Three Single Wheel Machines for Traction and Soil Compaction Research

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ABSTRACT

Three single wheel machines for traction and soil compaction research have been developed in recent years at the USDA-ARS National Soil Dynamics Laboratory. The Traction Research Vehicle has been used extensively for soil bin traction and soil compaction experiments. The vehicle uses feedback computer control to control tire dynamic load, forward velocity, inflation pressure, and in a given run, either travel reduction or net traction. The all-terrain vehicle (ATV) tire single wheel machine has been used in determining traction and motion resistance characteristics of ATV tires in soil bins. The ATV tire machine uses the forward velocity feedback computer control of the Traction Research Vehicle and uses deadweight loading for dynamic load. Tire angular velocity is manually controlled by the operator using a joystick. A single wheel traction research machine designed for use in the field has been developed, but computer control has not been completed.

Keywords: Tires, wheels, single tire tester, single wheel tester, soil-tire interaction, soil dynamics, computer control, USA

1. INTRODUCTION

Machines for operating a single wheel for traction and soil compaction research are commonly known as single tire testers or single wheel testers. Some single tire testers are large enough to accommodate the largest agricultural tractor drive tires currently available, which are up to approximately 2090 mm overall diameter [1]. Other single tire testers are designed to accommodate a smaller tire, such as a garden tractor rear tire with an overall diameter up to about 600 mm.

Various designs of single wheel traction research machines have been developed and used. Machines for operating a single tire on soils in soil bins include those described by Wells and Buckles (1987), Chen (1993), Wu (2000), Kawase et al. (2006), and Yahya et al. (2007). Single wheel traction research machines for operating a single tire in a field include those described by Dwyer (1972), Billington (1973), Dwyer (1985), Upadhyaya et al. (1986), and Ronai et al. (1994a and 1994b). Design and performance characteristics of several single wheel testers are presented by Way (2009). Characteristics of the three single wheel testers described in this article are presented in Way (2007).

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[1] Overall diameter, input torque, dynamic load, net traction, travel reduction, and some other terms are defined in *ASABE Standards* (2009).

At the USDA-ARS National Soil Dynamics Laboratory (NSDL) in Auburn, Ala., USA, a suspended tractor as described by Gill and Vanden Berg (1968) was used as a single tire traction research machine known as the Tire Test Car from 1948 through the mid-1970's on the soil bins (Reed and Shields (1950) and Gill (1990)). The suspended tractor powered a single tractor drive tire. The only component of the tractor that contacted the soil was the left rear tire, which was on the left half of the rear axle. The tractor differential was locked so the differential acted as only a bevel gear drive for transmitting engine power to the wheel. The sizes of commonly used tractor tires increased from 1965 to 1972, to a size that could no longer be used on this Tire Test Car (Gill, 1990). In 1977, the Laboratory began using a new Traction Research Vehicle (TRV) which ran on the soil bins and used a diesel engine-powered hydraulic system in place of the suspended tractor (Lyne et al., 1983). Design and operating characteristics of the TRV are described in Burt et al. (1980). Computer control of the dynamic load, net traction, and travel reduction developed for the TRV as of 1983 is described by Lyne et al. (1983). The hydraulic system and computer control system of the TRV were updated in 1993. Details about the load cell and torque transducer configurations and some operating characteristics of the TRV have not been published. Also, information about two other single tire research machines developed at the NSDL has not been published.

Therefore, the objectives of this paper are to:

1. Describe the updated Traction Research Vehicle and provide more information about its force and torque measurement systems.
2. Describe a single wheel traction research machine developed at the NSDL for operating an all-terrain vehicle (ATV) tire on the NSDL soil bins.
3. Describe a single wheel traction research machine that mounts to the NSDL Wide Frame Tractive Vehicle and is designed for operating a single agricultural tractor drive tire in the field.

2. TRACTION RESEARCH VEHICLE FOR USE ON SOIL BINS

The NSDL soil bin single wheel Traction Research Vehicle (TRV) (fig. 1) has been used extensively for traction and soil compaction experiments. Most experiments have been with agricultural tractor drive tires and a few have been with forestry drive tires and rigid wheels. The vehicle is designed to position the geometric center of the tire or set of multiple tires directly beneath the Normal Load load cell (fig. 2). This criterion and dimensions of the TRV components limit the maximum width of the undeflected sidewalls of a tire or set of tires that can be operated by the TRV to 810 mm. To date, the only multiple wheel set that has been used on the TRV is a pair of 13.6-38 tractor drive tires with a 100-mm lateral space between the undeflected sidewalls (Bailey and Burt, 1981). The largest tire overall diameter that will fit on the TRV is 1880 mm, so the TRV can accommodate an 18.4R42 R-1 tire with an overall diameter of 1860 mm. The smallest tire that can be used is a 12.4-28 tire, which has an overall diameter of 1260 mm.

The width of the soil in each of the NSDL soil bins is 6.1 m. The range of lateral positions of the test tire[2] (#8 in figure 2) central plane that can be achieved by the TRV is from 1.40 m to 4.60 m to the right of the left edge of the soil in the bin, as viewed when looking in the direction of

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[2] For projects in which a rigid wheel has been used, "test tire" here refers to the rigid wheel.

Figure 1. Traction Research Vehicle (TRV) controlling a single 30.5L-32 forestry drive tire on an outdoor soil bin at the National Soil Dynamics Laboratory. Control panel shown here at the TRV operator station is the panel used before the TRV was updated in 1993. In 1993, this panel was replaced with a smaller control panel and a screen and keyboard for the TRV personal computer. Direction of travel is right to left and the Instrumentation Vehicle is shown being towed behind the TRV. The TRV superstructure is the upper frame with its large I-beams. The diesel engine is mounted to the superstructure and when the tire is raised above the tractive surface, the superstructure can be moved to various lateral positions.

forward travel. In most traction and soil compaction experiments conducted on the soil bins, the minimum lateral spacing from one tire centerline to the next is twice the tire section width.

Input torque for the tire is measured by the torque transducer (fig. 2) and details are described in the Appendix. Dynamic load is measured using the three vertically-oriented load cells. The right-hand end of the torque transducer is mounted to the inner frame (#3 in figure 2), so if input torque is positive, the downward force applied by the Normal Load load cell (#2 in figure 2) must be greater than the dynamic load. Net traction is the sum of the tensile forces measured by the two longitudinal load cells (fig. 2). Each end of the two vertical load cells at the drawbar and the two longitudinal load cells has a rod end bearing attached to allow the load cell to maintain proper alignment and to minimize any moments that the frame members might tend to apply to the load cell. The lower end of the Normal Load load cell has a rod end bearing attached and the upper end is rigidly mounted to a hydraulic cylinder assembly that applies Normal Load. The upper end of this cylinder assembly has an attached rod end bearing, so this arrangement allows

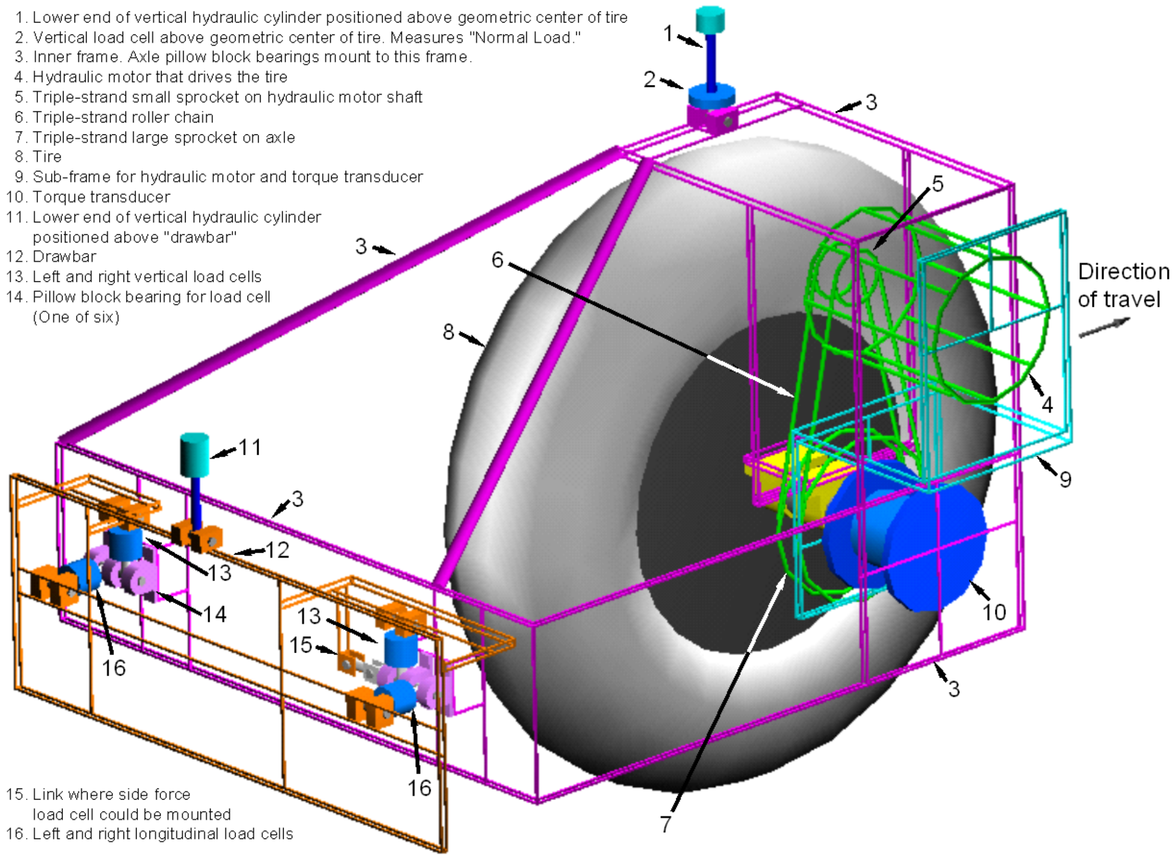

Figure 2. Drawing of the force and torque transducers and the frame assemblies to which they are mounted for the TRV. For clarity, components of frames 3, 9, and 12, and parts 4, 5, and 7 are shown here as stick parts. Actual parts are more substantial as shown in figure 1. The length of link #15 is in the lateral direction.

the load cell to maintain proper alignment and minimizes any moments that the frame members might tend to apply to the load cell. The TRV has no capability for changing the steer angle of the wheel, so the wheel axis of rotation is always in the lateral direction. A lateral link equipped with a rod end bearing at each end (#15 in figure 2) restrains the inner frame from moving laterally. The link could be replaced with a load cell, but this is thought to be unnecessary because the steer angle is always zero.

The TRV was updated in 1993 to replace its pressure-compensated hydraulic system with closed-loop hydrostatic hydraulic systems and newer pressure-compensated pumps, and to replace its electro-hydraulic servo control with personal computer-based digital control. A turbocharged Caterpillar[3] 3306 diesel engine rated at 149 kW (Caterpillar, Inc., Peoria, Ill., USA) on the TRV drives four hydraulic pumps. One pump drives the test tire, one is for the "car drive" which propels the vehicle on the steel I-beam rails of the soil bin, and one is a pressure-

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[3] Mention of trade names or commercial products in this paper is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

compensated pump for controlling tire vertical load. The fourth pump is a pressure-compensated pump to power a boom crane mounted to the TRV for use in removing the test tire wheel from, and mounting a wheel to, the TRV hub. The test tire drive and car drive each have a closed-loop hydrostatic system with an axial piston variable displacement pump equipped with electrical displacement control (EDC). Each of these two pumps drives a fixed displacement hydraulic motor. The test tire hydraulic motor drives a roller chain drive that powers the test tire axle (fig. 2) and the car drive motor drives a roller chain drive that powers the four rear wheels of the TRV's eight wheels that roll on the soil bin rails.

During planning of the 1993 TRV updating, the specifications in table 1 were used as design criteria. The capacity of the Normal Load load cell is 89 kN and the capacity of each of the four load cells (#13 and #16 in fig. 2) at the drawbar (fig. 2) is 44 kN.

Table 1. Wheel and tire variable specifications used when the Traction Research Vehicle was updated in 1993

Variable	Range
Dynamic load, kN	0 - 44
Forward velocity, m/s	0 - 1.0
Wheel angular velocity, rad/s	0 - 1.5
Travel reduction, %	0 - 30
Tire inflation pressure, kPa	0 - 210

Beginning in 1993, the operating system used on the TRV personal computer is the QNX operating system (QNX Software Systems, Ottawa, Ontario, Canada) and the computer has an Intel 80486 processor (Intel Corp., Santa Clara, Cal., USA). The computer program was developed by students in the Auburn University Department of Computer Science and Software Engineering (Auburn, Ala., USA) and by the NSDL staff.

The program that runs on the TRV personal computer has two modes. In its default mode, the two hydrostatic circuits, one for the test tire drive and the second for the car drive, and the tire load hydraulic circuit respond to the joysticks located at the TRV operator station. In the second mode, which is the feedback control mode, the program uses feedback control to control one or more of (a) test tire Normal Load, meaning it controls the downward vertical force applied by the Normal Load load cell to the inner frame (#3 in figure 2), (b) test tire angular velocity, and (c) forward velocity.

For the test tire drive and the car drive, when the default mode of the computer program runs, each joystick provides a DC voltage to the EDC, thereby controlling the displacement of each hydraulic pump. Assuming a constant engine speed, the pump displacement determines the angular velocity of the hydraulic motor driven by the pump. Changing the test tire joystick position therefore changes the angular velocity of the test tire and changing the car drive joystick position changes the travel velocity of the TRV along the soil bin. For safety, both joysticks are equipped with a center lock mechanism, so the operator must lift a collar on the joystick handle before the handle can be moved from the pump zero displacement position. When the handle is in the center lock position, the hydraulic motor does not rotate. If the operator's hand is removed from the joystick, springs in the joystick mechanism return the joystick to the center lock position. Both of the hydrostatic pump-motor systems allow bidirectional rotation of the motor, so the test tire joystick can be used to rotate the test tire in both the forward and reverse directions and the car drive joystick can be used to move the TRV both forward and rearward. For the tire load, when the default mode of the computer program runs, a third joystick can be used to manually move the test tire up and down, and to apply vertical load of the tire on the soil without feedback control. When the default mode of the program runs, if the operator is not using the tire load joystick, the program and electronics are designed to gradually move the test tire up to the highest position allowed by the hydraulic cylinders that control tire load. Whether the computer program is in the default mode or the feedback control mode, the program controls the elevation of the drawbar (fig. 2) to keep the elevation of the two longitudinal load cells at the same elevation of the test tire axle center. In so doing, the Normal Load load cell (fig. 2) is kept vertically oriented directly above the axle center. To achieve this, the control system monitors a cable-extension potentiometer that measures the vertical position of a point that is on the inner frame (fig. 2) above the axle centerline, and a second cable-extension potentiometer measures the vertical position of the drawbar. The control system uses these inputs to adjust hydraulic cylinder #11 (fig. 2) to control the height of the drawbar. This system maintains proper orientation of the load cell system when the vertical position of the test tire changes due to sinkage.

A Modcomp 7870 minicomputer (Modcomp Inc., Deerfield Beach, Fla., USA) in the Instrumentation Vehicle (fig. 1) was used as part of the data acquisition and feedback computer control system of the TRV before the TRV was updated in 1993 and is used following the 1993 updating. After the 1993 updating, the feedback control mode of the TRV is able to be run using the program running on the TRV personal computer without the Instrumentation Vehicle being part of the system. In this case, however, the accuracy with which tire angular velocity, tire dynamic load, and forward velocity can be controlled is limited, and there is no provision for saving tractive performance data. From the beginning of the planning for the 1993 updating and throughout that updating, we planned to have the Modcomp minicomputer in the Instrumentation Vehicle work in conjunction with the personal computer feedback control system of the TRV. This plan was successfully implemented, so the Modcomp minicomputer and personal computer feedback control system of the TRV provide an overall computer control of (a) forward velocity, (b) dynamic load, and (c) either travel reduction or net traction in any given tire run. This overall computer control is capable of controlling each of these variables at a constant level and is able to ramp dynamic load similar to the ramp mode described by Lyne et al. (1983). The minicomputer alone controls tire inflation pressure.

The program that runs on the TRV personal computer is written in the C language and part of the program is a proportional-integral-derivative (PID) controller. When the TRV was updated in 1993, various proportional, integral, and derivative control coefficients were tried and the system was found to perform well with the derivative coefficient set equal to zero, so the controller operates as a proportional-integral (PI) controller. For each of the controlled variables other than tire inflation pressure, the minicomputer provides the TRV personal computer with an error value, telling the personal computer how the controlled variable deviates from the set point for that variable. The TRV personal computer feedback control program then commands the EDC devices, which control the wheel drive and car drive, and the electronics that control the hydraulics for tire load, to respond, to reduce the errors. So, the PI controller of the TRV personal computer and the data acquisition and control program on the minicomputer run simultaneously during this overall minicomputer-personal computer feedback control. The minicomputer program uses a sampling and controlling rate of 33 Hz, so it generates error values at 33 Hz for the TRV personal computer to use. We chose this rate because it provides reasonably accurate feedback control, and allows the minicomputer to simultaneously perform the other tasks that need to be performed.

The zero conditions (*ASABE Standards*, 2009) used at the NSDL for determining the tire rolling radius that is used in travel reduction calculations typically consist of the tire operating at zero net traction on concrete. One of the NSDL outdoor soil bins has a concrete pad along the inner edge of the bin. We typically determine the rolling radii for a range of dynamic loads. This is done by using the computer control to control the net traction to be zero and to ramp-up (increase) the dynamic load from a relatively low value such as 3 kN, to a value that is about 5 kN greater than the maximum dynamic load we plan to use in the experiment to be conducted on soil. The computer control is designed to ramp-up dynamic load linearly as the distance of TRV forward travel increases.

The overall minicomputer-personal computer feedback control has been used for nearly all traction and soil compaction research projects conducted using the TRV following its updating in 1993. This overall computer control system stores data on the minicomputer hard disk. A personal computer in the Instrumentation Vehicle interfaces with the minicomputer, allowing the operator in the Instrumentation Vehicle to run the minicomputer program and to transfer data from the minicomputer hard disk to the personal computer hard disk and floppy disks. This program that runs on the personal computer in the Instrumentation Vehicle is written in the C language and was also developed by students in the Auburn University Department of Computer Science and Software Engineering and by the NSDL staff. The operating system on the personal computer is Microsoft DOS 6.2 (Microsoft Corporation, Redmond, Wash., USA) and the program allows the operator to have the minicomputer system take "biases" (described below). The program also allows the operator to input set points for use by the minicomputer system, to have the minicomputer system use its feedback control mode, and to use the personal computer to graphically display data collected during a test tire run.

The TRV has a rotating pneumatic coupling (not shown in figure 1) that allows controller air valves on the TRV frame that do not rotate with the tire to deliver air to the tire to increase inflation pressure or remove air from the tire to decrease inflation pressure, for on-the-go control of test tire inflation pressure. A pneumatic quick coupling allows the TRV operator to easily disconnect a hose that is connected to the tire inflation pressure system, from the pressure transducer that measures the inflation pressure of the test tire. Before each data collection run of a test tire on the tractive surface, with the TRV stationary, the TRV operator disconnects this quick coupling, so the pressure transducer is then subjected to atmospheric pressure. The minicomputer operator then uses the minicomputer and its associated signal conditioning system to take a "bias" on the pressure sensor. When this "bias" is taken, the minicomputer program considers that pressure reading to be 0 kPa inflation pressure. The hose is then reconnected to the pressure transducer. The overall computer control is then activated, meaning the TRV computer program is running and is in the feedback control mode, and the minicomputer program is running. With the tire raised to its maximum height and the drawbar height control system maintaining proper orientations of the five load cells, and while the TRV is stationary and the tire angular velocity is zero, the minicomputer operator uses the minicomputer and its associated signal conditioning system to take a "bias" on the five load cells and the torque transducer. When this "bias" is taken, the minicomputer program considers the readings taken to be values of 0 kN force for each of the load cells and 0 kN-m torque for the torque transducer. Therefore, after the "bias" is taken, as the tire operates during the run, the indicated forces and torques in the data are values relative to the forces and torque that existed when the "bias" was taken.

The diesel engine and pumps of the TRV are mounted to the superstructure (fig. 1) and the hydraulic motor for the test tire drive is mounted to the TRV inner frame (#3 in fig. 2). Hydraulic hoses convey the hydraulic oil between the pump for the test tire drive and the test tire hydraulic motor. After the "bias" of the transducers is taken and before data acquisition begins during the tire run, with the TRV traveling forward and the tire rotating, the tire is lowered down onto the tractive surface. This lowering of the tire causes the hydraulic hoses for the test tire drive to flex as the inner frame moves down. Any change in the forces and moments applied by these hoses to the inner frame while the tire is running on the soil, relative to the forces and moments present during the "bias", are included in the load cell and torque transducer data. The curved portions of these hoses have relatively large radii of curvature of about 300 mm. The forces and moments applied by the hoses to the inner frame are thought to be relatively constant as the inner frame moves up and down, so the influence of this hose flexing on the force and torque data is thought to be small.

The TRV with the minicomputer and its signal conditioning system is set up with the following sign convention. For each of the three vertically-oriented load cells (load cell #2 and the two labeled as #13 in figure 1), the force data become more positive as the compressive load on the load cell increases. For each of the two longitudinally-oriented load cells (the two labeled as #16 in figure 1), the force data become more positive as the tensile load on the load cell increases. For the torque transducer, the torque data become more positive as the input torque driving the tire in the counterclockwise direction, when viewed from the left side of the tire, increases.

Dynamic load is calculated as:

$$DL = NL - V1 - V2 \tag{1}$$

where:

DL = Dynamic load (kN)

NL = Force measured by the Normal Load load cell (#2 in figure 1) (kN)

V1 and V2 are the forces measured by the left and right vertical load cells just forward of the drawbar (the two labeled #13 in figure 1) (kN).

Net traction is calculated as:

$$NT = L1 + L2 \tag{2}$$

where:

NT = Net traction (kN)

L1 and L2 are the forces measured by the left and right longitudinal load cells just forward of the drawbar (the two labeled #16 in figure 1) (kN).

The test tire angular velocity is calculated from signals generated by a shaft encoder equipped with a rubber wheel about 25 mm in diameter that rolls against a cylindrical external portion of the hydraulic motor that drives the test tire. A non-pneumatic rubber wheel rolls on a steel rail of the soil bin and serves as the fifth wheel for the TRV. The outside diameter of the wheel is 300 mm and a shaft encoder rotates as the fifth wheel rotates and provides the minicomputer system and TRV personal computer system with forward velocity and travel distance data.

For nearly all research projects conducted using the TRV since its updating in 1993, a constant forward velocity of 0.15 m/s has been used. For controlled travel reduction runs, the travel reduction has been set to be a constant value throughout the run and for controlled net traction runs, the net traction has been set to be a constant value throughout the run.

In one project, the TRV wheel drive was modified to attain a relatively high wheel angular velocity. The purpose of the project was to determine sliding velocity effects on the coefficient of friction of rubber on soil (Plyler, 2002). A cylindrical steel wheel with rubber sheeting glued to its periphery was mounted on the TRV. The wheel outside diameter was 1370 mm and the width was 305 mm. We wanted to achieve rubber-on-soil sliding velocities up to 3.5 m/s, so we replaced the driven triple strand sprocket (#7 in figure 2) with a smaller diameter sprocket. The hydraulic motor of the wheel drive has two displacement settings, so to attain a greater motor maximum angular velocity, we changed the setting from the normal large displacement one to the low displacement setting. The wheel angular velocity was sufficient to provide sliding velocities up to 3.5 m/s while the TRV forward velocity was 0.15 m/s, resulting in a maximum travel reduction of 96%.

2.1 Test Tire Run with Constant Dynamic Load and Constant Travel Reduction

The TRV operator station includes the keyboard, mouse, and display for the TRV personal computer, and a control panel equipped with momentary switches. The following procedure is used for each tire run in which the overall computer control is used to attain constant dynamic load and constant travel reduction. The procedure for a constant net traction run has some small differences.

1. The minicomputer operator uses the minicomputer and its associated signal conditioning system to take a "bias" on the test tire inflation pressure transducer. With the TRV engine running, the test tire in its raised position, and the TRV personal computer controlling the elevation of the drawbar to keep the elevation of the two longitudinal load cells at the same elevation of the test tire axle center, the minicomputer system is used to take a "bias" on the five load cells and the torque transducer as described above. The TRV operator enters, to the TRV personal computer program, the set points for the angular velocity and dynamic load of the test tire, and the TRV forward velocity. The system uses these set points at the beginning of the test, until the TRV operator initiates overall computer control in step 5 below.
2. The minicomputer operator starts the data acquisition and control program on the minicomputer running. The program asks the operator for inputs including the tire rolling radius, the dynamic load set point, the forward velocity set point, the travel reduction set point, and the tire inflation pressure set point. The tire rolling radius would have been determined previously in a rolling radius run. When the last of these set up inputs is entered, the program begins feedback control of tire inflation pressure.
3. With the tire in its raised position and while the TRV and the test tire are still stationary, the TRV operator presses a momentary switch on the TRV operator panel to start rotation of the test tire, counterclockwise as viewed from the left side of the tire. At this point, the tire rotation is

being controlled by the feedback control system of the TRV personal computer, and the minicomputer has not yet started controlling tire angular velocity.

4. The TRV operator presses a momentary switch to start forward travel of the TRV. The TRV then smoothly accelerates from rest to a velocity that is close to the value of forward velocity that the minicomputer operator entered in the minicomputer program for this run.
5. The TRV operator presses a momentary switch that causes the overall computer control of dynamic load and travel reduction to start, so the minicomputer begins calculating tire dynamic load using equation 1 and begins calculating travel reduction, and begins providing error values of tire Normal Load and tire angular velocity to the TRV personal computer. During this feedback control of tire Normal Load and tire angular velocity, the TRV personal computer program adds the error value to its current reference input, so feedback control of dynamic load and travel reduction are achieved by the combination of the TRV personal computer system and error values provided by the minicomputer.
6. The TRV operator uses the tire load joystick to lower the tire to get the tire within a few cm of the tractive surface or to get the tire to apply a few kN of load to the tractive surface. The TRV operator then presses a momentary switch to begin minicomputer feedback control of dynamic load.
7. When the tire seems to have achieved a constant level of sinkage into the soil or a constant deflection if it is running on concrete, the TRV operator instructs the minicomputer operator to press a momentary switch at the minicomputer operator station to begin collecting data.
8. Starting here, the TRV operator only observes the tire and TRV, and the minicomputer operator observes the data as they are displayed in real time on the personal computer screen in the Instrumentation Vehicle.
9. When the tire has traveled the desired distance, the TRV operator instructs the minicomputer operator to press a momentary switch to cease collecting data.
10. The TRV operator then presses a momentary switch that causes the TRV to stop applying downward force on the tire and to begin raising the tire up from the tractive surface, to decelerate forward velocity to zero, and to decelerate the tire angular velocity to zero.
11. The minicomputer operator saves the data from this tire run to the minicomputer hard disk.

2.2 TRV Safety Features

Included on the TRV operator control panel is a red emergency stop switch to stop the TRV engine, in case the engine or TRV ever need to be stopped quickly. Operation of the switch is described in the Appendix.

During overall computer control, the minicomputer program controls the controller air valves that control tire inflation pressure. When computer control of tire inflation pressure is not in use, two hand-operated ball valves at the TRV operator station allow the TRV operator to increase or decrease inflation pressure. If computer control of inflation pressure malfunctions or if the hand-operated valves are used improperly, the tire inflation pressure could increase above the desired level. To safeguard against inflating the tire to an unsafe level, the tubing through which air is delivered to the tire is equipped with a pressure relief valve. The pressure relief valve is set to release air if the pressure exceeds 240 kPa, so this reduces the possibility for overinflating the tire. The flow of air through the relief valve is loud enough to be heard above the TRV engine noise, and this enhances the pressure relief safety feature, as this noise serves as an audible warning.

2.3 Tractive Performance Data

The TRV has been used in several traction and soil compaction research projects following the TRV updating in 1993. Figures 3 and 4 show some tractive performance data from one run of a radial-ply tractor drive tire on the NSDL Norfolk sandy loam soil bin from the experiment described in Way et al. (1997). The minicomputer was set up to collect data from all transducers

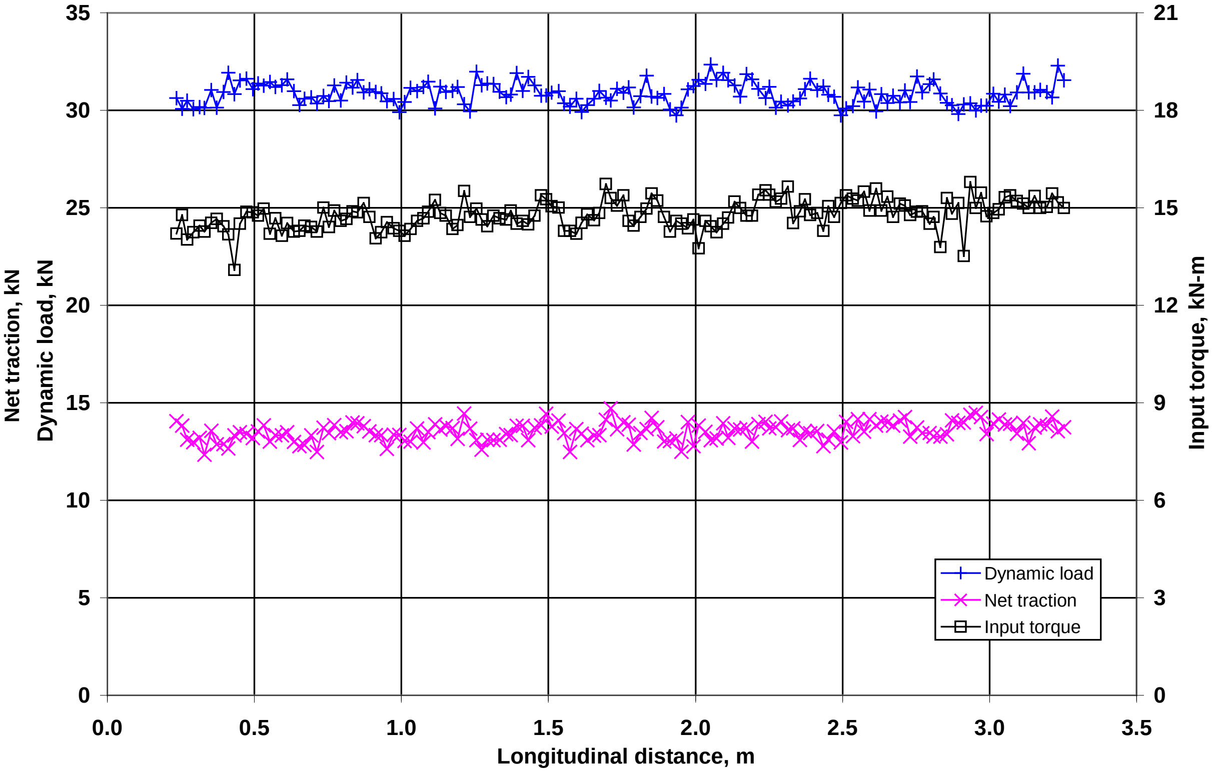

Figure 3. Net traction, dynamic load, and input torque data from a typical steady-state tire run. Tire was a Goodyear DT 820 650/75R32 167A8[4] R-1W radial-ply tractor drive tire (Goodyear Tire & Rubber Company, Akron, Ohio, USA). The computer control set point for dynamic load was 30.9 kN and the set point for travel reduction was 10%. Means for the net traction, dynamic load and input torque data shown here are 13.5 kN, 30.9 kN, and 14.8 kN-m, respectively and standard deviations are 0.463 kN, 0.553 kN, and 0.443 kN-m, respectively. Data here are from one of the four replications of the 30.9 kN dynamic load and 120 kPa inflation pressure combination for this tire on the loose Norfolk sandy loam soil overlying a hardpan in the experiment described by Way et al. (1997).

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[4] Load Index = 167 and Speed Symbol = A8.

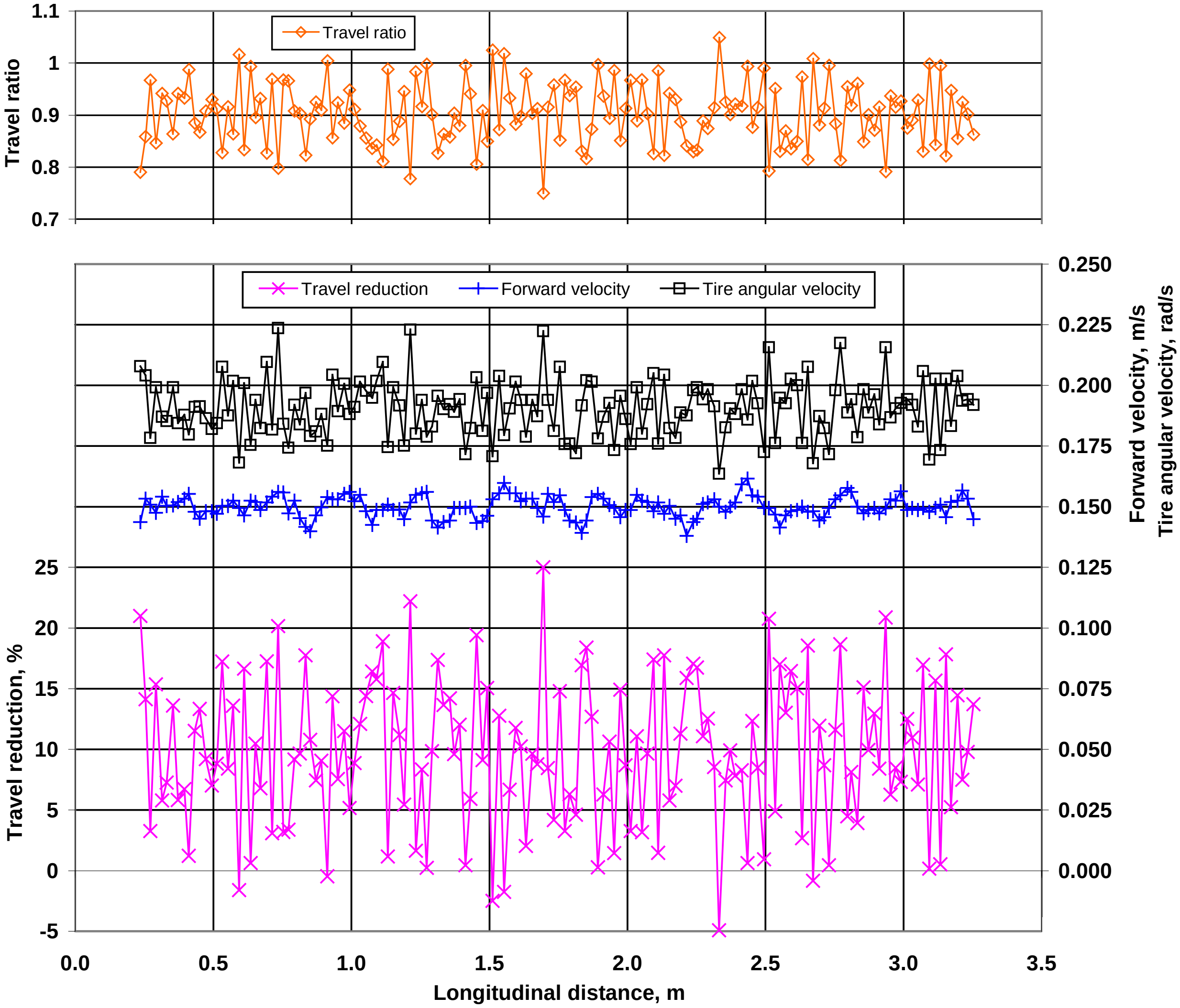

Figure 4. Travel reduction, forward velocity, tire angular velocity, and travel ratio for the steady-state tire run described in figure 3. Means for the travel reduction, forward velocity, tire angular velocity, and travel ratio data shown here are 9.71%, 0.150 m/s, 0.191 rad/s, and 0.903, respectively, with standard deviations of 6.01%, 0.0043 m/s, 0.0118 rad/s, and 0.060, respectively.

once per 20 mm of TRV distance traveled. A constant rolling radius value was used throughout the run for the particular tire, dynamic load, and inflation pressure used in the run. The tire inflation pressure set point for this run was 120 kPa. The mean inflation pressure (data not shown) for this run was 119.7 kPa and the standard deviation was 0.45 kPa.

Three variables (dynamic load, forward velocity, and travel reduction) of the six variables graphed in figures 3 and 4 are controlled by the TRV feedback control system. The minicomputer program contains the set point for travel reduction, which is 10% for this case, and the minicomputer provides an error value to the TRV personal computer control system, telling the system the amount by which the test tire angular velocity should be changed to achieve the desired travel reduction. The net traction and input torque data depend largely upon the tire angular velocity, the dynamic load, and the soil condition. As the tire travels on the soil, differences in the condition of the soil encountered by the tire during the tire run contribute to variability in net traction and input torque, which are uncontrolled variables.

Coefficients of variation for the net traction, dynamic load, and input torque data shown in figure 3 are 3.4%, 1.8%, and 3.0%, respectively. The travel ratio is the ratio of forward velocity to the product of angular velocity and tire rolling radius (*ASABE Standards*, 2009). Coefficients of variation for the travel reduction, forward velocity, tire angular velocity, and travel ratio data shown in figure 4 are 61.9%, 2.8%, 6.2%, and 6.7%, respectively. The small coefficient of variation for dynamic load demonstrates the very good computer control of dynamic load. The small coefficients of variation for net traction and input torque likely resulted from the small coefficients of variation for tire angular velocity and dynamic load, and the relatively consistent soil condition along the length of the tire run.

The relatively large variability in the travel reduction data shown in figure 4 and given by the 61.9% coefficient of variation, is typical of travel reduction data collected with the TRV. Travel reduction equals (1 - Travel Ratio) and importantly, the coefficient of variation of for the travel ratio was only 6.7%. So, the relatively high coefficient of variation for travel reduction was simply caused by the way travel reduction is calculated and it is important to realize that the coefficient of variation for the travel ratio, a variable used in calculating travel reduction, was relatively small. The mean travel reduction for this run, 9.71%, was quite close to the set point of 10%. This small difference of the mean travel reduction from the set point is typical of the closeness of the travel reduction mean to the set point for other experiments conducted using the TRV. The relatively small coefficients of variation of 2.8% and 6.2% for forward velocity and tire angular velocity, respectively, demonstrate the very good computer control of these variables.

3. ALL-TERRAIN VEHICLE (ATV) TIRE TRACTION RESEARCH MACHINE FOR USE ON SOIL BINS

A project was conducted to determine traction and motion resistance characteristics of all-terrain vehicle (ATV) tires. The load cell capacities, the lowest attainable axle height, and the wheel hub diameter of the TRV were too great for ATV tires. Therefore, we designed and constructed a single wheel traction research machine for ATV tires, and mounted the machine to the TRV (fig. 5 and 6).

The machine is designed for a maximum tire overall diameter of 690 mm, a maximum section width of 280 mm, and a maximum dynamic load of 2.7 kN. The capacity of each of the six load cells shown in figure 7 is 2.2 kN. The side force load cell is in the same vertical-lateral plane as the two vertical load cells and the axle centerline. The two longitudinal load cells, the side force load cell, and the axle centerline are all in the same horizontal plane. The torque load cell is oriented vertically and its centerline is in the central plane of the tire. The ATV tire machine has no capability for changing the steer angle of the wheel, so the tire axis of rotation is always in the lateral direction.

Figure 5. Left side view of all-terrain vehicle (ATV) single wheel traction research machine mounted to the TRV, operating a single ATV tire on firm Norfolk sandy loam soil. Direction of travel is right to left. TRV components that are orange here are gray in figure 1.

Figure 6. Left side view of ATV single wheel traction research machine equipped with a 25x10-12 ATV tire, with the tire in the raised position at the completion of a tire pass on loose Norfolk sandy loam soil. Direction of travel is right to left. Blue circular disk this side of the ATV tire is a spool mounted to the wheel axle and the cables shown unwrapping from the spool connect soil-tire interface pressure sensors that are mounted on the tire, to analog input channels of the data acquisition system. Soil-tire interface pressure sensors are similar to those described in Way and Kishimoto (2004).

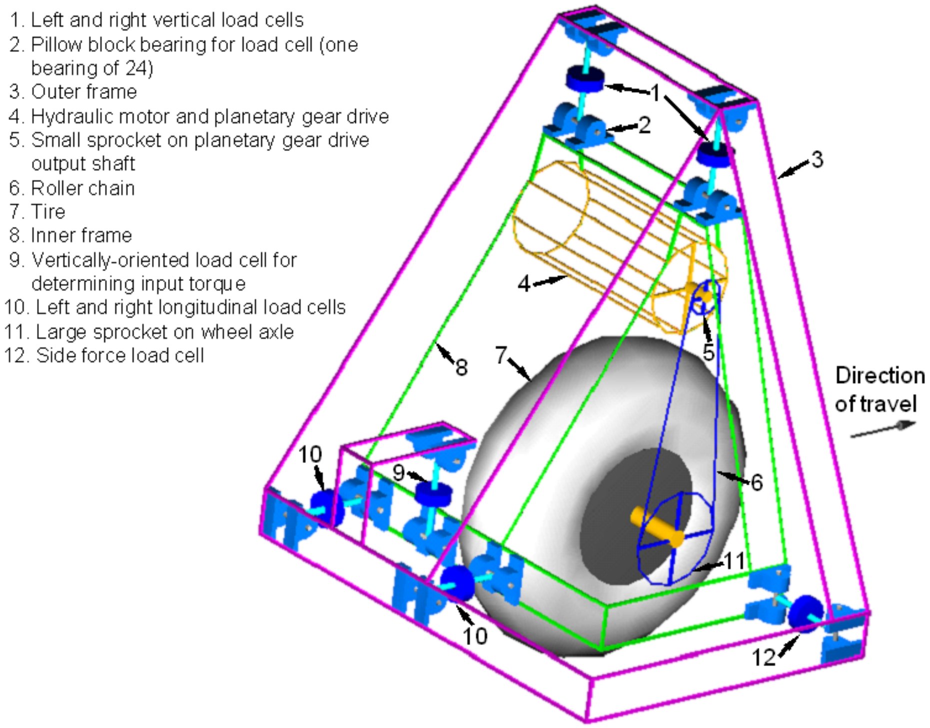

Figure 7. Drawing of the force and torque transducers and the frame assemblies to which they are mounted for the all-terrain vehicle (ATV) single wheel traction research machine. For clarity, components of frames 3 and 8, and parts 4, 5, and 11 are shown here as stick parts. Actual parts are more substantial as shown in figure 6. Axle is held by two pillow block bearings (not shown) mounted to the inner frame.

An axial piston fixed displacement hydraulic motor on the machine powers the ATV tire (fig. 7). The motor is powered by the TRV hydraulic pump that normally drives the TRV wheel drive, so the ATV tire angular velocity can be controlled using a joystick at the TRV operator station. The motor drives a planetary gear reduction drive that drives a roller chain drive, which in turn, powers the ATV tire axle. The TRV car drive is used for propelling the TRV.

Dynamic load for the ATV tire machine was achieved through deadweight loading, meaning the vertical load of the tire on the soil depends on the weight of the tire tester components, and that no external forces are applied to the components by a powered loading device such as a hydraulic cylinder. For the ATV tire machine, the yellow linkage in figure 5 is a four-bar parallel linkage and the axes of its four pivoting joints are in the lateral direction. The linkage allows the gray frame, which is the outer frame in figure 7, to move in translation, but does not allow it to rotate about a lateral, longitudinal, or vertical axis. Two of the pivot axes of the parallel linkage are located just forward of the gray rear vertical member of the outer frame (fig. 5) and the other two are just forward of the vertical yellow member at the rear of the parallel linkage.

A hydraulic cylinder was mounted so it extended down from its upper pivot point on the TRV superstructure (fig. 1) to a short chain attached to its lower end. The lower end of the chain connected to the upper end of a 4.4 kN capacity load cell and the lower end of that load cell connected to the top end of the outer frame (#3 in figure 7). The load measured by this load cell when the ATV tire was raised up in the air, was the load supported by the tire during the traction or motion resistance run. When the tire was run on the tractive surface, the hydraulic cylinder was extended and the chain became slack, so the chain and cylinder did not support any load. The hydraulic cylinder was controlled by a joystick at the TRV operator station.

For a single wheel machine that depends on deadweight loading, the pivoting links that maintain the proper orientation of the machine, such as the upper and lower links of the parallel linkage in figure 5, should apply no vertical force to the tire. This is described in the Appendix. In the configuration shown in figure 5, this means the horizontal links of the parallel linkage should remain horizontal. For the ATV tire machine, this was achieved by mounting the rear vertical link of the parallel linkage to the TRV drawbar (fig. 2). A cable-extension potentiometer was used to measure the vertical position of the ATV tire machine outer frame. The TRV control system then used that measurement and the drawbar vertical position measurement made by the second cable-extension potentiometer, to keep the upper and lower links of the four-bar parallel linkage horizontal.

Attached to the upper side of the upper yellow link of the parallel linkage in figure 5 is a black beam that extends to the rear of the upper rear pivot axis of the linkage. A black bracket hanging from the rear end of this beam holds the two solid steel pieces shown in figure 5. These pieces served as counterweights to reduce the dynamic load. A threaded rod mechanism provides adjustable longitudinal movement of the counterweight mounting location on the black beam, allowing adjustment of the reduction in dynamic load.

We wanted to conduct the ATV tire traction runs using a relatively constant travel reduction of 10%. We did not develop computer control of the ATV tire angular velocity, so the angular velocity was controlled by the TRV operator manually positioning the joystick at the operator station. We used the TRV personal computer control to control forward velocity. To attain travel reduction close to 10%, the TRV operator watched the tire as it ran on the soil and attempted to use a tire angular velocity joystick setting that caused the tire tread at the contact patch to just barely appear to move rearward relative to the soil. We did not use computer control of tire inflation pressure, so instead, we set the tire inflation pressure at the beginning of each run, when the tire was in the raised position, not in contact with the tractive surface.

The NSDL Instrumentation Vehicle with its minicomputer (fig. 1) was not used with the TRV when the ATV tire machine was used. Instead, a SoMat Model 2100 Field Computer System (SoMat Corporation, Champaign, Ill., USA) connected to a laptop personal computer was used for signal conditioning and data acquisition for the ATV tire runs. The SoMat system was connected to the six load cells of the ATV tire machine, the single load cell above the ATV tire, a shaft encoder mounted to the small drive sprocket (#5 in figure 7) for calculating tire angular velocity, and the shaft encoder of the TRV fifth wheel for forward velocity.

3.1 Tractive Performance Data

The ATV single wheel traction research machine has been used for determining traction and rut depth characteristics of ATV tires. Motion resistance (*ASABE Standards*, 2009) characteristics of ATV tires have been determined by disconnecting the roller chain drive that goes between the planetary gear drive sprocket and the sprocket on the ATV tire axle, and using the machine to push the rolling tire forward while measuring the pushing force sensed by the two longitudinal load cells.

Coefficients of variation for the net traction and input torque data shown in figure 8 are 9.0% and 5.8%, respectively. Coefficients of variation for the travel reduction, forward velocity, and tire angular velocity data shown in figure 9 are 29.4%, 2.5%, and 1.4%, respectively.

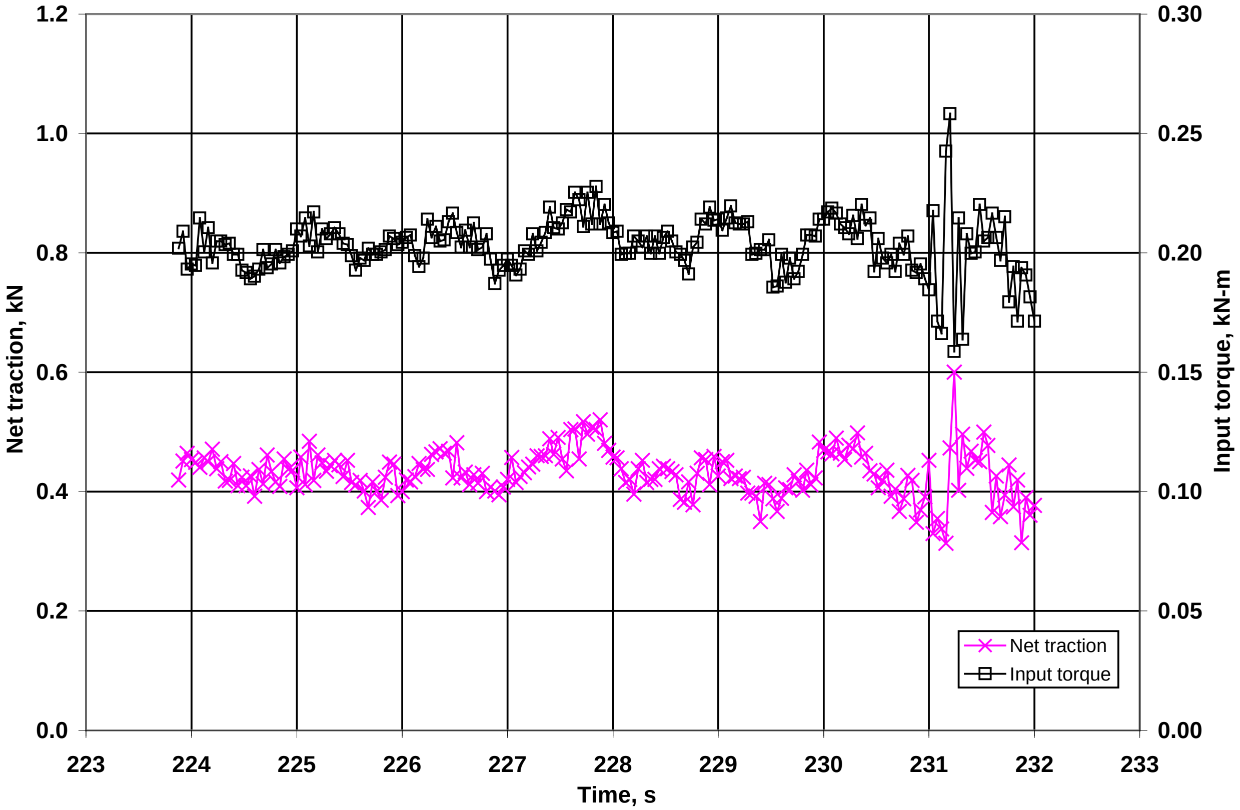

Figure 8. Net traction and input torque data from a typical steady-state tire run. Tire was a Goodyear Tracker Mud Runner 25x10-12 ATV tire. The dynamic load was 2.04 kN, inflation pressure was 50 kPa, and the target travel reduction was 10%. Means for the net traction and input torque data shown here are 0.431 kN and 0.203 kN-m, respectively and standard deviations are 0.0387 kN and 0.0118 kN-m, respectively.

4. SINGLE WHEEL TRACTION RESEARCH MACHINE FOR USE IN THE FIELD

The NSDL Wide Frame Tractive Vehicle (WFTV) gantry was developed for controlled-traffic research (Monroe and Burt, 1989). The WFTV is a heavy, powerful machine that spans a 6 m wide field lane, so the vehicle serves well as a mobile platform to which a single wheel traction

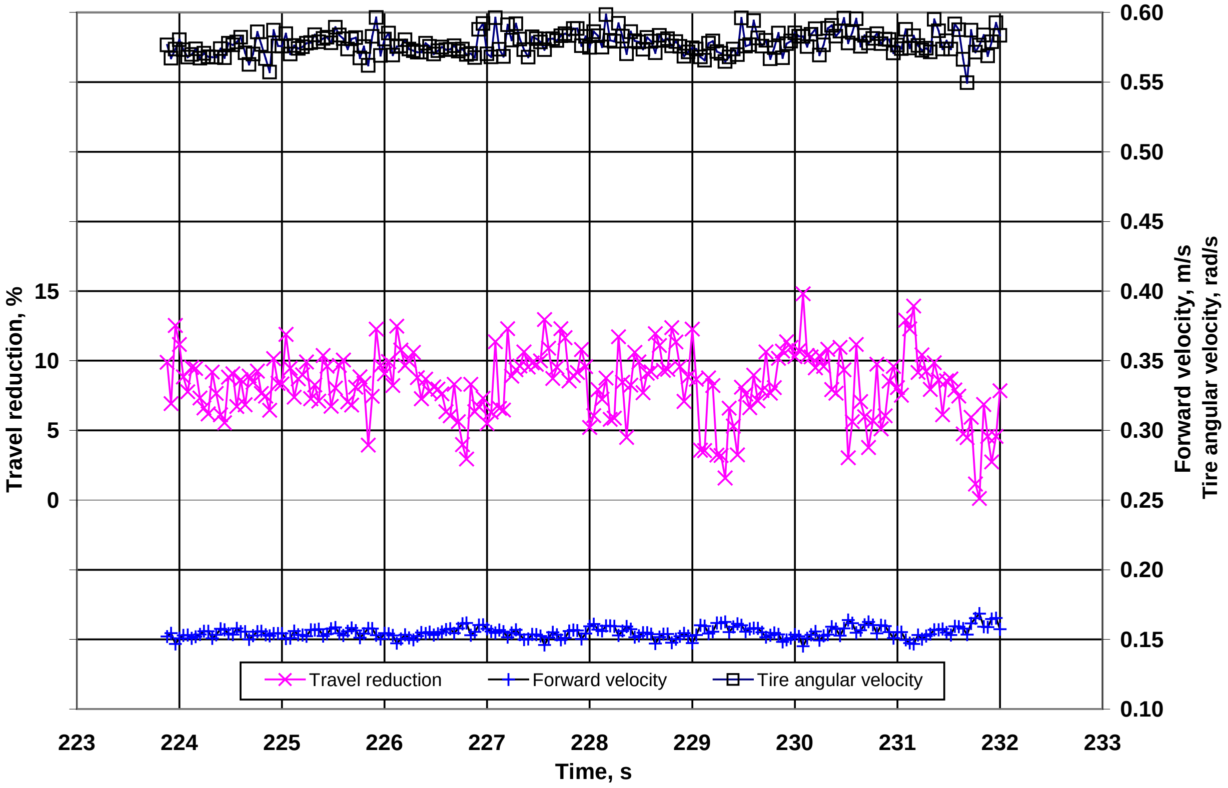

Figure 9. Travel reduction, forward velocity, and tire angular velocity for the steady-state tire run described in figure 8. Means for the travel reduction, forward velocity, and tire angular velocity data shown here are 8.29%, 0.155 m/s, and 0.578 rad/s, respectively, with standard deviations of 2.44%, 0.0039 m/s, and 0.0079 rad/s, respectively.

research machine can be mounted. A single wheel Traction Research Machine (TRM) that mounts to, and is powered by, the WFTV was developed to provide for traction and soil compaction research in field conditions (fig. 10). This TRM was designed for use with computer control, similar to the computer control capabilities of the NSDL soil bin Traction Research Vehicle. Development of the TRM was ceased, so to date, computer control of dynamic load has been achieved, but computer control of travel reduction or net traction, and tire inflation pressure have not been completed. The TRM was run for a field demonstration in 1993, but has not been used since, and no tractive performance data have been collected using the machine. During the demonstration the machine was run using its joysticks to control tire vertical load, tire angular velocity, and tire steer angle. The steer angle of the wheel on the TRM can be varied from straight-ahead travel (0°) to 30° to the left of straight-ahead travel.

The load cell system includes an instrumented drum containing a fixed displacement axial piston hydraulic motor and a planetary gear reduction drive, with the motor driving the planetary gear drive input shaft (fig. 11). The wheel axle is the output shaft of the planetary gear drive.

The computer control system that controls dynamic load uses the sum of the three vertically-oriented load cells (#8 and #10 in figure 11) as its measurement of dynamic load. The system then adjusts the downward force applied by the hydraulic cylinder positioned above the geometric center of the tire (#1 in figure 11), thereby changing the hydraulically-applied load to

Figure 10. Front view of the Traction Research Machine mounted to the Wide Frame Tractive Vehicle. Direction of forward travel is from background to foreground.

attain feedback control of dynamic load. Unlike the deadweight-loaded ATV tire machine, for which the fore-aft tilt of the four-bar parallel linkage affects dynamic load when net traction is not zero, the feedback control of dynamic load on the TRM causes dynamic load to be unaffected by the pitch of the upper and lower links of the parallel linkage.

The largest tire overall diameter that will fit on the machine is 2180 mm. To minimize any moment applied to the four-bar parallel linkage about a longitudinal axis, the machine is designed to have the geometric center of the tire or multiple wheel set positioned directly beneath the hydraulic cylinder (#1 in figure 11). The maximum section width of the tire or overall width of a set of tires operated by the machine is 865 mm. The smallest tire that will fit is a 12.4-28 tire. Performance specifications used in developing the TRM are shown in table 2.

Table 2. Performance specifications used in developing the Traction Research Machine

Variable	Range
Dynamic load, kN	0 - 66
Forward velocity, m/s	0 - 3.6
Wheel angular velocity, rad/s	- [1]
Travel reduction, %	0 - 30
Tire inflation pressure, kPa	0 - 210

[1] Development of the machine was stopped before wheel angular velocity criteria were specified.

The WFTV runs more smoothly and with better traction on prepared traffic lanes like the sod lanes just outside the edges of the tilled soil in figure 10, as compared to softer tractive surfaces. When the WFTV is stationary, and the test tire is raised above the tractive surface, the black frame of the TRM (fig. 10) can be moved laterally relative to the WFTV, so the test tire can be positioned at various lateral positions in the tilled soil in figure 10.

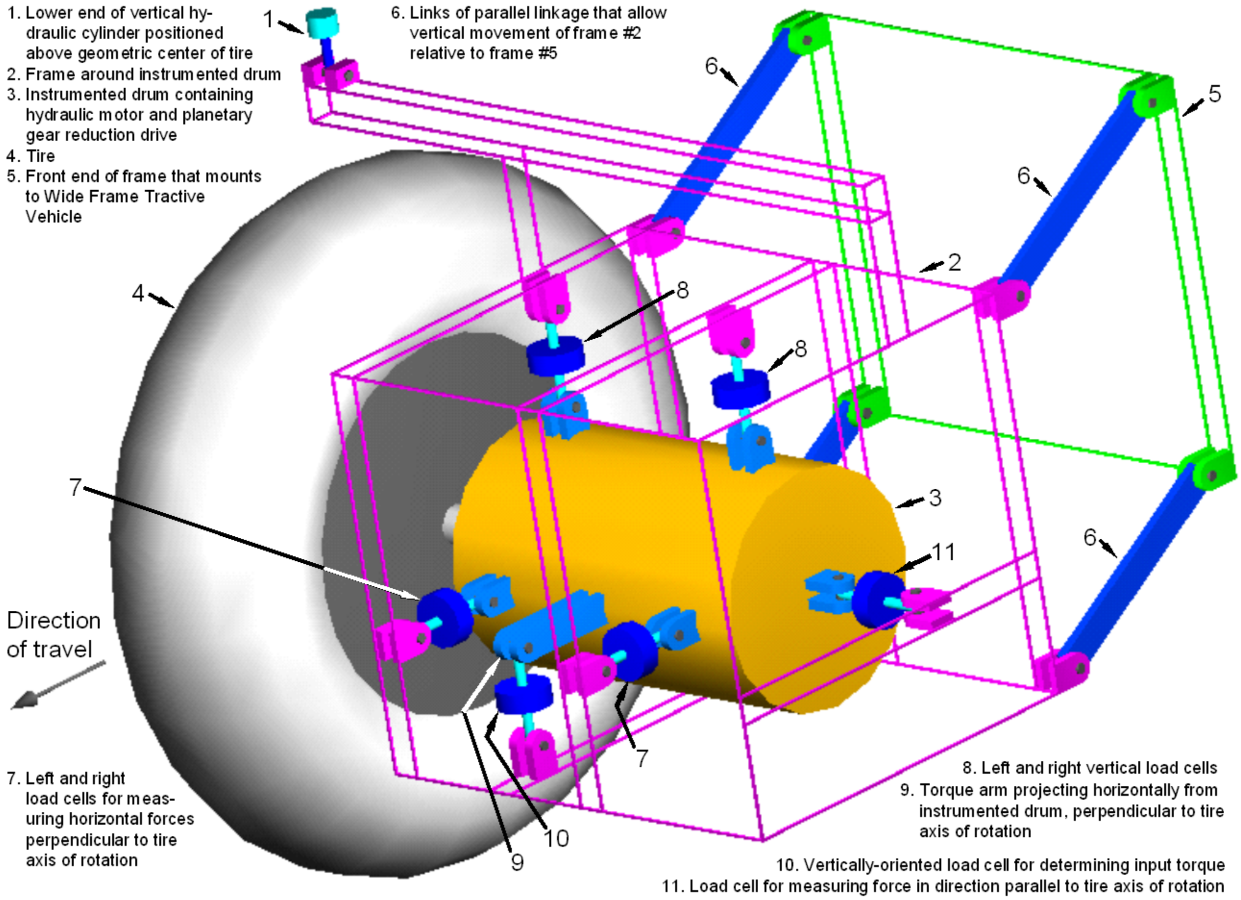

Figure 11. Drawing of the force and torque transducers and the frame assemblies to which they are mounted for the Traction Research Machine that mounts to the Wide Frame Tractive Vehicle. For clarity, components of frames 2 and 5 are shown here as stick parts. Actual parts are more substantial as shown in figure 10. Direction of travel shown here depicts direction of travel when the tire steer angle is zero, meaning the tire central plane is parallel to the direction of travel. A frame member (not shown) extends laterally between the two upper #6 links, so they pivot as one assembly, and the same is true for the two lower #6 links, so these #6 links resist rotation of frame #2 about a longitudinal axis.

5. CONCLUSIONS

Three single wheel machines for traction and soil compaction research have been developed at the USDA-ARS National Soil Dynamics Laboratory. The Traction Research Vehicle has been used extensively for soil bin traction and soil compaction experiments. The all-terrain vehicle (ATV) tire single wheel machine has been used in determining traction and motion resistance characteristics of ATV tires in soil bins. A single wheel traction research machine designed for use in the field has been developed, but computer control has not been completed.

6. ACKNOWLEDGMENTS

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8. APPENDIX

8.1 TRV Torque Transducer

The TRV torque transducer arrangement is described by Burt et al. (1980) as a reaction-type torque dynamometer. Figure 2 herein shows the torque transducer (#10) with its left face mounted to the sub-frame for the hydraulic motor (#9) and its right face mounted to the inner frame (#3). The lateral axis of the torque transducer is collinear with the wheel axis of rotation and the right-hand end of the wheel axle extends into the left end of the torque transducer. A bearing within the left end of the transducer allows the axle to rotate within the transducer while insuring that the transducer will not move vertically or longitudinally relative to the axle and that any rotation of the transducer and sub-frame #9 about a lateral axis will be about the axle axis of rotation. The arrangement insures that any torque applied to the axle or tire about the axle axis of rotation, by anything other than the tractive surface, must be applied by the component group comprised of the sprockets and chain (#4, #5, #6), and the sub-frame (#9). The right-hand end of this group of components is mounted to the left-hand end of the torque transducer, so any torque applied by this group to the axle, about the axle axis of rotation, is measured by the torque transducer.

8.2 TRV Engine Emergency Stop Switch

The TRV engine emergency stop switch causes a solenoid valve in a tube connected to the TRV engine oil system, to open. The valve is closed during normal engine operation, so during normal operation, the engine oil pressure is sensed by the engine's oil pressure-sensing safety system, and this allows the engine to run. When the valve is opened, this allows engine oil to flow from the engine oil pump to the engine oil pan, thereby causing the oil pressure sensed by the pressure-sensing safety system to decrease. When insufficient engine oil pressure is sensed by this safety system, the system causes the delivery of fuel to the fuel injectors to stop. Therefore, when the TRV operator presses the switch, the fuel injectors stop injecting fuel into the cylinders and the engine stops running.

8.3 Analysis of Forces for a Traction Research Machine Equipped with a Four-bar Parallel Linkage

A single wheel traction research machine equipped with a four-bar parallel linkage, with zero input torque and zero net traction, is shown in figure A1,a. The vertical load of the tire on the tractive surface is the static load, W_s, which is defined in *ASABE Standards* (2009) as the total force normal to the supporting surface on which the traction or transport device is standing with zero input torque. Figure A1,b shows the same equipment with a positive net traction being generated by the tire. The positive net traction and positive angle Θ cause the dynamic load, W_d in figure A1,b to be less than the static load, W_s, shown in figure A1,a. The reason is that, the upper and lower links are inclined, so when they are loaded by the longitudinal NT force, they also apply a net upward vertical force on the front link. Therefore, it is important for the angle Θ for the deadweight-loaded ATV tire machine to be zero. As described in the above description of the field TRM for the WFTV, the angle Θ for that machine does not need to be zero.

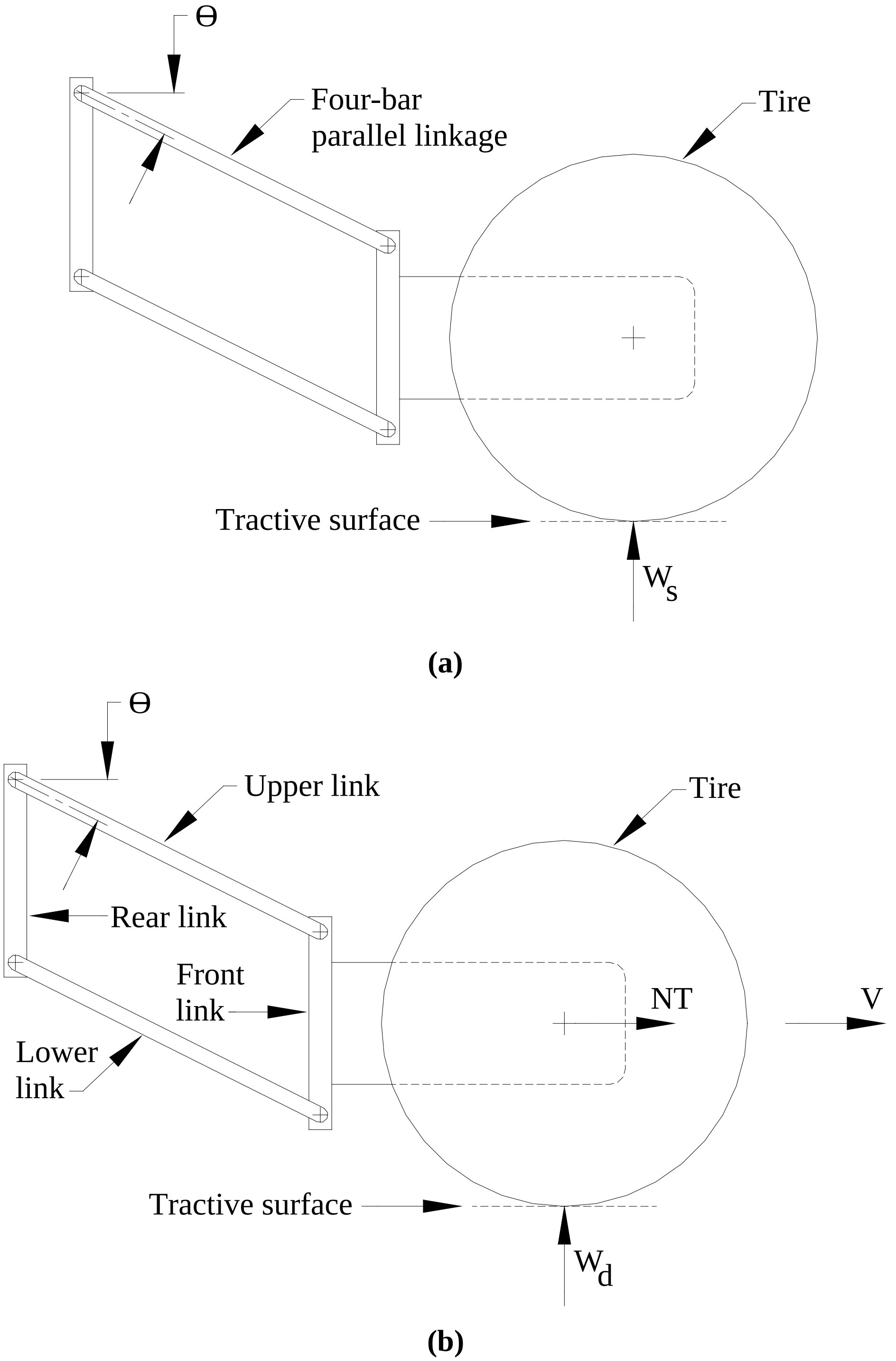

Figure A1. Right side views of a single wheel traction research machine equipped with a four-bar parallel linkage, shown with (a) zero input torque and zero net traction and (b) positive net traction. The net traction, NT, shown is the force applied by the wheel to the four-bar linkage. W_s is static load, W_d is dynamic load, and V is forward velocity.