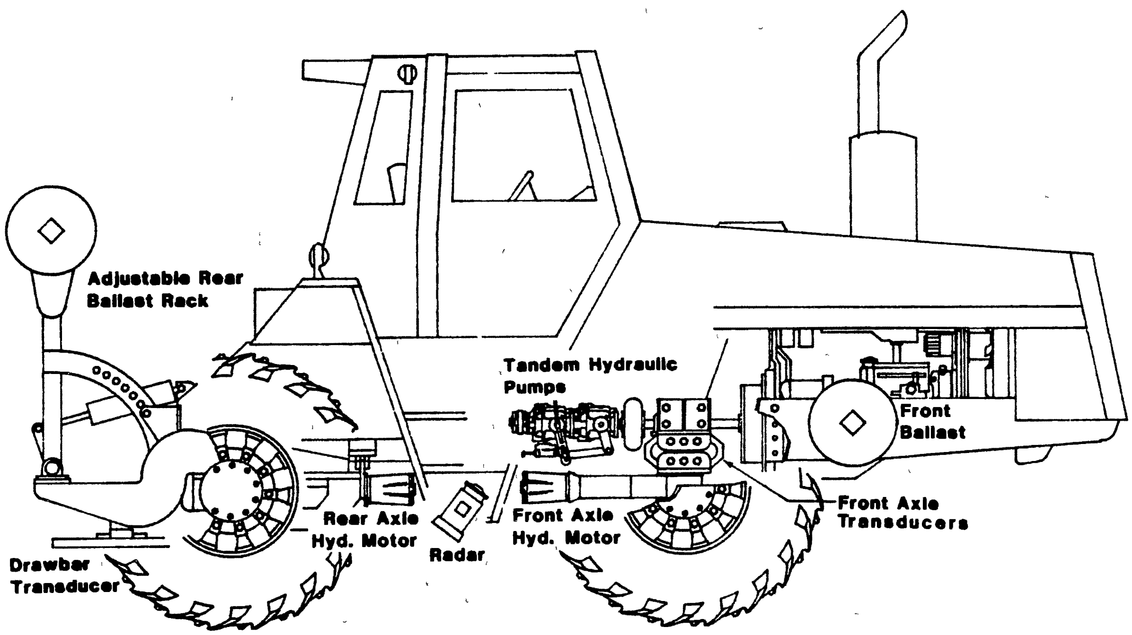


Figure 2. Detail Drawing of Four Wheel Drive Research Tractor Showing the Location of Major Components

General Tractor Modifications

An addition was constructed on the right side of the original cab (Figure 7) allowing two people to occupy the cab during an experiment. The person sitting in the original cab drove the tractor, set wheel speed ratio, set engine speed and operated the hydrostatic transmission. The person in the cab addition operated the computer and determined the correct setting for each test. The computer table swiveled to allow the computer to be optionally operated by the driver.

The original tractor engine needed significant and costly repairs and was replaced by a John Deere six cylinder, 10.1 liter engine. To accommodate this engine, the frame of the tractor was lengthened forward of the front axle by 66 cm. New 23.1-30, bias-ply tires were mounted on the tractor before testing.

Hydrostatic Transmission

The standard gear transmission, clutch and bell housing were replaced by a pair of variable displacement hydraulic transmissions; one to provide power to the front differential and the other to provide power to the rear differential. Power to the hydraulic pumps was provided by the engine through a large flexible coupling and drive shaft. The hydraulic pumps were a tandem pair of Cessna Fluid Power model 70543 variable displacement axial piston pumps (Figures 2 and 3). Each pump had a maximum displacement of 67 cm^3/rev and a maximum operating speed rating of 2500 rpm. The pumps were rated at 24.1 MPa oil pressure, but auxiliary pressure relief valves were obtained which allowed the maximum pressure to be raised to 27.6 MPa.

Figure 3. Tandem Hydraulic Variable Displacement Axial Piston Pumps

Even with the use of the auxiliary pressure relief valves, the hydraulic transmissions capabilities were below that of the four wheel drive tractor. Because of limitations in the hydraulic transmission torque capacity, the tractor was capable of only producing up to 35 percent dynamic traction ratio. This was adequate, but for other types of research, additional capability to produce higher drawbar pull in the range of 50 percent of tractor weight might be required.

Each pump drove a Cessna model 74704 fixed displacement hydraulic motor (Figure 2). The motors had a displacement of 144 cm^3/rev and a maximum speed rating of 1000 rpm. The motors could be operated up to 34.5 MPa oil pressure providing 610 N·m of torque at maximum pressure. The pumps drove the differentials through universal joint drivelines. The hydraulic transmission was capable of transmitting approximately 60 kW of power to each differential. Figure 4 shows the front differential removed from the tractor with the front pump and driveline in place. The rear pump had a similar mounting arrangement (Figure 5). Blocks were added between the rear axle and tractor frame which raised the frame 7.6 cm. The blocks were added to level the frame because of additional height from the installation of transducers between the front axle and tractor frame.

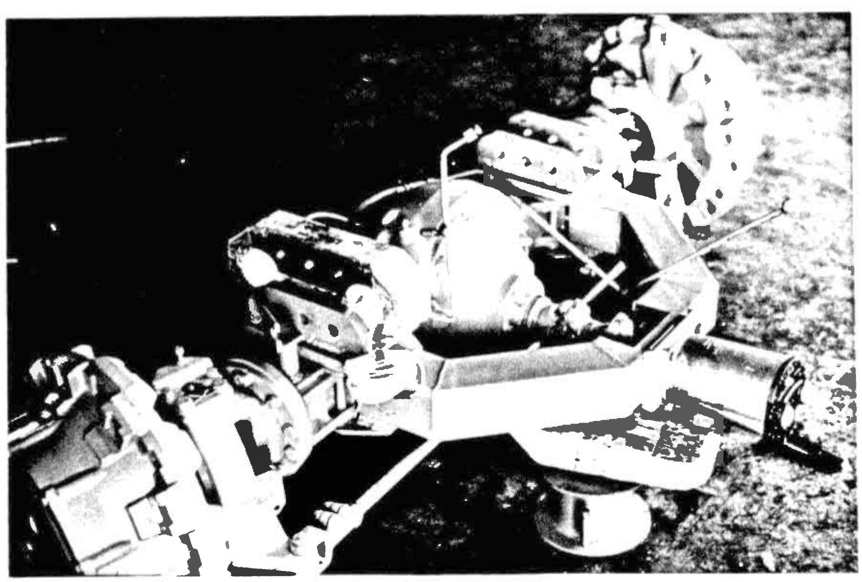


Figure 4. Front Differential, Hydraulic Motor, and One Front Axle Transducer

Figure 5. Rear Differential, Hydraulic Motor and Rear Spacers to the Tractor Frame

Four Bar Speed Control Mechanism

The output speed of each hydraulic motor was determined by: engine speed, swashplate angle and losses such as leakage and friction for each respective pump. For pump displacements of approximately the same magnitude with only a small difference in pump swashplate angle, the difference in motor output speed was proportional to the difference in swashplate angle. This was based on the assumption that the volumetric losses were the same for both pumps at similar swashplate angles. The relative displacements of the pump swashplates were used to control the ratio of output speeds of the motors and ratio of axle speeds of the tractor.

The mechanism to control the positions of the front and rear pump swashplates was designed to meet the following requirements: displacement of each pump must zero at the same time to prevent one pump from driving the tractor while the other has zeroed; desired ratio of pump displacements must remain constant through the entire range of displacements.

Several ideas were investigated to control the relative displacements of the two pumps. Initially the pump swashplates were positioned by two servo control valves, one for each pump. Each servo valve was controlled from the cab by sleaved cables. Excessive play in the cables and servo valves prevented this approach from succeeding. A four bar linkage with a variable joint position between two bars was designed (Figure 6). The position of the joint determined the ratio of displacements between the pumps. To ensure that the zero position of each pump occurred at the same position, the slot in which the movable joint traveled was cut at a radius equal to the length of bar two. When the rear pump has zero displacement, the position of the joint in the slot has no effect on the displacement of the front pump. When the position of the joint is such that the effective length of bar one is greater than bar three, the front pump swashplate is displaced farther than the rear swashplate resulting in a constant front to rear speed ratio greater than one. The converse results in a speed ratio

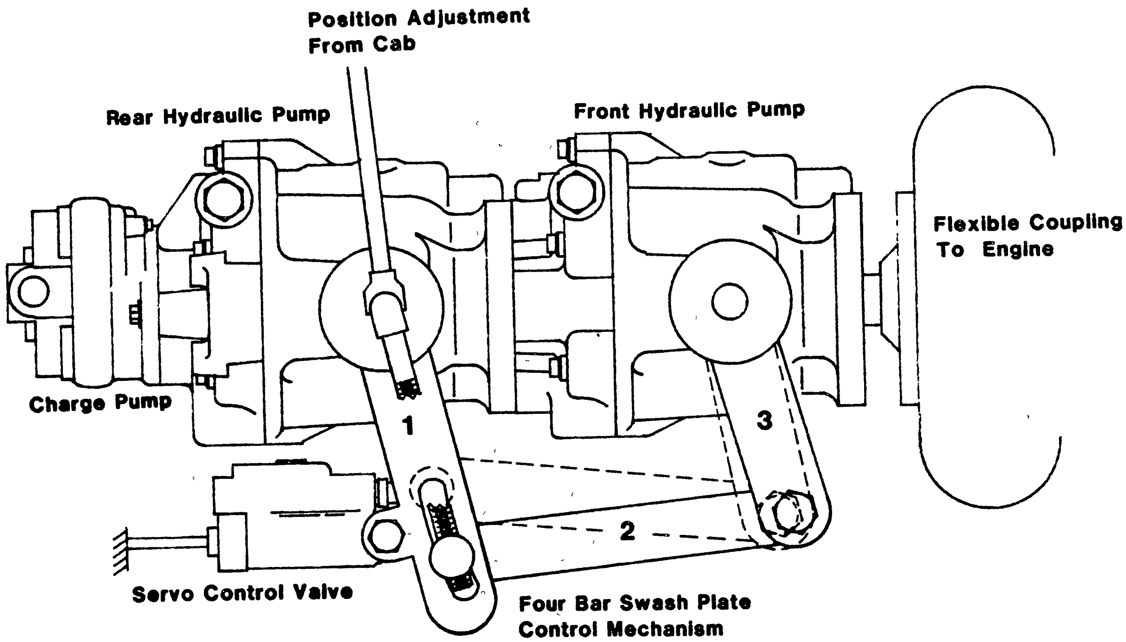


Figure 6. Tandem Hydraulic Pumps and Four Bar Wheel Speed Control Mechanism

less than one. When the effective length of bar one equals that of bar three, the pumps have the same displacement and a speed ratio equal to one.

To change speed ratio, a threaded rod was fixed at one end and threaded through a connector at the joint. The rod and variable position joint were controlled by a small hand wheel located in the cab. A mechanical rotational indicator was used to determine the position of the joint and therefore the speed ratio. One rotation of the threaded rod corresponded to a one percent change in displacement ratio and a indicator change of ten.

Ballast Rack

A ballast rack was constructed on the rear of the tractor and could be positioned hydraulically from within the cab. The ballast rack (Figures 2 and 7) had 2041 kg of ballast and was used to shift the mass distribution between the front and rear axles. The total mass of the tractor with fuel and two operators was 10851 kg.

The ballast consisted of molded lead ingots which were 51 cm in diameter by either 5 or 10 cm thick with a corresponding mass of 113 or 227 kg respectfully. Molded into the center of each was a 10 cm square steel tube cut to the corresponding thickness. This tube was used to mount the ballast by sliding it onto a smaller 8.9 cm square tube.

Figure 7. Adjustable Rear Ballast Rack

The rack pivoted at the bottom around a shaft and bearings using a pair of hydraulic cylinders to move between positions (Figure 8). The center of gravity of the ballast could be shifted from 0.13 to 2.24 m behind the rear axle (Appendix B-1); with 2041 kg of ballast on the rack this resulted in changing the mass distribution on the front axle from 35 to 52 percent. A set of pins held the rack in position and were operated from the cab. The rack could be located in twenty-two positions allowing mass distribution on the front axle to be varied between 35 and 52 percent.

Located on both sides of the tractor, 1.04 m forward of the front axle were stub brackets of the 8.9 cm square tube.

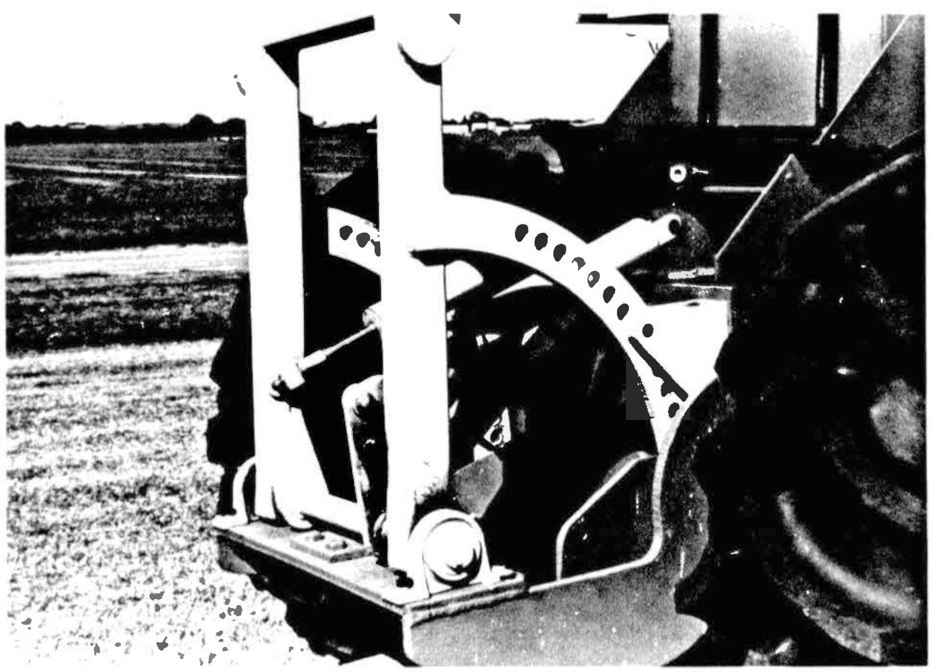


Figure 8. Ballast Rack Positioning Mechanism, Showing Locking Pin Positions and Hydraulic Cylinders

These were used to mount ballast removed from the rear ballast rack up to 340 kg on each side of the tractor (Figures 2 and 9). With 680 kg of ballast moved to the front racks, shifting the rear ballast rack varied the mass distribution on the front axle between 45 and 61 percent.

Rear static load was determined by placing the rear ballast rack in various positions and measuring the load on the rear axle using a large balance beam scale. Rear axle loads were measured with all ballast on the rear and with 680 kg of ballast moved to the front ballast racks (Appendix B-2). This data was incorporated into regression equations describing rear static load as a function of position with

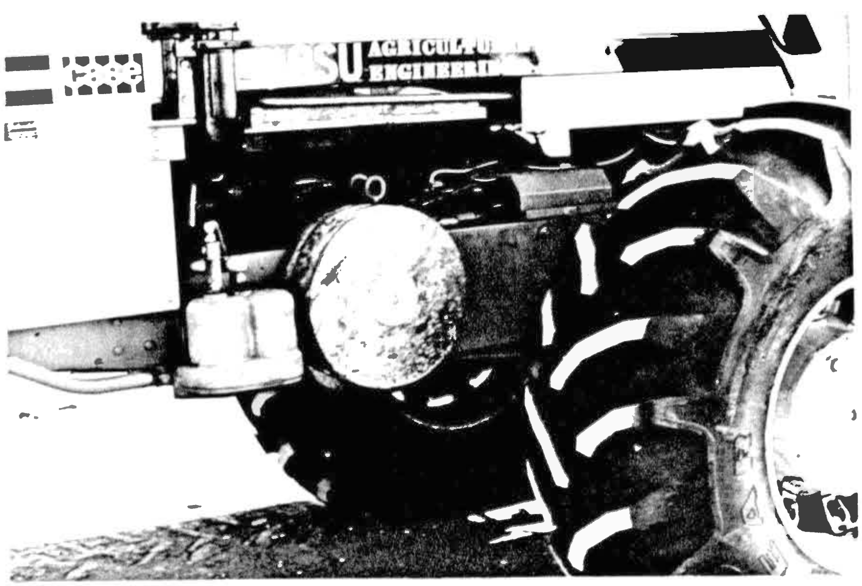


Figure 9. Front Ballast Rack

coefficients of determination greater than 0.9996:

$$W_r680 = 41403.0 + 538.2 \times (pos) + 18.8 \times (pos^2) - 0.77 \times (pos^3) \quad (12)$$

$$W_r0 = 51536.6 + 871.2 \times (pos) + 15.5 \times (pos^2) + 0.76 \times (pos^3) \quad (13)$$

Using Equations 12 and 13, and equations describing the dynamic load distribution of the tractor under steady drawbar load, graphs of percentage front dynamic load distribution were developed (Figure 10). This graph was used during testing to determine the proper position of the ballast rack.

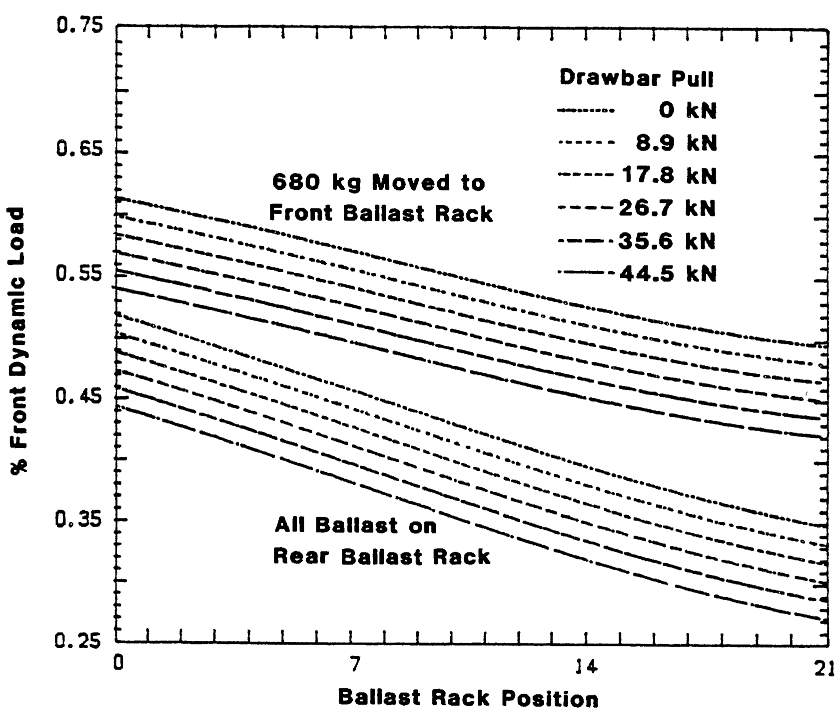


Figure 10. Percentage Front Dynamic Load Distribution as a Function of Ballast Rack Position

As dynamic load distribution changed, tire deflection and rolling radius changed. Rolling radius is defined as the rolling circumference divided by 6.283. The rolling circumference is the distance traveled per revolution of the traction device when operating at a specified zero condition (ASAE Standard S296.3, 1987). Rolling radius was measured on a hard soil, for a wheel speed ratio of 1.0, zero drawbar pull and eight levels of load distribution (Appendix B-3). The tractor was driven forward at a slow speed and the distance to produce five revolutions of both the front and rear tires was recorded. This was done twice for each load distribution. These data were incorporated into a regression equation describing rolling radius as a function of dynamic load on each axle with a coefficient of determination of 0.862:

$$rr = 83.527 - 0.06448 \times (W) \tag{14}$$

Tire deflection also reflects changes in dynamic load. Tire deflection was measured for twelve different levels of static load distribution (Appendix B-4). Tire deflection is the difference between the radius of the deformed tire and the unloaded radius. The unloaded radius of the tires was 83.18 cm. These data were incorporated into a regression equation describing tire deflection as a function of load on the axle with a coefficient of determination of 0.983:

$$TD = 83.184 - 0.1345 \times (W) \tag{15}$$

Drawbar Load Sled

A sled was built to load the tractor through the drawbar by providing different levels of near constant drawbar pull (Figure 11). Mass in the form of lead ingots was added to the sled to change the level of drawbar pull. The sled consisted of a flat plate with an angled nose to allow soil to pass under the sled. The attachment of the sled to the drawbar consisted of chains, the ends of which were adjusted vertically to maintain a horizontal drawbar pull. The sled was approximately 2.5 m wide by 4 m long and had a mass of 885 kg.

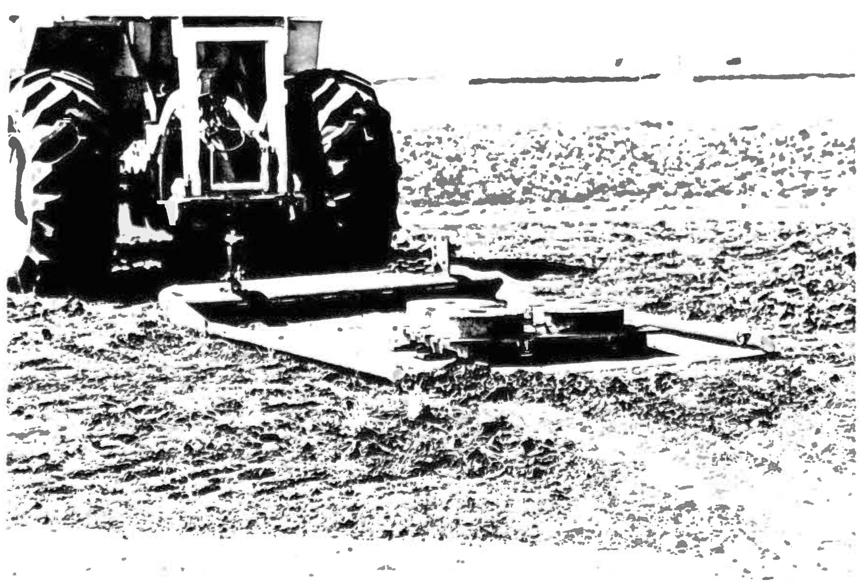


Figure 11. Drawbar Load Sled with Lead Mass

The sled was operated with three different masses. The sled was pulled empty, with 1827 kg and 2585 kg additional mass. One problem encountered with the sled to provide drawbar load was occasional accumulation of soil in front of the sled for high mass conditions, low forward speeds and "loose" soil conditions resulting in increased draft.

Instrumentation and Transducers

Front Axle Transducer

The connection between the front axle and the tractor frame was modified to measure the forces between the axle and frame. The forces of interest were the vertical load on the front axle and the tractive force supplied by the front wheels. In previous research the tractive force for each axle was not measured individually.

Extended split ring transducers were designed based on Hoag and Yoerger (1974) (Figures 2 and 12). The transducers were designed and built to measure front dynamic load and front axle net traction. The transducers were bolted between brackets attached to the tractor frame and front differential, one on each side of the tractor. These were designated as left and right transducers and measured left and right dynamic load and net traction.

The transducers were machined from 7075-T6511 aluminum which has a yield strength of 500 MPa and modulus of elasticity of 70 MPa. A detail drawing of the transducer is shown in Appendix C-1. Strain gages were applied to the

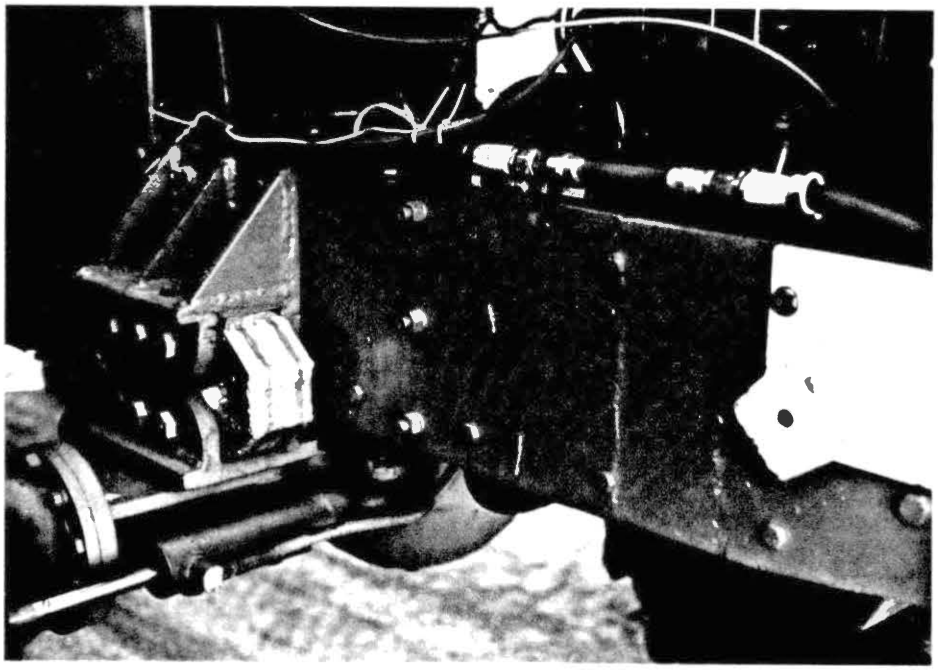


Figure 12. Front Axle Transducer Mounted Between Tractor Frame and Front Axle

transducers and wired in Wheatstone bridge arrangements to enable the measurement of the vertical and horizontal forces on the transducer. The strain gages were Micro-Measurements CEA-13-125UW-350 (Figure 13). A protective coating (Micro-Measurements M-COAT F) was applied to the transducers to prevent damage to the strain gages and associated wiring.

The transducers were calibrated by applying known static loads in the appropriate directions. Vertical force for calibrating dynamic load was supplied by lowering a large mass of steel beams onto the transducer. The beams were supported at each end by hydraulic jacks and

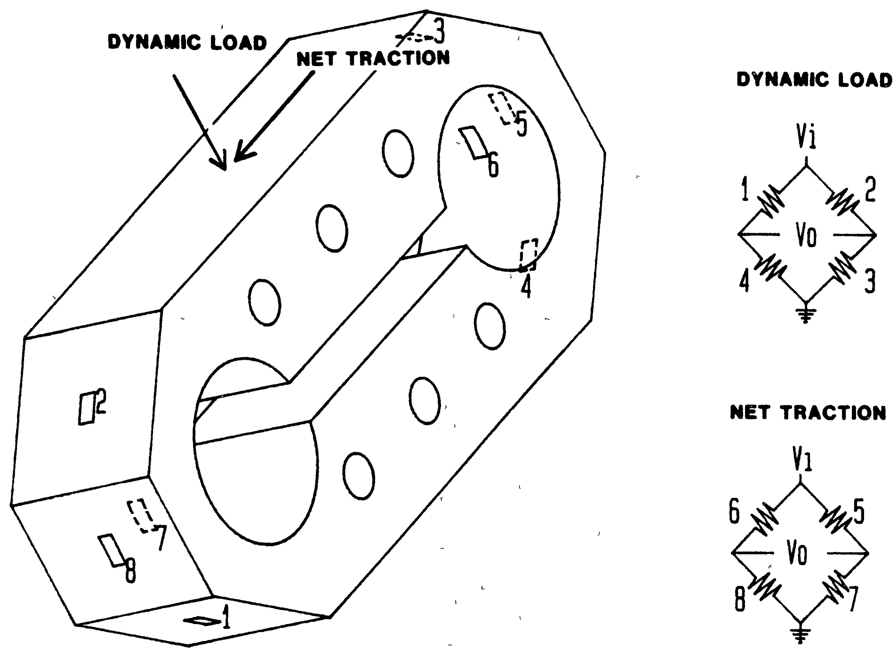


Figure 13. Front Axle Transducer Strain Gage Location and Wiring Configuration

incrementally lowered onto the transducer. The transducer was placed on a large balance beam scale which was used to measure the applied vertical force. Horizontal force for calibrating net traction was supplied by hanging known mass in the form of lead ingots from the transducer. The fixture for performing the horizontal force calibration is shown in Appendix C-2. For each transducer and type of loading, a calibration equation was developed. The calibration data is given in Appendix B-5 and B-6. For each type of loading both the horizontal and vertical force readings were observed, these were used to indicate the independence of the two measurements. The four calibration equations developed were:

$$RV = -11141.19 + 38.455 \times (A/D) \qquad (16)$$

$$RP = -42874.15 + 29.725 \times (A/D) \qquad (17)$$

$$LV = -2064.37 + 42.323 \times (A/D) \qquad (18)$$

$$LP = -43957.28 + 30.077 \times (A/D) \qquad (19)$$

The coefficient of determination (R^2) was found to be greater than 0.9997 for all four equations. Vertical and horizontal components of the transducers were independent.

Drawbar Transducer

The tractor's original drawbar was instrumented to measure both tensile and bending strains, which measure draft and vertical force respectfully. Through initial tests it was determined that the original steel drawbar did not exhibit the desired sensitivity to measure draft. The steel tractor drawbar was replaced by a drawbar constructed from 7075-T6511 aluminum (Figure 14) (Appendix C-3).

Strain gages were placed adjacent to the drawbar pin hole corresponding to the connection between the drawbar and tractor to increase draft sensitivity. A second set of gages to measure vertical force were located 13 cm from the centerline of the drawbar pin hole (Figure 15). The gages and wiring were covered by a protective coating to prevent mechanical or environmental damage. The gages were Micro-Measurements CEA-13-125UW-350 strain gages.

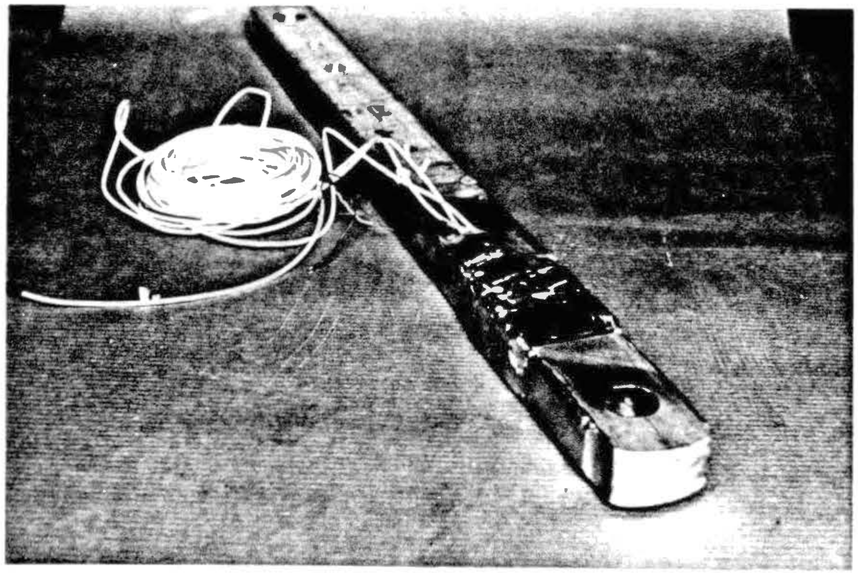


Figure 14. Drawbar Transducer for Measuring Draft and Vertical Load

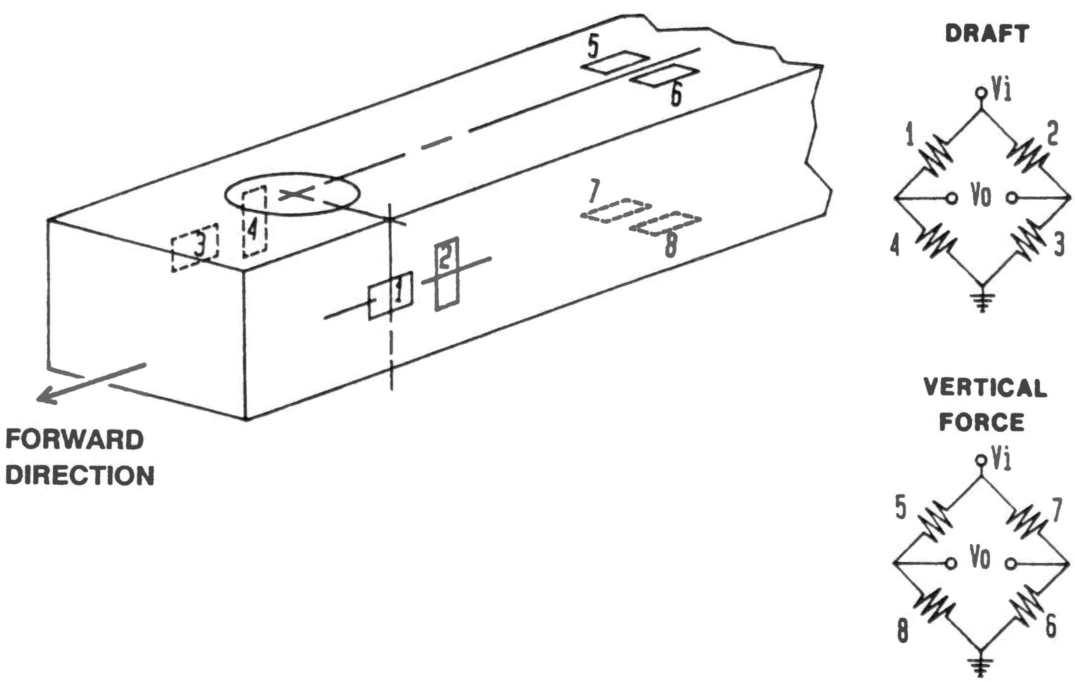


Figure 15. Drawbar Transducer Strain Gage Location and Wiring Configuration

Draft for the drawbar transducer was calibrated by applying a tensile force on the drawbar by the use of lead mass up to 39 kN. The drawbar was hung vertically with the pin hole corresponding to the connection point between the tractor and drawbar at the upper end. Pins equal in size to the holes in the drawbar were used as connection points to an overhead winch above and load rack below. Lead ingots of known mass were incrementally applied to develop the calibration data (Appendix B-7).

Vertical calibration was done with the drawbar mounted in place on the tractor. Separate calibration curves were developed for the "upward" and "downward" forces on the drawbar, because the mounting conditions changed with force direction. The downward vertical force on the drawbar was calibrated by hanging lead ingots of a known mass from the pin hole corresponding to the connection between the drawbar and implement. The upward vertical force on the drawbar was calibrated by applying an upward force through the use of a hydraulic jack. The magnitude of this upward force was measured by placing the hydraulic jack on a large balance beam scale. The calibration data are shown in Appendix B-8 and B-9. Coefficient of determination for the draft calibration was 0.9986, and for the vertical calibration was 0.9985 for both the upward and downward equations. The resulting calibration equations were:

$$P = -78270.38 + 123.591x(A/D) \tag{20}$$

$$DVd = -12202.42 + 8.585x(A/D) \quad (21)$$

$$DVu = -6441.65 + 5.894x(A/D) - 0.0009555x(A/D)^2 \quad (22)$$

The upward vertical force was not linear. This resulted from the mounting condition; the point of contact of the cantilevered drawbar moved with increasing load.

Tractor Speed Transducer

Tractor forward speed was measured using a TRW Model TGSS011 radar. The radar was mounted under the tractor between the front and rear wheels (Figures 2 and 16) at a 37 degree depression angle from horizontal. The radar calibration was verified by timing the tractor over a known

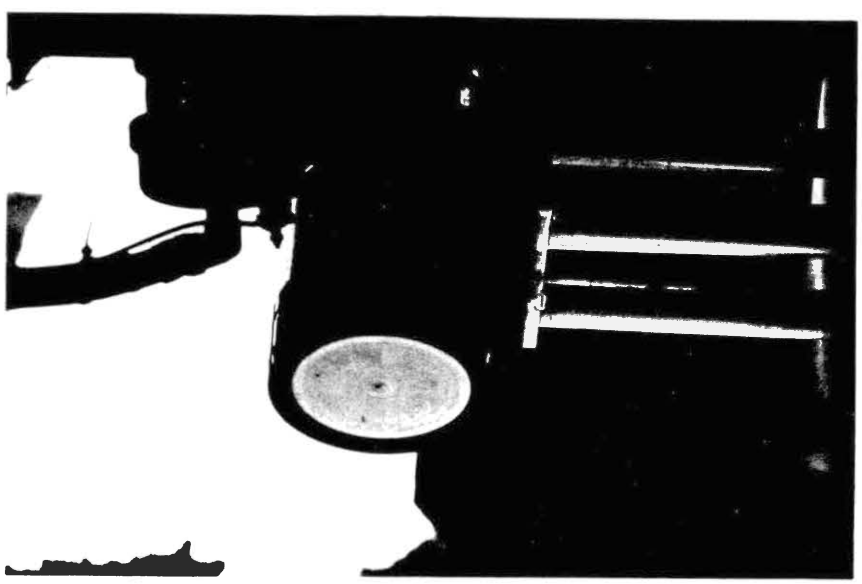


Figure 16. TRW Radar for Tractor Speed Measurement

distance and comparing the radar output with measured tractor speed. The difference between speed as indicated by radar and actual speed (time to travel 30 m) was less than 2 percent at 1 km/h. The error was less than 1 percent for speeds greater than 1.5 km/h which agrees with Tsuha et al. (1982).

$$V = \frac{Gp}{(T1 \times 35.7)} \tag{23}$$

where: 35.7 = Pulse frequency per km/h

<u>Torque Transducer</u>

Hydraulic motor torque was determined from the transmission pressure at each hydraulic motor and calibration data supplied by Cessna Fluid Power Division. Pressure was measured by a strain gage type pressure transducer (Omega PX306) in the high pressure line of each transmission (Figure 17). The transducers had a pressure rating of 35 MPa and a natural frequency of 10 kHz.

Data were supplied by Cessna Fluid Power relating output motor torque to input motor pressure for several motor speeds. Torque was linearly related to pressure and independent of motor speed. The calibration data are given in Appendix B-11. Coefficient of determination for the relationship between motor torque and pressure was 0.9986. Axle torque was determined from motor torque, differential and final drive gear reduction, and calibrated torque loss through the differential (Appendix B-12). Torque loss was

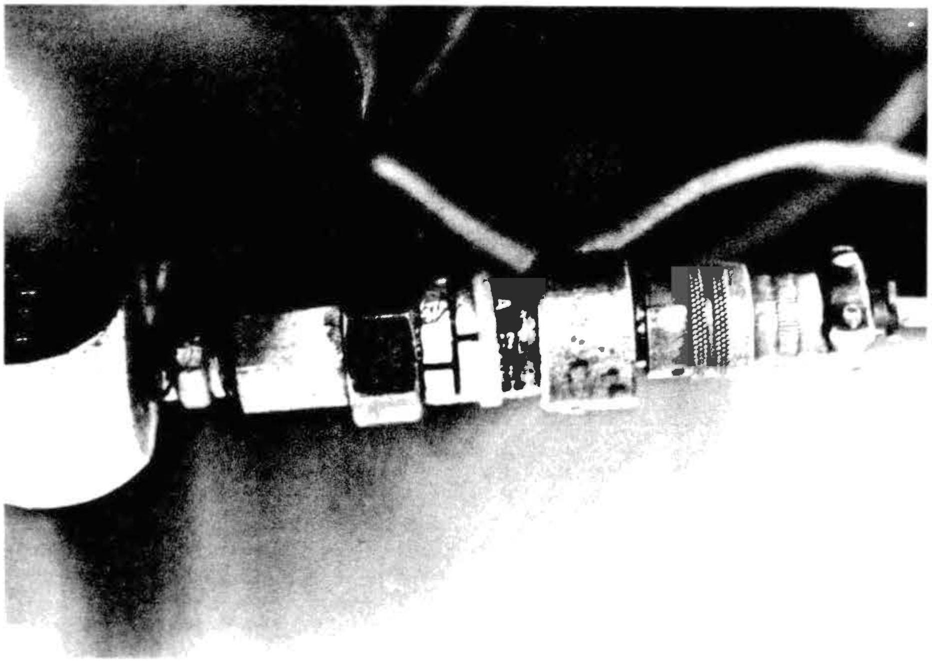


Figure 17. Pressure Transducer Mounted in the Elbow of the High Pressure Line of the Front Transmission

determined by elevating the tractor to remove all load on the axles, operating the ground drive and measuring the required motor torques to drive the differentials at various speeds. The second term in Equations 25 and 27 represents the torque loss through the differential and final drive. Torque loss was defined as the motor torque required to drive the differential at various speeds under no load conditions. The resulting calibration equations were:

$$F\_PR = 11.2219 \times (A/D) \quad (24)$$

$$T_f = \{(A+B \times F\_PR)-[A+B \times (2001.69+31.65 \times F\_RPM)]\} \times GR \quad (25)$$

$$R\_PR = 11.2219 \times (A/D) \quad (26)$$

$$T_r = \{(A+B \times R\_PR)-[A+B \times (2017.47+37.78 \times R\_RPM)]\} \times GR \quad (27)$$

where: A = -10.75
B = 0.02135

Transmission Speed Sensors

Rotational axle speed was used to determine theoretical speed for calculating wheel slip. Digital magnetic proximity sensors were mounted adjacent to 60 tooth sprockets on the drive shafts of both differentials (Figure 18). These speed sensors produced a pulse as each tooth passed the face of the sensor. Summation of pulses over a

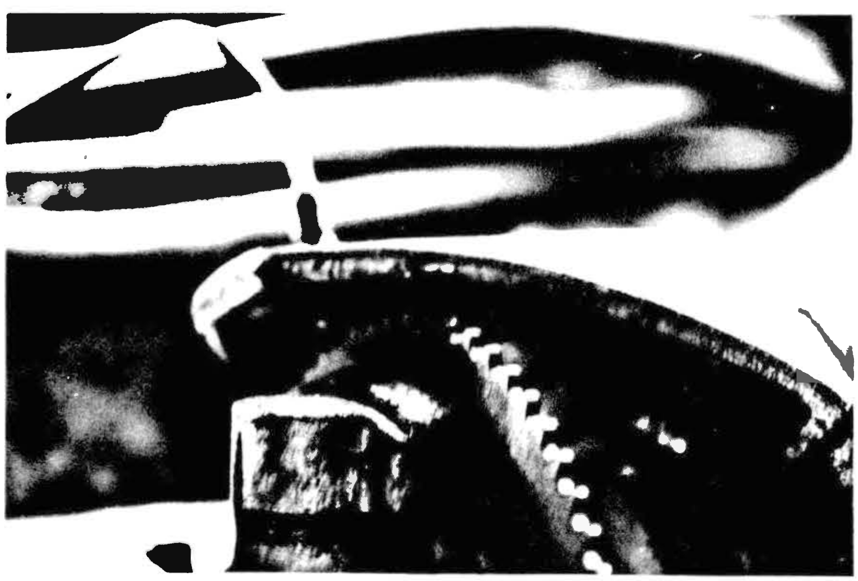


Figure 18. Axle Speed Sensor Mounted Adjacent to a Sprocket on the Drive Shaft for the Rear Differential

specific time interval was used to determine the rotational input speed to the front and rear differentials (Equations 28 and 29). The input speed to the differential was equivalent to the output speed of the hydraulic motors. Output speeds for the axles were calculated by:

$$\omega_f = \frac{Fp}{T2 \times GR} \tag{28}$$

$$\omega_r = \frac{Rp}{T3 \times GR} \tag{29}$$

Originally, the speed sensors were mounted on small cantilevered beams. This arrangement resulted in erroneous pulses as a result of vibration of the beams. The false readings were eliminated by replacing the beams by stiffer mounting brackets consisting of wedged shaped sections of pipe which were bolted to the differentials (Figure 18).

At low forward speed (1.7 km/h or less) and high axle torques, the speed sensors on the differential drive shafts indicated incorrect axle speeds. These were less than expected for the actual speeds measured and indicates that in this range of input speed, some sprocket teeth were not being counted. This resulted from misalignment of the sprocket. This misalignment caused the pole clearance between the sensor and tooth to exceed the maximum allowed for the peripheral velocity of the sprocket. These data points were eliminated from the final data set.

A magnetic proximity sensor was mounted adjacent to the ring gear on the engine flywheel (Figure 19). This sensor was used to measure the rotational speed of the engine and input speed to the hydraulic pumps (Equation 30).

$$Es = \frac{Ep \times 60}{T4 \times 147} \tag{30}$$

where: 147 = Number of teeth on the engine flywheel

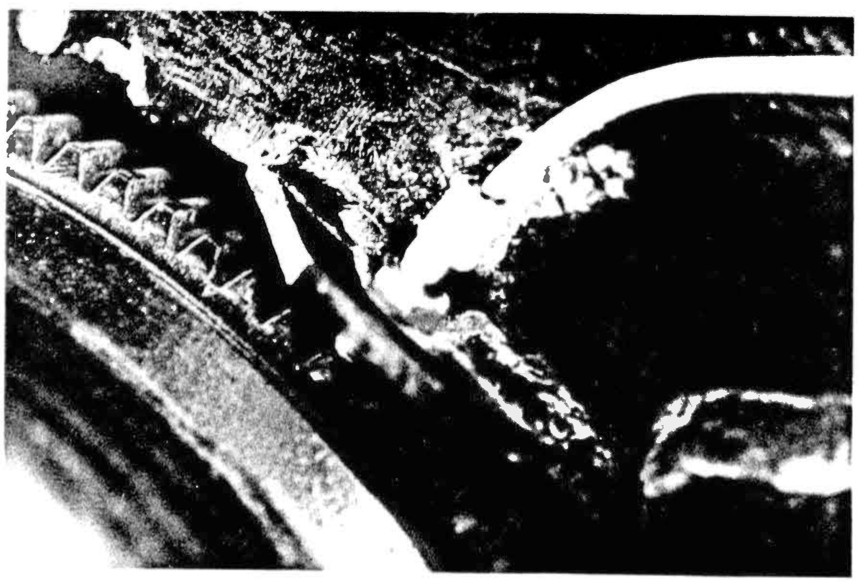


Figure 19. Engine and Transmission Speed Sensor Adjacent to the Engine Ring Gear

Computer Monitor

An AIM R6500 microcomputer was utilized to handle data acquisition, conversion to engineering units, and data storage (Summers et al. 1986) (Figure 20). The computer was equipped with a 20 column thermal printer, 160 character liquid crystal alphanumeric display, keyboard and disk drives for data storage.

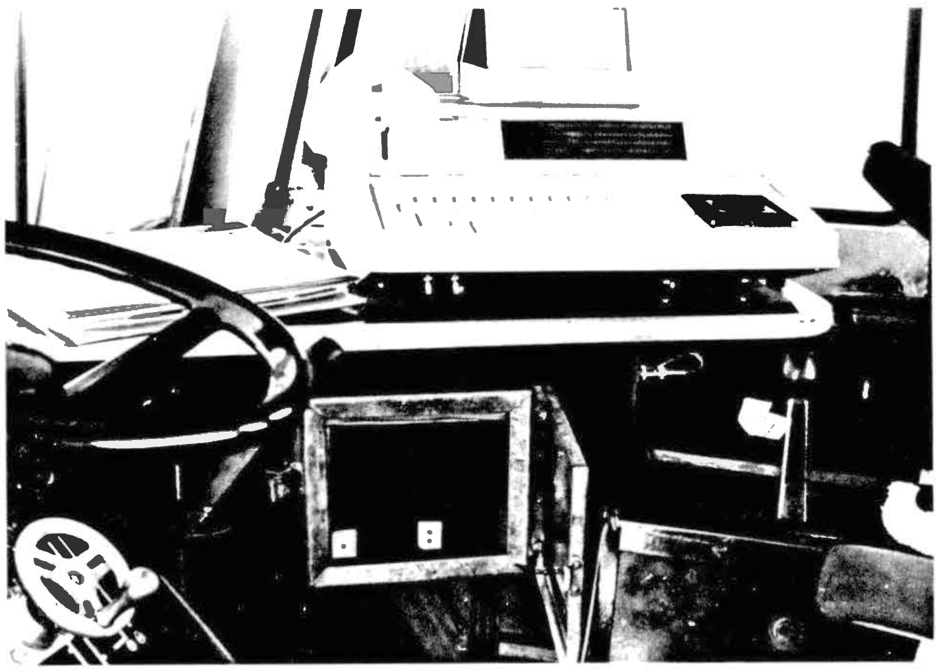


Figure 20. Computer Monitor and Two-Disk Drive Storage Housing

The computer monitor described by Summers et al. (1986) utilized a minicassette for data storage. Problems were encountered with retrieving stored data and programs. As a result, a two-disk drive storage system was constructed for data storage and retrieval. Because of possible problems associated with tractor vibrations and dust, precautions were taken to reduce possible disk failure. A pair of single sided disk drives were mounted in a foam padded case to reduce vibration. The door and housing were sealed to reduce dust contamination. The disk drives have worked well for several years with no loss of data.

Data Acquisition Program

The computer monitor was programed in BASIC and machine language to perform data collection. Information input, conversion to engineering units and storage of the final data was accomplished in a BASIC language program (Appendix D-1). Actual data acquisition was accomplished by a machine language program (Appendix D-2).

The basic program consisted of the following components: general information input, zeroing routine to find zero readings to compensate strain gage bridge drift, data collection, conversion to engineering units, hardcopy output to paper and storage on floppy disk.

Frequency data from the engine speed sensor and drive shaft speed sensors were converted to rotational speed, data from the radar were converted to forward speed. Frequency of the engine and drive shaft speed sensors were determined by counting pulses over a specific time interval. Pulses produced by the sensors were counted over time intervals determined from the machine language programming steps between the beginning and end of the timing sequence. The time intervals are shown in Appendix D-2 and above in equations 23,28,29 and 30. Data collection required approximately 1.6 seconds which corresponds to 3.6 m of plot length at 8 km/h.

Possible frequency components existed in the pressure and force measurements. Summers et al. (1985) reported frequencies of 2 to 10 Hz resulting from forces of various tillage tools. Pulses generated in the pressure signal resulting from the pump pistons were calculated to be in the range of 375 Hz. Sampling frequency must be sufficiently high to prevent aliasing. A good rule of thumb is a sampling frequency of six to ten times the highest frequency in the signal. Sampling frequency for the front axle transducers and drawbar transducer was 640 Hz. Sampling frequency for the pressure transducers was 3.85 kHz.

CHAPTER IV

EXPERIMENTAL PLAN AND PROCEDURES

The following variables were identified as probably affecting the tractive performance of a four wheel drive traction system: dynamic load distribution, forward speed, wheel slip, wheel speed ratio and soil characteristics as indicated by soil cone index. A paucity of information exists on the effects of wheel speed ratio in conjunction with the other listed variables in relation to tractive performance. Significant questions remain concerning the main effects and interactions of these variables under field conditions.

A field study examining the relationships among dynamic load ratio, wheel speed ratio, forward speed, wheel slip, soil strength and four wheel drive tractive performance was conducted at the South Central Research Station at Chickasha, Oklahoma, on approximately 6 ha of land. The textural analysis of the soil used in this study was 28 percent sand, 60 percent silt and 12 percent clay. The test field had a Reinach silt loam soil with level terrain. Wheat was mowed and bailed off the field several months before the test was conducted. The field was disked twice before the test.

Experimental Design

The experiment consisted of a factorial arrangement of treatments with one split and one strip variable in a randomized block design. The main factors were forward speed (3 levels), dynamic load ratio (3 levels) and wheel slip (4 levels). Slip was varied by changing drawbar draft. The strip variable was soil cone index (3 levels) and the split variable was wheel speed ratio (4 levels). This design resulted in thirty-six main plots per block and twelve subplots per main plot. Two blocks were included in the experiment for replication. The collected data are shown in Appendix A.

The majority of the data points fell in the following ranges: wheel speed ratio from 0.95 to 1.15, front dynamic load ratio from 0.30 to 0.60, forward speed from 2.5 to 9 km/h, wheel slip from 0 to 20 percent and soil cone index from 100 to 3500 kPa.

The treatments were randomly assigned to the plots and subplots (Table I). The plot code for block 1 and plot 1 (312-4231) represents the forward speed (V) at level 3, the dynamic load distribution (W) at level 1 and the wheel slip (S) at level 2; the remaining four numbers (4231) represent the four levels of wheel speed ratio (WSR) which were randomly assigned as split variables to each main plot.

Soil cone index was stripped across all plots in the order shown at the bottom of Table I. The main plots ran West to East. The order of the split plots and strip plots

TABLE I

RANDOMIZED PLOT PLAN

PLOT	BLOCK 1	BLOCK 2
	V W D WSR	V W D WSR
1	3 1 2 - 4 2 3 1[1]	1 1 1 - 2 4 1 3
2	1 2 3 - 4 3 1 2	2 1 4 - 2 3 4 1
3	2 2 1 - 3 1 2 4	2 2 4 - 3 1 4 2
4	1 3 4 - 2 4 3 1	2 2 3 - 4 2 3 1
5	3 3 3 - 1 4 2 3	3 1 4 - 4 3 2 1
6	2 3 2 - 2 3 4 1	1 3 1 - 1 4 3 2
7	2 2 2 - 2 4 1 3	3 1 2 - 1 3 4 2
8	1 3 1 - 2 3 1 4	2 1 2 - 4 1 2 3
9	1 1 2 - 2 1 3 4	2 3 4 - 1 3 2 4
10	1 3 2 - 1 3 2 4	1 3 2 - 2 4 1 3
11	3 2 4 - 3 1 4 2	3 1 1 - 3 1 4 2
12	3 1 3 - 3 1 2 4	1 1 4 - 4 3 2 1
13	1 2 2 - 2 1 4 3	2 2 2 - 3 1 4 2
14	2 1 4 - 1 4 2 3	1 2 2 - 1 2 3 4
15	2 3 1 - 4 3 1 2	2 3 2 - 4 1 2 3
16	2 1 2 - 4 3 2 1	3 3 4 - 4 1 2 3
17	1 3 3 - 3 4 1 2	2 1 3 - 1 2 4 3
18	3 3 4 - 3 1 4 2	3 3 2 - 4 1 3 2
19	3 1 1 - 3 4 1 2	1 2 4 - 4 3 1 2
20	3 3 2 - 2 4 1 3	2 1 1 - 3 1 4 2
21	1 2 1 - 2 1 3 4	1 1 3 - 3 2 4 1
22	2 1 3 - 3 4 1 2	2 3 1 - 2 3 4 1
23	2 1 1 - 4 3 1 2	2 2 1 - 1 4 3 2
24	3 2 1 - 4 3 1 2	3 2 4 - 4 2 1 3
25	3 2 2 - 3 1 2 4	3 2 2 - 2 1 4 3
26	2 2 3 - 2 4 1 3	1 1 2 - 3 4 2 1
27	2 3 4 - 2 1 3 4	3 1 3 - 3 2 4 1
28	1 2 4 - 4 3 2 1	1 3 4 - 1 4 3 2
29	1 1 4 - 1 4 3 2	1 3 3 - 1 2 3 4
30	1 1 3 - 4 2 3 1	1 2 3 - 4 1 3 2
31	1 1 1 2 4 1 3	2 3 3 - 1 4 3 2
32	2 3 3 - 3 2 4 1	3 2 1 - 1 3 2 4
33	3 3 1 - 4 3 2 1	1 2 1 - 2 4 3 1
34	2 2 4 - 1 4 3 2	3 2 3 - 4 2 3 1
35	3 2 3 - 2 4 3 1	3 3 3 - 2 1 3 4
36	3 1 4 - 4 2 1 3	3 3 1 - 3 1 2 4

1. Split and strip variable were ordered West to East

Soil cone index was laid out as:

Block 1 - 321 123 213 123

Block 2 - 231 123 132 321

refers to the tractor traveling West to East. The first two plots in Block 1 are shown in Figure 21. Each main plot was 3 m wide by 119 m long. Within each main plot were twelve subplots which were 9.1 m long. Between every three subplots were 3 m long alleys to allow the wheel speed ratio to be changed.

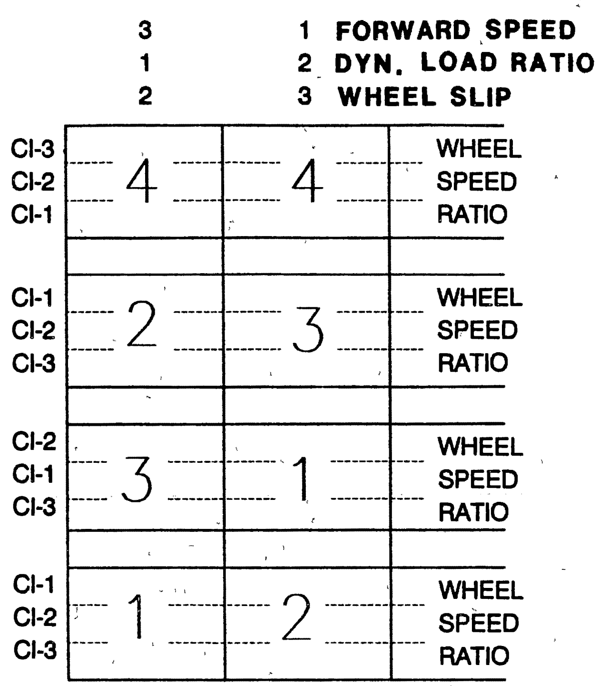


Figure 21. First Two Main Plots in Block I, Showing the Levels of the Main Variables and Layout of Split and Strip Variables

Experimental Procedure

The plots were compacted with a sheep's foot roller to the desired level of soil cone index (Figure 22). The

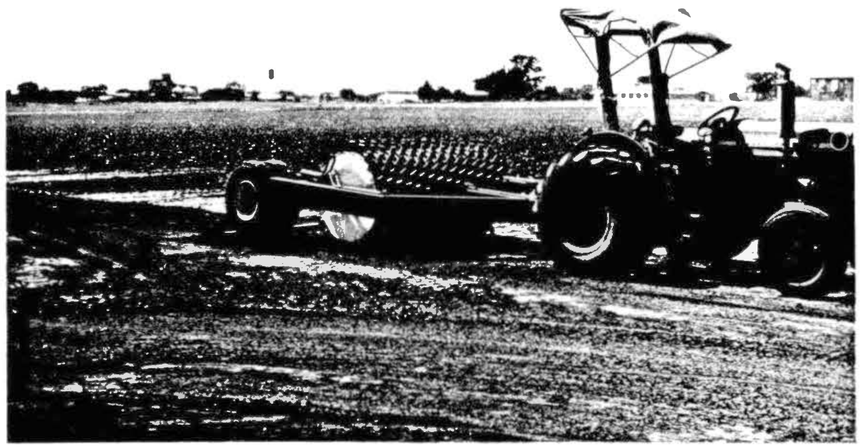


Figure 22. Sheep's Foot Roller with a Mass of 2721 kg

lowest level of soil cone index was produced by zero passes of the roller and had an average soil cone index of 391 kPa. The intermediate level was produced by two passes of the roller and had an average soil cone index of 1358 kPa. The highest level of soil cone index was produced by seven passes of the roller and had an average soil cone index of 2139 kPa. Typical values of soil cone index are: 600 kPa or less for a soft or heavily tilled soil, 800 to 1200 kPa for a medium or lightly tilled soil, 1500 to 2000 kPa for a firm untilled soil, and 2500 kPa or greater for a hard or compacted soil.

To quantify the effects of the roller and determine the condition of the soil for each plot, a tractor mounted, hydraulic soil cone penetrometer was used (Figure 23). Soil cone index readings were taken to a depth of 15 cm as suggested by Clark (1984). Five soil cone index readings were averaged for each plot. The average values were merged with the tractor performance data for analysis (Appendix A).

Before starting the tractor, zero readings were taken for each load cell to assure that residual forces between the axles and pressures in the hydraulic system were eliminated. Periodically additional zero readings were obtained to verify the original zero readings.

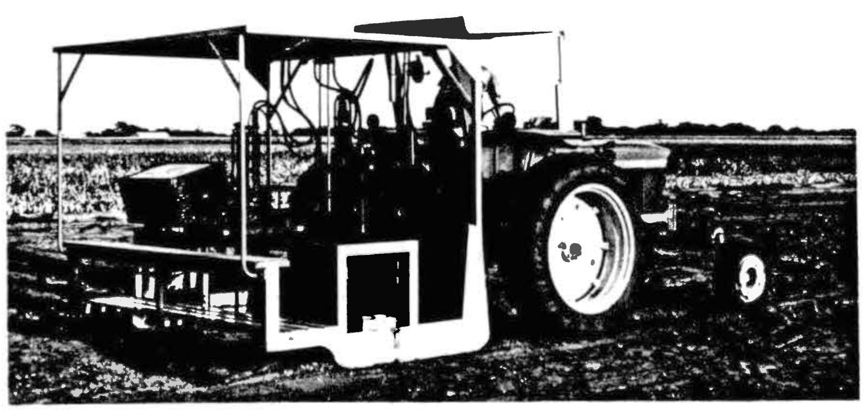


Figure 23. John Deere 2520 Diesel Tractor and Hydraulic Soil Cone Penetrometer

Before a test run, the mass on the load sled was adjusted to produce the desired level of drawbar pull. This estimate of draft was made from previous experience or by operating the tractor on an area of unused ground. Using this estimate of draft and the desired dynamic load ratio, Figure 10 was used to determine the proper position of the rear ballast rack. Forward speed was set by properly setting the engine speed. Before each test run, wheel speed ratio as indicated by the digital counter was set at the desired level.

The computer program was designed to obtain 12 sequential data files corresponding to the 12 subplots in the main plot. In order to keep track of the file names, the direction of travel, the order of the wheel speed ratio levels and the levels of the main variables were entered before beginning a test run. As the tractor proceeded across the plots, the computer was signaled to start a data acquisition sequence by pressing the "space-bar". After every three plots the wheel speed ratio was changed to the next level. After data had been obtained for all twelve plots, the data were printed to paper and stored on floppy disk. The tractor was then moved to the next plot corresponding to the set level of draft and dynamic load ratio.

The data disks were then hand carried to an "IBM PC" and read for storage and analysis. The data set was manipulated by "SAS" (Statistical Analysis System, 1982) on a personal computer and mainframe computer.

Experimental Analysis

Complications occurred which resulted in data from several treatments being deleted or never obtained. These were missing from the final data set that was analyzed. Problems were encountered with the pressure transducers which was noticed on the printed data after a test run. The pressure data were eliminated for these treatments and the transducers were repaired. A second problem occurred with the speed sensors used to measure axle speed. Soil would sometimes accumulate in front of the draft sled causing a significant increase in draft and corresponding decrease in forward speed. For forward speeds below 1.7 km/h and high torque requirements, the clearance between the sensor and the sprocket exceeded the recommended spacing causing an error in the axle speed measurement. Rotational speed data were eliminated for these data sets. Finally, because of hydraulic transmission failure towards the end of the field test, several plots were never tested and are missing from the final data set. Six-hundred and sixty observations were included in the final data set.

Because of the missing treatments, the data were analyzed as an unbalanced design using GLM in SAS (General Linear Models, Statistical Analysis System, 1982). The size of this data set required separate computer runs be made to analyze dynamic traction ratio, tractive efficiency and motion resistance.

One factor was not included in the analysis of variance; soil condition as measured by soil cone index was excluded from the analysis. The memory requirement to analyze the effects of soil cone index in an incomplete block design exceeded the available memory on the mainframe computer. But, soil cone index has been shown through previous literature and experience to be a significant factor in tractive performance and was included in the prediction models developed.

CHAPTER V

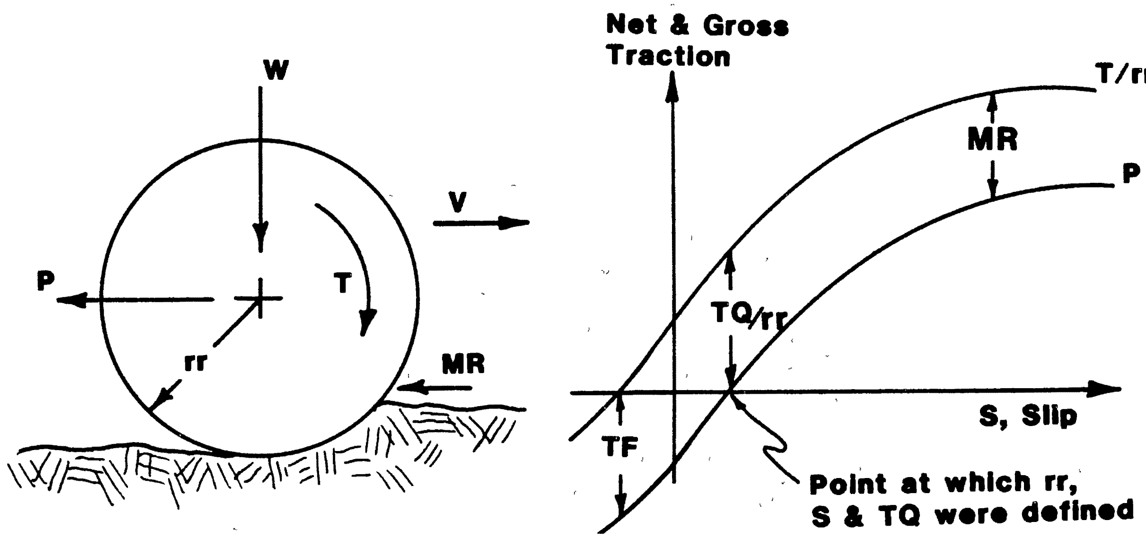
RESULTS AND DISCUSSION

Most traction prediction equations have been developed for single wheels and then extended to four wheel drive tractors. These equations do not take into account the interaction that occurs between axles on a four wheel drive system. No equations are available in literature describing the effects of dynamic load ratio and wheel speed ratio on tractive performance of a four wheel drive traction system.

Motion Resistance

As slip increases, both net traction and gross traction increase asymptotically towards a maximum value (Figure 24). Gross traction is defined as the total force at the soil tire interface in the direction of travel and is the input torque to the drive wheel divided by rolling radius. Net traction is the net force developed by the traction device and is equivalent to pull. Motion resistance is the difference between gross and net traction. Motion resistance is defined as the force or torque required to overcome rolling resistance.

Motion resistance is made up of several components, not all of which can be identified. Motion resistance is mainly



P = Net traction or pull
W = Dynamic load
T = Axle torque
V = Forward speed
MR = Motion resistance
rr = Rolling radius

T/rr = Gross traction (P+MR)
TQ = Self-propelled torque
TF = Towed force
S = Wheel slip (1-V/Vt)
Vt = Theoretical tractor speed

Figure 24. Single Wheel Traction Model

caused by: nonrecoverable energy used to deflect the soil and tire, bulldozing of soil ahead and to the side of the tire as it moves, and friction between the tire and soil along the sidewall and face of the tire.

Motion resistance can be measured as the force required to pull a tire over the soil or as the torque required to propel the tire over the soil with no drawbar pull. The second definition of a self-propelled tire is used in this analysis. Motion resistance was measured as the self-propelled torque of the front and rear axles required to move the tractor with no drawbar load. To produce a dimensionless term (TQ/(rrxW)), the self-propelled torque for each axle was divided by rolling radius and dynamic load.

Shown in Table II is the analysis of variance for motion resistance of the front axle. Shown in Table III is the analysis of variance for motion resistance of the rear axle. Self-propelled torque ratio was analyzed

TABLE II

ANALYSIS OF VARIANCE OF SELF-PROPELLED TORQUE TO DYNAMIC LOAD AND ROLLING RADIUS RATIO FOR THE FRONT AXLE

Source	D.F.	Sum of Square	F Ratio	Significance Level *
S (Wheel Slip)	3	0.37729	3.03	0.0753
W (Dynamic Load Ratio)	2	0.18087	2.18	0.1598
V (Forward Speed)	2	0.00741	0.09	0.9153
S*W	6	0.11907	0.48	0.8118
S*V	6	0.02257	0.09	0.9960
W*V	4	0.00714	0.04	0.9960
V*W*S	9	0.01683	0.05	1.0000
Error (Rep*V*S*W)	11	0.45714		
WSR (Wheel Speed Ratio)	3	0.01699	1.72	0.1821
WSR*V	6	0.00213	0.11	0.9949
WSR*W	6	0.01788	0.90	0.5035
WSR*S	9	0.02425	0.82	0.6036
WSR*V*W	12	0.00727	0.18	0.9983
WSR*V*S	18	0.02168	0.37	0.9866
WSR*S*W	16	0.04993	0.95	0.5292
WSR*S*W*V	26	0.01264	0.15	1.0000
Error (Rep*WSR*S*W*V)	33	0.10870		

* Probability of an error in rejecting the null hypothesis that the variable in question does not contribute to the variance.

TABLE III

ANALYSIS OF VARIANCE OF SELF-PROPELLED TORQUE TO DYNAMIC LOAD AND ROLLING RADIUS RATIO FOR THE REAR AXLE

Source	D.F.	Sum of Square	F Ratio	Significance Level *
S (Wheel Slip)	3	0.09589	2.34	0.1146
W (Dynamic Load Ratio)	2	0.15708	5.75	0.0140
V (Forward Speed)	2	0.01265	0.46	0.6381
S*W	6	0.06936	0.85	0.5541
S*V	6	0.05772	0.70	0.6510
W*V	4	0.02508	0.46	0.7647
V*W*S	11	0.05244	0.35	0.9579
Error (Rep*V*W*S)	15	0.20487		
WSR (Wheel Speed Ratio)	3	0.03742	4.91	0.0050
WSR*V	6	0.00603	0.40	0.8777
WSR*W	6	0.00674	0.44	0.8462
WSR*S	9	0.02780	1.22	0.3097
WSR*V*W	12	0.01570	0.52	0.8935
WSR*V*S	18	0.03402	0.74	0.7481
WSR*S*W	18	0.09203	2.01	0.0300
WSR*S*W*V	33	0.11397	1.36	0.1689
Error (Rep*WSR*S*W*V)	44	0.11174		

* Probability of an error in rejecting the null hypothesis that the variable in question does not contribute to the variance.

independently for each axle. Different error terms were used when evaluating the main factors (Forward Speed, Dynamic Load Ratio and Wheel Slip) and the split variable (Wheel Speed Ratio).

Using a significance level of 20 percent, Table II and Table III show that the main factors of wheel slip, dynamic load ratio and wheel speed ratio significantly affected motion resistance of each axle. Two interactions significantly affected motion resistance of the rear axle; wheel speed ratio by wheel slip by dynamic load ratio and wheel speed ratio by wheel slip by dynamic load ratio by forward speed. These interactions did not significantly affect the front axle.

Using the results of the analysis of variance as a starting point, several linear and nonlinear models were evaluated for predicting motion resistance (Statistical Analysis System, 1982). None of these regression equations had coefficients of determination (R^2) above 0.36. One main factor in the low R^2 was scatter in the data. There are several reasons for the scatter. Motion resistance cannot be measured directly for runs in which there is a drawbar load, but must be calculated using the difference between gross and net traction. The magnitude of gross and net traction are much larger than motion resistance. Since motion resistance is the difference between gross and net traction, a small error in gross or net traction can produce a large error in the magnitude of the difference. Gross and net traction ratio were calculated from the measurements produced by eight different transducers producing numerous sources of small measurement error.

To reduce the error in the measurement of motion resistance, the data set was reduced to include only data for no drawbar load. By definition, axle torque at zero pull is termed self-propelled torque (Figure 24). Equations

29 to 32 were developed using only data for no drawbar load. These nonlinear equations predict self-propelled torque ratio for either axle. A number of different models were evaluated and the best equations were:

$$\frac{TQ_f}{rr_f x W_f} = -2.63 + 2.57 x WSR_{f/r} + \frac{0.18}{Cn_f} - 0.34 x e^{-W_{f/r}} \quad (29)$$

$$\frac{TQ_f}{rr_f x W_f} = 0 \quad \text{for} \quad \frac{TQ_f}{rr_f x W_f} < 0 \quad (30)$$

$$\frac{TQ_r}{rr_r x W_r} = -2.63 + 2.57 x WSR_{r/f} + \frac{0.18}{Cn_r} - 0.34 x e^{-W_{r/f}} \quad (31)$$

$$\frac{TQ_r}{rr_r x W_r} = 0 \quad \text{for} \quad \frac{TQ_r}{rr_r x W_r} < 0 \quad (32)$$

where: $\frac{TQ}{rr x W}$ = Self-propelled torque ratio

As a measure of quality of fit for nonlinear equations, predicted values of self-propelled torque were compared against measured data. A perfect fit would produce a regression line with an intercept of 0.0, a slope of 1.0 and a coefficient of determination (R^2) of 1.0. For equations 29 to 32 the intercept was 0.01, slope was 0.80 and coefficient of determination was 0.85.

As wheel speed ratio is varied from a value of 1.0, the faster wheel provides torque to overcome its own motion resistance plus some of the motion resistance of the other axle. At the point where motion resistance goes to zero for one axle, the other axle of the pair is overcoming motion resistance of both axles.

Figure 25 shows a plot of self-propelled torque ratio as a function of wheel speed ratio for six dynamic load ratios, while Figure 26 shows a plot of self-propelled torque ratio as a function of wheel speed ratio for six wheel numerics. Increasing wheel speed ratio for a particular axle increases self-propelled torque ratio because this axle is providing an increased quantity of the motion resistance of the other axle. Increasing wheel numeric for an axle decreases self-propelled torque ratio because a "stronger" soil condition reduces the rolling losses.

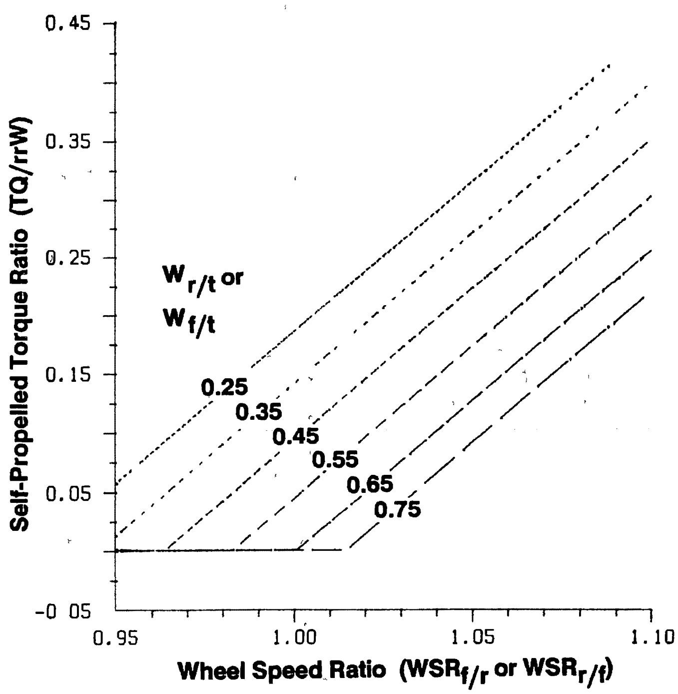


Figure 25. Self-Propelled Torque Ratio as a Function of Wheel Speed Ratio for Six Dynamic Load Ratios

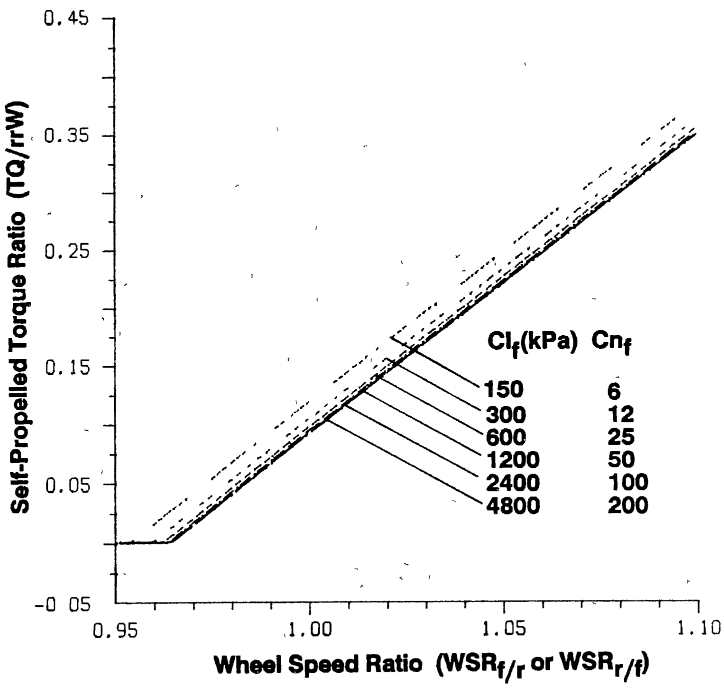


Figure 26. Self-Propelled Torque Ratio as a Function of Wheel Speed Ratio for Six Wheel Numerics

Increasing dynamic load on an axle decreases self-propelled torque ratio, even though increasing dynamic load increases self-propelled torque. This increase in self-propelled torque results from increased tire sinkage, increased tire profile and increased normal force between the tire and soil causing frictional forces to increase. But, the effects of increased dynamic load in the denominator of the self-propelled torque ratio term decreases overall self-propelled torque ratio.

Overall motion resistance of a four wheel drive tractor is not the sum of the torque ratios of the front and rear axles. Self-propelled torque ratio for the front and rear axles must be summed together with dynamic load ratio determining the distribution of self-propelled torque ratio as shown in Equation 37. Four wheel drive motion resistance is the force required to propel the tractor over the soil and is the sum of the motion resistance of the front axle and motion resistance of the rear axle:

$$TF_t = TF_f + TF_r \tag{35}$$

Towed force can be replaced by the self-propelled axle torque divided by the rolling radius. Then dividing both sides of Equation 35 by total tractor dynamic load yields Equation 36.

$$\frac{TF_t}{W_t} = \frac{\frac{TQ_f}{rr_f} + \frac{TQ_r}{rr_r}}{W_t} \tag{36}$$

Axle dynamic load ratios are defined as the ratio of axle dynamic load to total tractor dynamic load. Distributing total tractor dynamic load in the right half of Equation 36 and using the fact that axle dynamic load ratio multiplied by one over the axle dynamic load is equal to one over total tractor dynamic load, Equation 37 can be derived.

$$\frac{TF_t}{W_t} = W_{f/t} x \frac{TQ_f}{rr_f x W_f} + W_{r/t} x \frac{TQ_r}{rr_r x W_r} \tag{37}$$

Figure 27 shows total tractor motion resistance as a function of wheel speed ratio for six levels of front dynamic load ratio and front soil cone index of 600 kPa. Rear soil cone index was calculated using Equation 11. Figure 27 shows that operating with the majority of the dynamic load on one axle is best in terms of overall motion resistance. This results from the fact that it requires less torque to roll a single tire than it does a pair of tires as in the four wheel drive case. Wheel speed ratios around 1.0 result in reduced motion resistance. As the wheel speed ratio changes from 1.0, the force between the axles increases and results in increased motion resistance.

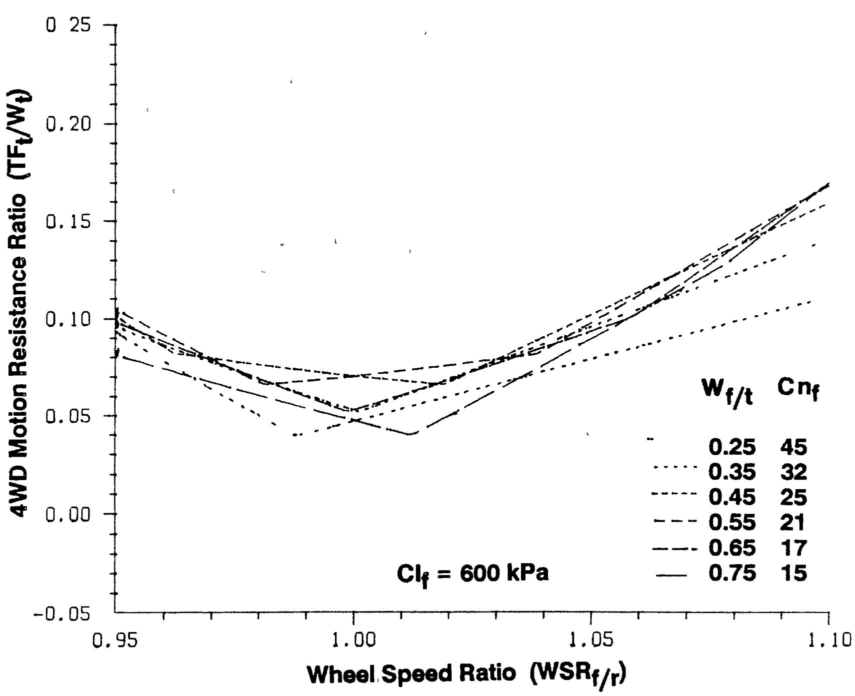


Figure 27. Four Wheel Drive (4WD) Motion Resistance as a Function of Wheel Speed Ratio for Six Front Dynamic Load Ratios

Motion resistance is a measure of the force or torque required to roll a traction device over the soil. This is lost energy and reduces the capacity of the tractor to produce useful work. Motion resistance by itself is not very useful for evaluating tractive performance but motion resistance for each axle is used together with dynamic traction ratio for predicting tractive efficiency.

Dynamic Traction Ratio

Net traction is the force developed by the traction device or devices and transferred to the vehicle (Figure 24). On a tractor, net traction of the powered wheels minus the motion resistance of any unpowered wheels is the drawbar pull developed by the tractor and is the manner in which engine power is converted to drawbar power. For a four wheel drive tractor both axles produce net traction and contribute to the total drawbar pull. A non-dimensionalized form is usually used, and is defined as dynamic traction ratio (P/W), which is the ratio of drawbar pull of the vehicle to the dynamic load on the traction devices (ASAE Standard S296.3, 1987). For a four wheel drive tractor this is simply the drawbar pull divided by the total dynamic load.

The results of an analysis of variance of four wheel drive traction ratio are shown in Table IV. Different error terms were used when evaluating the main factors (Forward Speed, Dynamic Load Ratio and Wheel Slip) and the split

TABLE IV

ANALYSIS OF VARIANCE OF FOUR WHEEL DRIVE DYNAMIC TRACTION RATIO

Source	D.F.	Sum of Square	F Ratio	Significance Level *
S (Wheel Slip)	3	4.32801	383.79	0.0001
W (Dynamic Load Ratio)	2	0.01804	2.40	0.1177
V (Forward Speed)	2	0.00863	1.15	0.3385
S*W	6	0.02088	0.93	0.4988
S*V	6	0.01986	0.88	0.5276
W*V	4	0.00474	0.32	0.8640
V*W*S	11	0.01051	0.25	0.9880
Error (Rep*V*W*S)	19	0.07142		
WSR (Wheel Speed Ratio)	3	0.00441	1.74	0.1683
WSR*V	6	0.00194	0.38	0.8868
WSR*W	6	0.00532	1.05	0.4024
WSR*S	9	0.00455	0.60	0.7923
WSR*V*W	12	0.00524	0.52	0.8954
WSR*V*S	18	0.00878	0.58	0.9013
WSR*S*W	18	0.02693	1.77	0.0508
WSR*S*W*V	33	0.03958	1.42	0.1172
Error (Rep*WSR*S*W*V)	44	0.05062		

* Probability of an error in rejecting the null hypothesis that the variable in question does not contribute to the variance.

variable (Wheel Speed Ratio). Using a significance level of 20 percent, Table IV shows that the main factors of wheel slip, dynamic load ratio and wheel speed ratio significantly affected four wheel drive dynamic traction ratio. Two interactions were also shown to significantly affect four wheel drive dynamic traction ratio, wheel speed ratio by wheel slip by dynamic load ratio and wheel speed ratio by wheel slip by dynamic load ratio by forward speed.

Four wheel drive dynamic traction ratio is the sum of individual axle dynamic traction ratio with dynamic load ratio determining the contribution to total pull produced by each axle (Equation 40). Four wheel drive net traction is the sum of the net traction of the front and rear axles (Equation 38):

$$P_t = P_f + P_r \tag{38}$$

Replacing net traction for each axle by dynamic traction ratio multiplied by dynamic load on that axle; then dividing both sides of Equation 38 by total dynamic load produces Equation 39.

$$\frac{P_t}{W_t} = \frac{W_f \times \frac{P_f}{W_f} + W_r \times \frac{P_r}{W_r}}{W_t} \tag{39}$$

Front and rear dynamic load ratio are defined as the ratio of dynamic load on the axle to total tractor dynamic load. Distributing total tractor dynamic load in the right half of Equation 39 and using the fact that axle dynamic load ratio multiplied by one over axle dynamic load is equal to one over total tractor dynamic load, Equation 39 yields Equation 40.

$$\frac{P_t}{W_t} = W_{f/t} \times \frac{P_f}{W_f} + W_{r/t} \times \frac{P_r}{W_r} \tag{40}$$

Equation 40 shows that four wheel drive dynamic traction ratio can be determined from front dynamic traction ratio, rear dynamic traction ratio and dynamic load distribution.

The same equation of dynamic traction ratio should fit both the front and rear with the only difference being soil condition as measured by soil cone index. Nonlinear regression was used to fit several forms of equations to four wheel drive dynamic traction ratio (Statistical Analysis System, 1982). The first form tried was given by Wismer and Luth (1974) and adopted in the ASAE Standard D230.4 (1987).

$$\frac{P}{W} = K1 \times (1 - e^{K2xSxCn}) \tag{41}$$

As a measure of quality of fit, predicted values of front and rear dynamic traction ratio given by Equation 41 were combined into Equation 40 and compared against measured data. For this analysis the coefficient of determination was 0.396. In an attempt to improve the equation, various modifications were tried. This produced no improvement in the prediction equation.

Several other models and variations were evaluated. The best equation was determined to be a form of Equation 6 (Brixius, 1987). The form used in the regression was:

$$\frac{P}{W} = K1 \times (1 - e^{K2xCn}) \times (1 - e^{K3xS}) \tag{42}$$

This same form of equation should fit both the front and rear dynamic traction ratios. Wheel numeric (Cn) for the front axle was calculated using measured soil cone index. Wheel numeric for the rear axle was calculated using predicted soil cone index. Soil cone index for the rear axle was predicted using both Equations 10 (R^2=0.569) and 11 (R^2=0.574). With a small difference in the prediction of four wheel drive dynamic traction ratio using Equations 10 and 11, Equation 11 was used because of its simple structure. Wheel numeric (Cn) was used instead of mobility number (Bn) as used by Brixius (1987), because no improvement in prediction was evident using mobility number.

Equation 42 was used to predict both front and rear dynamic traction ratio. Equation 42 for the front axle was combined with Equation 42 for the rear axle in Equation 40 to predict four wheel drive dynamic traction ratio (Equation 43).

$$\frac{P_t}{W_t} = W_{f/t} \times K1 \times (1-e^{K2 \times Cn_f}) \times (1-e^{K3 \times S_f}) + W_{r/t} \times K1 \times (1-e^{K2 \times Cn_r}) \times (1-e^{K3 \times S_r}) \qquad (43)$$

where: K1 = 0.82
K2 =-0.19
K3 =-4.69

As a measure of quality of fit, predicted values were regressed against measured data, a perfect fit would produce a line with a slope of 1.0, an intercept of 0.0 and a coefficient of determination of 1.0. Regressing Equation 43 versus measured data yielded a line with a slope of 0.71, an intercept of 0.02 and a coefficient of determination of 0.574. Dynamic load ratio determined the distribution of dynamic traction ratio between the front and rear axles. Wheel speed ratio determined the distribution of slip between the front and rear axles. Slip and wheel numeric determine the magnitude of the individual axle dynamic traction ratios.

For a single axle as slip increases, dynamic traction ratio increases asymptotically toward a maximum value (Figure 24). Slip of one axle can be determined from: slip of the other axle, wheel speed ratio and rolling radius ratio (Equation 50). Rolling radius ratio is a function of the dynamic load distribution as shown by Equation 14. Rear wheel slip is defined by Equation 44.

$$S_r = 1 - \frac{V}{Vt_r} \qquad (44)$$

Replacing theoretical speed by axle speed multiplied by rolling radius and then solving for axle speed yields Equation 45.

$$\omega_r = \frac{V}{rr_r - S_r x rr_r} \qquad (45)$$

Similar to Equation 44, front wheel slip can be defined by Equation 46 except that theoretical speed has already been replaced by the product of axle speed and rolling radius.

$$S_f = 1 - \frac{V}{\omega_f x rr_f} \qquad (46)$$

Multiplying and dividing the denominator of the right side of Equation 46 by rear axle speed yields Equation 47.

$$S_f = 1 - \frac{V}{\frac{(\omega_f x \omega_r x rr_f)}{\omega_r}} \qquad (47)$$

Front axle speed divided by rear axle speed is wheel speed ratio. Then replacing the remaining rear axle speed by Equation 45 yields Equation 48.

$$S_f = 1 - \frac{V}{\frac{WSR_{f/r} x rr_f x V}{rr_r - S_r x rr_r}} \qquad (48)$$

Rolling radius ratio is defined as the front axle rolling radius divided by the rear axle rolling radius (Equation 49).

$$S_f = 1 - \frac{V}{\frac{WSR_{f/r} x RR_{f/r} x V}{1 - S_r}} \qquad (49)$$

Equation 49 can be rewritten as Equation 50.

$$S_f = 1 - \frac{1 - S_r}{WSR_{f/r} x RR_{f/r}} \qquad (50)$$

Figure 28 is a plot of dynamic traction ratio as a function of rear wheel slip for six levels of wheel speed ratio, front dynamic load ratio of 0.45 and front axle wheel numeric of 50. As rear slip increases, four wheel drive dynamic traction ratio increases for a constant rear wheel slip. As expected, as wheel speed ratio increases, dynamic traction ratio increases because of increased slip of the front axle as given by Equation 50.

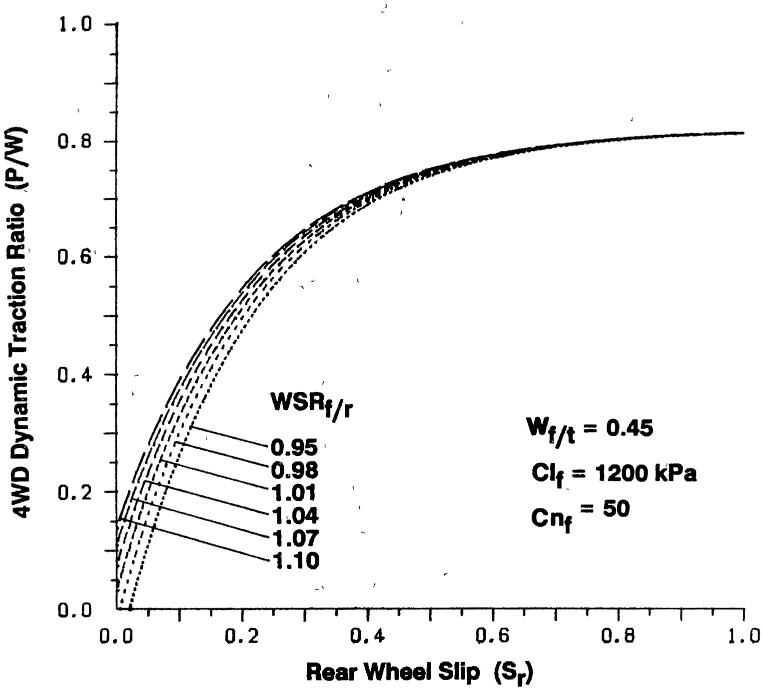


Figure 28. Four Wheel Drive (4WD) Dynamic Traction Ratio as a Function of Rear Wheel Slip for Six Wheel Speed Ratios

Figure 29 shows a plot of four wheel drive dynamic traction ratio as a function of rear wheel slip for six front dynamic load ratios. For this graph, front soil cone index was 300 kPa and wheel speed ratio was 1.05. Figure 29 shows that front dynamic load ratio from 35 to 55 percent is

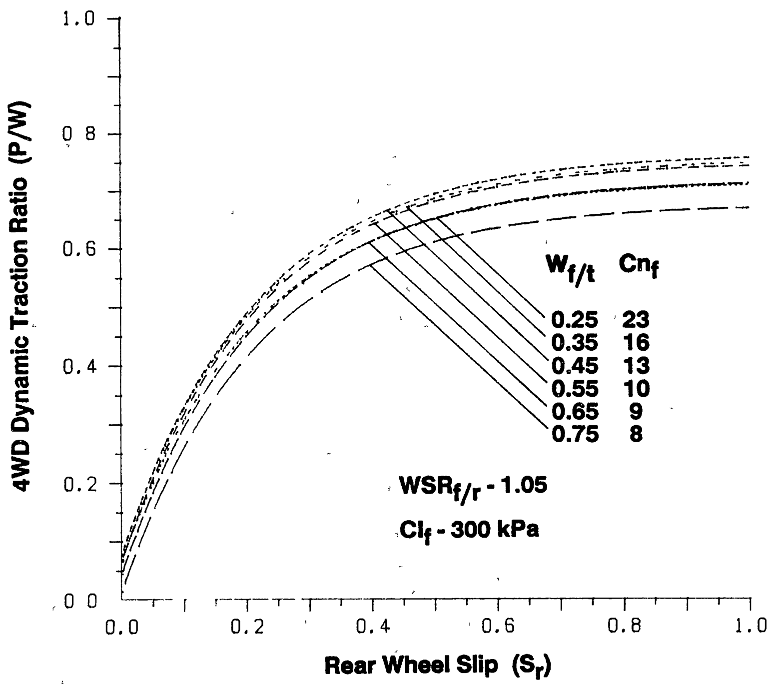


Figure 29. Four Wheel Drive (4WD) Dynamic Traction Ratio as a Function of Rear Wheel Slip for Six Dynamic Load Ratios

better than the other three load distributions for this soil condition and wheel speed ratio. Front dynamic load of 45 percent is best for any rear wheel slip for these conditions of soil cone index and wheel speed ratio. Figure 29 indicates no interaction between dynamic load ratio and rear wheel slip in the manner in which they affect dynamic traction ratio.

For a constant rear wheel slip the effect of changing either soil cone index or wheel speed ratio is shown in Figure 30. Figure 30 is a graph of dynamic traction ratio as a function of front dynamic load ratio for six soil cone

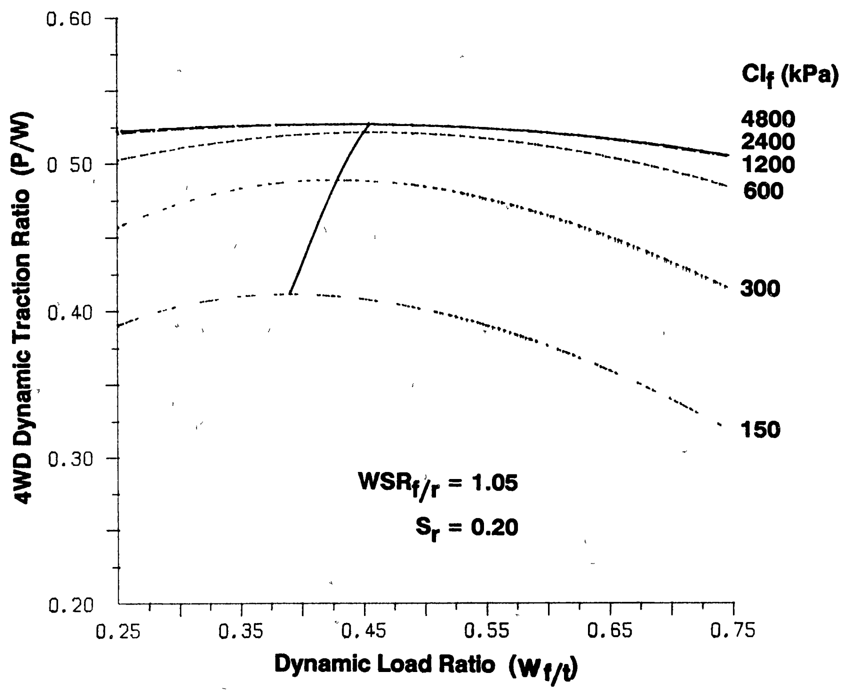


Figure 30. Four Wheel Drive (4WD) Dynamic Traction Ratio as a Function of Front Dynamic Load Ratio for Six Front Soil Cone Indexes

index levels, rear wheel slip of 0.20 and front wheel speed ratio of 1.05. The line drawn across the six curves is drawn through maximum dynamic traction ratio.

For the curve of 300 kPa which is a very soft or tilled soil, the maximum occurs at approximately 0.43 front dynamic load ratio. Varying front dynamic load ratio plus or minus 25 percent, reduces dynamic traction ratio approximately 2 percent. Generally, as soil strength increases as measured by soil cone index, dynamic load ratio should be increased to maintain maximum dynamic traction ratio. The effect of changing dynamic load ratio diminishes as soil cone index increases; this is evidenced by the flattening of the curves at higher soil cone index levels.

Figure 31 shows dynamic traction ratio as a function of front dynamic load ratio, for six levels of wheel speed ratio, soil cone index of 1200 kPa and rear slip of 20 percent. The line drawn across the curves is drawn through the points of maximum dynamic traction ratio. For a wheel speed ratio of 1.04, maximum dynamic traction ratio occurs at a front dynamic load ratio of approximately 0.42. Varying front dynamic load ratio plus or minus 25 percent reduced dynamic traction ratio less than 0.5 percent.

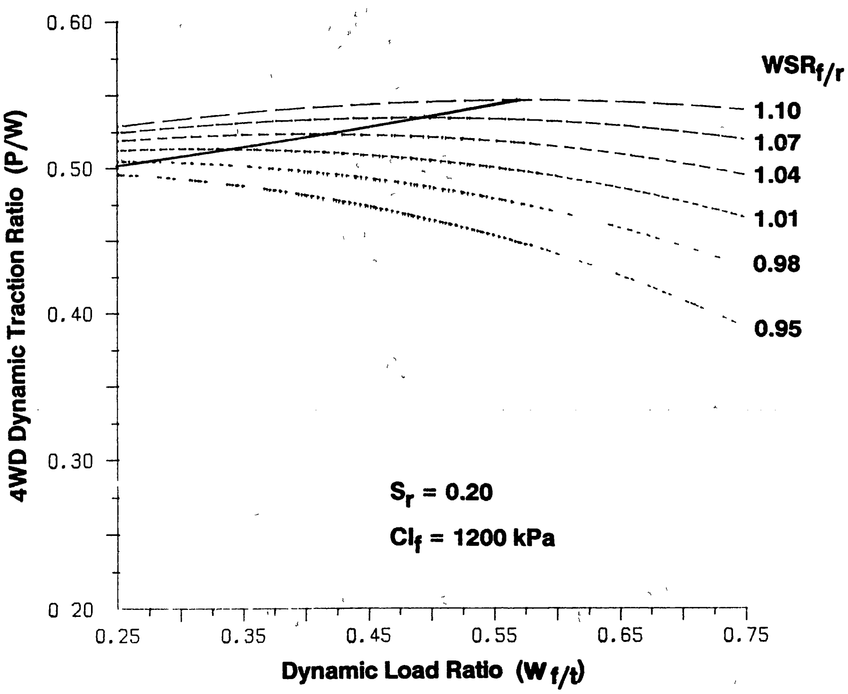


Figure 31. Four Wheel Drive (4WD) Dynamic Traction Ratio as a Function of Front Dynamic Load Ratio for Six Wheel Speed Ratios

Generally, as wheel speed ratio increases, front dynamic load ratio should be increased to maintain maximum dynamic traction ratio. For wheel speed ratios seen on most production four wheel drive tractors (1.01 to 1.03), varying dynamic load has only a small effect on dynamic traction ratio. Maintaining dynamic load ratio between 35 and 50 percent on the front axle will result in good tractive performance in terms of dynamic traction ratio for wheel speed ratios seen on most production four wheel drive agricultural tractors.

Tractive Efficiency

Tractive efficiency is an important consideration when evaluating the performance of an agricultural traction unit. Tractive efficiency indicates the efficiency in converting axle power into useful power at the drawbar. Four wheel drive tractive efficiency accounts for both axles and the interaction between them.

The results of an analysis of variance on four wheel drive tractive efficiency are shown in Table V. Different error terms were used when evaluating the main factors (Forward Speed, Dynamic Load Ratio and Wheel Slip) and the split variable (Wheel Speed Ratio). Using a significance level of 20 percent, Table V shows that wheel slip, dynamic load ratio and wheel speed ratio significantly affected four wheel drive tractive efficiency. One interaction also significantly affected four wheel drive tractive efficiency,

TABLE V

ANALYSIS OF VARIANCE OF FOUR WHEEL DRIVE TRACTIVE EFFICIENCY

Source	D.F.	Sum of Square	F Ratio	Significance Level*
S (Wheel Slip)	3	30.11908	88.34	0.0001
W (Dynamic Load Ratio)	2	1.05694	4.65	0.0373
V (Forward Speed)	2	0.02941	0.13	0.8801
S*W	6	0.46070	0.68	0.6731
S*V	6	0.04882	0.07	0.9978
W*V	4	0.09316	0.20	0.9299
V*W*S	11	0.11745	0.11	0.9984
Error (Rep*V*W*S)	10	1.13652		
WSR (Wheel Speed Ratio)	3	0.08766	3.72	0.0242
WSR*V	6	0.06062	1.29	0.2979
WSR*W	6	0.06364	1.35	0.2714
WSR*S	9	0.04968	0.70	0.6991
WSR*V*W	12	0.05673	0.60	0.8189
WSR*V*S	18	0.08958	0.64	0.8378
WSR*S*W	15	0.19430	1.65	0.1291
WSR*S*W*V	25	0.16045	0.82	0.6891
Error (Rep*WSR*S*W*V)	25	0.19586		

* Probability of an error in rejecting the null hypothesis that the variable in question does not contribute to the variance.

wheel speed ratio by slip by dynamic load ratio. As discussed previously, soil cone index was not included in the analysis of variance but was included in the equation predicting four wheel drive tractive efficiency.

Tractive efficiency is defined as the ratio of output power to input power. Tractive efficiency for a four wheel drive system can be shown to be a mathematical combination of dynamic traction ratio and axle motion resistance.

Four wheel drive tractive efficiency is defined as the output power at the drawbar divided by the input power at the axles.

$$TE = \frac{P_t x V}{\frac{T_f x Vt_f}{rr_f} + \frac{T_r x Vt_r}{rr_r}} \qquad (51)$$

Equation 52 is derived by dividing the numerator and denominator of Equation 51 by four wheel drive dynamic load and rear axle theoretical speed.

$$TE = \frac{\frac{P_t}{W_t} x \frac{V}{V_t}}{\frac{\frac{T_f}{rr_f} x \frac{Vt_f}{Vt_r} + \frac{T_r}{rr_r}}{W_t}} \qquad (52)$$

Equation 53 is derived by replacing actual tractor speed divided by rear axle theoretical speed in the numerator of Equation 52 by one minus wheel slip for the rear axle, replacing theoretical speed of the front axle divided by theoretical speed of the rear axle in the denominator of Equation 52 by wheel speed ratio multiplied by rolling radius ratio, distributing the total tractor dynamic load in the denomintor and recalling that axle dynamic load ratio is the ratio of the axle dynamic load to total tractor dynamic load and replace one over total tractor dynamic load by dynamic load ratio of an axle multiplied by one over axle dynamic load. Then after rearranging Equation 53 is:

$$TE = \frac{\frac{P_t}{W_t} \times (1-S_r)}{W_{f/t} \times \frac{T_f}{rr_f x W_f} \times WSR_{f/r} x RR_{f/r} + W_{r/t} \times \frac{T_r}{rr_r x W_r}} \quad (53)$$

Replace the gross traction ratios for both axles in the denominator of Equation 53 by dynamic traction ratio plus self-propelled torque ratio. This yields Equation 54:

$$TE = \frac{\frac{P_t}{W_t} \times (1-S_r)}{W_{f/t} x (\frac{P_f}{W_f} + \frac{TQ_f}{rr_f x W_f}) x WSR_{f/r} x RR_{f/r} + W_{r/t} x (\frac{P_f}{W_f} + \frac{TQ_f}{rr_f x W_f})} \quad (54)$$

Figure 32 shows a plot of four wheel drive tractive efficiency as a function of rear wheel slip. The six curves correspond to six wheel speed ratios, front soil cone index of 300 kPa and front dynamic load ratio of 0.45. This results in a front wheel numeric of 13.

Figure 32 shows curves which generally fit the "normal" curves for tractive efficiency as a function of slip, where the curves increase quickly as slip increases, reach their peak and then slowly decrease as slip continues to increase. For this dynamic load ratio and front soil cone index, a wheel speed ratio between 0.98 and 1.04 appears best. As soil strength is increased as measured by soil cone index, the curves in Figure 32 move upward and slightly left.

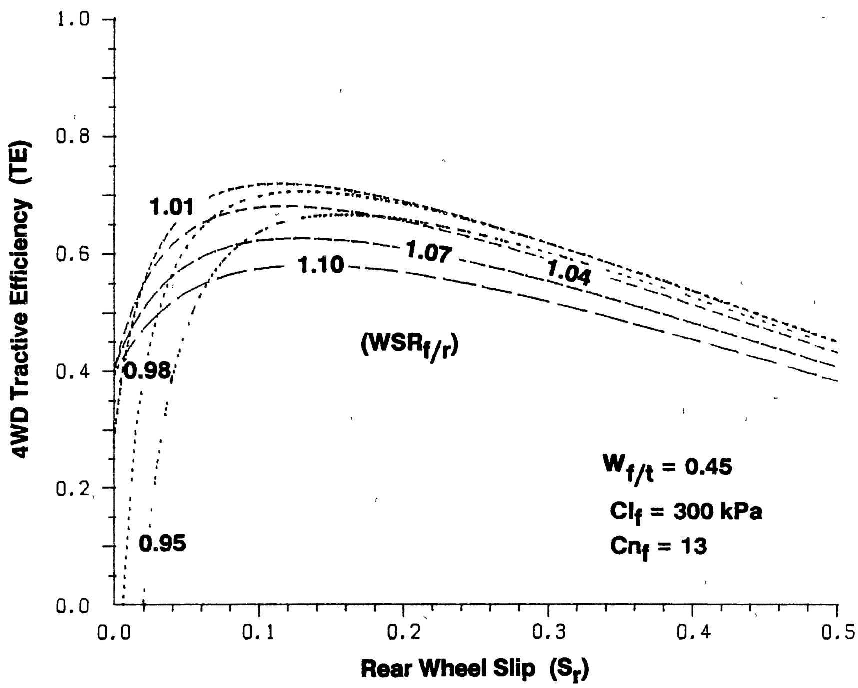


Figure 32. Four Wheel Drive (4WD) Tractive Efficiency as a Function of Rear Wheel Slip for Six Wheel Speed Ratios

For a fixed soil cone index and forward speed, a implement requires a fixed level of drawbar pull. This corresponds to a constant dynamic traction ratio. Figure 33 shows a graph of four wheel drive tractive efficiency as a function of wheel speed ratio for six dynamic traction ratios, soil cone index of 1200 kPa and dynamic load ratio of 0.45. Wheel speed ratio has a small effect on four wheel drive tractive efficiency except at very low slip levels corresponding to low dynamic traction ratio (P/W=0.20). As slip increases beyond the point corresponding to maximum

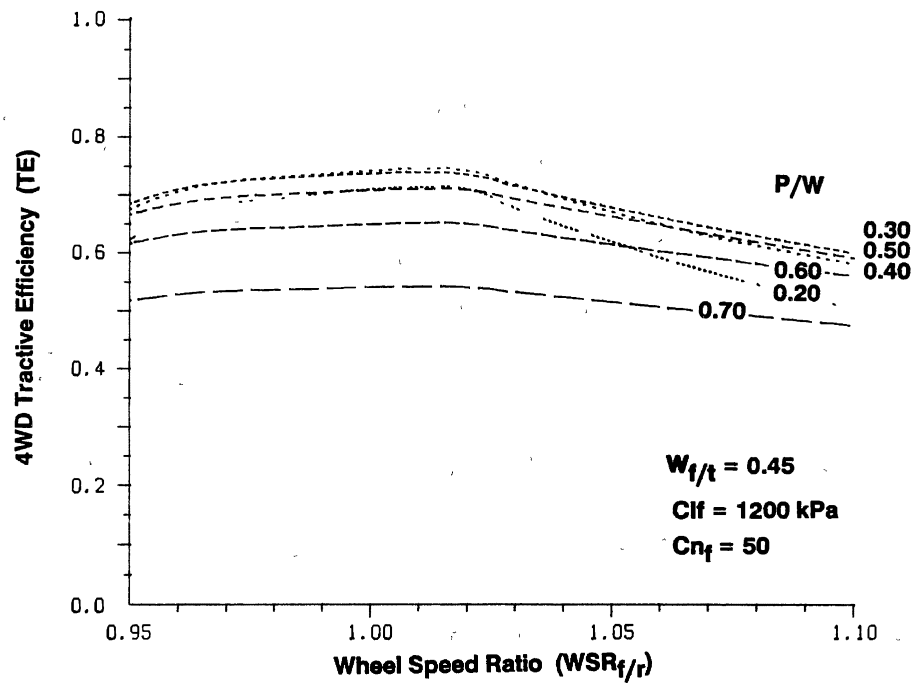


Figure 33. Four Wheel Drive (4WD) Tractive Efficiency as a Function of Wheel Speed Ratio for Six Dynamic Traction Ratios

tractive efficiency (refer to Figure 32) a small change in slip results in a very small change in tractive efficiency.

Changing wheel speed ratio for any dynamic traction ratio increases slip for one axle and decreases slip for the other. This results in a small decrease in efficiency for one axle, an increase in the other axle, and little change in overall tractive efficiency. Figure 33 shows that the effect of changing dynamic traction ratio generally shifts the curve vertically but does not affect the wheel speed ratio level corresponding to maximum tractive efficiency.

The flat portion of the curves in Figure 33 generally shift slightly to the right with increasing front dynamic load.

Soil strength as measured by soil cone index will affect tractive efficiency. Figure 34 shows four wheel drive tractive efficiency as a function wheel speed ratio for six levels of front soil cone index, front dynamic load of 0.45 and a dynamic traction ratio of 0.50. As undisturbed soil cone index increases, four wheel drive tractive efficiency increases, but the rate of increase is markedly reduced at higher soil cone index levels. Maximum tractive efficiency as a function of wheel speed ratio is

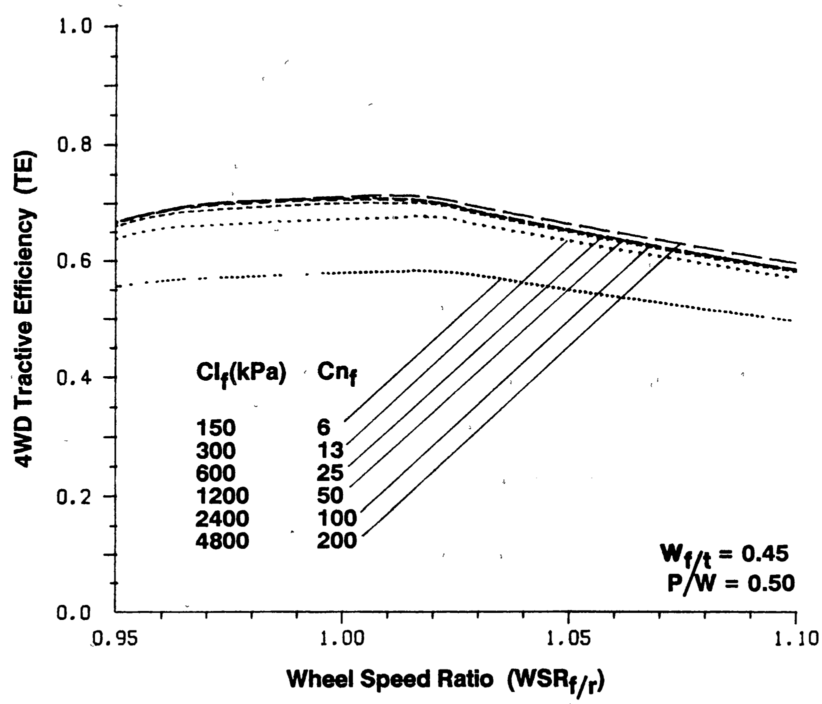


Figure 34. Four Wheel Drive (4WD) Tractive Efficiency as a Function of Wheel Speed Ratio for Six Front Soil Cone Indexes

unaffected by soil cone index level.

Figure 35 shows four wheel drive tractive efficiency as a function of wheel speed ratio for six levels of front dynamic load ratio, front soil cone index of 1200 kPa and constant dynamic traction ratio of 0.50. Figure 35 shows that changing dynamic load ratio only has a small effect on four wheel drive tractive efficiency. At a wheel speed ratio of 1.04, varying front dynamic load ratio between 0.25 and 0.75 changes four wheel drive tractive efficiency by less than 3 percent.

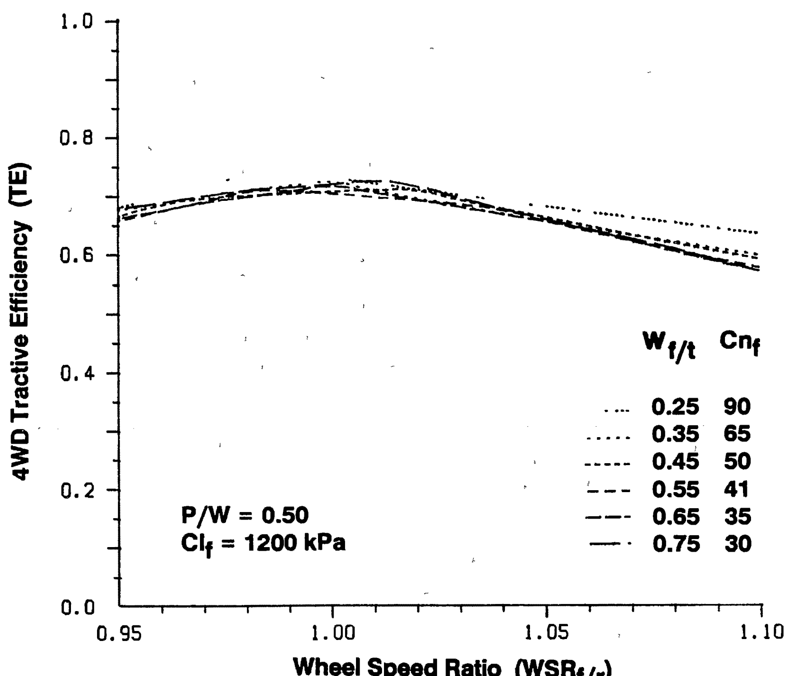


Figure 35. Four Wheel Drive (4WD) Tractive Efficiency as a Function of Front Wheel Speed Ratio for Six Front Dynamic Load Ratios

Four Wheel Drive Tractor Operation

Most tractor manufacturers recommend anywhere from 60 to 65 percent of total static load be placed on the front axle. John Deere in their tractor weight guide recommended that their four wheel drive tractors be ballasted with 60 percent of the total load on the front axle. Recommended in literature from J. I. Case concerning the Case 2470 used in this research and in a paper presented by Kravig (1986) was that 65 percent of the total static load be placed on the front axle.

To produce the maximum pull, Figures 30 and 31 indicate that front dynamic load ratio should be in the range of 0.35 to 0.50 for wheel speed ratios seen on most production four wheel drive tractors (from 1.01 to 1.03). To produce front dynamic load ratios in this range with front static load around 60 percent requires very high drawbar pull. For the Case 2470 tractor, to produce 45 percent front dynamic load required a dynamic traction ratio of 0.85, an impossible requirement. With 55 percent front static load, to produce 45 percent front dynamic load ratio required 0.58 dynamic traction ratio, still a very high quantity. High dynamic traction ratio requires high wheel slip. It is desirable to reduce front static load to between 50 and 55 percent.

To maximize efficiency, wheel slip should be kept relatively low (refer to Figure 32). Generally, wheel slip should be in the range of 10 to 20 percent. High wheel slip used to produce the high draft requirement for large dynamic load transfer from the front axle to the rear results in several undesirable conditions. High slip levels result in reduced tractive efficiency. Another reason to maintain relatively low slip levels is concern for drive train life. To utilize the engine power and increase drive train life, instead of high slip or draft, it would be better to maintain faster forward speeds. Bowers (1978) and Kravig (1986) suggest speeds in the range of 8 km/h.

In terms of four wheel drive tractive efficiency, wheel speed ratio and dynamic load ratio have a small effect. To maximize four wheel drive tractive efficiency, wheel speed ratio should be in the range of 1.0 to 1.03. This is close to the range where most four wheel drive tractors operate now. To maximize four wheel drive tractive efficiency front axle dynamic load should be in the range of 35 to 50 percent. This is less than the front dynamic load that most production tractors operate now.

Automatically controlling dynamic load distribution would yield little, if any, improvement in tractive performance. Four wheel drive tractors are very large pieces of off-road equipment, tractors having a ballasted mass greater than 10000 to 15000 kg are common. Moving the quantity of mass required for shifting only 5 percent of the dynamic load distribution would be difficult and costly. For the four wheel drive Case tractor used in this research, shifting dynamic load distribution from 45 to 50 percent on the front axle required moving the ballast rack 1.14 m forward with 1360 kg on the rack. For an automatic control system to be successful, significant improvements in tractive performance would need to be realized to make shifting large amounts of mass reasonable. Besides the difficulty in moving this large amount of mass, very little change in performance will result from having the ability to automatically shift dynamic load distribution. As shown in Figure 30, for the curve of 300 kPa, shifting dynamic load distribution plus or minus 25 percent from the maximum reduced the dynamic traction ratio approximately 2 percent. For soil cone index greater than 600 kPa the percentage change would be much less than 2 percent.

The effect of wheel speed ratio has much less effect on tractive performance than previously thought. Automatically controlling wheel speed ratio would yield little, if any, improvement in tractive performance. Controlling wheel speed ratio would be difficult and costly. An additional transmission would have to be installed between the output of the normal transmission and the front axle. This transmission would be costly, and would result in a reduction in efficiency of power transmission to the front axle. Therefore, to justify this additional expense and loss in transmission efficiency, significant improvement in overall tractor performance would need to be realized. As shown in Figures 33 and 34, wheel speed ratio has only a small effect on tractive efficiency. Varying wheel speed ratio from the point corresponding to maximum tractive efficiency only reduced four wheel tractive efficiency slightly.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

The effects of wheel speed ratio and dynamic load ratio on four wheel drive tractive performance were evaluated by an instrumented four wheel drive tractor. The tractor's instrumentation system measured wheel speeds, axle torques, forward speed, drawbar pull, vertical force on the drawbar, net traction of the front axle and dynamic load ratio. The performance of each axle as well as the total tractor were measured.

A large field test was conducted to evaluate the effects of wheel speed ratio, dynamic load ratio, wheel slip, forward speed and soil cone index on tractive performance. Prediction equations for single axle and four wheel drive motion resistance, dynamic traction ratio and tractive efficiency were developed. These equations were then used to evaluate the effects of wheel speed ratio and dynamic load distribution on four wheel drive tractive performance.

The instrumented tractor, developed for this research, worked well. The wheel speed control mechanism worked adequately, with some variation in wheel speed ratio under different loads. Changing static load distribution by use of the ballast rack worked very well. Setting drawbar load by a load sled worked well except under very soft soil conditions. This could be solved by making a smoother transition to allow soil to more easily pass under the sled. Overall, the tractor worked well and could be used to perform traction research on four wheel drive tractors that is not available elsewhere.

Motion resistance for both the front and rear axles measured by self-propelled torque ratio was significantly affected by wheel slip, dynamic load ratio and wheel speed ratio. The rear axle was significantly affected by a three way interaction between wheel speed ratio, wheel slip and dynamic load ratio, and a four way interaction between wheel speed ratio, wheel slip, dynamic load ratio and forward speed. Self-propelled torque for each axle was increased by increasing the wheel speed ratio of one axle in relation to the other axle, shifting dynamic load from one axle to the other axle, decreasing soil strength as measured by soil cone index and increasing tire width or diameter.

Dynamic traction ratio for a four wheel drive tractor was significantly affected by wheel slip, dynamic load ratio and wheel speed ratio. Four wheel drive dynamic traction ratio was also significantly affected by a three way interaction between wheel speed ratio, wheel slip and dynamic load ratio. Dynamic traction ratio was increased by increasing slip for either axle and increasing wheel numeric for either axle. The following conclusions were made concerning the effects of wheel speed ratio, dynamic load ratio and soil strength (soil cone index) on four wheel drive dynamic traction ratio: to maintain the ability to obtain maximum dynamic traction ratio as soil strength increases, dynamic load on the front axle should be increased; to maintain the ability to obtain maximum dynamic traction ratio as wheel speed ratio of the front wheels to the rear wheels increases, dynamic load on the front axle should be increased; but overall the effects of changing wheel speed ratio and dynamic load ratio are small. The effect of varying dynamic load ratio diminishes with increasing soil strength.

Four wheel drive tractive efficiency was significantly affected by wheel slip, dynamic load ratio, wheel speed ratio and a three way interaction between wheel speed ratio, wheel slip and dynamic load ratio. The following conclusions were made concerning the effects of wheel slip, wheel speed ratio, dynamic load ratio and soil strength (soil cone index) on four wheel drive tractive efficiency: wheel speed ratio in the range of 1.0 to 1.03 will provide good tractive performance in terms of four wheel drive tractive efficiency; as undisturbed soil cone index increases, four wheel drive tractive efficiency increases; wheel slip should be kept relatively low, in the range of 10 to 20 percent; dynamic load ratio has little affect on four wheel drive tractive efficiency.

Maintaining dynamic load ratio between 35 and 50 percent on the front axle will result in good tractive performance for wheel speed ratios seen on most agricultural four wheel drive tractors. Static load distribution should be in the range of 50 to 55 percent on the front axle so that wheel slip can be maintained at a lesser value and weight transfer can bring the dynamic load into the desired range of 35 to 50 percent.

Conclusions

From the field experiment and resulting data analysis, the following conclusions were deduced:

1. The following relationships were determined from the analysis of variance for four wheel drive tractor performance.

    (a) Axle motion resistance is significantly affected by wheel slip, dynamic load distribution, wheel speed ratio and interactions between wheel slip, dynamic load ratio and wheel speed ratio, and wheel slip, dynamic load ratio, wheel speed ratio and forward speed.

    (b) Four wheel drive dynamic traction ratio is significantly affected by wheel slip, dynamic load ratio, wheel speed ratio and interactions between wheel slip, dynamic load ratio and wheel speed ratio, and wheel slip, dynamic load ratio, wheel speed ratio and forward speed.

(c) Four wheel drive tractive efficiency is significantly affected by wheel slip, dynamic load ratio, wheel speed ratio and an interaction between wheel slip, dynamic load ratio and wheel speed ratio.

(d) There is no evidence to conclude that tractor forward speed has any affect on tractor performance.

2. The relationship between dynamic load distribution, wheel slip, wheel speed ratio, soil strength and tractive performance of a four wheel drive tractor can be predicted by the following equations:

The equations predicting motion resistance of each axle of a four wheel drive tractor are:

$$\frac{TQ_f}{rr_f x W_f} = -2.63 + 2.57 x WSR_{f/r} + \frac{0.18}{Cn_f} - 0.34 x e^{-W_{f/r}}$$

$$\frac{TQ_f}{rr_f x W_f} = 0 \quad \text{for} \quad \frac{TQ_f}{rr_f x W_f} < 0$$

$$\frac{TQ_r}{rr_r x W_r} = -2.63 + 2.57 x WSR_{r/f} + \frac{0.18}{Cn_r} - 0.34 x e^{-W_{r/f}}$$

$$\frac{TQ_r}{rr_r x W_r} = 0 \quad \text{for} \quad \frac{TQ_r}{rr_r x W_r} < 0$$

where:

TQ/(rrxW)	=	Self-propelled torque ratio
TQ	=	Self-propelled torque
rr	=	Rolling radius
W	=	Dynamic load
WSR	=	Wheel speed ratio
Cn	=	Wheel numeric defined as CIxbxd/W where CI is soil cone index, b and d are tire width and diameter

f,r = Subscripts refer to front axle and rear axle respectfully

The equation predicting dynamic traction ratio of a four wheel drive tractor is:

$$\frac{P_t}{W_t} = W_{f/t} \times K1 \times (1-e^{K2xCn_f}) \times (1-e^{K3xS_f}) +$$
$$W_{r/t} \times K1 \times (1-e^{K2xCn_r}) \times (1-e^{K3xS_r})$$

where: P/W = Dynamic traction ratio
P = Net traction
S = Wheel slip
K1 = 0.82
K2 =-0.19
K3 =-4.69

The equation predicting tractive efficiency of a four wheel drive tractor is:

$$TE = \frac{\frac{P_t}{W_t} x\ (1-S_r)}{W_{f/t}x(\frac{P_f}{W_f}+\frac{TQ_f}{rr_f xW_f})xWSR_{f/r}xRR_{f/r} + W_{r/t}x(\frac{P_f}{W_f}+\frac{TQ_f}{rr_f xW_f})}$$

where: TE = Four wheel drive tractive efficiency
RR = Rolling radius ratio
t = Subscript refers to four wheel drive tractor

The following conclusions concerning the effects of dynamic load ratio, wheel speed ratio, wheel slip and soil strength on four wheel drive tractive performance were deduced using the developed prediction equations shown previously:

(a) In terms of dynamic traction ratio, dynamic load should be in the range of 35 to 50 percent on the front axle; front static load distribution should be reduced from the normal 60 to 65 percent to within the range of 50 to 55 percent. Increasing wheel slip increases net traction; and increasing soil strength as measured by soil cone index increases net traction. The effects of varying dynamic load ratio on dynamic traction ratio diminish significantly at soil cone indexes above 600 kPa.

(b) In terms of four wheel drive tractive efficiency: dynamic load ratio has almost no effect for a wide range of values; wheel speed ratio should be in the range of 1.0 to 1.03; rear wheel slip should generally be in the range of 10 to 20 percent; tractive efficiency increases with increasing soil strength as measured by soil cone index.

(c) Varying wheel speed ratio or dynamic load ratio slightly outside the ranges discussed will only result in a small reduction in four wheel drive tractive performance.

3. From the prediction equations and analysis, it does not appear that any significant improvement in tractive performance would result from automatically controlling either wheel speed ratio or dynamic load ratio. Besides the negligible tractive performance gains, controlling either wheel speed ratio or dynamic load distribution would be very

costly in terms of equipment and efficiency. Operating a four wheel drive tractor with the proper ballast configuration will provide tractive performance as good as could be obtained using automatic control.

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APPENDIX A

MEASURED DATA FROM FIELD TEST

APPENDIX A-1

MEASURED DATA FROM FIELD TEST

FIRST TEN VARIABLES

	Main Variable Levels						Drawbar Forces		Front Axle Forces	
OBS[1]	REP	V	W	S	WSR	CI	Pull (N)	Vertical (N)	Net Traction (N)	Dynamic Load (N)
1	1	3	1	1	3	3	0	0	-891	55705
2	1	3	1	1	3	2	0	0	-954	56130
3	1	3	1	1	3	1	0	0	-1062	55917
4	1	3	1	1	4	1	0	0	279	55917
5	1	3	1	1	4	2	0	0	-112	56130
6	1	3	1	1	4	3	0	0	224	56236
7	1	3	1	1	1	2	0	0	112	56130
8	1	3	1	1	1	1	0	0	-840	56023
9	1	3	1	1	1	3	0	0	-112	56449
10	1	3	1	1	2	1	0	0	493	54854
11	1	3	1	1	2	2	0	0	387	55279
12	1	3	1	1	2	3	0	0	283	56661
13	1	2	1	1	4	3	0	0	715	55067
14	1	2	1	1	4	2	0	0	762	54429
15	1	2	1	1	4	1	0	0	1792	52728
16	1	2	1	1	3	3	0	0	1321	55067
17	1	2	1	1	3	1	0	0	1544	55173
18	1	2	1	1	3	2	0	0	1042	54854
19	1	2	1	1	1	3	0	0	-165	55279
20	1	2	1	1	1	2	0	0	-165	55173
21	1	2	1	1	1	1	0	0	592	53897
22	1	2	1	1	2	1	0	0	1636	54535
23	1	2	1	1	2	2	0	0	1912	54641
24	1	2	1	1	2	3	0	0	499	55492
25	1	1	1	1	2	3	0	0	1216	55279
26	1	1	1	1	2	2	0	0	1632	54429
27	1	1	1	1	2	1	0	0	1264	54960
28	1	1	1	1	4	1	0	0	2484	54004
29	1	1	1	1	4	2	0	0	279	55811
30	1	1	1	1	4	3	0	0	1693	54641
31	1	1	1	1	1	2	0	0	55	55598
32	1	1	1	1	1	1	0	0	-494	54960
33	1	1	1	1	1	3	0	0	-389	55598
34	1	1	1	1	3	1	0	0	1927	55067
35	1	1	1	1	3	2	0	0	1652	55067
36	1	1	1	1	3	3	0	0	891	55705
37	1	3	1	2	4	3	6093	338	5627	54110

38	1	3	1	2	4	2	6329	186	5357	53578
39	1	3	1	2	4	1	6454	440	6549	53685
40	1	3	1	2	2	1	8193	378	4860	52834
41	1	3	1	2	2	2	8615	355	4696	53366
42	1	3	1	2	2	3	7761	293	3632	54216
43	1	3	1	2	3	2	6520	195	4752	54004
44	1	3	1	2	3	1	7841	409	5143	53578
45	1	3	1	2	3	3	8139	560	5789	54110
46	1	3	1	2	1	1	6938	440	2245	53472
47	1	3	1	2	1	2	7997	720	2839	53578
48	1	3	1	2	1	3	6632	400	2139	54854
49	1	2	1	2	4	3	7410	289	7060	53897
50	1	2	1	2	4	2	6987	240	7257	53366
51	1	2	1	2	4	1	6885	373	7122	53153
52	1	2	1	2	3	1	8713	653	8352	51240
53	1	2	1	2	3	2	8553	444	6493	54110
54	1	2	1	2	3	3	8477	342	6737	53472
55	1	2	1	2	2	2	7263	329	4599	54110
56	1	2	1	2	2	1	8277	315	4572	53791
57	1	2	1	2	2	3	8824	502	5052	54323
58	1	2	1	2	1	1	6912	387	2064	54323
59	1	2	1	2	1	2	8833	604	2993	54429
60	1	2	1	2	1	3	8807	413	2377	55279
61	1	3	1	3	3	3	19864	1494	24697	51027
62	1	3	1	3	3	2	17293	938	11280	50814
63	1	3	1	3	3	1	20211	1347	11460	50708
64	1	3	1	3	1	1	24014	2055	10227	49645
65	1	3	1	3	1	2	25375	1908	9330	50708
66	1	3	1	3	1	3	21910	1948	7255	52196
67	1	3	1	3	2	2	16866	1089	9026	51877
68	1	3	1	3	2	1	19820	1628	9479	51240
69	1	3	1	3	2	3	22858	2250	11162	50283
70	1	3	1	3	4	1	18388	1396	12451	51452
71	1	3	1	3	4	2	24971	2682	14866	48901
72	1	3	1	3	4	3	21675	1837	13184	50708
73	1	2	1	3	3	3	14847	1547	12170	50708
74	1	2	1	3	3	2	17075	1205	11838	51027
75	1	2	1	3	3	1	19762	1574	12491	49964
76	1	2	1	3	4	3	20451	2192	14979	48476
77	1	2	1	3	4	1	19242	1494	13084	49751
78	1	2	1	3	4	2	22533	2095	14618	49220
79	1	2	1	3	1	3	19491	1952	8507	51559
80	1	2	1	3	1	2	19193	1783	7479	52303
81	1	2	1	3	1	1	17458	1370	8386	51452
82	1	2	1	3	2	1	21590	2143	11641	49539
83	1	2	1	3	2	2	20256	2259	11517	49858
84	1	2	1	3	2	3	21105	1703	10380	51133
85	1	1	1	3	4	3	30295	1841	13594	49432
86	1	1	1	3	4	2	26883	1583	13000	50389
87	1	1	1	3	4	1	24045	1690	13383	49751
88	1	1	1	3	2	1	26314	1983	12617	48157
89	1	1	1	3	2	2	25375	2152	11077	50814
90	1	1	1	3	2	3	24232	1401	10409	51027
91	1	1	1	3	3	2	21408	1294	10320	51346

92	1	1	1	3	3	1	22079	1401	11311	50495
93	1	1	1	3	3	3	24001	1694	12139	49751
94	1	1	1	3	1	1	20234	1672	7429	51240
95	1	1	1	3	1	2	22453	3371	10027	50389
96	1	1	1	3	1	3	22351	1814	8576	51665
97	1	1	1	4	2	3	37527	-778	11419	52622
98	1	1	1	4	2	2	27746	-671	11086	53047
99	1	1	1	4	2	1	27408	-649	12074	52728
100	1	1	1	4	3	3	19887	-769	13494	52303
101	1	1	1	4	3	1	20322	-667	13488	51877
102	1	1	1	4	3	2	19806	-858	14259	51665
103	1	1	1	4	4	3	18730	-1236	15796	51452
104	1	1	1	4	4	2	19366	-782	15293	52196
105	1	1	1	4	4	1	19010	-685	15459	51877
106	1	1	1	4	1	1	18770	-1312	9186	52196
107	1	1	1	4	1	2	21781	-1534	9423	52941
108	1	1	1	4	1	3	18334	-991	8983	53791
109	1	2	1	4	1	3	16052	-1134	8839	53897
110	1	2	1	4	1	2	17516	-778	9892	52622
111	1	2	1	4	1	1	17191	-1116	9510	52834
112	1	2	1	4	4	1	19855	-1249	15429	50921
113	1	2	1	4	4	2	21964	-902	16122	51346
114	1	2	1	4	4	3	21612	-787	15602	51665
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418	1	1	1	2	4	1	8366	920	8749	51771
419	1	1	1	2	4	2	8913	556	8788	52941
420	1	1	1	2	4	3	8460	440	7304	54110
421	2	2	2	1	1	2	0	0	3913	45499
422	2	2	2	1	1	3	0	0	3719	45924
423	2	2	2	1	1	1	0	0	3822	44967
424	2	2	2	1	4	1	0	0	842	44330
425	2	2	2	1	4	2	0	0	403	44861
426	2	2	2	1	4	3	0	0	451	45180
427	2	2	2	1	3	1	0	0	-852	44861
428	2	2	2	1	3	3	0	0	-1089	45393
429	2	2	2	1	3	2	0	0	-998	45393
430	2	2	2	1	2	3	0	0	-2925	45712
431	2	2	2	1	2	2	0	0	-3725	46562
432	2	2	2	1	2	1	0	0	-3237	44967
433	2	3	2	1	4	1	0	0	1017	44223
434	2	3	2	1	4	2	0	0	807	44861
435	2	3	2	1	4	3	0	0	322	46031
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437	2	3	2	1	2	3	0	0	-3084	46031
438	2	3	2	1	2	1	0	0	-3275	46137
439	2	3	2	1	3	3	0	0	-701	46775
440	2	3	2	1	3	2	0	0	-603	46456
441	2	3	2	1	3	1	0	0	-1260	46668
442	2	3	2	1	1	1	0	0	-5549	46243
443	2	3	2	1	1	3	0	0	-4716	46243
444	2	3	2	1	1	2	0	0	-5075	46137
445	2	1	2	1	2	2	0	0	-4256	46775
446	2	1	2	1	2	3	0	0	-4153	46668
447	2	1	2	1	2	1	0	0	-3731	45499
448	2	1	2	1	4	1	0	0	140	46881
449	2	1	2	1	4	2	0	0	94	47306
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452	2	1	2	1	3	3	0	0	-1557	47200
453	2	1	2	1	3	2	0	0	-1406	46881
454	2	1	2	1	1	3	0	0	-4673	45818
455	2	1	2	1	1	2	0	0	-4817	46775
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457	2	3	3	1	4	1	0	0	1757	33167
458	2	3	3	1	4	2	0	0	2069	33380
459	2	3	3	1	4	3	0	0	1447	35294
460	2	3	3	1	2	2	0	0	-2007	34018
461	2	3	3	1	2	3	0	0	-2217	33593
462	2	3	3	1	2	1	0	0	-2016	32530
463	2	3	3	1	1	3	0	0	-3514	32848
464	2	3	3	1	1	2	0	0	-3817	33486
465	2	3	3	1	1	1	0	0	-4171	32848
466	2	3	3	1	3	1	0	0	2343	35506
467	2	3	3	1	3	3	0	0	1055	35187
468	2	3	3	1	3	2	0	0	821	35719
469	2	1	3	1	2	1	0	0	3252	34975

470	2	1	3	1	2	2	0	0	3659	35187
471	2	1	3	1	2	3	0	0	2866	35825
472	2	1	3	1	3	2	0	0	3027	36038
473	2	1	3	1	3	3	0	0	2849	35612
474	2	1	3	1	3	1	0	0	3256	35400
475	2	1	3	1	4	3	0	0	2758	35825
476	2	1	3	1	4	2	0	0	3053	35506
477	2	1	3	1	4	1	0	0	3997	34762
478	2	1	3	1	1	1	0	0	2107	34549
479	2	1	3	1	1	3	0	0	1724	35931
480	2	1	3	1	1	2	0	0	2398	34762
481	2	3	2	2	2	2	9545	-146	6764	47306
482	2	3	2	2	2	3	9914	-502	6467	48263
483	2	3	2	2	2	1	12089	-182	6922	47413
484	2	3	2	2	1	1	4866	-1716	5393	47306
485	2	3	2	2	1	2	11333	-702	4919	47306
486	2	3	2	2	1	3	10190	-355	4295	48263
487	2	3	2	2	4	1	9234	-378	8687	46456
488	2	3	2	2	4	3	10048	-467	8996	46137
489	2	3	2	2	4	2	9781	-329	8100	47094
490	2	3	2	2	3	3	7121	-467	7711	46456
491	2	3	2	2	3	2	8384	-289	7159	47413
492	2	3	2	2	3	1	9309	-382	7843	46137
493	2	2	2	2	2	1	12196	-524	7689	45499
494	2	2	2	2	2	2	11324	-373	7651	45818
495	2	2	2	2	2	3	10724	-315	7352	46243
496	2	2	2	2	4	2	9558	-462	9942	45605
497	2	2	2	2	4	3	9785	-378	9460	45924
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499	2	2	2	2	1	3	6716	-1263	4900	46668
500	2	2	2	2	1	2	10452	-226	4651	46987
501	2	2	2	2	1	1	9260	-511	4936	46137
502	2	2	2	2	3	1	12796	-622	9984	45180
503	2	2	2	2	3	3	9127	-1196	10031	45393
504	2	2	2	2	3	2	10203	-556	8996	46137
505	2	1	2	2	1	2	5737	-489	3801	47519
506	2	1	2	2	1	3	7045	-636	3754	47519
507	2	1	2	2	1	1	7592	-333	3691	47944
508	2	1	2	2	2	1	12899	-404	7454	45180
509	2	1	2	2	2	2	6720	-2744	8147	46031
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511	2	1	2	2	3	1	11511	-284	9012	45286
512	2	1	2	2	3	3	12049	-529	9042	46137
513	2	1	2	2	3	2	10261	-266	7994	47306
514	2	1	2	2	4	3	10234	-315	9126	46562
515	2	1	2	2	4	2	8753	-244	8278	47306
516	2	1	2	2	4	1	10194	-320	9117	45818
517	2	1	3	2	3	1	6627	-1877	8311	33380
518	2	1	3	2	3	2	10421	-1049	9290	33061
519	2	1	3	2	3	3	6832	-1201	8316	33805
520	2	1	3	2	1	2	8566	-413	4414	34762
521	2	1	3	2	1	3	5729	-1134	4660	34018
522	2	1	3	2	1	1	6654	-1120	3306	34443
523	2	1	3	2	4	3	9376	-1209	9972	33805

524	2	1	3	2	4	2	10359	-182	9247	34124
525	2	1	3	2	4	1	10782	-235	9321	34018
526	2	1	3	2	2	1	5257	-1983	7433	32317
527	2	1	3	2	2	3	11573	-876	7107	34337
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530	2	2	3	2	4	3	9847	-653	9449	33274
531	2	2	3	2	4	1	9478	-360	9368	33699
532	2	2	3	2	1	1	10257	-1223	5560	33699
533	2	2	3	2	1	2	6618	-1570	5136	34018
534	2	2	3	2	1	3	8664	-765	5168	34230
535	2	2	3	2	2	1	9376	-1112	6998	33167
536	2	2	3	2	2	3	7632	-1427	7382	34018
537	2	2	3	2	2	2	9612	-658	6702	34549
538	2	2	3	2	3	3	10199	-529	8044	34230
539	2	2	3	2	3	2	6347	-489	8128	34443
540	2	2	3	2	3	1	9345	-716	8907	33486
541	2	3	3	2	2	2	8620	-1997	7316	32955
542	2	3	3	2	2	3	8615	-1031	7029	32848
543	2	3	3	2	2	1	7357	-1441	6766	32848
544	2	3	3	2	3	1	5408	-1169	8237	33486
545	2	3	3	2	3	2	9999	-547	8087	32742
546	2	3	3	2	3	3	6903	-1227	7303	32317
547	2	3	3	2	1	1	5506	-2344	4785	33699
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551	2	3	3	2	4	2	6142	-1214	9623	34124
552	2	3	3	2	4	1	9794	-529	8804	34124
553	2	3	2	3	4	2	9603	-1427	14343	42310
554	2	3	2	3	4	3	12774	-2006	13248	42735
555	2	3	2	3	4	1	19895	-2313	13681	41459
556	2	3	2	3	2	1	14246	-2980	12769	41459
557	2	3	2	3	2	2	19033	-3131	12902	41353
558	2	3	2	3	2	3	23570	-854	11410	42735
559	2	3	2	3	3	1	22698	-854	12439	41885
560	2	3	2	3	3	3	22671	-1147	12937	42416
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562	2	3	2	3	1	3	14353	-2370	8956	43267
563	2	3	2	3	1	2	16257	-1183	8514	44117
564	2	3	2	3	1	1	21012	-564	8632	43160
565	2	1	2	3	2	1	25100	-1547	14187	40077
566	2	1	2	3	2	2	26056	-876	14046	40715
567	2	1	2	3	2	3	24179	-685	12820	42310
568	2	1	2	3	3	2	22876	-1116	8631	43373
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570	2	1	2	3	3	1	22538	-782	8034	42735
571	2	1	2	3	1	3	24139	-854	12112	42204
572	2	1	2	3	1	2	22564	-782	11381	42948
573	2	1	2	3	1	1	23160	-680	11948	42522
574	2	1	2	3	4	1	24530	-1418	11606	42204
575	2	1	2	3	4	3	24615	-556	12313	41459
576	2	1	2	3	4	2	26074	-533	11724	42948
577	2	2	2	3	4	2	16911	-676	12083	40822

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579	2	2	2	3	4	1	18054	-769	11831	39971
580	2	2	2	3	2	1	23116	-582	10274	40290
581	2	2	2	3	2	2	23054	-667	10530	40503
582	2	2	2	3	2	3	23832	-747	9876	41672
583	2	2	2	3	3	1	20749	-449	10664	40396
584	2	2	2	3	3	3	24553	-978	10986	41459
585	2	2	2	3	3	2	22604	-409	10806	41247
586	2	2	2	3	1	3	23414	-324	7729	41778
587	2	2	2	3	1	2	22555	-520	7356	42522
588	2	2	2	3	1	1	22484	-458	8289	41034
589	2	1	3	3	4	1	24290	-1356	11930	27427
590	2	1	3	3	4	2	19629	-3184	7922	29340
591	2	1	3	3	4	3	25722	-1080	6521	30191
592	2	1	3	3	3	2	16119	-2575	5100	30722
593	2	1	3	3	3	3	23387	-1979	5266	30616
594	2	1	3	3	3	1	22093	-1330	5229	30403
595	2	1	3	3	2	3	21492	-2339	5938	30297
596	2	1	3	3	2	2	24406	-511	5259	30403
597	2	1	3	3	2	1	26385	-204	5914	29872
598	2	1	3	3	1	1	18343	-3967	8010	29234
599	2	1	3	3	1	3	25607	-3500	8155	29872
600	2	1	3	3	1	2	21034	-271	3488	31148
601	2	3	3	3	2	2	24962	-987	3864	31679
602	2	3	3	3	2	3	23641	-1076	3423	31998
603	2	3	3	3	2	1	18156	-547	4165	30403
604	2	3	3	3	1	1	10368	-1009	3482	33805
605	2	3	3	3	1	2	11747	-2375	2498	34230
606	2	3	3	3	1	3	16382	-489	2537	34762
607	2	3	3	3	3	1	17102	-400	6322	35719
608	2	3	3	3	3	3	13464	-898	7150	35400
609	2	3	3	3	3	2	15301	-702	7554	34975
610	2	3	3	3	4	3	19629	-560	9141	33486
611	2	3	3	3	4	2	10697	-889	9401	35081
612	2	3	3	3	4	1	15888	-845	9644	33486
613	2	2	3	3	2	1	23156	-2299	19707	31785
614	2	2	3	3	2	2	19575	-1143	5230	31892
615	2	2	3	3	2	3	19210	-840	4591	33274
616	2	2	3	3	3	2	18984	-640	6690	32636
617	2	2	3	3	3	3	18050	-596	7109	32317
618	2	2	3	3	3	1	16862	-658	6831	32530
619	2	2	3	3	4	3	17107	-520	8545	32742
620	2	2	3	3	4	2	18361	-814	8945	32530
621	2	2	3	3	4	1	18503	-587	8578	32742
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623	2	2	3	3	1	3	19678	-765	5382	32423
624	2	2	3	3	1	2	18988	-596	3229	32955
625	2	1	3	4	1	2	10946	-1205	8889	33167
626	2	1	3	4	1	3	15737	-1285	9361	32848
627	2	1	3	4	1	1	19339	-902	8550	32636
628	2	1	3	4	4	1	16955	-1797	10503	32317
629	2	1	3	4	4	2	21443	-725	8211	33380
630	2	1	3	4	4	3	17676	-2379	8889	33167
631	2	1	3	4	3	1	17316	-894	7577	33380

632	2	1	3	4	3	3	22053	-636	8103	33486
633	2	1	3	4	3	2	20798	-778	6372	34443
634	2	1	3	4	2	3	22444	-533	7210	33380
635	2	1	3	4	2	2	21710	-729	7143	34018
636	2	1	3	4	2	1	20362	-814	8283	32742
637	2	3	3	4	3	1	18864	-2246	7480	32104
638	2	3	3	4	3	2	21639	-3233	9695	32104
639	2	3	3	4	3	3	23663	-1472	7694	32742
640	2	3	3	4	2	2	18606	-836	6281	33593
641	2	3	3	4	2	3	18926	-814	6538	32530
642	2	3	3	4	2	1	18334	-1218	5054	33699
643	2	3	3	4	1	3	21746	-1045	6393	32955
644	2	3	3	4	1	2	21292	-680	5789	33274
645	2	3	3	4	1	1	21083	-1330	7514	32530
646	2	3	3	4	4	1	20274	-1543	8677	31785
647	2	3	3	4	4	3	21119	-1485	8844	32636
648	2	3	3	4	4	2	19531	-733	7703	33061
649	2	2	3	4	1	2	10252	-1547	6909	33380
650	2	2	3	4	1	3	12383	-1214	5528	34124
651	2	2	3	4	1	1	20549	-1797	8642	31892
652	2	2	3	4	3	1	22035	-1183	8743	31679
653	2	2	3	4	3	2	15305	-4514	7076	33699
654	2	2	3	4	3	3	18708	-2290	6085	33805
655	2	2	3	4	2	1	17903	-1703	7909	31892
656	2	2	3	4	2	3	21844	-974	7989	32742
657	2	2	3	4	2	2	19584	-2384	4826	34230
658	2	2	3	4	4	3	19798	-676	7640	33805
659	2	2	3	4	4	2	21515	-742	7546	32955
660	2	2	3	4	4	1	15412	-1997	8709	32742

1. Observations (OBS) for Appendix A-1 correspond to observations for Appendices A-2 and A-3

APPENDIX A-2

MEASURED DATA FROM FIELD TEST

SECOND SIX VARIABLES

O B S_1	Percent Front Dynamic Load	Hydraulic Motor Inlet Pressure Front (kPa)	Hydraulic Motor Inlet Pressure Rear (kPa)	Hydraulic Motor Output Torque Front (N·m)	Hydraulic Motor Output Torque Rear (N·m)	Engine Speed (RPM)
1	0.5	5350	6515	123	173	2273
2	0.5	5778	6660	146	181	2273
3	0.5	6274	6929	172	196	2272
4	0.5	8377	6405	284	171	2270
5	0.5	6681	6639	193	181	2271
6	0.5	6722	5722	192	129	2272
7	0.5	6819	6143	204	160	2275
8	0.5	6908	6446	208	175	2274
9	0.5	6274	6481	174	175	2275
10	0.5	8418	6426	285	171	2270
11	0.5	7219	6502	221	174	2271
12	0.5	6998	5619	206	124	2272
13	0.5	7288	4798	233	95	1955
14	0.5	7577	4812	248	96	1955
15	0.5	9935	4743	372	95	1950
16	0.5	7715	4488	257	82	1955
17	0.5	9535	4433	353	80	1953
18	0.5	7619	4502	253	84	1955
19	0.5	5778	5343	161	131	1957
20	0.5	6274	5895	187	160	1955
21	0.5	7219	6315	237	183	1953
22	0.5	9322	4461	344	85	1953
23	0.5	8742	4750	314	99	1953
24	0.5	6391	4440	190	81	1957
25	0.5	7088	3385	236	38	1541
26	0.5	8425	4309	306	86	1539
27	0.5	9577	3868	366	64	1538
28	0.5	9680	3730	367	52	1536
29	0.5	6715	3661	212	47	1542
30	0.5	7536	3895	255	59	1540
31	0.5	5943	5653	178	157	1540
32	0.5	6936	6081	230	180	1539
33	0.5	5205	4861	139	115	1543
34	0.5	9294	3585	349	46	1536
35	0.5	7956	3599	279	46	1539
36	0.5	7129	3661	236	49	1540
37	0.5	13838	6308	572	173	2260
38	0.5	13652	6398	562	177	2260

39	0.5	16017	6322	686	175	2256
40	0.5	13934	9694	582	355	2253
41	0.5	12769	8418	521	288	2255
42	0.5	11314	7184	445	223	2260
43	0.5	12935	6184	527	168	2262
44	0.5	14762	6895	622	206	2259
45	0.5	14155	6377	591	180	2261
46	0.5	9997	11218	379	434	2261
47	0.5	10163	12431	388	498	2260
48	0.5	8949	10949	324	420	2263
49	0.5	15872	4557	685	91	1901
50	0.5	16458	4564	715	92	1900
51	0.5	17313	4605	760	94	1899
52	0.5	18389	7563	819	251	1895
53	0.5	15886	5674	688	152	1903
54	0.5	15320	5626	659	149	1903
55	0.5	12921	7929	535	269	1903
56	0.5	14300	9135	607	333	1901
57	0.5	13066	8115	543	280	1904
58	0.5	10377	11776	405	471	1905
59	0.5	10480	11859	411	476	1905
60	0.5	9204	10583	344	409	1909
61	0.5	22657	14500	1039	609	2240
62	0.5	22064	13403	1007	551	2243
63	0.5	23884	14996	1103	635	2239
64	0.5	22098	24587	1015	1138	2233
65	0.5	19685	22629	888	1034	2239
66	0.5	16024	19561	697	874	2245
67	0.5	19064	15789	853	676	2243
68	0.5	20540	17044	930	742	2240
69	0.5	22174	20616	1016	929	2235
70	0.5	25373	11328	1177	442	2236
71	0.5	27814	17995	1307	792	2226
72	0.5	25325	12583	1175	508	2236
73	0.5	23863	15417	1107	663	1885
74	0.5	23394	14121	1083	596	1887
75	0.5	25081	16499	1285	720	1882
76	0.5	27897	16761	1317	734	1876
77	0.5	26180	12348	1227	503	1883
78	0.5	27573	15506	1300	669	1878
79	0.5	18244	20298	818	919	1889
80	0.5	16789	18761	742	839	1893
81	0.5	18320	20305	822	919	1889
82	0.5	24229	20409	1129	925	1880
83	0.5	22601	19361	1043	870	1883
84	0.5	20753	17361	947	765	1888
85	0.5	25635	14996	1204	647	1532
86	0.5	24346	12886	1137	537	1536
87	0.5	26304	15251	1239	661	1532
88	0.5	25504	23187	1201	1076	1527
89	0.5	21877	19878	1012	903	1536
90	0.5	20595	18485	944	830	1538
91	0.5	21333	14451	981	619	1540
92	0.5	22043	15755	1019	688	1538

93	0.5	23905	18754	1116	845	1533
94	0.5	18292	20609	826	942	1539
95	0.5	20333	24153	933	1127	1533
96	0.5	17871	21215	804	973	1541
97	0.5	22222	21126	1029	967	1493
98	0.5	21133	19851	972	900	1498
99	0.5	22829	21229	1060	973	1494
100	0.5	24987	17278	1171	766	1494
101	0.5	25932	17030	1220	753	1493
102	0.5	25945	18457	1221	828	1492
103	0.5	27773	16223	1315	711	1488
104	0.5	27359	13948	1293	592	1491
105	0.5	27697	14838	1311	639	1491
106	0.5	20554	26669	944	1257	1494
107	0.5	19112	25773	869	1209	1497
108	0.5	17864	24856	803	1161	1498
109	0.5	18113	23911	811	1106	1870
110	0.5	19588	24284	888	1126	1868
111	0.5	19285	24635	873	1145	1868
112	0.5	28124	18113	1329	805	1859
113	0.5	28166	16775	1331	735	1861
114	0.5	27462	14196	1293	600	1864
115	0.5	20760	19416	948	872	1871
116	0.5	23539	21298	1093	971	1865
117	0.5	23284	22629	1080	1040	1864
118	0.5	25801	17871	1209	792	1864
119	0.5	26607	18775	1251	839	1862
120	0.5	24884	17658	1161	781	1866
121	0.4	8315	4212	294	73	1902
122	0.4	9156	4109	338	68	1901
123	0.4	10859	4274	428	79	1899
124	0.4	6046	8315	180	291	1901
125	0.4	5309	7632	141	255	1902
126	0.4	4923	5943	121	167	1906
127	0.4	7439	4730	250	102	1902
128	0.4	8701	5302	316	132	1900
129	0.4	5964	4488	173	89	1905
130	0.4	9308	4261	344	74	1898
131	0.4	9604	4364	359	79	1897
132	0.4	7453	4530	246	86	1900
133	0.4	8873	3785	328	57	1529
134	0.4	9639	3675	368	52	1528
135	0.4	11307	3550	456	47	1524
136	0.4	9694	3488	373	44	1528
137	0.4	10411	3806	410	61	1527
138	0.4	8894	3613	331	51	1530
139	0.4	4447	7756	102	268	1530
140	0.4	4405	8129	100	288	1530
141	0.4	4709	7274	116	243	1531
142	0.4	9004	5764	339	164	1526
143	0.4	8039	5233	288	137	1529
144	0.4	6957	4392	231	92	1531
145	0.4	7198	6584	224	182	2260
146	0.4	7425	6646	236	186	2260

147	0.4	7453	6536	238	181	2261
148	0.4	9066	5991	327	158	2260
149	0.4	6502	6729	190	192	2262
150	0.4	6619	6557	197	184	2262
151	0.4	5791	7708	159	250	2261
152	0.4	6033	8984	173	317	2259
153	0.4	5867	6639	162	194	2263
154	0.4	7736	6371	260	180	2262
155	0.4	6888	6391	215	181	2262
156	0.4	6653	6288	202	175	2263
157	0.3	10108	3599	392	48	1505
158	0.3	9942	3578	384	47	1505
159	0.3	13955	3475	594	44	1498
160	0.3	4750	6805	119	219	1507
161	0.3	6653	10059	218	389	1501
162	0.3	5419	7625	154	262	1507
163	0.3	11328	3461	458	44	1499
164	0.3	8625	3468	317	43	1508
165	0.3	11749	3709	481	57	1500
166	0.3	10397	7184	412	240	1498
167	0.3	8970	4847	338	117	1504
168	0.3	7501	3812	261	63	1508
169	0.3	7860	4433	267	81	1926
170	0.3	10135	4254	387	73	1922
171	0.3	10473	4323	405	77	1922
172	0.3	11369	4171	454	72	1922
173	0.3	8108	4281	283	77	1926
174	0.3	8446	4212	301	73	1927
175	0.3	5357	7067	144	225	1926
176	0.3	5984	7839	177	265	1925
177	0.3	5254	6701	138	206	1928
178	0.3	8191	5047	290	119	1925
179	0.3	8156	4909	288	112	1925
180	0.3	6977	4337	226	81	1928
181	0.3	5860	7625	164	246	2267
182	0.3	5978	7646	169	247	2267
183	0.3	6371	9577	191	349	2264
184	0.3	6998	6177	221	169	2268
185	0.3	8239	7129	286	220	2265
186	0.3	7184	6198	231	171	2267
187	0.3	6888	6743	211	193	2266
188	0.3	6895	6826	210	196	2265
189	0.3	8956	6281	321	172	2264
190	0.3	9584	6488	350	180	2262
191	0.3	8253	6764	280	192	2263
192	0.3	7163	6322	221	166	2264
193	0.3	20298	24477	922	1135	1959
194	0.3	21209	24897	970	1157	1956
195	0.3	21795	25097	1001	1168	1956
196	0.3	25842	28014	1216	1327	1950
197	0.3	19388	26442	878	1239	1942
198	0.3	17354	24560	772	1141	1946
199	0.3	22801	20036	1052	904	1941
200	0.3	22346	21788	1028	996	1940

201	0.3	22670	22719	1045	1045	1940
202	0.3	24642	18058	1146	801	1939
203	0.3	25228	21160	1176	963	1936
204	0.3	24497	18864	1138	843	1940
205	0.3	18051	26731	814	1261	1532
206	0.3	16499	24828	733	1161	1536
207	0.3	19064	26752	867	1263	1531
208	0.3	22450	23539	1040	1094	1528
209	0.2	23091	24104	1074	1123	1525
210	0.3	22987	23436	1069	1089	1527
211	0.3	23332	20257	1084	922	1527
212	0.3	23808	19354	1109	875	1527
213	0.2	24408	22036	1141	1016	1525
214	0.3	22070	26676	1023	1258	1527
215	0.3	21167	26111	976	1229	1529
216	0.3	19361	24091	881	1123	1533
217	0.3	20740	20147	941	905	2241
218	0.3	21581	20926	985	946	2239
219	0.3	22250	21677	1020	986	2237
220	0.2	20271	27180	923	1277	2238
221	0.3	19175	26242	865	1226	2239
222	0.3	16982	25201	750	1171	2243
223	0.3	23491	18678	1082	829	2237
224	0.3	22932	22132	1054	1010	2233
225	0.3	23815	21498	1099	977	2234
226	0.3	20202	23491	916	1081	2239
227	0.3	20926	24477	954	1133	2237
228	0.3	19037	23160	855	1064	2241
229	0.4	20278	22760	920	1043	2239
230	0.4	20360	22574	924	1033	2238
231	0.4	22312	24173	1027	1118	2235
232	0.4	27000	21360	1267	970	2228
233	0.4	26835	19292	1258	861	2229
234	0.3	27269	20760	1281	938	2228
235	0.4	19568	25780	886	1203	2239
236	0.4	17575	24642	781	1142	2241
237	0.4	20843	26194	953	1225	2237
238	0.4	25187	22719	1174	1041	2231
239	0.4	25690	23215	1201	1067	2230
240	0.4	24387	21822	1132	994	2234
241	0.4	25594	19485	1204	883	1533
242	0.4	25215	18423	1184	827	1535
243	0.4	26711	20588	1263	941	1530
244	0.4	24897	23256	1169	1080	1533
245	0.4	24242	23029	1135	1068	1534
246	0.4	23091	22119	1075	1021	1535
247	0.4	20450	23256	939	1080	1540
248	0.4	21215	23946	979	1116	1539
249	0.4	22788	26304	1061	1240	1533
250	0.4	20650	26925	951	1273	1536
251	0.4	21719	26987	1007	1277	1535
252	0.4	18809	26518	855	1251	1539
253	0.4	22698	24056	1052	1117	1873
254	0.4	21636	22215	996	1021	1879

255	0.4	23829	25118	1111	1173	1871
256	0.3	28869	26856	1374	1267	1862
257	0.3	26966	24284	1273	1130	1866
258	0.4	26497	23539	1248	1090	1906
259	0.4	27173	19899	1281	900	1907
260	0.4	27552	19485	1301	878	1907
261	0.3	28593	21836	1356	1001	1902
262	0.4	25028	27255	1176	1288	1909
263	0.4	23518	26897	1097	1268	1912
264	0.4	21857	26511	1010	1247	1914
265	0.4	. 2	22201	. 2	1012	2251
266	0.4	.	21767	.	990	2252
267	0.4	.	22877	.	1048	2249
268	0.4	.	20202	.	909	2240
269	0.4	.	17292	.	756	2245
270	0.4	.	17237	.	753	2246
271	0.4	.	19650	.	879	2249
272	0.4	.	19871	.	892	2247
273	0.4	.	20105	.	904	2249
274	0.4	.	26021	.	1213	2254
275	0.4	.	26745	.	1251	2252
276	0.4	.	25497	.	1186	2255
277	0.4	.	18430	.	823	1887
278	0.4	.	17416	.	769	1890
279	0.4	.	19202	.	863	1884
280	0.4	.	26966	.	1270	1887
281	0.4	.	24601	.	1146	1892
282	0.4	.	25773	.	1207	1890
283	0.4	.	15513	.	671	1885
284	0.4	.	14486	.	617	1888
285	0.4	.	16851	.	741	1885
286	0.4	.	21291	.	973	1857
287	0.4	.	23332	.	1080	1867
288	0.4	.	22015	.	1011	1907
289	0.4	.	16155	.	709	1525
290	0.4	.	15155	.	657	1526
291	0.4	.	16947	.	751	1523
292	0.4	.	21153	.	971	1521
293	0.4	.	20760	.	950	1523
294	0.4	.	18085	.	810	1529
295	0.4	.	23518	.	1094	1531
296	0.4	.	24160	.	1128	1529
297	0.4	.	24849	.	1164	1527
298	0.4	.	22057	.	1018	1524
299	0.4	.	22967	.	1066	1522
300	0.4	.	21926	.	1011	1525
301	0.3	.	19340	.	864	2248
302	0.3	.	17520	.	769	2251
303	0.3	.	20567	.	930	2244
304	0.3	.	22719	.	1042	2248
305	0.3	.	23001	.	1057	2247
306	0.3	.	22395	.	1025	2247
307	0.3	.	16527	.	718	2246
308	0.3	.	15424	.	660	2247

309	0.3	.	18526	.	823	2243
310	0.3	.	26552	.	1244	2246
311	0.3	.	25442	.	1186	2248
312	0.3	.	23367	.	1076	2251
313	0.3	19967	25001	910	1167	1901
314	0.3	19037	23856	862	1107	1904
315	0.3	19016	24049	861	1117	1904
316	0.3	26207	20174	1231	915	1893
317	0.3	24835	18092	1159	806	1897
318	0.3	25911	18940	1216	851	1895
319	0.3	21250	22691	976	1047	1903
320	0.3	21367	21043	982	961	1904
321	0.3	21939	22174	1012	1020	1902
322	0.3	23787	20395	1107	928	1899
323	0.3	24146	20085	1126	911	1900
324	0.3	22946	19037	1063	856	1902
325	0.3	17830	15555	796	672	1902
326	0.3	17354	15534	771	671	1903
327	0.3	18513	16189	832	705	1900
328	0.3	21636	14996	993	643	1894
329	0.3	20850	12873	952	532	1899
330	0.3	19057	11797	858	475	1903
331	0.3	22043	10239	1012	394	1897
332	0.3	22574	10583	1040	412	1897
333	0.3	20926	10142	953	388	1900
334	0.3	14527	18906	626	847	1904
335	0.3	15162	19464	660	877	1902
336	0.3	13990	18244	598	813	1905
337	0.3	20636	10508	945	415	1513
338	0.3	20809	10073	954	392	1513
339	0.3	21477	11942	989	490	1510
340	0.3	15658	15265	688	663	1519
341	0.3	16182	16030	716	703	1517
342	0.3	16582	17003	737	754	1515
343	0.3	18678	13403	844	566	1514
344	0.3	18202	11535	819	468	1518
345	0.3	19188	13631	871	578	1512
346	0.3	14810	19954	646	908	1516
347	0.3	14410	20181	625	920	1515
348	0.3	13155	18492	559	831	1520
349	0.3	16251	15058	709	640	2263
350	0.3	16575	15410	726	658	2262
351	0.3	17161	15872	757	683	2260
352	0.3	21698	11225	989	440	2254
353	0.3	20609	10266	932	389	2258
354	0.3	20167	10342	909	393	2258
355	0.3	14024	18554	595	823	2261
356	0.3	14700	19078	631	851	2260
357	0.3	14458	19409	618	868	2259
358	0.3	19788	13010	892	533	2256
359	0.3	19788	13121	892	539	2255
360	0.3	18630	12652	832	516	2258
361	0.4	19554	11880	885	481	1885
362	0.4	19071	11169	859	443	1888

363	0.4	20636	12838	942	531	1882
364	0.4	13900	18382	594	821	1889
365	0.4	14900	19188	646	863	1887
366	0.4	14431	18726	622	839	1888
367	0.4	20919	9253	954	343	1884
368	0.4	20409	8784	927	318	1887
369	0.4	21712	9956	996	380	1882
370	0.4	18568	16430	836	719	1901
371	0.4	17403	15189	774	654	1905
372	0.4	15830	13603	692	571	1910
373	0.4	15327	14727	672	635	1519
374	0.4	15086	14700	659	634	1518
375	0.4	16148	15706	715	686	1515
376	0.4	14300	19630	620	892	1514
377	0.4	12838	18768	544	847	1517
378	0.4	12328	18106	517	812	1518
379	0.4	19499	8977	887	335	1511
380	0.4	19643	9239	895	349	1510
381	0.4	19278	8998	875	336	1512
382	0.4	18389	12245	831	506	1511
383	0.4	18616	12576	842	524	1509
384	0.4	17196	11480	768	466	1514
385	0.4	20133	9866	908	368	2251
386	0.4	19526	9715	876	360	2252
387	0.4	21353	10018	972	377	2249
388	0.4	15782	15175	685	647	2255
389	0.4	16492	15596	722	669	2254
390	0.4	16672	15830	732	682	2254
391	0.4	13603	18713	574	832	2256
392	0.4	13472	18326	567	812	2257
393	0.4	13893	18913	589	843	2255
394	0.4	19471	12762	877	522	2251
395	0.4	18844	11983	843	480	2252
396	0.4	18382	11693	819	465	2254
397	0.3	18733	18161	849	815	1519
398	0.3	19540	19133	891	866	1515
399	0.3	19678	20305	898	927	1514
400	0.3	20126	21091	921	968	1507
401	0.3	20140	18871	922	853	1510
402	0.3	20140	18120	921	813	1512
403	0.3	16299	24387	724	1141	1516
404	0.3	18899	24746	860	1159	1515
405	0.3	16789	25587	750	1203	1515
406	0.3	18981	22643	863	1050	1513
407	0.3	18830	22208	856	1027	1515
408	0.3	17885	21002	806	962	1517
409	0.5	13631	7681	578	264	1528
410	0.5	13403	7405	567	250	1528
411	0.5	16479	9653	727	367	1518
412	0.5	10563	11363	420	457	1527
413	0.5	11507	12142	470	497	1523
414	0.5	10935	12080	440	494	1524
415	0.5	16161	5460	709	148	1520
416	0.5	15382	5185	668	134	1522

417	0.5	18182	6508	815	203	1515
418	0.5	21153	5578	968	154	1510
419	0.5	19078	4612	860	104	1514
420	0.5	16106	4323	704	87	1520
421	0.4	. 2	. 3	. 2	. 3	1929
422	0.4	.	.	.	.	1930
423	0.4	.	.	.	.	1929
424	0.4	.	.	.	.	1923
425	0.4	.	.	.	.	1922
426	0.4	.	.	.	.	1925
427	0.4	.	.	.	.	1920
428	0.4	.	.	.	.	1926
429	0.4	.	.	.	.	1924
430	0.4	.	.	.	.	1925
431	0.4	.	.	.	.	1927
432	0.4	.	.	.	.	1921
433	0.4	.	.	.	.	2251
434	0.4	.	.	.	.	2253
435	0.4	.	.	.	.	2260
436	0.4	.	.	.	.	2255
437	0.4	.	.	.	.	2257
438	0.4	.	.	.	.	2252
439	0.4	.	.	.	.	2260
440	0.4	.	.	.	.	2258
441	0.4	.	.	.	.	2262
442	0.4	.	.	.	.	2257
443	0.4	.	.	.	.	2259
444	0.4	.	.	.	.	2258
445	0.4	.	.	.	.	1502
446	0.4	.	.	.	.	1504
447	0.4	.	.	.	.	1498
448	0.4	.	.	.	.	1501
449	0.4	.	.	.	.	1507
450	0.4	.	.	.	.	1506
451	0.4	.	.	.	.	1500
452	0.4	.	.	.	.	1506
453	0.4	.	.	.	.	1505
454	0.4	.	.	.	.	1502
455	0.4	.	.	.	.	1504
456	0.4	.	.	.	.	1501
457	0.3	.	.	.	.	2253
458	0.3	.	.	.	.	2254
459	0.3	.	.	.	.	2261
460	0.3	.	.	.	.	2262
461	0.3	.	.	.	.	2263
462	0.3	.	.	.	.	2259
463	0.3	.	.	.	.	2260
464	0.3	.	.	.	.	2262
465	0.3	.	.	.	.	2261
466	0.3	9459	6398	346	178	2272
467	0.3	6522	6895	191	200	2274
468	0.3	6467	7039	188	207	2274
469	0.3	10783	4143	432	82	1498
470	0.3	9811	3957	382	72	1498

471	0.3	8425	3826	309	65	1501
472	0.3	8867	3695	330	56	1500
473	0.3	8749	3681	324	55	1500
474	0.3	10673	3647	425	54	1498
475	0.3	8005	3875	283	62	1501
476	0.3	8770	3881	323	63	1500
477	0.3	11500	3737	466	57	1497
478	0.3	8398	6219	310	191	1500
479	0.3	6308	4392	200	95	1507
480	0.3	8094	5743	294	166	1500
481	0.4	15272	9908	656	370	2264
482	0.5	15065	9549	645	352	2265
483	0.4	16223	10563	706	405	2262
484	0.4	14369	15610	612	669	2261
485	0.4	12790	14872	529	632	2263
486	0.5	11473	13155	460	541	2266
487	0.4	18837	6564	837	201	2260
488	0.4	18692	6791	830	. 4	2260
489	0.4	17106	6460	746	.	2263
490	0.4	16775	7639	732	.	2263
491	0.4	16051	7377	694	.	2265
492	0.4	17961	8012	794	.	2261
493	0.4	17409	10583	773	.	1899
494	0.4	16927	9990	748	.	1900
495	0.4	16155	9025	708	.	1903
496	0.4	19678	5398	887	.	1898
497	0.4	19726	5812	890	.	1897
498	0.4	19595	5660	883	.	1896
499	0.4	12280	12873	508	.	1905
500	0.4	11804	12286	482	.	1906
501	0.4	13624	13769	578	.	1901
502	0.4	20540	7915	934	.	1896
503	0.4	19561	7619	883	.	1898
504	0.4	18113	6812	807	.	1900
505	0.4	11431	12879	469	539	1519
506	0.4	10983	12500	445	519	1520
507	0.5	11169	11790	455	482	1522
508	0.4	16892	12666	752	528	1506
509	0.4	16906	11542	753	469	1507
510	0.4	15003	10011	653	390	1512
511	0.4	19340	7901	878	279	1504
512	0.4	18092	8336	813	302	1506
513	0.4	16244	6267	717	194	1513
514	0.4	18485	5812	832	169	1508
515	0.4	17058	4626	757	107	1512
516	0.4	19712	6508	896	206	1505
517	0.3	19002	10197	861	399	1517
518	0.3	18719	9356	846	355	1518
519	0.3	17182	7832	765	276	1523
520	0.3	10873	12100	440	498	1529
521	0.3	11473	13507	471	572	1526
522	0.3	12128	14362	506	616	1525
523	0.3	19354	6839	877	224	1519
524	0.3	18244	5840	819	171	1522

525	0.3	19574	6577	889	210	1521
526	0.3	17182	14907	768	645	1515
527	0.3	14645	11073	635	445	1525
528	0.3	14127	9653	608	371	1526
529	0.3	19292	6481	868	198	1903
530	0.3	18416	6371	822	192	1905
531	0.3	19726	6536	890	200	1902
532	0.3	13555	15044	575	646	1907
533	0.3	12645	13907	527	587	1909
534	0.3	12169	13231	502	552	1911
535	0.3	15686	11590	684	466	1906
536	0.3	15224	10639	659	416	1907
537	0.3	14479	8894	620	325	1911
538	0.3	16279	7122	712	232	1909
539	0.3	16320	6729	715	211	1909
540	0.3	18189	7887	812	272	1904
541	0.3	16030	11845	696	473	2251
542	0.3	15493	11431	668	451	2251
543	0.3	14989	11983	642	480	2251
544	0.3	17078	8715	749	308	2250
545	0.3	17072	9308	749	340	2250
546	0.3	16554	9211	721	334	2251
547	0.3	12052	14258	491	599	2254
548	0.3	11769	13514	476	560	2254
549	0.3	12321	14238	505	598	2253
550	0.3	20333	9721	917	361	2246
551	0.3	18878	7722	841	256	2249
552	0.3	18244	7281	807	232	2251
553	0.4	. 2	15017	. 2	637	2229
554	0.4	.	14996	.	636	2232
555	0.4	.	15038	.	639	2230
556	0.4	.	22925	.	1053	2228
557	0.4	.	22946	.	1054	2228
558	0.4	.	20071	.	903	2236
559	0.4	.	17796	.	784	2231
560	0.4	.	18264	.	809	2233
561	0.4	.	15403	.	658	2238
562	0.4	.	21760	.	991	2239
563	0.4	.	19623	.	879	2242
564	0.4	.	20836	.	943	2240
565	0.4	.	19443	.	882	1522
566	0.4	.	17692	.	790	1525
567	0.4	.	15451	.	673	1531
568	0.4	.	20988	.	962	1538
569	0.4	.	22346	.	1033	1535
570	0.4	.	21388	.	983	1536
571	0.4	.	17837	.	798	1531
572	0.4	.	15789	.	691	1535
573	0.4	.	16513	.	729	1532
574	0.4	.	20126	.	918	1533
575	0.4	.	20988	.	963	1531
576	0.4	.	16885	.	749	1535
577	0.4	.	13190	.	550	1884
578	0.4	.	13052	.	542	1884

579	0.4	.	14203	.	603	1882
580	0.4	.	20664	.	941	1884
581	0.4	.	19657	.	889	1886
582	0.4	.	17885	.	796	1889
583	0.4	26111	15941	1227	694	1884
584	0.4	25546	17285	1198	765	1886
585	0.4	29393	15548	1397	674	1888
586	0.4	. 2	20767	. 2	947	1892
587	0.4	.	19830	.	898	1893
588	0.4	13727	22236	587	1024	1886
589	0.3	. 2	23436	. 2	1093	1532
590	0.3	.	25263	.	1188	1540
591	0.3	.	24704	.	1158	1545
592	0.3	.	25263	.	1188	1547
593	0.3	.	25449	.	1198	1545
594	0.3	.	25518	.	1202	1544
595	0.3	.	25994	.	1233	1547
596	0.3	.	25787	.	1223	1548
597	0.3	.	25794	.	1224	1547
598	0.3	.	25870	.	1233	1545
599	0.3	.	25580	.	1220	1543
600	0.3	.	25621	.	1216	1544
601	0.3	.	27324	.	1294	2244
602	0.3	.	26980	.	1275	2244
603	0.3	.	27028	.	1279	2243
604	0.3	8129	27614	289	1293	2260
605	0.3	9804	26532	375	1235	2264
606	0.3	9363	26090	352	1212	2266
607	0.3	16789	18285	733	804	2265
608	0.3	16189	19009	702	842	2264
609	0.3	15989	18506	692	815	2264
610	0.3	19492	18154	872	797	2259
611	0.3	19257	15348	860	650	2262
612	0.3	20471	17975	923	788	2259
613	0.3	14286	26256	612	1228	1923
614	0.3	13865	25952	590	1211	1923
615	0.3	12149	24615	501	1141	1927
616	0.3	15755	20795	686	942	1925
617	0.3	16086	22229	704	1017	1923
618	0.3	16975	21891	750	999	1922
619	0.3	18444	18299	824	812	1923
620	0.3	19002	18237	853	808	1922
621	0.3	19106	20271	859	914	1920
622	0.3	12300	27462	511	1292	1925
623	0.3	12879	27559	542	1298	1924
624	0.3	10121	27283	398	1282	1917
625	0.3	18382	27966	835	1332	1535
626	0.3	18933	27952	863	1332	1534
627	0.3	18913	27931	863	1330	1532
628	0.3	22374	27324	1040	1294	1526
629	0.3	18009	26132	812	1229	1532
630	0.3	19237	27159	876	1284	1528
631	0.3	17906	27414	808	1298	1531
632	0.3	17995	27421	813	1299	1531

633	0.3	23539	27152	1100	1283	1534
634	0.3	25787	27607	1218	1309	1532
635	0.3	23463	27559	1097	1306	1533
636	0.3	19340	27807	884	1322	1530
637	0.3	27959	28552	1325	1351	2243
638	0.3	30820	28793	1475	1366	2240
639	0.3	25718	28545	1209	1350	2243
640	0.3	21422	28841	988	1367	2246
641	0.3	25980	28979	1225	1375	2244
642	0.3	27049	28697	1279	1359	2245
643	0.3	18837	29207	857	1391	2245
644	0.3	17251	29014	773	1380	2247
645	0.3	18389	28717	834	1366	2244
646	0.3	20712	27138	947	1276	2238
647	0.3	21029	27069	963	1272	2243
648	0.3	18968	26931	855	1263	2243
649	0.3	22987	28648	1073	1364	1912
650	0.3	14858	28586	650	1359	1916
651	0.3	20843	28352	964	1352	1911
652	0.3	28028	27717	1334	1314	1907
653	0.3	24435	27952	1146	1324	1910
654	0.3	21677	27724	1002	1311	1912
655	0.3	29317	28317	1401	1346	1909
656	0.3	23291	28090	1089	1334	1909
657	0.3	20505	28255	943	1340	1914
658	0.3	17789	26600	798	1251	1910
659	0.3	18216	26401	820	1240	1909
660	0.3	20554	27283	943	1289	1905

1. Observations (OBS) for Appendix A-2 correspond to observations for Appendices A-1 and A-3
2. Missing data resulting from front pressure transducer failure
3. Missing data resulting from rear pressure transducer failure
4. Missing data resulting from rear speed transducer failure

APPENDIX A-3

MEASURED DATA FROM FIELD TEST

THIRD FIVE VARIABLES

OBS[1]	Forward Speed (km/h)	Front Axle (RPM)	Rear Axle (RPM)	Wheel Speed Ratio (f/r)	Soil Cone Index (kPa)
1	9.44	30.98	30.85	1.00	2026
2	9.25	30.31	30.29	1.00	1229
3	9.20	29.87	29.92	1.00	1012
4	8.62	28.60	28.51	1.00	110
5	9.25	30.28	30.01	1.01	1411
6	9.78	32.19	31.88	1.01	2449
7	8.48	27.83	27.62	1.01	1798
8	8.50	28.02	28.04	1.00	121
9	8.95	29.07	28.90	1.01	2463
10	8.83	29.16	29.11	1.00	98
11	9.25	30.26	30.01	1.01	1299
12	9.86	32.37	32.05	1.01	2308
13	7.67	25.29	24.96	1.01	1727
14	7.66	25.05	24.75	1.01	1067
15	7.34	24.15	23.73	1.02	322
16	7.18	23.63	23.29	1.01	1687
17	7.10	23.20	22.98	1.01	263
18	7.08	23.24	22.95	1.01	1174
19	6.40	21.01	20.92	1.00	2135
20	6.39	20.77	20.61	1.01	1479
21	6.15	20.24	20.18	1.00	1421
22	6.60	21.60	21.24	1.02	1019
23	6.61	21.94	21.56	1.02	1095
24	6.82	22.56	22.35	1.01	2366
25	5.08	16.99	16.75	1.01	2135
26	5.08	16.73	16.44	1.02	810
27	5.05	16.41	16.35	1.00	192
28	5.70	18.87	18.61	1.01	983
29	6.03	19.68	19.52	1.01	702
30	5.87	19.47	19.15	1.02	2364
31	4.83	15.90	15.78	1.01	1219
32	4.78	15.70	15.64	1.00	764
33	4.92	16.34	16.26	1.00	2030
34	5.37	18.05	17.88	1.01	335
35	5.57	18.20	18.03	1.01	1000
36	5.58	18.46	18.15	1.02	2077
37	7.66	26.05	25.32	1.03	2117
38	7.79	26.07	25.31	1.03	987
39	7.56	25.38	24.66	1.03	477

40	6.79	22.65	22.23	1.02	181
41	6.82	22.85	22.51	1.01	1417
42	6.95	23.11	22.75	1.02	2429
43	7.47	24.87	24.32	1.02	1926
44	7.32	24.25	23.65	1.02	1376
45	7.14	24.34	23.63	1.03	1895
46	6.61	21.75	21.93	0.99	1144
47	6.48	21.70	21.67	1.00	1479
48	6.66	22.01	21.99	1.00	944
49	6.44	21.59	20.84	1.04	2204
50	6.24	21.42	20.52	1.04	3843
51	6.29	21.10	20.39	1.03	1849
52	5.70	19.24	18.61	1.03	1892
53	5.84	19.77	19.17	1.03	1822
54	5.81	19.77	19.13	1.03	2684
55	5.73	19.27	18.92	1.02	2086
56	5.62	18.86	18.59	1.01	488
57	5.76	18.90	18.59	1.02	2727
58	5.36	17.87	17.88	1.00	408
59	5.44	17.80	17.83	1.00	1608
60	5.50	. 2	. 2	. 2	3156
61	5.95	20.62	19.89	1.04	2533
62	6.02	20.85	20.22	1.03	866
63	5.89	20.18	19.70	1.02	173
64	5.07	17.32	17.45	0.99	269
65	5.20	18.00	18.25	0.99	1961
66	5.53	18.73	18.76	1.00	2257
67	5.94	20.23	19.91	1.02	1527
68	5.79	19.51	19.37	1.01	192
69	5.53	18.99	18.52	1.02	2105
70	6.36	22.06	20.85	1.06	696
71	5.71	20.27	19.25	1.05	1706
72	6.23	21.67	. 2	. 2	2094
73	4.88	17.08	16.45	1.04	1483
74	5.02	17.11	16.63	1.03	1338
75	4.78	16.52	16.00	1.03	411
76	4.68	16.92	15.88	1.06	1893
77	5.02	17.54	16.65	1.05	474
78	4.78	16.78	15.95	1.05	1836
79	4.49	15.34	15.35	1.00	2516
80	4.55	15.49	15.52	1.00	1655
81	4.49	15.24	15.34	0.99	357
82	4.46	15.45	15.23	1.01	419
83	4.54	15.92	15.62	1.02	1035
84	4.70	16.33	16.04	1.02	2172
85	4.02	14.21	13.40	1.06	2251
86	4.10	14.26	13.58	1.05	958
87	3.97	13.63	. 2	. 2	125
88	3.41	11.82	11.80	1.00	222
89	3.65	12.34	12.24	1.01	1024
90	3.75	12.85	12.75	1.01	2535
91	3.99	13.71	13.33	1.03	1544
92	3.86	13.31	12.93	1.03	458
93	3.67	12.84	12.28	1.05	1527

94	3.49	11.84	12.08	0.98	135
95	3.27	11.21	11.26	1.00	888
96	3.46	11.83	11.87	1.00	2200
97	3.64	12.92	12.74	1.01	2421
98	3.83	13.20	12.95	1.02	1460
99	3.75	12.85	12.70	1.01	665
100	3.89	13.75	13.18	1.04	2704
101	3.91	13.63	13.21	1.03	125
102	3.86	13.61	13.11	1.04	1974
103	4.01	14.27	13.46	1.06	2729
104	4.02	14.38	13.65	1.05	1234
105	4.04	14.25	13.61	1.05	945
106	3.38	11.73	11.96	0.98	254
107	3.51	12.02	12.28	0.98	1195
108	3.54	12.29	12.49	0.98	2205
109	4.51	15.38	15.44	1.00	1684
110	4.38	14.95	15.19	0.98	1566
111	4.33	14.80	14.93	0.99	222
112	4.63	16.47	15.78	1.04	227
113	4.70	16.88	16.04	1.05	1430
114	4.86	17.36	16.36	1.06	2179
115	4.62	15.91	15.72	1.01	1290
116	4.46	15.47	15.40	1.00	459
117	4.39	15.44	15.16	1.02	2157
118	4.65	16.39	15.87	1.03	360
119	4.62	16.16	15.58	1.04	1404
120	4.63	16.33	15.69	1.04	2102
121	6.13	20.55	20.54	1.00	2168
122	6.13	20.26	20.26	1.00	1859
123	5.86	19.41	19.47	1.00	97
124	5.42	17.80	18.23	0.98	120
125	5.45	18.17	18.43	0.99	1132
126	5.58	18.48	18.72	0.99	2495
127	5.82	19.16	19.31	0.99	1182
128	5.78	18.89	19.22	0.98	104
129	5.92	19.51	19.59	1.00	1841
130	6.44	21.50	21.62	0.99	124
131	6.44	21.52	21.51	1.00	1226
132	6.65	22.21	22.26	1.00	1869
133	5.20	17.35	17.31	1.00	2834
134	5.13	17.06	16.95	1.01	1636
135	4.92	16.58	16.43	1.01	144
136	4.84	16.11	16.04	1.00	1966
137	4.70	15.85	15.75	1.01	880
138	4.79	16.01	15.97	1.00	1672
139	4.52	14.82	15.08	0.98	2445
140	4.39	14.77	14.98	0.99	1464
141	4.44	14.48	14.89	0.97	413
142	4.44	15.07	15.17	0.99	259
143	4.57	15.22	15.30	1.00	1120
144	4.68	15.53	15.57	1.00	2213
145	8.27	27.51	27.76	0.99	2524
146	8.24	27.26	27.58	0.99	1252
147	8.19	26.93	27.12	0.99	493

148	7.35	24.28	24.35	1.00	969
149	7.96	26.49	26.70	0.99	1981
150	7.90	25.99	26.20	0.99	2151
151	6.82	22.58	22.89	0.99	2137
152	6.65	21.99	22.40	0.98	1146
153	6.98	23.06	23.29	0.99	1886
154	6.87	22.83	23.00	0.99	193
155	6.97	23.16	23.36	0.99	1858
156	7.18	23.62	23.79	0.99	1777
157	5.10	17.13	17.14	1.00	2145
158	5.00	17.13	17.13	1.00	1389
159	4.63	16.22	15.96	1.02	172
160	4.34	14.47	14.90	0.97	1906
161	4.23	14.01	14.43	0.97	292
162	4.20	14.21	14.61	0.97	1444
163	4.62	15.68	15.54	1.01	2133
164	4.89	16.13	16.29	0.99	1307
165	4.55	15.34	15.32	1.00	76
166	4.14	14.21	14.33	0.99	321
167	4.36	14.53	14.78	0.98	1318
168	4.49	14.83	14.98	0.99	1616
169	6.69	22.23	22.51	0.99	1772
170	6.39	21.54	21.58	1.00	1926
171	6.31	21.32	21.40	1.00	899
172	5.82	19.84	19.93	1.00	331
173	6.08	20.45	20.68	0.99	1563
174	6.11	20.40	20.53	0.99	2262
175	5.50	18.21	18.74	0.97	1875
176	5.44	18.07	18.63	0.97	398
177	5.53	18.31	18.85	0.97	2902
178	5.68	19.00	19.25	0.99	293
179	5.68	19.05	19.32	0.99	1815
180	5.89	19.70	20.06	0.98	2318
181	6.69	22.02	22.68	0.97	2104
182	6.84	22.37	22.99	0.97	1272
183	6.55	21.29	21.93	0.97	214
184	6.95	23.14	23.58	0.98	1985
185	6.89	22.71	23.04	0.99	226
186	6.90	22.89	23.41	0.98	975
187	7.79	26.01	26.59	0.98	1350
188	7.88	26.35	26.89	0.98	993
189	7.32	24.31	24.78	0.98	192
190	7.79	26.20	26.55	0.99	158
191	7.98	26.73	27.31	0.98	855
192	8.50	28.41	28.92	0.98	2472
193	4.54	16.82	15.83	1.06	3613
194	4.42	16.43	15.57	1.05	920
195	4.36	16.15	15.33	1.05	240
196	3.25	13.47	11.55	1.17	416
197	4.17	14.95	14.68	1.02	1238
198	4.30	15.44	15.25	1.01	2273
199	4.54	17.19	15.88	1.08	2319
200	4.49	17.33	15.62	1.11	721
201	4.39	16.94	15.25	1.11	1880

202	4.76	18.16	16.27	1.12	463
203	4.49	17.99	15.69	1.15	920
204	4.70	18.15	16.10	1.13	1978
205	3.17	11.50	11.19	1.03	2395
206	3.39	11.83	11.93	0.99	1388
207	3.06	11.26	11.10	1.01	409
208	3.38	13.06	11.94	1.09	1798
209	3.39	13.02	11.94	1.09	685
210	3.36	12.81	11.87	1.08	985
211	3.54	14.11	12.61	1.12	2843
212	3.65	14.02	12.78	1.10	1347
213	3.43	13.59	12.13	1.12	140
214	3.17	11.80	11.18	1.05	96
215	3.17	11.89	11.37	1.05	1057
216	3.35	12.19	11.82	1.03	1697
217	5.18	19.38	18.27	1.06	2336
218	5.15	19.08	18.01	1.06	1684
219	5.04	18.84	17.84	1.06	504
220	4.23	15.64	15.06	1.04	203
221	4.51	16.26	15.98	1.02	1310
222	4.60	16.66	16.49	1.01	2724
223	5.31	20.39	18.48	1.10	1769
224	5.08	20.17	17.51	1.15	172
225	5.10	20.14	17.75	1.13	2107
226	5.00	17.87	17.41	1.03	172
227	4.78	17.50	16.92	1.03	1910
228	4.91	17.83	17.23	1.03	2405
229	5.00	17.44	17.21	1.01	1996
230	5.08	17.53	17.37	1.01	1291
231	4.70	16.75	16.61	1.01	135
232	5.15	19.12	17.62	1.08	1672
233	5.26	19.27	18.21	1.06	269
234	5.08	18.84	17.68	1.07	1436
235	4.54	15.91	15.92	1.00	1661
236	4.86	16.69	16.86	0.99	1904
237	4.34	15.32	15.36	1.00	241
238	4.92	17.97	17.18	1.05	173
239	4.88	17.60	16.90	1.04	841
240	5.00	18.26	17.54	1.04	1770
241	3.57	12.84	12.22	1.05	2614
242	3.65	12.91	12.44	1.04	1871
243	3.43	12.44	11.96	1.04	364
244	3.30	11.79	11.58	1.02	381
245	3.35	11.79	11.54	1.02	1214
246	3.38	12.14	11.77	1.03	1939
247	3.31	11.56	11.54	1.00	1655
248	3.25	11.41	11.42	1.00	115
249	3.04	10.96	10.87	1.01	1948
250	2.85	10.39	10.42	1.00	107
251	2.72	10.31	9.94	1.04	1538
252	3.01	10.73	10.66	1.01	1892
253	3.91	13.95	13.76	1.01	1704
254	4.04	14.03	13.95	1.01	927
255	3.80	13.34	13.25	1.01	368

256	3.39	12.80	11.68	1.10	1657
257	3.89	14.09	13.50	1.04	630
258	4.10	14.61	13.99	1.04	1874
259	4.23	15.62	14.53	1.07	1397
260	4.30	15.64	14.71	1.06	1234
261	4.01	14.98	14.08	1.06	1239
262	3.27	11.65	11.60	1.00	427
263	3.39	12.11	12.13	1.00	1066
264	3.54	12.64	12.54	1.01	2505
265	5.28	18.42	18.22	1.01	2605
266	5.33	18.38	18.25	1.01	1108
267	5.16	17.91	17.80	1.01	250
268	5.20	19.10	17.99	1.06	240
269	5.50	19.74	18.59	1.06	1312
270	5.50	20.00	18.70	1.07	2006
271	5.34	18.97	18.34	1.03	1321
272	5.18	18.39	17.97	1.02	152
273	5.28	18.77	18.01	1.04	2135
274	4.86	16.70	16.87	0.99	278
275	4.75	16.39	16.56	0.99	1283
276	4.96	16.72	16.99	0.98	2056
277	4.39	15.60	15.00	1.04	1914
278	4.49	15.74	15.26	1.03	1571
279	4.26	15.11	14.65	1.03	659
280	3.75	13.11	13.14	1.00	1345
281	3.89	13.32	13.57	0.98	87
282	3.81	13.23	13.31	0.99	2550
283	4.38	16.07	15.17	1.06	1490
284	4.57	16.27	15.45	1.05	1399
285	4.38	15.90	14.91	1.07	403
286	4.05	14.08	13.93	1.01	513
287	3.88	13.76	13.52	1.02	842
288	4.10	14.38	14.11	1.02	1908
289	3.72	13.07	12.56	1.04	1551
290	3.73	13.13	12.71	1.03	765
291	3.56	12.90	12.35	1.04	678
292	3.31	11.92	11.62	1.03	165
293	3.41	12.02	11.66	1.03	1370
294	3.56	12.55	12.30	1.02	2479
295	3.30	11.42	11.43	1.00	1219
296	3.23	11.20	11.19	1.00	67
297	3.20	11.07	11.09	1.00	1874
298	3.30	11.62	11.49	1.01	228
299	3.23	11.33	11.16	1.01	796
300	3.27	11.64	11.43	1.02	2288
301	5.10	18.74	17.79	1.05	1977
302	5.31	18.87	18.22	1.04	1431
303	4.92	18.07	17.10	1.06	139
304	4.75	17.37	16.88	1.03	1920
305	4.78	17.05	16.56	1.03	136
306	4.78	17.07	16.71	1.02	957
307	5.23	19.79	18.06	1.10	2643
308	5.34	19.62	18.27	1.07	1461
309	4.89	19.51	17.48	1.12	138

310	4.23	15.48	15.02	1.03	856
311	4.44	15.86	15.68	1.01	906
312	4.76	16.47	16.53	1.00	1962
313	3.88	13.64	13.60	1.00	1733
314	3.88	13.60	13.73	0.99	1295
315	3.77	13.41	13.49	0.99	614
316	4.02	15.97	13.88	1.15	2036
317	4.12	16.17	14.34	1.13	558
318	4.04	15.70	13.98	1.12	1264
319	3.88	14.25	13.47	1.06	1633
320	3.93	14.19	13.76	1.03	1041
321	3.80	13.95	13.39	1.04	224
322	3.83	14.70	13.52	1.09	255
323	3.89	14.70	13.55	1.08	619
324	4.01	15.06	13.88	1.08	2484
325	4.62	15.80	15.78	1.00	1671
326	4.52	15.67	15.64	1.00	1573
327	4.44	15.44	15.42	1.00	124
328	4.41	16.03	15.41	1.04	134
329	4.70	16.39	16.04	1.02	1056
330	4.76	16.71	16.41	1.02	2422
331	4.96	17.47	16.71	1.04	1221
332	4.88	17.21	16.56	1.04	144
333	4.97	17.70	16.84	1.05	1791
334	4.26	14.62	14.95	0.98	126
335	4.25	14.31	14.68	0.97	1140
336	4.33	14.79	15.14	0.98	1884
337	3.86	13.67	13.16	1.04	2275
338	3.86	13.59	13.29	1.02	1358
339	3.64	13.31	12.75	1.04	92
340	3.64	12.48	12.64	0.99	2357
341	3.52	12.18	12.33	0.99	165
342	3.52	12.10	12.10	1.00	1157
343	3.72	13.08	12.75	1.03	2568
344	3.78	13.15	13.12	1.00	1207
345	3.62	12.79	12.61	1.01	108
346	3.39	11.55	11.73	0.98	237
347	3.46	11.65	11.86	0.98	915
348	3.52	11.91	12.26	0.97	1518
349	5.47	18.84	18.99	0.99	2386
350	5.50	18.74	18.83	1.00	593
351	5.44	18.53	18.61	1.00	540
352	5.65	20.44	19.36	1.06	142
353	5.82	20.68	19.93	1.04	1646
354	5.89	20.82	19.93	1.04	2146
355	5.33	17.63	18.11	0.97	1180
356	5.08	17.29	17.84	0.97	304
357	5.15	17.41	17.82	0.98	1831
358	5.55	19.37	18.92	1.02	141
359	5.47	19.36	18.86	1.03	1704
360	5.58	19.08	18.55	1.03	1778
361	4.75	16.22	15.92	1.02	2162
362	4.84	16.47	16.28	1.01	1298
363	4.57	15.62	15.42	1.01	92

364	4.31	14.42	14.69	0.98	2093
365	4.26	14.11	14.40	0.98	303
366	4.26	14.21	14.48	0.98	942
367	4.88	17.07	16.31	1.05	2184
368	5.02	17.19	16.69	1.03	1301
369	4.78	16.57	16.02	1.03	175
370	4.42	14.88	14.91	1.00	179
371	4.52	15.21	15.25	1.00	963
372	4.62	15.65	15.70	1.00	1797
373	3.60	12.19	12.34	0.99	1979
374	3.67	12.26	12.59	0.97	801
375	3.49	11.95	12.50	0.96	133
376	3.25	11.22	11.53	0.97	757
377	3.36	11.45	11.68	0.98	1214
378	3.41	11.61	11.87	0.98	2724
379	3.78	13.16	13.15	1.00	1551
380	3.68	12.98	13.06	0.99	915
381	3.85	13.19	13.37	0.99	1488
382	3.59	12.29	12.56	0.98	159
383	3.54	12.22	12.40	0.98	1740
384	3.68	12.65	12.87	0.98	3080
385	5.89	20.52	19.85	1.03	2381
386	6.10	20.67	20.24	1.02	2549
387	5.86	19.83	19.45	1.02	734
388	5.42	18.42	18.48	1.00	2246
389	5.41	18.20	18.28	1.00	111
390	5.41	18.05	18.03	1.00	2264
391	5.21	17.37	17.68	0.98	2128
392	5.26	17.39	17.71	0.98	1783
393	5.15	17.05	17.42	0.98	629
394	5.41	18.52	18.23	1.02	122
395	5.60	19.09	18.84	1.01	1430
396	5.62	19.25	18.91	1.02	1706
397	3.41	12.22	11.82	1.03	1947
398	3.33	11.93	11.66	1.02	782
399	3.20	11.80	11.30	1.04	302
400	3.07	11.96	11.14	1.07	152
401	3.27	12.12	11.39	1.06	2348
402	3.35	12.35	11.60	1.06	1115
403	2.99	10.83	10.61	1.02	1189
404	2.90	10.76	10.61	1.01	274
405	2.83	10.93	10.55	1.04	1395
406	3.04	11.35	10.77	1.05	101
407	3.04	11.01	11.02	1.00	1717
408	3.14	11.31	11.99	0.94	1779
409	4.54	15.42	15.06	1.02	2764
410	4.60	15.33	14.99	1.02	1354
411	4.39	14.78	14.59	1.01	549
412	4.41	. 2	. 2	. 2	2576
413	4.28	14.23	14.25	1.00	217
414	4.31	14.29	14.26	1.00	1688
415	4.76	16.10	15.52	1.04	2130
416	4.79	16.01	15.51	1.03	1047
417	4.60	15.48	15.13	1.02	181

418	4.67	16.09	15.34	1.05	147
419	4.86	16.26	15.63	1.04	1117
420	5.05	16.87	16.22	1.04	1652
421	5.71	19.58	19.25	1.02	1782
422	5.84	19.64	19.30	1.02	4078
423	5.42	18.71	18.29	1.02	855
424	8.22	27.43	27.59	0.99	1102
425	8.24	27.50	27.63	1.00	2090
426	8.24	27.70	27.76	1.00	3488
427	8.06	26.69	27.21	0.98	153
428	8.19	27.02	27.49	0.98	1829
429	8.14	26.95	27.35	0.98	1270
430	7.84	25.89	26.73	0.97	2731
431	7.96	26.03	26.89	0.97	1225
432	7.82	25.57	26.59	0.96	196
433	9.51	31.92	32.31	0.99	230
434	9.72	32.21	32.36	1.00	1355
435	9.85	32.40	32.58	0.99	2264
436	9.22	30.29	31.22	0.97	1542
437	9.27	30.45	31.43	0.97	1856
438	9.19	29.78	31.08	0.96	111
439	9.67	31.90	32.26	0.99	2475
440	9.51	31.80	32.21	0.99	1333
441	9.59	31.22	31.81	0.98	503
442	8.93	28.92	30.72	0.94	689
443	9.14	29.77	31.03	0.96	4063
444	8.98	29.45	30.83	0.95	1300
445	6.10	19.90	20.62	0.96	1947
446	6.15	19.94	20.70	0.96	4898
447	5.97	19.48	20.37	0.96	232
448	6.39	21.37	21.54	0.99	495
449	6.53	21.66	21.80	0.99	1260
450	6.55	21.60	21.78	0.99	1738
451	6.23	20.30	21.03	0.96	130
452	6.42	20.97	21.34	0.98	1898
453	6.37	20.87	21.35	0.98	869
454	5.95	19.27	20.15	0.96	2188
455	5.99	19.48	20.41	0.95	1538
456	5.78	18.46	19.62	0.94	351
457	9.44	32.04	32.47	0.99	105
458	9.64	32.09	32.53	0.99	1378
459	9.88	32.63	33.03	0.99	1854
460	9.28	30.54	31.97	0.95	1168
461	9.43	30.77	32.21	0.95	2717
462	9.35	30.18	31.94	0.94	119
463	9.01	29.08	30.92	0.94	1505
464	9.27	29.62	31.59	0.94	1326
465	9.04	29.12	31.29	0.93	316
466	7.37	25.11	25.17	1.00	152
467	7.90	26.27	26.85	0.98	3416
468	8.06	26.56	27.23	0.97	1437
469	4.20	14.24	14.27	1.00	127
470	4.26	14.40	14.43	1.00	1102
471	4.38	14.67	14.73	1.00	1685

472	4.75	15.69	15.78	0.99	1269
473	4.68	15.77	15.81	1.00	2029
474	4.55	15.24	15.33	0.99	218
475	5.08	17.09	17.23	0.99	2224
476	5.10	16.87	16.90	1.00	939
477	4.76	16.17	15.99	1.01	192
478	4.01	13.39	13.66	0.98	120
479	4.18	13.87	14.11	0.98	2218
480	4.04	13.42	13.65	0.98	992
481	5.95	20.24	19.93	1.02	1456
482	5.95	20.24	19.82	1.02	4803
483	5.86	19.90	19.76	1.01	881
484	5.23	18.22	18.44	0.99	178
485	5.45	18.66	18.16	1.03	1576
486	5.71	19.00	18.99	1.00	2982
487	6.48	22.42	. 2	. 2	163
488	6.40	22.39	.	.	2945
489	6.65	22.92	.	.	958
490	6.16	21.45	.	.	1910
491	6.39	21.53	.	.	1602
492	6.15	21.00	.	.	132
493	4.76	16.20	.	.	1037
494	4.78	16.32	.	.	1165
495	4.83	16.49	.	.	1764
496	5.33	18.64	.	.	1723
497	5.20	18.55	.	.	1838
498	5.23	18.45	.	.	450
499	4.60	15.53	.	.	2350
500	4.75	15.96	.	.	1114
501	4.60	15.44	.	.	352
502	4.97	17.26	.	.	644
503	5.12	17.59	.	.	3749
504	5.20	17.82	.	.	1711
505	3.72	12.56	12.70	0.99	2096
506	3.77	12.61	12.73	0.99	2301
507	3.72	12.61	12.80	0.98	456
508	3.78	12.69	12.56	1.01	423
509	3.72	12.69	12.62	1.01	1056
510	3.81	13.05	12.85	1.02	2938
511	3.86	13.35	13.09	1.02	531
512	3.93	13.51	13.01	1.04	1321
513	4.07	13.85	13.49	1.03	1676
514	4.25	14.52	13.86	1.05	2123
515	4.33	14.75	14.29	1.03	1526
516	4.07	14.11	13.61	1.04	864
517	3.73	13.39	12.77	1.05	173
518	3.86	13.57	12.94	1.05	898
519	3.89	13.85	13.23	1.05	1949
520	3.72	12.52	12.72	0.98	1427
521	3.64	12.30	12.46	0.99	2349
522	3.56	12.15	12.37	0.98	174
523	3.99	14.43	13.40	1.08	1966
524	4.10	14.55	13.83	1.05	1152
525	4.07	14.39	13.63	1.06	123

526	3.51	12.26	12.12	1.01	165
527	3.72	12.86	12.74	1.01	1457
528	3.77	13.03	12.92	1.01	1903
529	5.16	18.30	17.24	1.06	1413
530	5.16	18.57	17.30	1.07	2301
531	5.12	18.38	17.31	1.06	1012
532	4.52	15.03	15.15	0.99	333
533	4.44	15.24	15.36	0.99	1500
534	4.55	15.42	15.52	0.99	2146
535	4.63	16.15	15.67	1.03	609
536	4.71	16.33	15.88	1.03	2440
537	4.83	16.51	16.26	1.01	1753
538	4.96	17.51	16.70	1.05	2225
539	4.96	17.44	16.79	1.04	1874
540	5.00	17.25	16.55	1.04	256
541	5.58	19.59	19.10	1.03	1091
542	5.65	19.58	19.19	1.02	1613
543	5.66	19.52	19.03	1.03	1394
544	5.82	20.69	20.00	1.03	885
545	5.78	20.54	19.60	1.05	1284
546	5.68	20.68	19.83	1.04	4195
547	5.37	18.43	18.61	0.99	1904
548	5.50	18.70	18.89	0.99	2553
549	5.36	18.35	18.53	0.99	1090
550	5.89	21.24	19.66	1.08	3262
551	5.99	21.62	20.41	1.06	2329
552	6.16	21.78	20.69	1.05	180
553	5.73	20.47	19.13	1.07	2025
554	5.60	20.64	19.00	1.09	2758
555	5.52	20.36	18.79	1.08	501
556	4.75	17.30	16.75	1.03	334
557	4.70	17.20	16.49	1.04	1597
558	5.07	18.08	17.49	1.03	1868
559	5.20	18.72	17.85	1.05	188
560	5.21	19.02	17.80	1.07	2058
561	5.55	19.55	18.59	1.05	1036
562	4.91	17.39	17.24	1.01	2015
563	5.10	17.75	17.71	1.00	1574
564	5.02	17.51	17.48	1.00	622
565	3.41	12.71	11.77	1.08	303
566	3.54	12.99	11.95	1.09	1474
567	3.68	13.42	12.45	1.08	2698
568	3.31	11.65	11.71	1.00	1192
569	3.20	11.65	11.46	1.02	2285
570	3.30	11.46	11.45	1.00	176
571	3.48	12.45	11.89	1.05	1842
572	3.59	12.75	12.31	1.04	1227
573	3.52	12.47	12.11	1.03	453
574	3.28	11.70	11.49	1.02	833
575	3.20	11.66	11.21	1.04	2772
576	3.41	12.11	11.82	1.02	1643
577	4.54	16.34	15.27	1.07	1430
578	4.54	16.47	15.42	1.07	1570
579	4.38	16.14	15.10	1.07	192

580	4.04	13.91	13.63	1.02	149
581	3.99	14.06	13.78	1.02	854
582	4.12	14.40	14.12	1.02	2251
583	4.23	15.02	14.55	1.03	256
584	4.14	14.95	14.22	1.05	1448
585	4.28	15.13	14.56	1.04	1483
586	3.91	13.38	13.40	1.00	2127
587	3.97	13.54	13.65	0.99	832
588	3.78	12.90	12.99	0.99	217
589	2.77	11.31	9.95	1.14	294
590	2.61	.[2]	.[2]	.[2]	1358
591	2.65	.	.	.	1730
592	2.62	.	.	.	1389
593	2.51	.	.	.	1773
594	2.49	.	.	.	410
595	1.71	.	.	.	2067
596	1.80	.	.	.	1930
597	1.64	.	.	.	114
598	1.14	.	.	.	233
599	0.88	.	.	.	4168
600	1.61	.	.	.	1624
601	2.90	10.78	10.47	1.03	1504
602	3.01	10.64	10.85	0.98	2601
603	2.77	9.82	10.16	0.97	1579
604	5.20	17.72	18.57	0.95	99
605	5.42	18.14	19.13	0.95	1145
606	5.42	18.25	19.29	0.95	1816
607	5.84	20.85	20.70	1.01	609
608	5.79	20.93	20.62	1.01	2583
609	5.91	20.83	20.64	1.01	1511
610	5.95	22.00	20.59	1.07	2137
611	6.03	22.08	21.13	1.04	1477
612	5.99	21.69	20.67	1.05	212
613	4.38	15.30	15.75	0.97	196
614	4.49	15.51	15.97	0.97	1179
615	4.60	15.83	16.28	0.97	2145
616	4.79	16.84	16.83	1.00	1234
617	4.78	16.71	16.55	1.01	2492
618	4.75	16.53	16.56	1.00	155
619	4.94	17.95	17.17	1.04	2266
620	4.94	17.80	17.19	1.03	2078
621	4.92	17.74	16.94	1.05	229
622	4.05	13.97	14.72	0.95	504
623	3.97	13.77	14.27	0.96	2599
624	4.17	14.23	14.99	0.95	1646
625	2.32	.[2]	7.83	.[2]	2353
626	2.22	.	7.71	.	2937
627	2.19	.	7.82	.	1049
628	2.86	11.07	10.39	1.06	560
629	3.25	11.72	11.69	1.00	1129
630	3.12	11.48	11.16	1.03	2323
631	3.01	10.75	10.63	1.01	308
632	2.88	10.76	10.30	1.04	1572
633	3.14	11.09	11.28	0.98	948

634	2.67	. 2	. 2	. 2	1859
635	2.64	.	.	.	1076
636	2.46	.	.	.	144
637	3.94	13.71	13.70	1.00	394
638	3.48	12.91	12.40	1.04	1392
639	3.85	13.78	13.78	1.00	1987
640	3.62	12.63	12.93	0.98	1625
641	3.56	12.44	12.49	1.00	2863
642	3.77	12.87	13.27	0.97	263
643	2.91	10.61	10.39	1.02	3132
644	3.11	11.15	11.09	1.00	1786
645	2.83	10.31	10.20	1.01	1015
646	3.94	14.65	14.35	1.02	320
647	4.15	14.96	14.80	1.01	1899
648	4.41	15.56	15.71	0.99	1931
649	2.62	. 2	. 2	. 2	1440
650	2.74	.	.	.	2183
651	2.20	.	7.95	.	259
652	2.86	10.78	10.35	1.04	132
653	3.30	11.61	11.66	1.00	797
654	3.46	12.07	12.20	0.99	1780
655	2.82	10.38	10.17	1.02	336
656	2.75	10.19	10.10	1.01	2619
657	3.15	10.96	11.32	0.97	1299
658	3.62	13.08	13.07	1.00	1706
659	3.72	13.11	13.21	0.99	1080
660	3.28	12.12	11.71	1.03	228

1. Observations (OBS) for Appendix A-3 correspond to observations for Appendices A-1 and A-2
2. Missing data resulting from axle speed sensor failure

APPENDIX B

CALIBRATION DATA FOR THE FOUR WHEEL DRIVE RESEARCH TRACTOR AND TRANSDUCERS

APPENDIX B-1

HORIZONTAL CENTER OF GRAVITY OF THE BALLAST BEHIND THE REAR AXLE AS A FUNCTION OF POSITION

Ballast Rack Position	Horizontal Distance (cm)
0	13.3
1	18.4
2	29.5
3	38.4
4	51.8
5	63.2
6	74.6
7	86.1
8	97.5
9	108.8
10	120.1
11	131.4
12	142.6
13	153.7
14	164.1
15	174.6
16	183.3
17	192.0
18	200.7
19	208.3
20	215.9
21	223.5

APPENDIX B-2

REAR AXLE LOAD WITH AND WITHOUT FRONT BALLAST

	Ballast Distribution (kg)	
Rear	2041	1361
Front	0	680
Rack Position	Rear Axle Mass (kg)	Rear Axle Mass (kg)
0	5255	4236
1	5349	4272
2	5429	4333
3	5531	4395
4	5635	4467
5	5737	4535
6	5844	4592
7	5927	4667
8	6018	4751
9	6109	4821
10	6222	4889
11	6327	4952
12	6417	5025
13	6508	5093
14	6590	5147
15	6685	5206
16	6766	5265
17	6844	5313
18	6912	5361
19	6975	5401
20	7043	5447
21	7098	5501

* Total tractor mass was 10851 kg with fuel and two operators

APPENDIX B-3

ROLLING RADIUS AS A FUNCTION OF DYNAMIC LOAD

Dynamic Axle Load (kN)	Tire Rolling Radius (cm)
36.70	81.1
36.70	81.4
41.54	80.8
41.54	80.6
52.35	80.5
52.35	80.4
52.46	79.7
52.46	79.8
53.84	79.9
53.84	80.3
53.95	79.9
53.95	79.9
64.76	79.6
64.76	79.7
69.61	78.7
69.61	78.7

APPENDIX B-4

TIRE DEFLECTION AS A FUNCTION OF DYNAMIC LOAD

Dynamic Axle Load (kN)	Static Loaded Radius (cm)	Tire Deflection (cm)
0.0	83.2	0.0
52.84	76.0	7.1
53.24	75.8	7.3
54.82	75.7	7.5
56.55	75.6	7.6
58.49	75.4	7.8
60.40	75.2	7.9
62.43	74.9	8.3
64.18	74.6	8.6
65.90	74.4	8.8
67.43	74.1	9.0
68.70	73.8	9.4
70.90	73.5	9.7

APPENDIX B-5

FRONT AXLE TRANSDUCERS A/D READINGS AS A FUNCTION OF CALIBRATION FORCE FOR NET TRACTION

Net Tractive Force (N)	Front Axle Transducer A/D Readings[1,2]			
	Right Tranducer		Left Transducer	
	Net Traction	Dynamic Load	Net Traction	Dynamic Load
0	1444	290	1462	33
	1444	290	1462	33
			1462	33
			1462	33
133	1447	288	1464	30
	1447	288	1465	30
	1447	289	1465	31
			1465	31
267	1450	288		
	1451	288		
	1451	288		
1197	1482	288	1501	30
	1482	288	1501	30
	1482	288	1501	30
2980	1542	287	1560	31
	1542	287	1560	31
	1542	287	1560	31
	1542	287		
4777	1601	287	1620	33
	1602	287	1620	33
	1602	287	1620	33
	1602	287		
6561	1662	287	1679	33
	1662	287	1679	33
	1662	287		
8345	1722	287	1738	33
	1722	287	1738	34
	1722	287	1738	33
10142	1783	287	1798	33
	1783	287	1798	33
	1784	288		
	1784	288		
11926	1843	289	1858	34
	1844	289	1858	34
	1844	288	1858	34
	1844	289	1858	34

1 Each A/D reading is an average of 10 or more
2 A/D Readings are for a 4.99 volt supply

APPENDIX B-6

FRONT AXLE TRANSDUCERS A/D READINGS AS A FUNCTION OF CALIBRATION FORCE FOR DYNAMIC LOAD

Dynamic Load (N)	Right Transducer A/D Reading		Dynamic Load (N)	Left Transducer A/D Reading[1,2]	
	Net Traction	Dynamic Load		Net Traction	Dynamic Load
0	1438	283	0	1466	45
	1438	283		1466	45
4003	1438	398	4310	1459	147
	1438	398		1459	148
6050	1435	453	6428	1460	198
	1435	453		1459	199
8719	1436	520	7638	1458	228
	1436	520		1458	228
11565	1433	595	10275	1460	292
	1433	596		1460	293
14128	1435	659	12989	1458	357
22188	1423	879		1458	358
	1423	880	15769	1455	424
26440	1430	974		1455	425
	1431	974	15542	1455	420
27690	1429	1006	18594	1454	490
	1429	1006		1454	491
	1429	1006	22228	1454	575
33157	1428	1146		1454	575
	1427	1146		1454	575
	1428	1146	25057	1453	641
				1453	641
			26133	1456	666
				1456	666
			28579	1457	723
				1457	723
			30328	1458	763
				1458	764
			32383	1463	812
				1464	813
			34064	1463	852
				1463	852
				1463	852

1 Each A/D reading is an average of 10 or more
2 A/D Readings are for a 4.99 volt supply

APPENDIX B-7

DRAWBAR TRANSDUCER A/D READING AS A FUNCTION OF DRAWBAR PULL

Drawbar Pull (N)	A/D Readings[1,2] Drawbar Pull	Drawbar Vertical
0	635	1396
	634	1396
2224	650	1424
	651	1424
4248	668	1436
	668	1436
7517	694	1453
	694	1453
9070	707	1458
	707	1458
10853	719	1462
	719	1462
13567	741	1464
	742	1465
15444	758	1459
	758	1459
18171	778	1457
	778	1457
21552	804	1446
	804	1446
22659	814	1443
	814	1443
24510	829	1444
	828	1444
26867	850	1434
	849	1434
28958	867	1425
	867	1425
31226	886	1422
	886	1422
33851	907	1410
	907	1410
35585	924	1413
	924	1413
36765	942	1429
	942	1429

1 All A/D readings are an average of 10 or more

2 A/D readings are for a 9.99 volt supply

APPENDIX B-8

DRAWBAR TRANSDUCER A/D READING AS A FUNCTION OF DOWNWARD VERTICAL LOAD

Downward Vertical Load (N)	A/D Readings[1,2] Drawbar Vertical	Drawbar Pull
0	1414	635
489	1472	635
1050	1542	637
	1541	638
1610	1612	639
	1612	639
2193	1678	641
	1677	640
2553	1722	643
	1724	643
489	1475	636
	1476	635
4070	1906	654
	1907	653
4631	1965	651
	1964	653
5191	2032	658
	2031	659
5774	2088	669
	2088	669
6214	2106	667
	2105	664
4070	1909	648
	1910	650
7651	2331	661
	2331	661
8211	2374	661
	2379	663
8772	2453	666
	2449	670
9355	2500	669
	2495	665
9715	2529	670
	2529	669
7651	2336	667
	2334	666

APPENDIX B-8 (Continued)

4070	1915	653
	1919	654
489	1477	637
	1476	638

1 All A/D readings are an average of 10 or more

2 A/D readings are for a 9.99 volt supply

APPENDIX B-9

DRAWBAR TRANSDUCER A/D READING AS A FUNCTION OF UPWARD VERTICAL LOAD

Upward Vertical Load (N)	A/D Readings[1,2] Drawbar Vertical	Drawbar Pull
0	1411	636
	1409	636
1423	1042	672
	1042	671
2669	722	694
	723	693
4003	423	716
	426	716
5338	203	725
	208	723
0	1406	640
	1407	639

1 All A/D readings are an average of 10 or more

2 A/D readings are for a 9.99 volt supply

APPENDIX B-10

FORWARD VELOCITY AS MEASURED BY RADAR AS A FUNCTION OF ACTUAL VELOCITY

Actual[1] Velocity (km/h)	Velocity[2] by Radar (km/h)
1.12	1.10
1.28	1.29
1.52	1.51
2.12	2.13
2.40	2.38
3.14	3.09
3.98	4.02
3.98	3.97

1. As timed over a 33 m interval
2. Average of 5 or more measurements

APPENDIX B-11

HYDRAULIC MOTOR TORQUE AS A FUNCTION OF PRESSURE AND SPEED

Inlet Pressure (MPa)	Motor Speed (RPM)	Motor Torque (N·m)
3.56	100	66.9
7.20	100	147.0
10.22	100	206.6
14.21	100	287.0
17.25	100	355.7
20.89	100	424.6
24.05	100	501.4
27.92	100	569.1
31.92	100	647.0
3.28	250	68.6
6.85	250	138.9
9.88	250	208.2
14.14	250	281.1
17.56	250	354.5
21.34	250	436.6
23.31	250	500.4
28.15	250	585.3
31.08	250	655.2
3.31	500	64.1
6.79	500	133.9
10.38	500	209.2
14.09	500	288.4
17.60	500	363.3
20.46	500	428.0
24.22	500	508.2
28.51	500	597.5
31.57	500	799.5
3.38	750	63.2
7.06	750	139.9
10.40	750	208.4
14.18	750	290.2
17.56	750	358.0
20.78	750	434.0
24.31	750	514.2
27.87	750	591.3
31.40	750	664.7
3.46	1000	61.1
7.14	1000	138.2
10.30	1000	204.4

APPENDIX B-11 (continued)

13.89	1000	281.9
17.55	1000	359.4
20.77	1000	428.4
24.41	1000	517.5
28.41	1000	598.9
31.29	1000	677.4

APPENDIX B-12

TORQUE LOSS THROUGH DIFFERENTIAL AND FINAL DRIVE

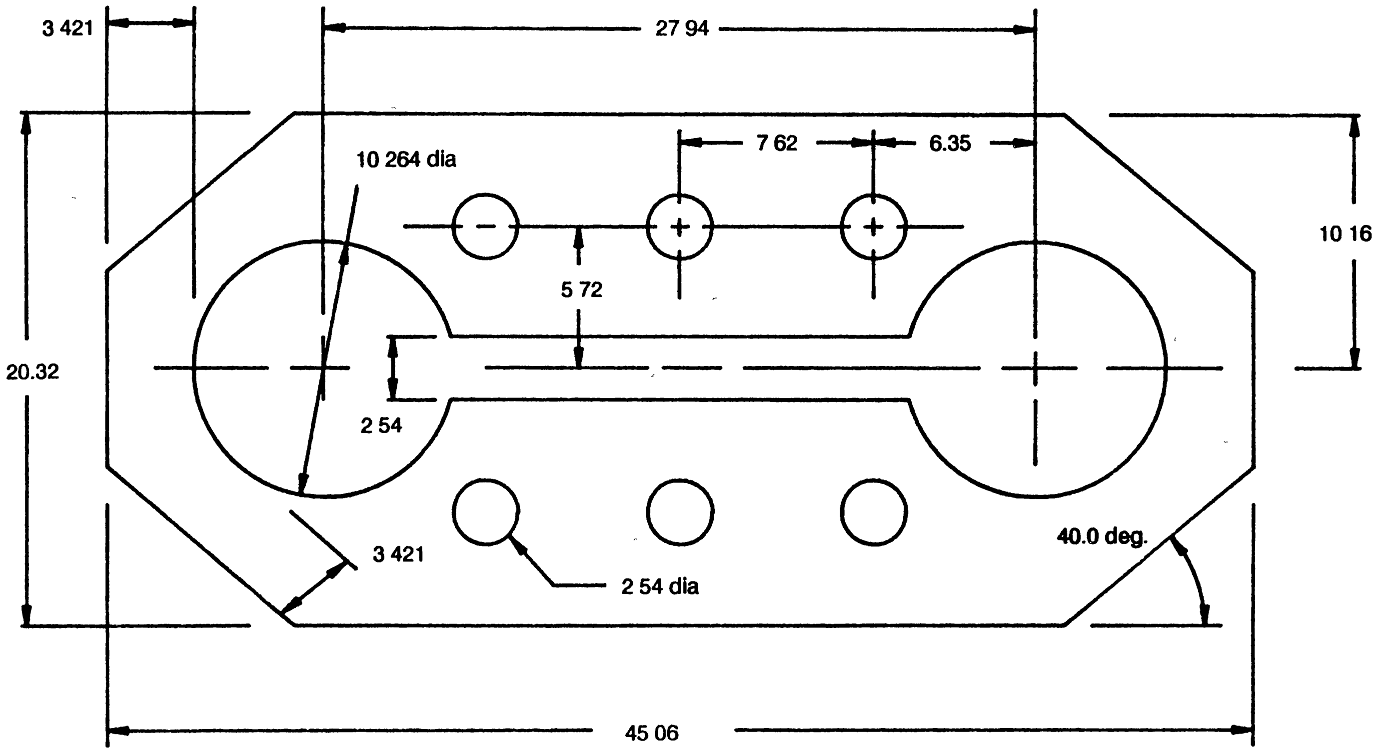
Front Speed (RPM)	Front Input Pressure (MPa)	Rear Speed (RPM)	Rear Input Pressure (MPa)
0.00	1689	0.00	1993
0.65	2165	1.21	2282
1.51	2062	2.06	2296
2.15	2075	2.74	2275
3.00	2144	3.63	2379
4.66	2154	9.54	2434
5.42	2206	10.40	2455
7.53	2275	14.54	2544
8.90	2331	15.08	2655
14.14	2406	17.39	2751
15.72	2489	19.86	2834
16.62	2530	21.61	2903
0.00	1710		
5.95	2234	10.65	2489
24.98	2813	32.92	3296
24.98	2792	32.93	3275
24.99	2799	32.96	3261
20.43	2661	26.94	3034
20.44	2655	26.97	3020
16.20	2489	20.62	2772
16.17	2475	20.59	2779
11.34	2337	16.04	2593
10.93	2344	16.00	2620
6.02	2193	10.74	2406

APPENDIX C

DESIGN DRAWINGS FOR FRONT AXLE TRANSDUCER, CALIBRATION BRACKET AND DRAWBAR TRANSDUCER

APPENDIX C-1

DESIGN DRAWING OF FRONT AXLE TRANSDUCER

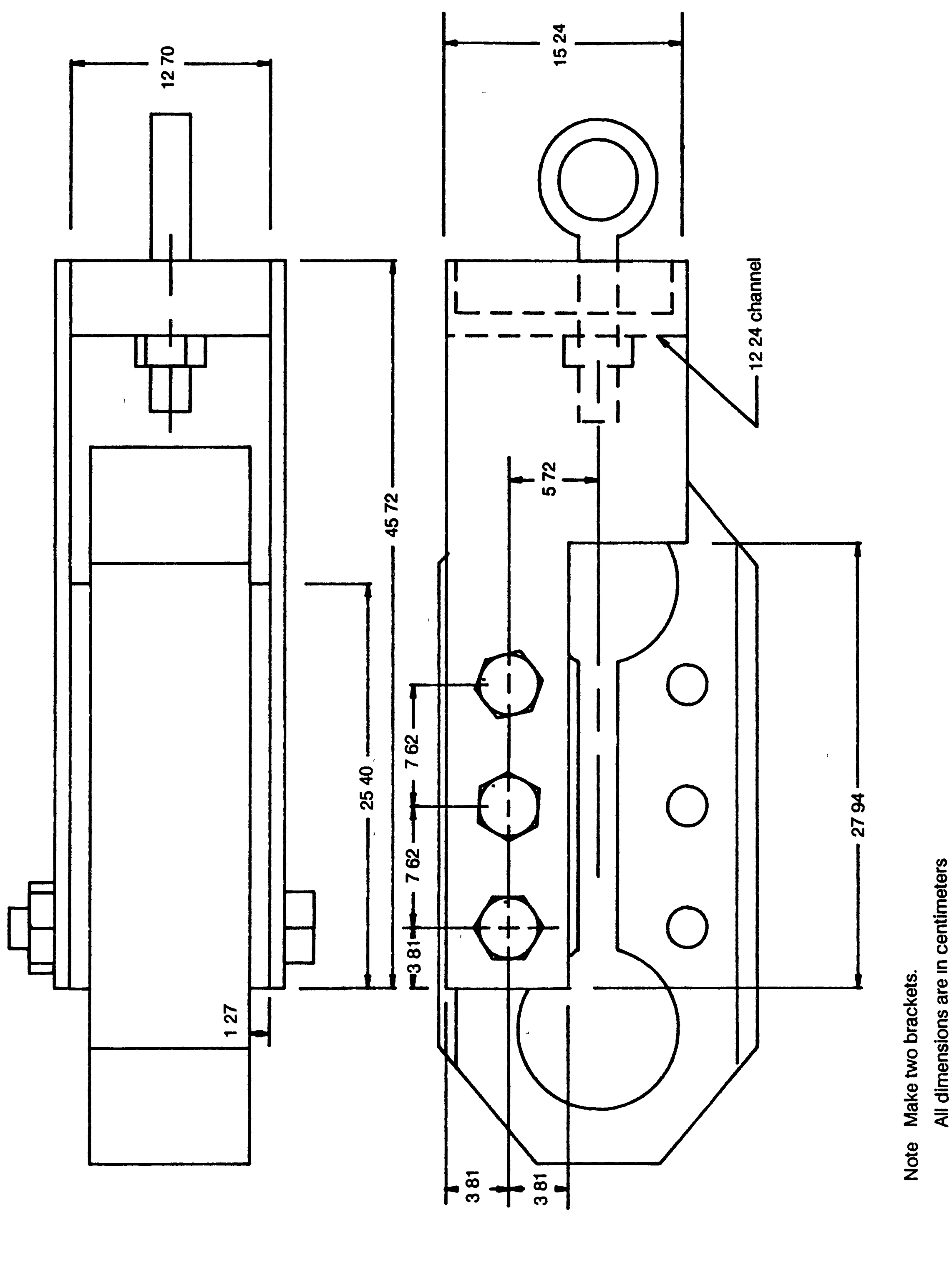


Note Machine two pieces 10 16 cm thick

All dimensions are in centimeters

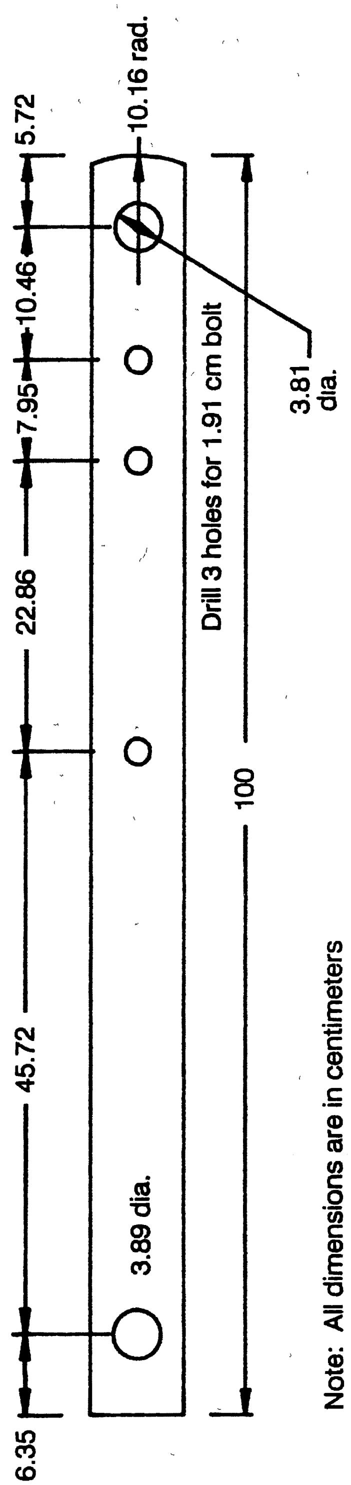
APPENDIX C-2

DESIGN DRAWING OF FRONT AXLE TRANSDUCER CALIBRATION BRACKET



APPENDIX C-3

DESIGN DRAWING OF DRAWBAR TRANSDUCER



APPENDIX D

DATA ACQUISITION PROGRAMS

APPENDIX D-1

BASIC PROGRAM FOR FOUR WHEEL DRIVE TRACTOR DATA ACQUISITION

```
0002 DIM RV(13),RP(13),LV(13),LP(13),DP(13),DV(13),PF(13)
0003 DIM PR(13),ES(13),FS(13),RS(13),GS(13),FR(13),RR(13)
0004 DIM SF(13),SR(13),RA(13),LF(13),FP(13),NF$(12)
0005 POKE 42001,0
0007 REM ***** PRINT SUBROUTINE
0008 GOTO 70
0010 FOR ZR=0 TO 39
0020 ZZ$=MID$(AA$,ZR+1,1)
0030 ZX=USR((128+ASC(ZZ$))*256+ZL*64+ZR)
0040 NEXT
0050 RETURN
0060 REM***** MAIN PROGRAM
0070 POKE 4,176
0075 POKE 5,222
0090 REM***** MUX CHANNELS FOR TRANSDUCERS
0100 REM***** 0-RT VERT, 1-RT PULL, 2-LT VERT, 3-LT PULL
0110 REM***** 4-DB PULL, 5-DB VERT, 6-FR PRES, 7-RE PRES.
0120 REM***** REGRESSION CONSTANTS FOR LOAD CELLS
0130 REM **** A_ = INTERCEPT, B_ = SLOPE, C_ = SLOPE
0140 REM **** 1=RIGHT VERT TRANS, 2=RIGHT PULL TRANS
0150 REM **** 3=LEFT VERT TRANS , 4=LEFT PULL TRANS
0160 REM **** 5=DRAWBAR PULL    , 6&7=DRAWBAR VERTICAL
0170 REM **** 8=PRESSURE FRONT  , 9=PRESSURE REAR
0180 B1=8.6449374
0190 B2=6.6823351
0200 B3=-9.514522
0210 B4=6.7616181
0220 B5=27.78445
0230 B6=1.92985
0240 B7=1.325     : C7=-.0002148
0250 B8=-1.627604
0260 B9=-1.627604
0270 REM***** TIME CONSTANTS FOR TIMERS IN SECONDS
0280 REM***** T1-RADAR, T2-F SPD, T3-R SPD, T4-ENG SPD
0290 REM***** CONTAINS CONSTS TO CONVERT COUNTS TO RPM
0300 T1=1.598152*57.5
0310 T2=1.59804*2*29.25
0320 T3=1.598076*2*29.25
0330 T4=1.598014*4.90
0340 ZL=3
0350 AA$="     FOUR WHEEL DRIVE DATA PROGRAM      "
0360 GOSUB 10
0370 ZL=1
0380 AA$="ENTER DISK FILE NAME (4 CHARACTERS LONG)"
0390 GOSUB 10
0400 ZL=2
```

```
0410 AA$="& THE BLOCK & TREATMENT WILL BE APPENDED"
0420 GOSUB 10
0430 ZL=3
0440 AA$="PLACE DATA DISK INTO DRIVE NUMBER ONE  "
0450 GOSUB 10
0460 INPUT FF$
0465 IF LEN(FF$)>4 PRINT"FF$ TOO LONG": GOTO 340
0466 IF LEN(FF$)<4 PRINT"FF$ TOO SHORT": GOTO 340
0470 AA$="                                          "
0480 GOSUB 10
0490 ZL=2
0500 GOSUB 10
0510 ZL=1
0520 AA$=" WISH TO TAKE A ZERO READING <Y/N> "
0525 GOSUB 10
0530 INPUT ZO$
0535 IF ZO$="Y" THEN GOSUB 1650
0540 IF PR(0)=0 THEN PRINT"NEED ZERO READING":GOSUB 1650
0550 AA$=" ENTER THE ORDER OF PULL RATIOS LEVELS  "
0560 GOSUB 10
0563 AA$=" FOR EXAMPLE (1324)                     "
0565 ZL=2: GOSUB 10
0570 INPUT PL$
0580 AA$="                                        "
0590 GOSUB 10
0600 ZL=1
0610 AA$="ENTER BLK,VEL,DWR,PULL LEVELS (4 CHARS) "
0620 GOSUB 10
0630 INPUT RT$
0635 IF LEN(RT$)<4 THEN PRINT"RT$ TOO SHORT": GOTO 610
0637 IF LEN(RT$)>4 THEN PRINT"RT$ TOO LONG ": GOTO 610
0640 BK$=LEFT$(RT$,1)
0641 IF BK$="1" THEN CI$="321123213123" :GOTO 650
0642 IF BK$="2" THEN CI$="231123132321" :GOTO 650
0643 IF BK$="3" THEN CI$="321123213231" :GOTO 650
0644 IF BK$="4" THEN CI$="213213132123" :GOTO 650
0645 PRINT"ERROR IN NAME " : GOTO 610
0650 ZL=1
0651 AA$=" ENTER DIR OF TRAVEL (E-EAST, W-WEST)  "
0652 GOSUB 10
0653 INPUT DR$
0654 IF DR$="E" GOTO 656
0655 IF DR$<>"W" GOTO 651
0656 AA$="                                         "
0657 ZL=1 : GOSUB 10
0658 POKE 42001,0 : ZL=2 : GOSUB 10
0659 FOR I=1 TO 12
0660 IF I<4  THEN TL$=MID$(PL$,1,1):GOTO 666
0661 IF I<7  THEN TL$=MID$(PL$,2,1):GOTO 666
0662 IF I<10 THEN TL$=MID$(PL$,3,1):GOTO 666
0663 TL$=MID$(PL$,4,1)
0664 IF DR$="E" THEN CL$=MID$(CI$,I,1)
0665 IF DR$="W" THEN CL$=MID$(CI$,(13-I),1)
0666 NF$(I)=FF$+RT$+TL$+CL$
```

```
0667 IF LEN(NF$(I))<10  GOTO 645
0668 IF LEN(NF$(I))>10  GOTO 645
0669 IF I>1 THEN PRINT"WAITING FOR START":GOTO 680
0670 AA$=" PRESS 'SPACE BAR' TO START COLLECTION   "
0675 GOSUB 10
0680 GET SS$
0690 IF SS<>" " GOTO 680
0700 PRINT"START OF COLLECTION"
0720 REM***** GOTO FORCE READING SUBROUTINE
0730 POKE 4,132
0740 POKE 5,8
0750 ZZ=USR(W)
0760 POKE 4,176
0770 POKE 5,222
0780 POKE 42001,0 : PRINT"** FINISHED PLOT-";I
0800 REM***** READ DATA FROM MEMORY
0810 RV(I)=(PEEK(28672)+PEEK(28673)*256)
0815 RV(I)=(RV(I)+PEEK(28674)*65536)/1024
0820 RP(I)=(PEEK(28676)+PEEK(28677)*256)
0825 RP(I)=(RP(I)+PEEK(28678)*65536)/1024
0830 LV(I)=(PEEK(28680)+PEEK(28681)*256)
0835 LV(I)=(LV(I)+PEEK(28682)*65536)/1024
0840 LP(I)=(PEEK(28684)+PEEK(28685)*256)
0845 LP(I)=(LP(I)+PEEK(28686)*65536)/1024
0850 DP(I)=(PEEK(28688)+PEEK(28689)*256)
0855 DP(I)=(DP(I)+PEEK(28690)*65536)/1024
0860 DV(I)=(PEEK(28692)+PEEK(28693)*256)
0865 DV(I)=(DV(I)+PEEK(28694)*65536)/1024
0870 PF(I)=(PEEK(28696)+PEEK(28697)*256)+PEEK(28698)
          *65536)
0880 PF(I)=(PF(I)+PEEK(28699)*16777216)/6144
0890 PR(I)=(PEEK(28700)+PEEK(28701)*256+PEEK(28702)*65536)
0900 PR(I)=(PR(I)+PEEK(28703)*16777216)/6144
0910 ES(I)=(65535-PEEK(28704)-PEEK(28705)*256)
0920 FS(I)=(65535-PEEK(28706)-PEEK(27)*256)
0930 RS(I)=(65535-PEEK(28708)-PEEK(28709)*256)
0940 GS(I)=(65535-PEEK(28710)-PEEK(28711)*256)
0955 NEXT
0960 REM***** CONVERT DATA TO ENGINEERING UNITS
0970 FOR I=1 TO 12
0980 RV(I)=INT(B1*(RV(I)-RV(0))+(FW/2))
0990 RP(I)=INT(B2*(RP(I)-RP(0)))
1000 LV(I)=INT(B3*(LV(I)-LV(0))+(FW/2))
1001 FR(I)=(INT((32.88445-.0001136143*(RV(I)+LV(I))
1003 FR(I)=(INT(FR(I)*1000+.5))/1000
1004 RR(I)=(INT(RR(I)*1000+.5))/1000
1010 LP(I)=INT(B4*(LP(I)-LP(0)))
1020 DP(I)=INT(B5*(DP(I)-DP(0)))
1030 IF DV(I)>DV(0) THEN DV(I)=INT(B6*(DV(I)-DV(0))):
     GOTO 1047
1045 DV(I)=INT(B7*(DV(I)-DV(0))+C7*
     (DV(I)*DV(I)-DV(0)*DV(0)))
1047 RR(I)=(INT((32.88445-.0001136143*(SW-RV(I)-LV(I)
          +DV(I))
```

```
1050 PF(I)=INT(B8*(PF(I)-PF(0)))
1060 PR(I)=INT(B9*(PR(I)-PR(0)))
1070 ES(I)=INT(ES(I)/T4)
1080 FS(I)=(INT((FS(I)/T2)*100+.5))/100
1090 RS(I)=(INT((RS(I)/T3)*100+.5))/100
1100 GS(I)=(INT((GS(I)/T1)*98.05+.5))/100
1110 IF FS(I)=0 THEN FS(I)=.00001
1120 IF RS(I)=0 THEN RS(I)=.00001
1130
  SF(I)=(INT((1-(GS(I)/(FS(I)*FR(I)/168.07)))*1000+.5))/10
1140
  SR(I)=(INT((1-(GS(I)/(RS(I)*RR(I)/168.07)))*1000+.5))/10
1150 RA(I)=(INT((FS(I)/RS(I))*100+.5))/100
1160 LF(I)=INT(((RV(I)+LV(I))/(SW+DV(I))*100+.5)
1165 IF DP(I)=0 THEN FP(I)=0: GOTO 1180
1170 FP(I)=INT(((RP(I)+LP(I))/DP(I))*100+.5)
1180 REM ***** PRINT DATA TO PAPER
1185 POKE 42001,128
1187 PRINT"-------------------"
1190 PRINT "FILE NM=";NF$(I)
1200 PRINT "FRR=";FR(I);"RRR=";RR(I)
1210 PRINT "RV=";RV(I);"LV=";LV(I)
1220 PRINT "RP=";RP(I);"LP=";LP(I)
1230 PRINT "DP=";DP(I);"DV=";DV(I)
1240 PRINT "PF=";PF(I);"PR=";PR(I)
1250 PRINT "ERPM";ES(I);"VEL";GS(I)
1260 PRINT "FRPM";FS(I);"RRPM";RS(I)
1270 PRINT "%FSL";SF(I);"%RSL";SR(I)
1280 PRINT "%FDL";LF(I);"%FPL";FP(I)
1290 PRINT "FS/RS";RA(I);"STW=";SW
1300 NEXT
1304 PRINT"-------------------"
1305 POKE 42001,0
1310 AA$="  SAVE THIS DATA TO DISK (Y/N)          "
1320 GOSUB 10
1340 INPUT YN$
1350 IF YN$="N" THEN GOTO 1590
1360 IF YN$<>"Y" THEN GOTO 1340
1365 POKE 42001,0
1370 POKE 4,0
1380 POKE 5,8
1390 POKE 1281,0
1400 POKE 1283,0
1410 POKE 1285,0
1420 FOR J=0 TO 9
1425 FD$=FF$+RT$+"  "
1430 POKE (1304+J),(ASC(MID$(FD$,J+1,1)
1435 NEXT
1440 Z=USR(W)
1460 FOR I=1 TO 12
1470 PRINT NF$(I)
1475 PRINT SW
1480 PRINT FR(I);RR(I)
1490 PRINT RV(I);RP(I)
```

```
1500 PRINT LV(I);LP(I)
1510 PRINT DP(I);DV(I)
1520 PRINT PF(I);PR(I)
1530 PRINT ES(I);GS(I)
1540 PRINT FS(I);RS(I)
1550 NEXT
1570 POKE 4,40
1580 Z=USR(W)
1585 POKE 42001,128
1590 POKE 4,176
1600 POKE 5,222
1610 GOTO 510
1620 END
1630 REM ***** START OF ZERO SUBROUTINE
1650 AA$=" ENTER VALUES <E> OR GET NEW VALUES <N> "
1660 GOSUB 10
1670 INPUT ZO$
1680 IF ZO$="N" GOTO 1745
1685 POKE 42001,128
1690 PRINT"ENTER ZERO VALUES"
1700 INPUT"RV(0)=";RV(0) : INPUT"RP(0)=";RP(0)
1710 INPUT"LV(0)=";LV(0) : INPUT"LP(0)=";LP(0)
1720 INPUT"DP(0)=";DP(0) : INPUT"DV(0)=";DV(0)
1730 INPUT"PF(0)=";PF(0) : INPUT"PR(0)=";PR(0)
1732 SW=23900 : PRINT"SW=";SW
1733 INPUT"WT POS (0-21)";PO
1734 INPUT"1500# FRONT (Y/N)";YN$
1735 IF YN$="N" GOTO 1738
1736 FW=9308.939+121.008*PO+4.23165*PO*PO
     -.1752306*PO*PO*PO
1737 GOTO 1739
1738 FW=11587.76+195.88*PO+3.486966*PO*PO
     -.1715958*PO*PO*PO
1739 FW=SW-FW : PRINT"TOT ST FW=";FW
1740 POKE 42001,0 : ZL=1 : RETURN
1745 AA$="ROUTINE TAKES ZERO'S FOR FORCES, DO YOU "
1746 ZL=1
1747 GOSUB 10
1748 ZL=2
1750 AA$="WISH NEW ZERO'S FOR PRESSURE ALSO <Y/N> "
1751 GOSUB 10
1753 INPUT ZP$
1754 IF ZP$="Y" THEN MX=7 : PF(0)=0:PR(0)=0: GOTO 1757
1755 IF ZP$="N" THEN MX=5 : GOTO 1757
1756 GOTO 1753
1757 RV(0)=0:RP(0)=0:LV(0)=0:LP(0)=0:DP(0)=0:DV(0)=0
1758 NB=100
1759 POKE 42001,0
1760 FOR L=1 TO NB
1761 PRINT"WAIT";NB+1-L
1763 FOR K=0 TO MX
1770 POKE 40954,K
1780 FOR I=1 TO 25: NEXT
1790 POKE 40955,0
```

```
1800 FOR I=1 TO 25: NEXT
1805 RD=PEEK(40957)*256+PEEK(40958)
1810 IF K=0 THEN RV(0)=RD+RV(0) :GOTO 1870
1820 IF K=1 THEN RP(0)=RD+RP(0) :GOTO 1870
1830 IF K=2 THEN LV(0)=RD+LV(0) :GOTO 1870
1840 IF K=3 THEN LP(0)=RD+LP(0) :GOTO 1870
1850 IF K=4 THEN DP(0)=RD+DP(0) :GOTO 1870
1860 IF K=5 THEN DV(0)=RD+DV(0) :GOTO 1870
1864 IF K=6 THEN PF(0)=RD+PF(0) :GOTO 1870
1865 IF K=7 THEN PR(0)=RD+PR(0)
1870 NEXT K
1880 NEXT L
1881 POKE 42001,128 : SW=23900  : PRINT"SW=";SW
1882 INPUT"WT POS (0-21)";PO
1883 INPUT"1500# FRONT (Y/N)";YN$
1884 IF YN$="N" GOTO 1887
1885 FW=9308.939+121.008*PO+4.23165*PO*PO
     -.1752306*PO*PO*PO
1886 GOTO 1888
1887 FW=11587.76+195.88*PO+3.486966*PO*PO
     -.1715958*PO*PO*PO
1888 FW=SW-FW : POKE 42001,128 : PRINT"TOT ST FW=";FW
1890 RV(0)=RV(0)/NB : PRINT "RV(0)=";RV(0)
1900 RP(0)=RP(0)/NB : PRINT "RP(0)=";RP(0)
1910 LV(0)=LV(0)/NB : PRINT "LV(0)=";LV(0)
1920 LP(0)=LP(0)/NB : PRINT "LP(0)=";LP(0)
1930 DP(0)=DP(0)/NB : PRINT "DP(0)=";DP(0)
1940 DV(0)=DV(0)/NB : PRINT "DV(0)=";DV(0)
1950 IF ZP$="Y" GOTO 1990
1960 PRINT "PF(0)=";PF(0)
1965 PRINT "PR(0)=";PR(0)
1980 POKE 42001,0 : ZL=1 : RETURN
1990 PF(0)=PF(0)/NB : PRINT "PF(0)=";PF(0)
2000 PR(0)=PR(0)/NB : PRINT "PR(0)=";PR(0)
2010 GOTO 1980
2240 END
```

APPENDIX D-2

MACHINE LANGUAGE PROGRAM FOR FOUR WHEEL DRIVE TRACTOR DATA ACQUISITION

TIME CONSTANTS

Total Time to Collect Four Sets of 256 Readings

1-RADAR = 1.598152 s
2-FRONT SPEED = 1.598040 s
3-REAR SPEED = 1.598076 s
4-ENGINE SPEED = 1.598014 s

Storage Locations for Force Readings Sum

A/D Channel	Load Transducer	Address For Force Readings Low byte	2nd byte	3rd byte	Hi byte
0	Right Vert	$7000	$7001	$7002	$7003
1	Right Pull	$7004	$7005	$7006	$7007
2	Left Vert	$7008	$7009	$700A	$700B
3	Left Pull	$700C	$700D	$700E	$700F
4	Drawbar Pull	$7010	$7011	$7012	$7013
5	Drawbar Vert	$7014	$7015	$7016	$7017
6	Front Press	$7018	$7019	$701A	$701B
7	Rear Press	$701C	$701D	$701E	$701F

Storage Locations for Timer Readings

Counter	Name	Address for timer readings Low byte	Hi byte
1	Radar	$7026	$7027
2	Front Speed	$7022	$7023
3	Rear Speed	$7024	$7025
4	Engine Speed	$7020	$7021

SUBROUTINES

```
***** FRSUB  (Force reading subroutine)
***** This subroutine brings to it the multiplex channel
***** to be read.  The routine then stores the data from
***** previous read and stores the force reading in the
***** address according to the value of the index y.
0851 STA $9FFA   4              SET MUX CHANNEL
0854 CLC         2
0855 LDA $9FFE   4              READ LOW BYTE FROM A/D
0858 ADC $7000,Y 4              ADD PREVIOUS ZERO BYTE SUM
085B STA $7000,Y 5              STORE IN ZERO BYTE ADDRESS
```

```
085E LDA $9FFD   4              READ HI BYTE FROM A/D
0861 ADC $7001,Y 4              ADD PREVIOUS 1ST BYTE SUM
0864 STA $7001,Y 5              STORE IN 1ST BYTE ADDRESS
0867 LDA  #$00   2              LOAD 00 AND
0869 ADC $7002,Y 4              ADD PREVIOUS 2ND BYTE SUM
086C STA $7002,Y 5              STORE IN 2ND BYTE ADDRESS
086F LDA  $#00   2              LOAD 00 AND
0871 ADC $7003,Y 4              ADD PREVIOUS 3RD BYTE SUM
0874 STA $7003,Y 5              STORE IN 3RD BYTE ADDRESS
0877 STA $9FFB   4              START A/D CONVERSION
087A NOP         2
087B NOP         2
087C NOP         2
087D NOP         2
087E NOP         2
087F RTS         6
                74

***** INITILIZE AND START COUNTERS
0884 LDA  #$7F   2
0886 STA $920E   4             DISABLE VIA INTERUPT
0889 LDA  #$00   2             INPUT CONFIGURATION
088B STA $9202   4             PORT AUXILERY
088E LDA  #$20   2             SET BIT 5 FOR PULSE COUNTING
0890 STA $920B   4               OF ACR FOR TIMER 1
0893 LDA  #$FF   2             STORE FF IN LOW BYTE OF
0895 STA $9208   4               COUNTER 1
0898 LDA  #$FF   2             STORE FF IN HI BYTE OF
089A STA $9209   4 ST RADAR SPEED COUNTER ; START COUNT 1
089D LDA  #$7F   2
089F STA $921E   4              DISABLE VIA INTERUPT
08A2 LDA  #$00   2              INPUT CONFIGURATION
08A4 STA $9212   4              PORT AUXILERY
08A7 LDA  #$20   2              SET BIT 5 FOR PULSE COUNT
08A9 STA $921B   4                OF ACR FOR TIMER 2
08AC LDA  #$FF   2              STORE FF IN LOW BYTE OF
08AE STA $9218   4                COUNTER 2
08B1 LDA  #$FF   2              STORE FF IN HI BYTE OF
08B3 STA $9219   4 ST FRNT SPEED COUNTER ; START CNT 2
08B6 LDA  #$7F   2
08B8 STA $903E   4              DISABLE VIA INTERUPT
08BB LDA  #$00   2              INPUT CONFIGURATION
08BD STA $9032   4              PORT (B)
08C0 LDA  #$20   2              SET BIT 5 FOR PULSE COUNT
08C2 STA $903B   4                OF ACR FOR TIMER 3
08C5 LDA  #$FF   2              STORE FF IN LOW BYTE OF
08C7 STA $9038   4                COUNTER 3
08CA LDA  #$FF   2              STORE FF IN HI BYTE OF
08CC STA $9039   4 ST REAR SPEED COUNTER 3; START CNT 3
08CF LDA  #$7F   2
08D1 STA $902E   4              DISABLE VIA INTERUPT
08D4 LDA  #$00   2              INPUT CONFIGURATION
08D6 STA $9022   4              PORT (B)
08D9 LDA  #$20   2              SET BIT 5 FOR PULSE COUNT
```

```
08DB STA $902B   4                    OF ACR FOR TIMER 4
08DE LDA  #$FF   2                  STORE FF IN LOW BYTE OF
08E0 STA $9028   4                    COUNTER 4
08E3 LDA  #$FF   2                  STORE FF IN HI BYTE OF
08E5 STA $9029   4 ST ENGINE SPEED COUNTER ; START CNT 4

***** TIME TO THIS POINT FOR CNT 1-RADAR      = 90us
*****                        CNT 2-FNT SPEED = 60us
*****                        CNT 3-REAR SPEED= 30us
*****                        CNT 4-ENG SPEED =  0us
08E8 LDY  #$28   2                   ZERO MEMORY LOCATIONS
08EA LDA  #$00   2  ZERO             PLACE 00 INTO LOCATIONS
08EC STA $7000,Y 5                   $7000 TO $7028
08EF DEY         2                   DECREMENT Y TO 0
08F0 BPL  ZERO   2,3                 BRANCH IF NON NEGATIVE
08F2 LDA  #$04   2                   SET INDEX FOR 04 DATA SETS
08F4 STA   $E6   3                   ADDRESS FOR INDEX
08F6 LDY   $FF   2                   LOAD DUMMY INX FOR 1st STA
*****          500us                 TIME FROM LDY#$28

08F8 LDX  #$00   2   AGAIN           LOAD X WITH 00
08FA LDA  #$06   2   L256            SET MUX TO READ CHANNEL 6
08FC JSR FRSUB   6+74                GOTO FORCE READING SUB.
08FF LDY  #$18   2                   INDEX FOR STORAGE OF CH 6
0901 LDA  #$07   2                   SET MUX TO READ CHANNEL 7
0903 JSR FRSUB   6+74                GOTO FORCE READING SUB.
0906 LDY  #$1C   2                   INDEX FOR STORAGE OF CH 7
0908 LDA  #$00   2                   SET MUX TO READ CHANNEL 0
090A JSR  FRSUB  6+74                GOTO FORCE READING SUB.

                                     ADDED STEPS TO MAKE SAMPLE
090D NOP         2                     TIMES FOR L256 LOOP
090E NOP         2                     CONSTANT FOR ALL DATA
090F NOP         2
0910 NOP         2
0911 LDY  #$00   2                   INDEX FOR STORAGE OF CH 0
0913 LDA  #$06   2                   SET MUX TO READ CHANNEL 6
0915 JSR FRSUB   6+74                GOTO FORCE READING SUB.
0918 LDY  #$18   2                   INDEX FOR STORAGE OF CH 6
091A LDA  #$07   2                   SET MUX TO READ CHANNEL 7
091C JSR FRSUB   6+74                GOTO FORCE READING SUB.
091F LDY  #$1C   2                   INDEX FOR STORAGE OF CH 7
0921 LDA  #$01   2                   SET MUX TO READ CHANNEL 1
0923 JSR FRSUB   6+74                GOTO FORCE READING SUB.

                                     ADDED STEPS TO MAKE SAMPLE
0926 NOP         2                     TIMES FOR L256 LOOP
0927 NOP         2                     CONSTANT FOR ALL DATA
0928 NOP         2
0929 NOP         2
092A LDY  #$04   2                   INDEX FOR STORAGE OF CH 1
092C LDA  #$06   2                   SET MUX TO READ CHANNEL 6
092E JSR FRSUB   6+74                GOTO FORCE READING SUB.
0931 LDY  #$18   2                   INDEX FOR STORAGE OF CH 6
```

```
0933 LDA   #$07    2              SET MUX TO READ CHANNEL 7
0935 JSR FRSUB     6+74           GOTO FORCE READING SUB.
0938 LDY   #$1C    2              INDEX FOR STORAGE OF CH 7
093A LDA   #$02    2              SET MUX TO READ CHANNEL 2
093C JSR FRSUB     6+74           GOTO FORCE READING SUB.

                                  ADDED STEPS TO MAKE SAMPLE
093F NOP           2                TIMES FOR L256 LOOP
0940 NOP           2                CONSTANT FOR ALL DATA
0941 NOP           2
0942 NOP           2
0943 LDY   #$08    2              INDEX FOR STORAGE OF CH 2
0945 LDA   #$06    2              SET MUX TO READ CHANNEL 6
0947 JSR FRSUB     6+74           GOTO FORCE READING SUB.
094A LDY   #$18    2              INDEX FOR STORAGE OF CH 6
094C LDA   #$07    2              SET MUX TO READ CHANNEL 7
094E JSR FRSUB     6+74           GOTO FORCE READING SUB.
0951 LDY   #$1C    2              INDEX FOR STORAGE OF CH 7
0953 LDA   #$03    2              SET MUX TO READ CHANNEL 3
0955 JSR FRSUB     6+74           GOTO FORCE READING SUB.

                                  ADDED STEPS TO MAKE SAMPLE
0958 NOP           2                TIMES FOR L256 LOOP
0959 NOP           2                CONSTANT FOR ALL DATA
095A NOP           2
095B NOP           2
095C LDY   #$0C    2              INDEX FOR STORAGE OF CH 3
095E LDA   #$06    2              SET MUX TO READ CHANNEL 6
0960 JSR FRSUB     6+74           GOTO FORCE READING SUB.
0963 LDY   #$18    2              INDEX FOR STORAGE OF CH 6
0965 LDA   #$07    2              SET MUX TO READ CHANNEL 7
0967 JSR FRSUB     6+74           GOTO FORCE READING SUB.
096A LDY   #$1C    2              INDEX FOR STORAGE OF CH 7
096C LDA   #$04    2              SET MUX TO READ CHANNEL 4
096E JSR FRSUB     6+74           GOTO FORCE READING SUB.

                                  ADDED STEPS TO MAKE SAMPLE
0971 NOP           2                TIMES FOR L256 LOOP
0972 NOP           2                CONSTANT FOR ALL DATA
0973 NOP           2
0974 NOP           2
0975 LDY   #$10    2              INDEX FOR STORAGE OF CH 4
0977 LDA   #$06    2              SET MUX TO READ CHANNEL 6
0979 JSR FRSUB     6+74           GOTO FORCE READING SUB.
097C LDY   #$18    2              INDEX FOR STORAGE OF CH 6
097E LDA   #$07    2              SET MUX TO READ CHANNEL 7
0980 JSR FRSUB     6+74           GOTO FORCE READING SUB.
0983 LDY   #$1C    2              INDEX FOR STORAGE OF CH 7
0985 LDA   #$05    2              SET MUX TO READ CHANNEL 5
0987 JSR FRSUB     6+74           GOTO FORCE READING SUB.
098A LDY   #$14    2              INDEX FOR STORAGE OF CH 5
098C DEX           2              DECREMENT X AND BRANCH
098D BNE   LOOP1   2,3            UNTIL X=0 (256 READINGS)
098F JMP   LOOP2   3              JUMP AROUND JUMP TO L256
```

```
0992 JMP   L256    3    LOOP1       JUMP TO L256 (256 READINGS)
0995 DEC    $E6    5    LOOP2       DEC MEM LOC E6 AND BRANCH
0997 BNE   LOOP3   2,3              UNTIL 4 SET OF 256 READINGS
0999 JMP   LOOP4   3                JUMP AROUND JUMP TO AGAIN
099C JMP   AGAIN   3    LOOP3       JUMP TO AGAIN

*****                               LOOP TIME FROM AGAIN
*****                      1198133  us for 3 sets of 256
*****                      1597510 us for 4 sets of 256


***** Read speed counters.
***** TIME FROM THIS POINT FOR CNT 1-RADAR     = 52us
*****                          CNT 2-FNT SPEED = 20us
*****                          CNT 3-REAR SPEED= 36us
*****                          CNT 4-ENG SPEED =  4us
099F LDA $9029    4 LOOP4  STOP READ HI BYTE OF ENG SPEED
09A2 STA $7021    4             STORE HI BYTE OF ENG SPEED
09A5 LDA $9028    4             READ LOW BYTE OF ENG SPEED
09A8 STA $7020    4             STORE LOW BYTE OF ENG SPEED
09AB LDA $9219    4 STOP FRT CT READ HI BYTE OF FRONT SPEED
09AE STA $7023    4             STORE HI BYTE OF FRNT SPEED
09B1 LDA $9218    4             READ LOW BYTE OF FRNT SPEED
09B4 STA $7022    4             STORE LOW BYTE OF FRNT SPD
09B7 LDA $9039    4 STOP RER CT READ HI BYTE OF REAR SPEED
09BA STA $7025    4             STORE HI BYTE OF REAR SPEED
09BD LDA $9038    4             READ LOW BYTE OF REAR SPEED
09C0 STA $7024    4             STORE LOW BYTE OF REAR SPD
09C3 LDA $9209    4 STOP RAD CT READ HI BYTE OF RADAR
09C6 STA $7027    4             STORE HI BYTE OF RADAR
09C9 LDA $9208    4             READ LOW BYTE OF RADAR
09CC STA $7026    4             STORE LOW BYTE OF RADAR
09CF RTS          6             RETURN TO BASIC PROGRAM
```

VITA

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Candidate for the Degree of

Doctor of Philosophy

Thesis: DYNAMIC LOAD AND WHEEL SPEED RATIO EFFECTS ON FOUR WHEEL DRIVE TRACTIVE PERFORMANCE

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