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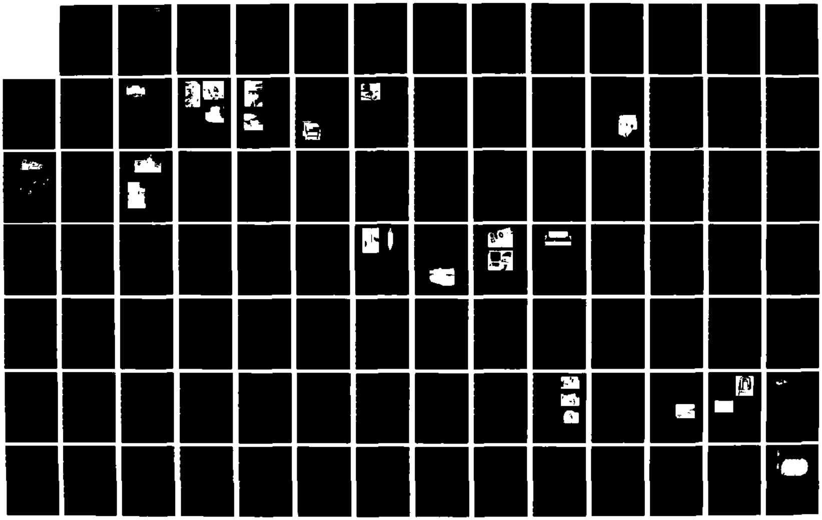

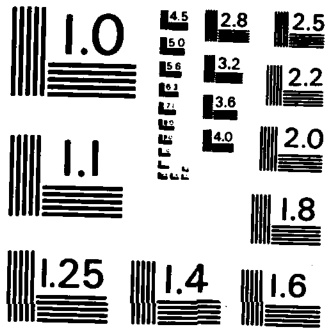

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PROCEEDINGS OF THE ISTVS WORKSHOP ON MEASUREMENT AND EVALUATION OF TIRE PERFORMANCE UNDER WINTER CONDITIONS

Alta, Utah, 11-14 April 1983

George L. Blaisdell and Raymond N. Yong, Editors

Sponsored by:
International Society for Terrain-Vehicle Systems
Geotechnical Research Center of McGill University
U.S. Army Cold Regions Research and Engineering Laboratory

Corps of Engineers, United States Army
Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire 03755-1290

PREFACE

The International Society for Terrain-Vehicle Systems (ISTVS) Workshop on Measurement and Evaluation of Tire Performance under Winter Conditions was held in Alta, Utah, 11-14 April 1983. The Workshop was jointly sponsored by the ISTVS, the Geotechnical Research Centre of McGill University (Montreal, Canada) and the U.S. Army Cold Regions Research and Engineering Laboratory (Hanover, New Hampshire). The intent of the Workshop was to gather together representatives from all of the groups who must grapple with winter tire performance evaluation and prediction in a spirit of mutual cooperation.

The *ISTVS* Committee on Snow, which organized the Workshop, acknowledges the valuable contributions and support provided by Alta Ski Lifts Corporation, DataMotive Inc., and Goldminer's Daughter Lodge.

The committee also wishes to gratefully acknowledge the hospitality of Jim and Alfreda Shane of the Goldminer's Daughter Lodge.

CONTENTS

ISTVS WORKSHOP ATTENDEES

Steven H. Altenberndt
General Motors Corporation
General Motors Proving Ground, 25-TWS
Milford, MI 48042

George Blaisdell
U.S. Army Cold Regions Research
and Engineering Laboratory
72 Lyme Road
Hanover, NH 03755

Lt. Col. Nicholas H. Collins
U.S. Army Transportation School
P.O. Box 4178
Ft. Eustis, VA 23604

Douglas Domeck
Smithers Scientific Services
1150 N. Freedom St.
P.O. Box 351
Ravenna, Ohio 44266

Col. R. Fidanza
Corpo Tecnico Esercito Italiano
Via Antonio Scarpa 18
00161 ROMA (Italy)

Zane L. Frazier
Michelin Tire, Canada
86 Argyle Drive
Kirkland, Quebec
Canada H9H 3H8

William Harrison
Sno-Mech
Route 103A
New London, NH 03257

Henry C. Hodges
Hodges Transportation, Inc.
P.O. Box 234
Carson City, NV 89701

Daniel W. Hoffman
Sperry Corp.
640 N. 2200 West
Salt Lake City, UT 84116

Carter Jackson
USATACOM
Warren, MI 48090

William R. Janowski
DataMotive, Inc.
14041 Mt. Bismark
Reno, NV 89506

Thomas R. King
General Tire and Rubber Co.
10265 Carlswood Ave.
Hartville, OH 44632

Ted Knowles
Uniroyal Tire Technical Center
P.O. Box 3940
Troy, MI 48007-3940

Minoru Komatsu
Faculty of Agriculture
Tottori University
Koyama, Tottori 680 Japan

Frank E. Matyja
General Tire and Rubber Co.
685 Longacre Drive
Akron, OH 44319

George E. Pollard
The Goodyear Tire and Rubber Co.
Akron, OH 44316

Boone Y. Richardson
Forest Service Equipment and
Development Center
444 E. Bonita Ave.
San Dimas, CA 91773

Gen. Valentino Romano
Gorpo Tecnico Esercito Italiano
Via Antonio Scarpa 18
00161 ROMA (Italy)

Adam A. Rula
127 Lightcap Blvd.
Vicksburg, MS 39180

John Rumel
Goodyear D/461G
1144 E. Market St.
Akron, Ohio 44316

Greg S. Sanderson
National Defense Canada
Bourque Memorial Bldg.
305 Rideau St.
Ottawa, Ontario
Canada K1N 9E5

Henry C. Schwerdtfeger
Michelin Tire Corp.
One Marcus Ave.
Lake Success, NY 11042

William Straub
Firestone Tire and Rubber Co.
1200 Firestone Parkway
Akron, OH 44317

Frank E. Timmons
Rubber Manufacturers Association
1901 Pennsylvania Ave., NW
Washington, DC 20006

Arthur W. Trantham
U.S. Army Cold Regions Test Center
Fort Greely, Alaska
APO Seattle, WA 98733

Takehiro Tsukamoto
Bridgestone Research, Inc.
350 Fifth Ave.
Suite 4202
New York, NY 10118

Gerald W. Turnage
Mobility Research Section
Waterways Experiment Station
P.O. Box 631
Vicksburg, MS 39180

Raymond N. Yong
McGill University
Geotechnical Research Centre
817 Sherbrooke Street, W.
Montreal, P.Q., Canada H3A 2K6

THE NEED FOR SNOW TIRE CHARACTERIZATION AND EVALUATION

Raymond Yong and George L. Blaisdell

INTRODUCTION AND PROBLEM IDENTIFICATION

The problem of specification of required tire performance characteristics for operation in off-road situations can be a simple or complicated circumstance--depending on the sets of perspectives that are brought to bear in the evaluation of tire performance. The more detailed an individual is in specification of performance, the more complicated the issue becomes; primarily because the means for evaluation of performance cannot always be rigorously or exactly stated. Because a) proper first evaluation of tires requires actual on-terrain running interaction, b) test terrain variabilities cannot be readily described, and c) test measurement systems and techniques have yet to be fully delineated and rationalized, we are left with the situation of developing whole sets of procedures and standards that need to be continually upgraded or fine-tuned as more information becomes available.

The above problems become considerably compounded when attention is focused on winter tire usage--particularly since the technology for tire design and manufacture has seen tremendous advance in the recent decade. The need for snow tire characterization and performance evaluation is indeed obvious. The Rubber Manufacturers' Association (RMA) snow tire definition (April 1981) provides us with a certain amount of latitude in meeting the required physical characteristics of "winter tires."

TIRE PERFORMANCE UNDER WINTER CONDITIONS

From the preceding section, several questions and problems can be readily identified:

1) Measurement of tire performance under winter surface conditions
   - Test techniques and devices
   - Measurement systems
   - Procedures and protocol
   - Rationalization and acceptance
   - Standardization and criteria
2) Characterization of "winter surface"
   - Identification and classification
   - Test techniques and devices
   - Measurement and characterization
   - Requirements and control
   - Procedures and protocol
   - Rationalization and acceptance
   - Standardization and criteria
3) Analyses and prediction
   - Methods and requirements
   - Model reconciliation and calibration
   - Validation and acceptance
4) Tire specifications and characterization
   - Manufacturer's specifications
   - Requirements and standards
   - Evaluation
   - Criteria

Because of the many problems and issues identified above, it was felt that a Workshop on Winter Tire Testing and Evaluation would be most useful--if the various participants from the U.S. manufacturer and tester industries interacted in a spirit of "a common problem situation." To that end, a workshop was organized for 11-14 April, 1983 at Alta, Utah, under the joint sponsorship of the ISTVS, Geotechnical Research Center, McGill University, and U.S. Army Cold Regions Reseach and Engineering Laboratory.

A list of the participants is included in these Proceedings. The formal program was designed to proceed from presentation of measurement devices through testing techniques and evaluation schemes to prediction methods and modeling. Participants in the Workshop were working representatives of each of these areas. An awareness of the techniques, state-of-the-art and subjects where further work is needed in each area were aired in a spirit of mutual cooperation, resulting in an enhanced understanding of the unique problems facing each of the groups working in winter tire performance assessment.

RMA SNOW TIRE DEFINITION

"A mud and snow passenger or light truck (LT) tire is a tire which, when compared with conventional rib type tires, has a relatively aggressive tread pattern and is designed to provide additional starting, stopping, and driving traction in mud and snow. The tread has ribs, lugs, blocks, or buttons, is generally discontinuous, and has the following marking and characteristics when inflated:

a) A substantial portion of the lug, block, or rib edges in the tread design is at an angle greater than 30 degrees to the tire circumferential center line.

b) On at least one side of the tread design, the shoulder lugs protrude at least 1/2-in. in a direction generally perpendicular to the direction of travel.

c) Passenger tires manufactured after 1 January 1976 and light truck (LT) tires manufactured after 1 March 1981 will be permanently labeled on at least one sidewall with the words 'MUD AND SNOW' or any contraction using the letters 'M' and 'S' (e.g. MS, M/S, M-S, M&S, etc.)."

SESSION I: TIRE TESTING ON SNOW AND ICE

The purpose of this session was to discuss the merits of devices and equipment currently in use for measuring tire performance under winter surface conditions. The continued refinement of tire design, consumer demands for more effective tires, and the additional requirements for test documentation by government agencies have resulted in considerable improvement in techniques and devices for tire testing.

The papers contained in this section present the latest and the best of these systems. In addition to the four vehicles discussed in print here, informal presentations of similar instrumented vehicles were given by Doug Domeck (Smither's Scientific Services vehicle) and Henry Hodges, Sr. (Canadian National Defense vehicle).

GENERAL MOTORS SINGLE WHEEL TEST TRUCK*

Steve Altenberndt General Motors Corporation, General Motors Proving Ground, 25-TWS, Milford, Michigan, U.S.A. 48042

DRIVE TRACTION TRUCK

The GMPG drive traction test vehicles are used to determine the driving traction performance of a tire under specified test conditions. This system utilizes two self-contained four-wheel, rear-wheel-drive test vehicles (Chevrolet C-20 and "LUV" pickups) with specially-instrumented axles to measure the fore-aft and vertical forces on a driven tire.

Test vehicle mechanical function

Test vehicle load ranges are determined by practical operating load limits.

"LUV" - 275 kg to 685 kg per tire
"C-20" - 500 kg to 1135 kg per tire

Automatic throttle appliers with variable application rates are incorporated on both test vehicles.

Each vehicle is equipped with an electro-hydraulic control system which controls the brake system to deactivate the test wheel brake upon initiation of a tire test.

An onboard hydraulic jacking system is used to raise the truck rear axle to facilitate zeroing the transducers and changing test tires between tests.

Test loads are adjusted by distributing ballast uniformly in the bed of the test vehicle. Additional ballast can be attached to the front bumper to off-load the test wheel position to achieve minimum test load.

Vehicle speed is measured with a tach generator attached to a front wheel of the vehicle. The test wheel speed is monitored using a tach generator connected to speedometer output of the transmission.

To obtain proper transducer orientation due to differences in test load and test tire diameter, high pressure lifting shocks are used in place of the original rear vehicle shock absorbers to adjust the vehicle ride height.

A position transducer is used in conjunction with the lifting shocks to measure the distance between the vehicle frame and rear axle. The distance required for transducer alignment is determined during calibration using specific test loads and tire size combinations to be tested.

Drive traction load cell

Transducers capable of measuring fore-aft and vertical load on a driven tire are spliced into the rear axle of the respective test vehicles. The transducer load cells utilize four parallel beams gauged in bending.

It is important that the orthogonal measuring axes be properly oriented to the plane of the road surface. Improper orientation of the transducer can cause a loss of input force signal. Misalignment can result from initial setting of transducer angle, dynamic change due to suspension "wind-up," or dynamic change due to ride motion.

The transducers were fabricated with elongated mounting holes to allow adjustment of initial measurement axes. This adjustment is accomplished by first adjusting the test vehicle to the normal

* From the General Motors Tire-Wheel Systems Tire Performance Criteria procedures and specifications.

test ride height. Then a precision level is placed on the transducer body, which is rotated until it is level. Prior to any testing, the ride height can be adjusted using the high pressure lifting shocks to position the transducer.

Parallel control arm suspension systems are incorporated to minimize transducer angular change due to axle "wind-up."

Dynamic transducer angular change due to normal expected test vehicle ride motion was measured at the transducer body and found to be less than ± 0.5 degrees.

A wheel offset effect exists on the "LUV" test vehicle because all fore-aft and vertical forces are transmitted to the axle housing through a pair of axle bearings. The outboard bearing is an integral part of the load sensing transducer, so the forces transmitted through this bearing are measured. The inboard bearing, located near the differential side gear, also carries some of the load. However, this force is not measured. This factor is compensated for by using a known offset during calibration and maintaining this reference offset during testing, using known rim offsets and proper wheel spacers.

The configuration of the "C-20" rear axle allows design of all load-carrying bearings to be incorporated into the load cell. This results in no force transmission path other than through the transducer from the tire and wheel assembly to the axle housing. This allows tire and wheel combinations with reasonable offset differences to be used with negligible force errors from the reference calibration offset.

Electrical and control logic

Two separate 12-volt electrical systems are utilized in each test vehicle to supply adequate power and isolate the following items:

Original vehicle battery and alternator system.

- Normal engine and vehicle electrical systems.
- Hydraulic pump for jack system.
- Amber warning beacon.

Auxiliary battery and alternator system.

- 12-VDC to 120-VAC 60-Hz invertor used to supply 120 vac power to the analog recorder, digital voltmeter, computer printer, and throttle applier motor.
- Signal conditioning instrument power.
- System logic power.

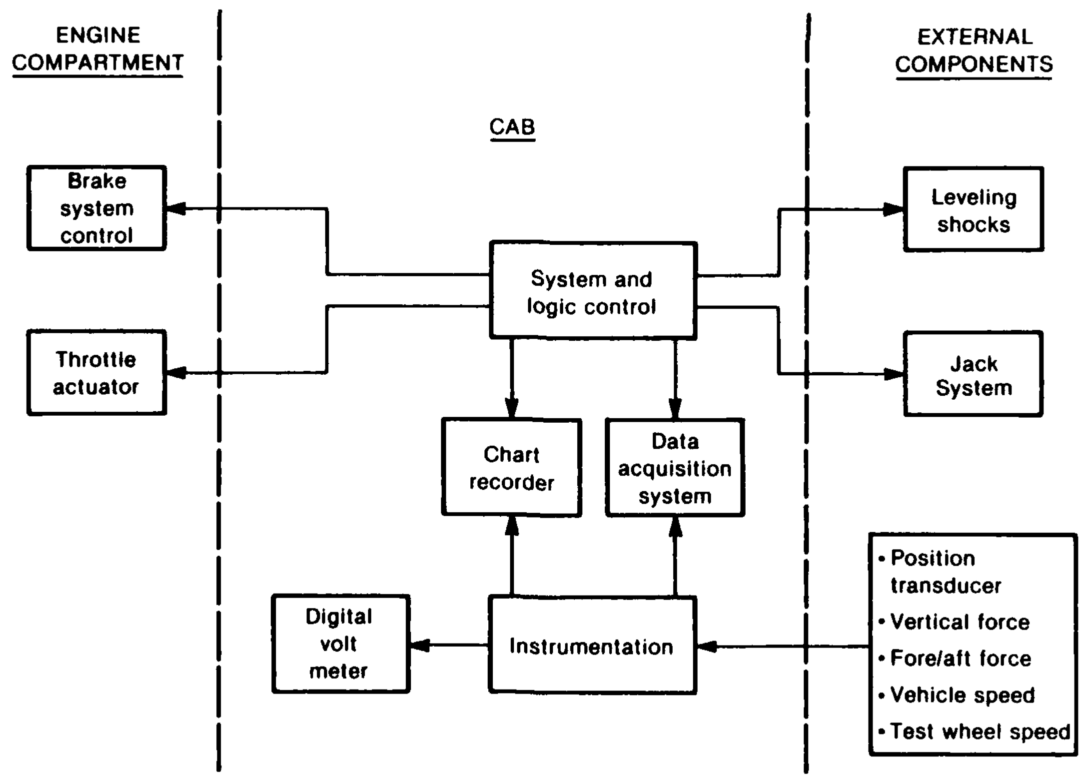

Figure 1. Drive traction truck operational flow chart.

- Data acquisition system power.
- Electro-hydraulic brake control system.

A simplified truck operational flow chart is shown in Figure 1.

Data acquisition system and data processor

Tire-Wheel Systems has incorporated a GM-designed-and-built Data Acquisition System (DAS) which utilizes commercially available components.

The TWS DAS was designed to 1) provide onboard data sampling and filtering, 2) make coefficient calculations, 3) provide data to driver (including overall averages, standard deviations, and outlier deletion), and 4) provide permanent data storage via cassette tape.

An on-site portable computer is used in conjunction with the DAS to provide final data analysis. Individual tire run

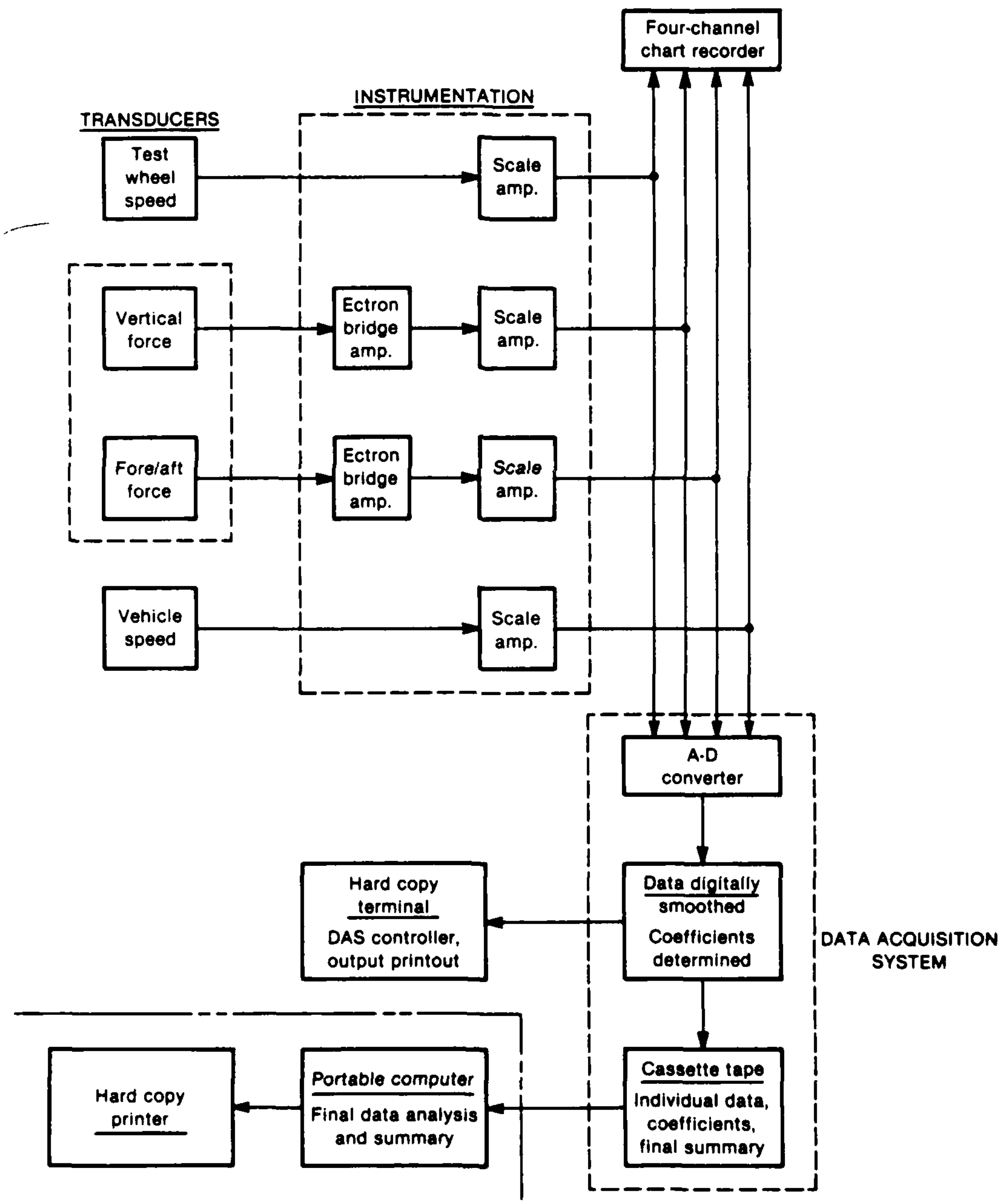

Figure 2. Drive traction truck data system.

data stored on the DAS cassette tape is transferred to the computer through a communication interface. After data transfer is complete, the computer summarizes the data using overall control tire test data, calculates significant differences of test tire measured performance, and computes GM TPC test tire ratings. (See schematic details in Figure 2.)

SYSTEM CALIBRATION

Both vertical and fore-aft force outputs are calibrated with a calibration platform (a bi-directional force transducer) using a typical calibration setup. Calibration platform load ratings should be sufficient to evaluate the respective force outputs over expected usage range. The calibration platform is isolated from the floor by three air bearings. The test vehicle attitude during calibration should be representative of actual test usage. The transducer being calibrated is positioned such that any component of the vertical load is nulled from the fore-aft channel.

This is accomplished by 1) removing all vertical load from the load cell by lifting the axle; 2) zeroing the fore-aft force channel, 3) setting the test wheel back down; and 4) removing any induced signal in the fore-aft channel by adjusting the test vehicle transducer position.

NOTE: This is actually a leveling technique in that it uses the weight of the truck as the indicator of transducer angulation. Any components of the vertical load which are introduced into the fore-aft channel (i.e., $\sin \alpha \times$ vertical load, where α = position error angle) are nulled by physically rotating the transducer until true vertical force (gravity) and the fore-aft measuring channel are perpendicular.

DESIGN AND USE OF THE CRREL INSTRUMENTED VEHICLE FOR COLD REGIONS MOBILITY MEASUREMENTS*

George L. Blaisdell U.S. Army Cold R.gions Research and Engineering Laboratory
Hanover, New Hampshire 03755-1290

ABSTRACT

The U.S. Army Cold Regions Research and Engineering Laboratory has recently acquired an instrumented vehicle for the measurement of forces at the tire/surface material interface. The CRREL instrumented vehicle (CIV) is equipped with moment-compensated triaxial load cells mounted in the front wheel assemblies. Forces are measured in the vertical, longitudinal (in the direction of motion) and side directions. In addition, accurate wheel and vehicle speeds and rear axle torque and speed are measured.

Modifications to the vehicle (to facilitate the performance of traction and motion resistance tests) include four lock-out type hubs to allow front-, rear- or four-wheel drive and a dual brake system for front-, rear- or four-wheel braking. A mini-computer-based data acquisition system is installed in the vehicle to control data collection and for data processing, analysis and display.

Discussion of the vehicle includes its operation and use for the evaluation of the tire performance and surface material properties of motion resistance and traction.

INTRODUCTION

The quantities of traction and motion resistance have characteristically been used to establish vehicle mobility (or immobility), especially on deformable surface materials. It is reasonable to conclude that these quantities are primarily a measure of the strength of the tire/material system, provided the vehicle is adequately powered. In the past, traction testing involved using a dynamometer (hold back) vehicle equipped with a load cell drawbar. Calculations were necessary to determine traction based on the measured drawbar pull, motion resistance, and appropriate correction factors. Two methods were used to find motion resistance--measuring vehicle deceleration and towing or pushing the vehicle.

Traction and motion resistance as quantities are just measures of the forces that are developed or are found present between the vehicle (namely, its tires) and its supporting surface. However, past testing measured quantities that are physically removed from the vehicle/material interface. With the development of a sophisticated load cell and a specially equipped vehicle, direct measurement of these forcesis now possible. The CRREL instrumented vehicle (CIV) is one such vehicle that is being used to study the variation in tire/surface material forces for various cold regions materials. Specifically, the vehicle is being used as a measurement device for establishing data and parameters by which different snows (as well as ice, slush and thawing soils) may be categorized for vehicle mobility purposes.

INSTRUMENTED VEHICLE--MECHANICAL AND ELECTRONIC HARDWARE

The CIV was originally constructed by the Nevada Automotive Test Center (NATC) in Carson City, Nevada, and is based on a 1977AMC Jeep Cherokee frame

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Figure 3. Instrumented vehicle.

and chassis (Fig. 3). Mechanical modifications and electronic instrumentation of the vehicle have been performed by NATC and CRREL, respectively.

The instrumented vehicle is equipped with Warn locking hubs on all four axles. This allows the vehicle to be operated as a four-wheel-drive, rear-wheel-drive or front-wheel-drive unit. This versatility is made possible by the Quadra-Trac full-time four-wheel-drive system, which was stock equipment on the vehicle before its modification. With the Quadra-Trac system, engine torque is delivered from the transmission to a controlled-slip third differential (or transfer case). The transfer case, in turn, transmits torque along the front and rear propeller shafts to the differentials located between the front and rear sets of wheels.

With all four Warn hubs locked, the vehicle operates as a normal fulltime four-wheel-drive unit. Two-wheel-drive (front or rear) is not as straightforward. Since the Quadra-Trac transfer case is sending torque to the propeller shafts in proportion to their needs, having two hubs (both front or both rear) in the free position causes them to appear to be most in need of torque. The transfer case thus sends all of the torque to the differential of the free axles, which produces no vehicle movement. However, the vehicle is equipped with an Emergency Drive system (stock equipment), which, when engaged, nullifies the differential action of the transfer case. An equivalent amount of torque is thus sent to each propeller shaft and two-wheel-drive is achieved.

A dual brake system has also been built into the CIV. This system allows hydraulic pressure to be applied (through the standard brake pedal) to all four disc brakes, to the front wheel brakes only, or to the rear wheel brakes only. The valves for changing the brake configuration are located on the floor at the left side of the driver's seat.

Four air-adjustable shock absorbers take the place of the standard shocks. These are connected in pairs (front two and rear two) to a vacuum-actuated air compressor which can be manually controlled. This system allows the vertical force on the front or rear wheels to be varied by up to 20 lb through inflation of one set of shocks and deflation of the other set. In addition, greater wheel well clearance for certain oversize tires can be obtained by shock absorber inflation. Vehicle trim is also controlled by appropriate inflation and deflation of the shocks. This is important for proper alignment of the load cell axes based on the tire size being tested.

Electrical power (500 watts) is supplied for most of the instrumentation from a 12-VDC to 115-VAC sine wave static inverter. The inverter is mounted in the cargo area of the CIV next to a 12-volt (lead-acid) battery which provides its input. The battery is charged by an oversized auxiliaryalternator. Output from the inverter is sent to an outlet block located in the instrumentation section of the vehicle.

The vehicle is also equipped with swivel seats for both the driver and passenger to allow normal vehicle operation or instrumentation operation. Shock-mounted supports are provided for all of the instrumentation.

Central to the instrumentation in the CIV are the moment-compensated triaxial load cells mounted in the two front wheel assemblies.[1]* The load cells are mounted so that they become a vertical section of the cantilevered rod that supports the wheel (Fig. 4). Since the load cells add 10 inches (5 inches each) of width to the overall wheelbase width, each of the two front axles (from the steering universal out) was replaced with a longer shaft. Each load cell is annular to allow passage of the axle.

The load cells each contain three complete strain gage Wheatstone bridges

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* Numbers designate references at end of paper.

Figure 4. Cantilevered rod.

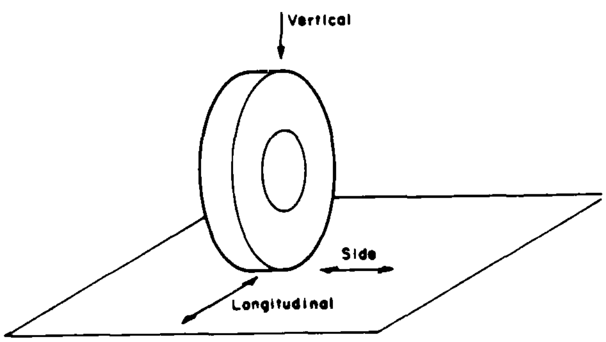

Figure 5. Axis convention for triaxial load cells.

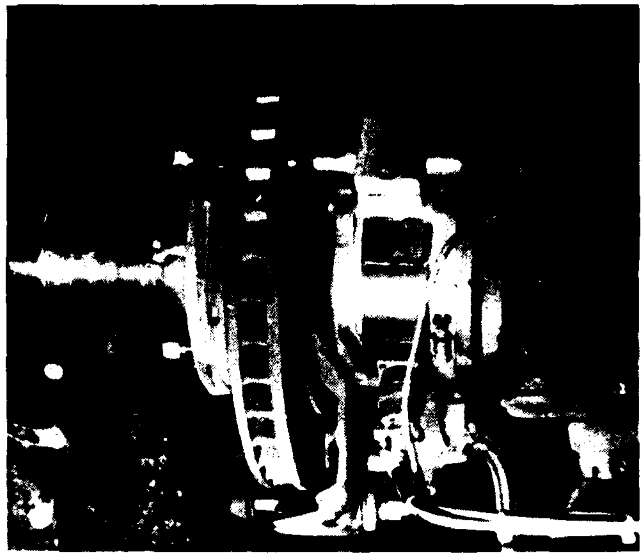

Figure 6.

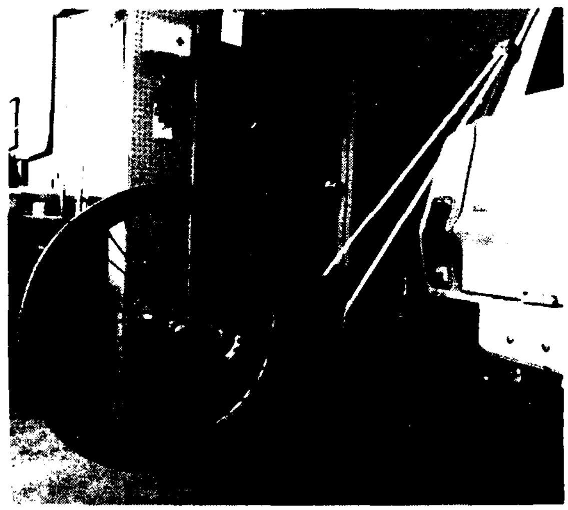

Figure 7. Fifth-wheel assembly.

for measurement of forces acting in three mutually perpendicular directions (orientation shown in Figure 5) and will be referred to as vertical, longitudinal and side directions. Moment compensation is performed by the strain gage bridges so that the forces read by the bridge represent the forces acting at the tire contact patch. It should also be mentioned that the compensation is such that a torque or a couple applied to the tire registers no force on the load cell.

Each front brake disc is equipped with 100 equally spaced steel nodes on an 8-inch-diameter circle. A counting proximity detector is mounted within 0.05 inch of the ends of the nodes (Fig. 6). Upon conversion, this signal yields exact individual wheel distance and velocity values. A similar arrangement is present on the rear propeller shaft so that the average rear wheel speed may be measured. A strain gage shaft torque sensor is also mounted on the rear propellor shaft. This signal can be used as a measure of the energy input to the rear wheels during driving and braking.

A 5th-wheel assembly is attached to

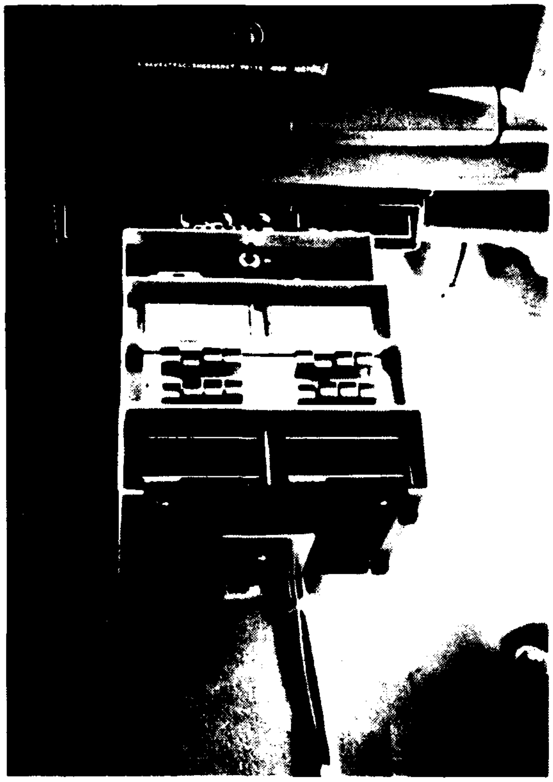

Figure 8. Driver read-out display unit.

Figure 9. Fifth-wheel speed is read on a digital meter mounted on top of the dash.

the rear bumper for accurate measurements of vehicle speed and distance (Fig. 7). A chain has been installed on the tire to eliminate slippage during operation on ice and other low-coefficient-of-friction materials. This increases the wheel circumference and a new calibration must be performed to attain accurate speed and distance measurements.

To allow immediate feedback of force and velocity values, and to allow the use of a particular measured quantity as a control parameter, a driver read-out display unit has been installed (Fig. 8) between the driver's and passenger's seats. The main unit consists of three pulse counters (front two wheels and 5th wheel), a right and left side digital panel meter (DPM), and two sets of switches (right and left side). Each switch set contains four push-button switches that select vertical, longitudinal, or side force, or wheel speed. A second set of switches and DPM's are present to accommodate future instrumentation of the rear wheels. Fifth-wheel speed is read on a digital meter mounted on the top of the dash directly in front of the driver (Fig. 9).

The DPM's receive their input signal through the selector switches. When displaying load cell readings, the DPM's read in hundredths of millivolts and represent the actual force in newtons. A decimal point is added to the DPM display when a velocity channel is displayed (read-out in km/hr).

To facilitate driver read-out in actual force (newtons) and speed (km/hr), the input signal must be zero adjusted and scaled. This is accomplished by a differential amplifier which, for space and convenience considerations, was constructed on a blank load cell signal conditioner card (signal conditioner will be discussed later) and housed in the signal conditioner box.

DATA ACQUISITION AND MANIPULATION EQUIPMENT

Up to this point, the description of the CIV has involved basically non-removable or integral parts of the vehicle. (The external 5th-wheel assembly is removable.) Provided the proper inputs to, and outputs from, the previously mentioned measuring devices are satisfied, any system for read-out and recording could be attached. This section will be devoted to a description of the equipment presently used for data acquisition and its operation. Figure 10 depicts a general block diagram of this equipment.

Eleven channels of information have been identified: seven are force measurements and four velocity measurements. Each channel (except the 5th-

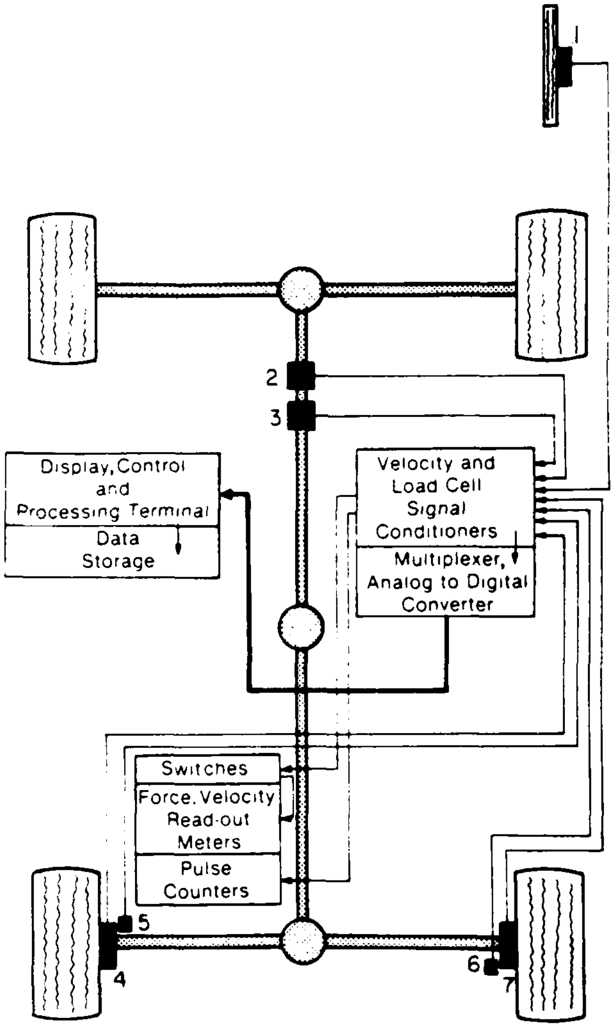

Figure 10. Block diagram of vehicle's instrumentation, 1-fifth wheel, 2 and 3-rear propeller shaft speed and torque sensors, 4 and 7-triaxial load cells, 5 and 6-front tire speeds.

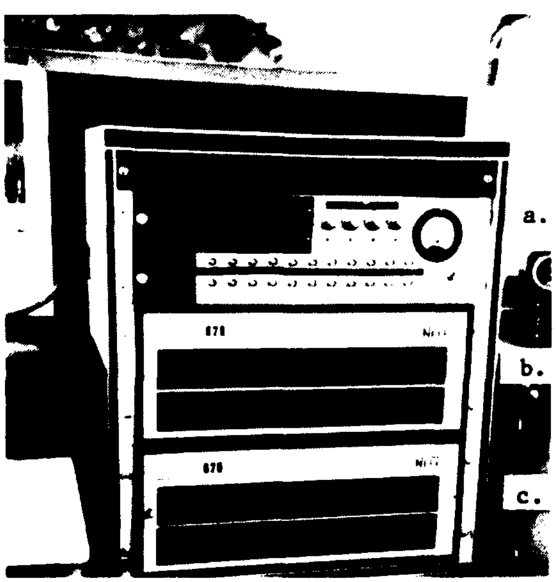

Figure 11. Signal conditioners.

wheel DC tachometer) requires an excitation or power source in order to function. This power is supplied by two signal conditioners, one for load cells and the other to configure velocity channels.

The load cell signal conditioner is a Neff Series 300 model (Fig. 11c) and allows each channel to be separately configured for a particular transducer type. The signal conditioner provides a constant voltage (2-10 volts) or a constant current (2-50 milliamps) excitation. It also furnishes circuitry for bridge completion and remotely controlled calibration. (The system is normally adjusted to provide 10-volt excitation to each of the seven load cell channels.) Calibration is obtained by shunt resistance substitution.

A second signal conditioner (Fig. 11a) provides the necessary circuitry for the velocity channels. This unit was initially constructed by NATC and has subsequently been modified by CRREL in order to properly function with the new instrumentation. The primary function of the velocity signal conditioner is to convert the incoming pulse frequency (from the proximity detectors) to a DC voltage, which represents speed. Three of these converters are present, one for each front wheel and one for the rear propeller shaft. Frequency to DC conversion for the 5th wheel is not necessary since a speed-representative DC signal is output from the assembly's tachometer generator. Circuitry is provided for scaling adjustment and filtering.

Conditioned analog (DC voltage) signals from each of the 11 data channels are output from the two signal conditioners into a Neff Series 400 multiplexer (Fig. 11b). The Series 400 contains a high speed analog signal multiplexer, programmable gain amplifiers, a sample-and-hold amplifier, an analog-to-digital converter and logic for interface control. The unit houses Differential Input Multiplexer Plug-in Circuit Cards containing 10-Hz low-pass filters and remote-control channel switches for 16 channels. The output from the Multiplexer card is applied to a two-stage programmable gain amplifier that allows input sensitivities from 5 mV a 10.24 V. The signal is then passed through a sampling rate filter and sample-and-hold amplifier before analog-to-digital conversion and output.

The Series 300 and 400 are remotely operated by a Hewlett-Packard 9845B minicomputer (Fig. 12). The computer, through a 16-bit-parallel interface, sends instructions that set appropriate

Figure 12. Hewlett-Packard 9845B mini-computer.

switches, furnish sequential/random sampling, gain and channel address information, and initiate conversion cycles. Data words sent back by the Series 400 are read and stored for later manipulation.

The 9845 has two 217K byte tape cartridge drives which are used for mass storage of data and programs. A 187K byte read/write memory is available for working semiconductor memory. Data and programs can be displayed in video or hard copy form with the computer's 20-line, 80-column CRT or the 80-column internal thermal printer. A graphics read-only memory (ROM) allows data plots to be generated and output in video or hard copy form. The 9845 also has a real-time clock which is used to accurately measure time intervals and to generate interrupts for initiating a sampling scan or data conversion cycle. Actual operation of the whole system is accomplished through

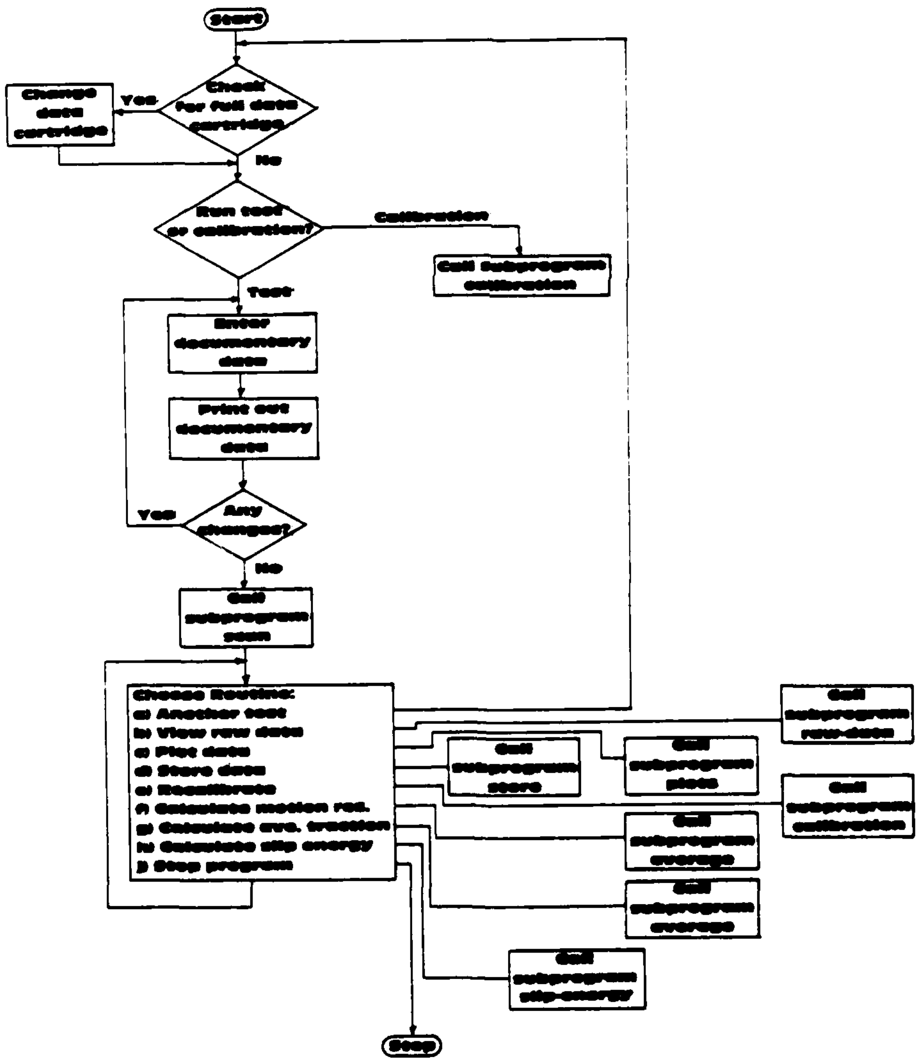

Figure 13. Flow chart for data acquisition program DATACQ.

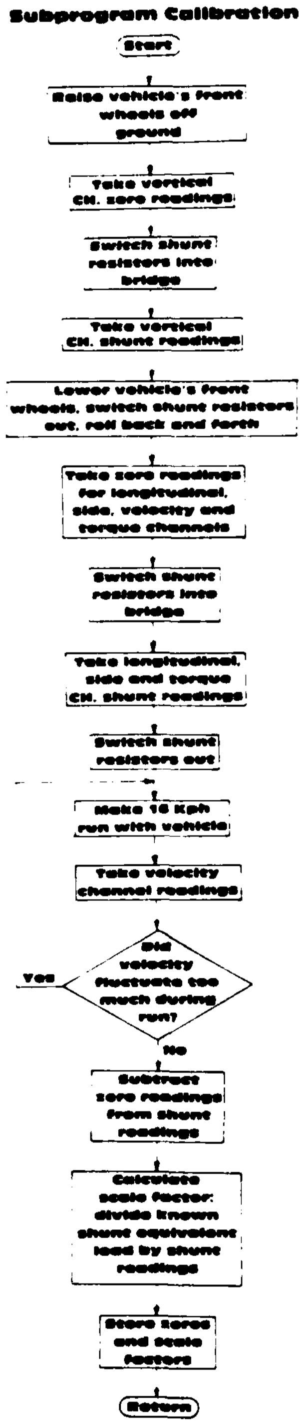

Figure 14. Flow chart for Subprogram Calibration.

the software instructions used by the computer.

SOFTWARE

The HP9845 computer programs for use with the CIV are written in BASIC programming language. Two primary programs are present, one that controls and acquires data during operation of the vehicle (DATACQ) and one that reads and manipulates stored data (READ-2). The programs are written in an interactive mode and prompt the user for the required input. Where convenient, a menu is provided to allow the user to choose the routine he desires.

The data acquisition program (DATACQ) is divided into a main program, which gathers documentary information about the locality and conditions present in the test area, and several subprograms (Fig. 13).

The user must first choose whether to proceed into the main program (documentary data) or to run the calibration subprogram (Calibration, Fig. 14). The purpose of the calibration subprogram is to take zero load/zero speed readings and and shunt resistance/fixed speed readings and calculate the appropriate scale factors for each channel. The subprogram stores the zeros and scale factors in a calibration file. A new calibration file is created each time the front tires are changed, the air pressure in the shock absorbers is changed or the data acquisition system is turned on.

Following input of the documentary data, a channel sampling subprogram (Scan, Fig. 15) is called, which performs the actual data sampling and transfer. Subprogram Scan is set up with a series of two interrupts. The computer's real-time clock is used to generate interrupts at a user-chosen rate. This rate represents the frequency with which a call is made to the subroutine Sample which sequentially collects a data word from each channel in the system. The clock interrupts a meaningless infinite loop which allows the sample routine to be addressed as quickly as possible following the clock signal.

Data acquisition may be terminated in two ways. The clock interrupts and the sample routine are automatically disabled when 1400 data scans (the program is set up to hold a maximum of 1400 data points per channel) have been completed. Should the test be finished before the maximum number of scans is completed, data acquisition can be terminated by a user interrupt. Following the test event (data acquisition completed), a menu is offered the user. Included are: store data, view raw data, plot data, stop program, re-run program, calibrate system, and several value-generating subprograms. The Store subprogram saves the documentary data gathered in the main program

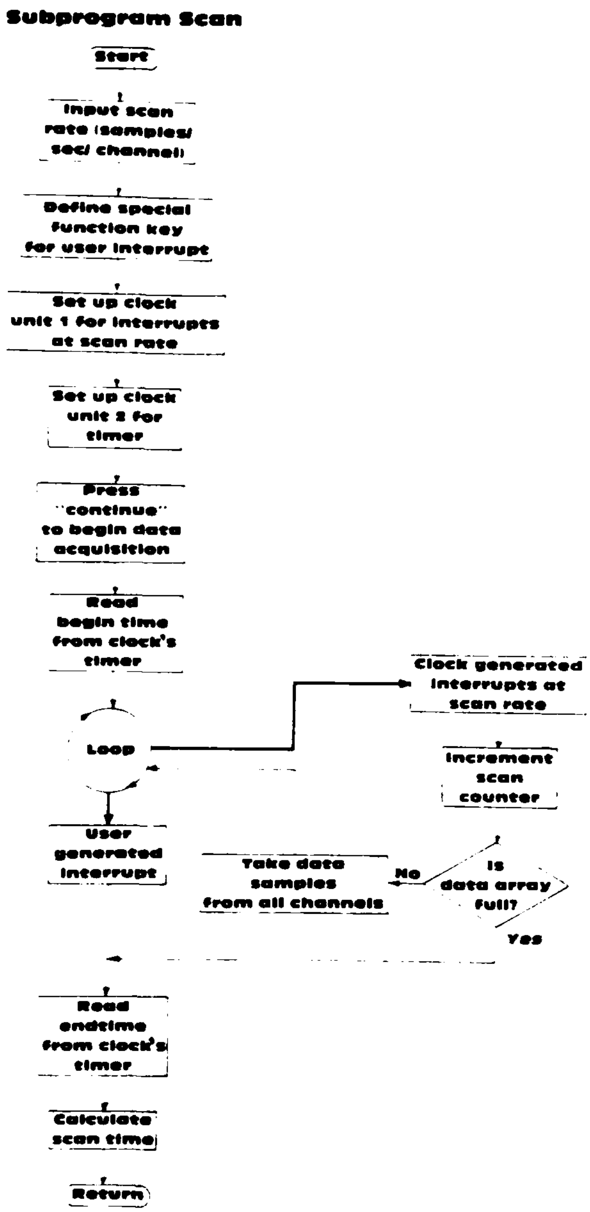

Figure 15. Flow chart for sampling Subprogram Scan.

and all of the data acquired by Scan. The data taken in Scan is stored in its internal, unformatted binary form. This greatly conserves storage space on the tape cartridge. Any subprogram which requires viewing or calculation of meaningful numbers requires conversion of the data acquired in Scan. The Convert subprogram is automatically accessed when a subprogram requiring meaningful values is chosen from the menu. Using a variable-to-variable transfer and the appropriate calibration file, the binary data is converted to numbers in units of newtons and kilometers per hour.

Data plots can be created with the Plots subprogram. Any of the measured quantities may be chosen for the ordinate, while time, distance or differential interface velocity (DIV) are the choices for the abscissa. Both the right and left wheel data (for the chosen quantity) are plotted on a single graph. Distance, although not measured directly, is found by integration of the speed/time data. Since both wheel and vehicle (5th wheel) speeds are being measured, plots can be based on wheel or vehicle distance.

Several value-generating subprograms are presently included in DATACQ. The Average subprogram gives the user the choice of which data channels he wants average force or speed values for. The value returned can be the average for any percent (user chosen) of the data points taken. Subprogram Average sorts the data into an ascending order array and then averages the upper percent chosen by the user.

Subprogram Slip-energy is an integration routine which finds the area under the tractive force versus distance or DIV curve. The distance-based energy term generated by the subprogram can be relative to wheel or vehicle distance.

Program READ-2 is designed to access data files which were acquired and stored by DATACQ. This program is also structured with a main program and several subprograms (Fig. 16). The main program requests the file name of the data file to be viewed and proceeds to read the documentary and test data from the file. Test data is then converted with subroutine Convert, just as in DATACQ. Access to the subprogram is through a menu item selection. The READ-2 menu contains the same routines as DATACQ except Store and Calibration.

CALIBRATION

In-field or pre-test, calibration is essentially a self-directed process performed by the Calibration subprogram. The program collects zero and shunt resistance values for the vertical force channels with the front of the vehicle elevated. Upon lowering, the vehicle is rocked back and forth by switching the gear shift between forward and reverse. It is then allowed to roll to a stop (transmission in neutral) and zero and shunt resistance readings are taken for the longitudinal and side force channels and zero readings are taken for the vel-

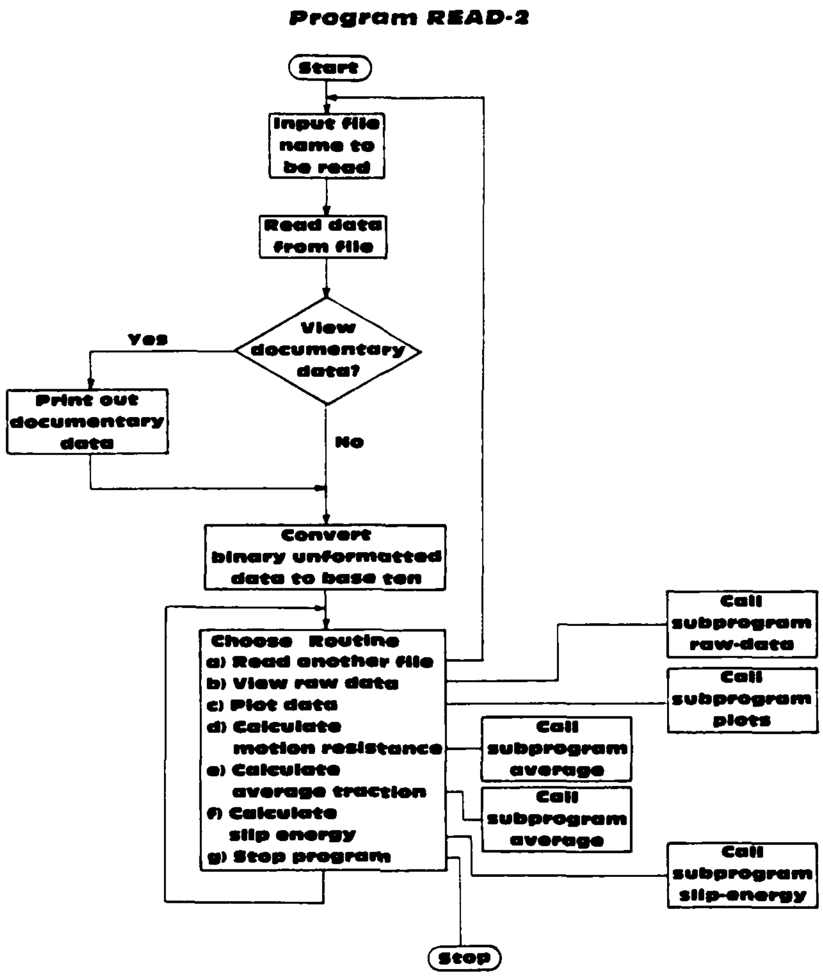

Figure 16. Flow chart for data reading Program READ-2.

ocity channels. The rolling back and forth procedure is performed to remove any "unnatural" forces developed when the tires were lowered back onto the pavement following vertical force channel sampling.

The velocity channels are scaled by driving at a constant speed of 16 km/hr while data sampling occurs on those channels.

During the program-directed calibration procedure, the driver read-out unit may be adjusted, if necessary. When elevated (vertical channel zeros) and after rolling back and forth (longitudinal, side and velocity channel zeros) the zero pots on the driver read-out amplifier can be adjusted to yield a zero reading on the DPM's. Likewise, when shunt resistance is substituted into the bridge, the gain pots of the amplifier may be adjusted to display the shunt resistance load values on the DPM's. The velocity channel pots can be adjusted during the 16-km/hr run.

The subprogram finally calculates scaling factors and stores these and the zero readings in a calibration file.

As previously mentioned, a new calibration file is collected each time the front tires are changed (to zero out the weight of the tire), inflation pressure of the shock absorbers is changed, or the system is turned on.

A whole system calibration is only performed periodically (approximately every 100 hours of use or whenever concerns about the validity of the data arise). Two forms of whole system calibration will be discussed. The first is perhaps better identified as a system adjustment.

The system adjustment is performed to obtain maximum sensitivity from the instrumentation. The Series 400 Multiplexer returns digital values (counts) in the range from -2048 to +2047. System adjustment zeros and scales the incoming signals so that the expected range of these signals is spread over the largest portion of the numbers from -2048 to

+2047 but does not fall outside them. Ideally, the vertical force channels should have zero values near -2048 (or well into the negative numbers) since the vertical force varies between zero and approximately 9000 newtons (it does not go negative). The longitudinal and side forces both are two-directional forces, yielding positive and negative force values. The side forces are symmetric and thus the zero load reading should yield a digital count near zero. Longitudinal forces are not symmetric in that, generally, force magnitudes in traction (positive) can range up to twice as much as resistance (negative) forces. Thus, the zero load count for longitudinal forces should be about -700.

Scaling of the load cell channels can only be done in integer multiples by changing the gain code (set in program DATACQ) in the Series 400. Changing the gain code increases or decreases the sensitivity with which the Series 400 reads the input data as shown in Table 1.

Table 1. Gain/Full Scale Scale Sensitivity Values

Gain	Sensitivity
2048	5mV
1024	10
512	20
256	40
128	80
64	160
32	320
16	640
8	1.28V
4	2.57
2	5.12
1	10.24

The velocity channels have no voltage output when the vehicle is at rest. Thus, the Series 400 returns a digital count near zero for the zero-velocity value. Once scaling (gain) is set for the load cell channels, the velocity digital count is checked for a speed of 16 km/hr. Adjustment of the digital count for 16 km/hr can be accomplished with the knurled variable resistors (top row) on the front of the velocity signal conditioner (Fig. 11a). Since zero speed gives a count of zero, the maximum speed expected should be set equal to a count of +2047. The count which should output from the calibration procedure (= 16 km/hr) can be found by multiplying the ratio of calibration speed to maximum expected speed by +2047.

The second form of whole system calibration is quite involved and should be performed at least annually. The procedure really involves checking the accuracy of the shunt resistors and the 5th-wheel assembly. Since no variable scaling can be performed on the load cell channels, system accuracy is wholly contingent on the accuracy of the shunt resistance substitution.

The reason for including the 5th wheel in the calibration is that it is used to scale all the other velocity channels. (The 16-km/hr speed maintained during subprogram Calibration is based on the 5th-wheel read-out.) Calibration of the 5th-wheel assembly involves operating it over an accurately measured course of at least 1 km. The vehicle should be carefully aligned at the beginning and end course markers and the accumulated pulse counts read from the driver read-out unit. If the measured and true distances vary by less than 0.2%, the 5th-wheel tire pressure can be varied to bring the two into agreement. The 5th-wheel speed is automatically calibrated by calibrating distance since a crystal clock is used for obtaining velocity.

To check the shunt resistor values, a special wheel has been constructed (Fig. 17). This wheel is used to cali-

Figure 17. Wheel used to calibrate longitudinal and side forces.

brate the longitudinal and side forces. When the calibration wheel is being used the axle housing is supported by a stable jack stand which is placed only slightly outside the centerline of the vehicle (toward the side with the calibration wheel). This allows the suspension to act as uninhibited by the jack stand as possible. If the calibration wheel chain is tensioned with an accurate load cell inserted in the force train, a known load can be applied along the longitudinal or side directions. Care is taken to insure that the direction of pull is directly along the longitudinal or side axes. If the external load cell reading differs from the value read out by the subprogram Rawdata of DATACQ, then the value of the shunt resistor for the channel needs to be changed.

A similar sequence, using a flat load cell, is performed for calibration of the vertical force channels. In this case the vehicle retains its normal front wheels and tires. In order to insure loading along the vertical axis, it is best if the external load cell is placed in a recess which allows the vehicle to drive directly onto it. If a check of the external load cell reading shows different values from that registered by the triaxial load cell, the vertical channel shunt resistor value is corrected.

Care must be used when performing the procedures for reevaluating the shunt resistance values. The accuracy of the external load measuring devices should be within 1% or less. (The triaxial load cells have an accuracy of better than 1%.) Alignment when applying external forces must be as exact as possible. Several repetitions of each step are also recommended; significant differences in repetition results should be scrutinized.

For ultimate accuracy, the shunt resistor calibration sequence should be performed on an air-bearing plate. These devices, however, are not in great abundance and take significant amounts of time to learn to use. Presently, three-dimensional air-bearing plates are non-existent, although development is in progress. A two-dimensional plate can be used though, but care must be taken to insure that no load is being imparted in the third direction.

BASIC OPERATION--MOTION RESISTANCE

Vehicle motion resistance is measured with the instrumented vehicle in a two-part procedure. With the front wheels free-wheeling while the rear tires drive, the resistance due to front tire flexing and surface material compaction is measured. Subsequently, the front tires are driven while the rear wheels are free, which measures the resistance due to rear tire flexing, movement of the vehicle's mass and any additional sinkage (compaction) resistance generated at the rear tires. Summation of these two quantities yields total vehicle motion resistance.

The motion resistance test is performed on a straight and level portion of the test course for a distance of 10 meters. Vehicle speed is held constant at 8 km/hr during the test run and a sampling rate of 60 samples per second (per channel) is maintained. The resistance value is computed as the average of the longitudinal force readings during the test run. Typical output for a resistance test is shown in Figures 18 and 19.

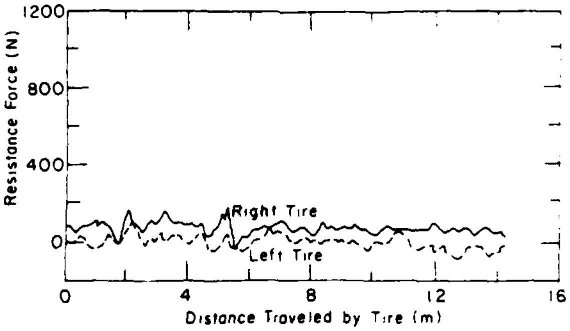

Figure 18. Motion resistance test on a hard surface (rear wheels driving).

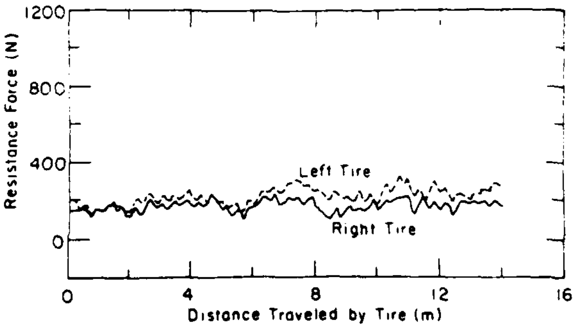

Figure 19. Motion resistance test on a hard surface (front wheels driving).

BASIC OPERATION - TRACTION

Traction testing is performed with the instrumented vehicle in its front-wheel-drive, rear-wheel-braking mode.

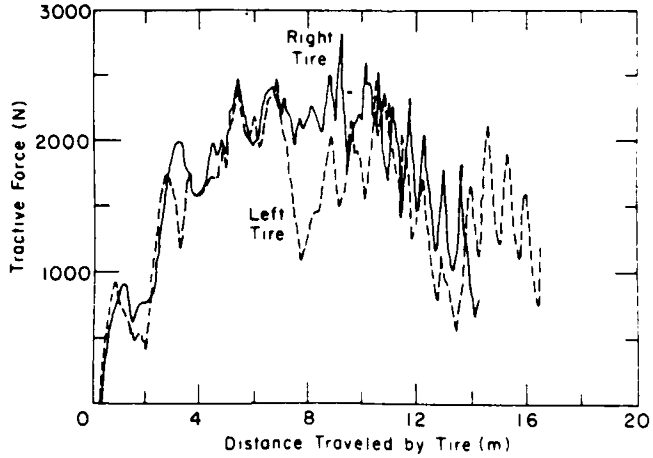

Figure 20. Tractive force vs tire distance plot for a traction test on packed snow.

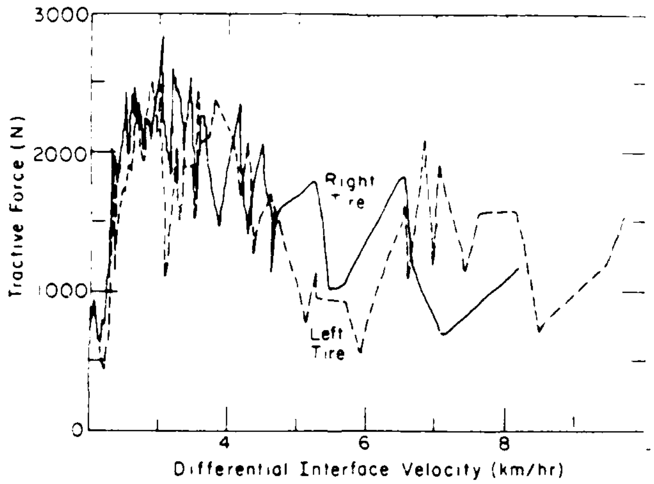

Figure 21. Tractive force vs differential interface velocity plot for a traction test on packed snow (same test as Fig. 20).

The test is run by accelerating the front wheels while braking the rear wheels to hold vehicle speed near 8 km/hr. This results in driving the front tires through all ranges of slip, starting with zero slip and proceeding to at least a 2.2 m/s rate of slip. This is accomplished by the driver observing vehicle speed (output from the 5th wheel) and tire speed on the driver read-out unit and adjusting his application of the brake and accelerator pedals.

The traction test is also performed on a level, straight section of the test area. The distance covered by each test varies, depending on the rate at which the operator passes through the range of slip values. Tractive effort is established from plots of tractive force versus tire distance (Fig. 20) and differential interface velocity (Fig. 21).

Details of snow surface and tire performance evaluation are presented in reference number 2.

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THE NATC DYNAMIC FORCE MEASUREMENT VEHICLE

Henry c. Hodges, Sr. Nevada Automotive Test Center
PO Box 234, Carson City, Nevada 89701

BACKGROUND

The need for quantification of mobility terms (gradeability, traction, trafficability, sinkage, soil type, angles of approach and departure, breakover angles, side slopes, turning radii and others) was identified in the early 1950's. A variety of technical studies have been performed since that time in response to this requirement.

The need for quantifying vehicle durability in terms that relate to service conditions was also considered in the early 1950's.

Terrain measuring devices, such as a single-trailed wheel which measured the vertical excursion of the terrain by plotting the single wheel displacement relative to the vehicle towing it, were tried and discarded. Civil engineering tools such as chains and transits are still in use. These instruments failed to record the topography of the test course in detail sufficient enough to isolate terrain features that produce critical vehicle/terrain failures, both in terms of mobility and durability, as a function of exposure time.

Instruments were also introduced to measure the reaction of the driver or the vehicle to the vertical excursions of a test course. Metal strain or sprung mass acceleration instruments detect relative levels of vehicle stress. Mass accelerometers were fastened to the driver or passenger to establish levels of acceleration and hence estimates of fatigue.

The problem with all these methods was the sensitivity of the measuring sensor to the dynamic peculiarities of the system component to which the sensor was affixed.

In 1968, the Nevada Automotive Test Center developed triaxial proof ring force sensors. These sensors measured the forces acting on the hitch point between towing and towed vehicles.

In 1973, utilizing the 1968 sensor system concept, the Nevada Automotive Test Center expanded the system to allow attachment of the sensors to each wheel of a vehicle. This refined system developed a uniquely low level of crosstalk between the three axes (nominally less than 3%). The triaxial sensor units built in 1968 experienced no change in calibration or sensitivity after more than 100,000 miles of test, indicating that proof ring durability was acceptable.

Since 1973, a total of seven Dynamic Force Measurement Vehicle Systems (DFMVS) have been designed, fabricated and validated at NATC (one such vehicle is shown in Figure 22). In addition to the four systems currently owned and operated by NATC, systems have been delivered to the Canadian Department of Defense, U.S. Department of Transportation (NHTSA) and the U.S. Forest Service (now owned by the U.S. Army Cold Regions Research and Engineering Laboratory). These systems range in size from a 2400-lb 4×4 to a 32,000-lb 6×6 vehicle.

DYNAMIC FORCE MEASUREMENT VEHICLE DESCRIPTION

The DFMV systems were designed by Hodges Transportation, Inc. (HTI) at the Nevada Automotive Test Center (NATC) in order to measure and record the dynamic interaction at the ground/tire or track interface. This dynamic interaction is

Figure 22. Dynamic Force Measurement Vehicle System.

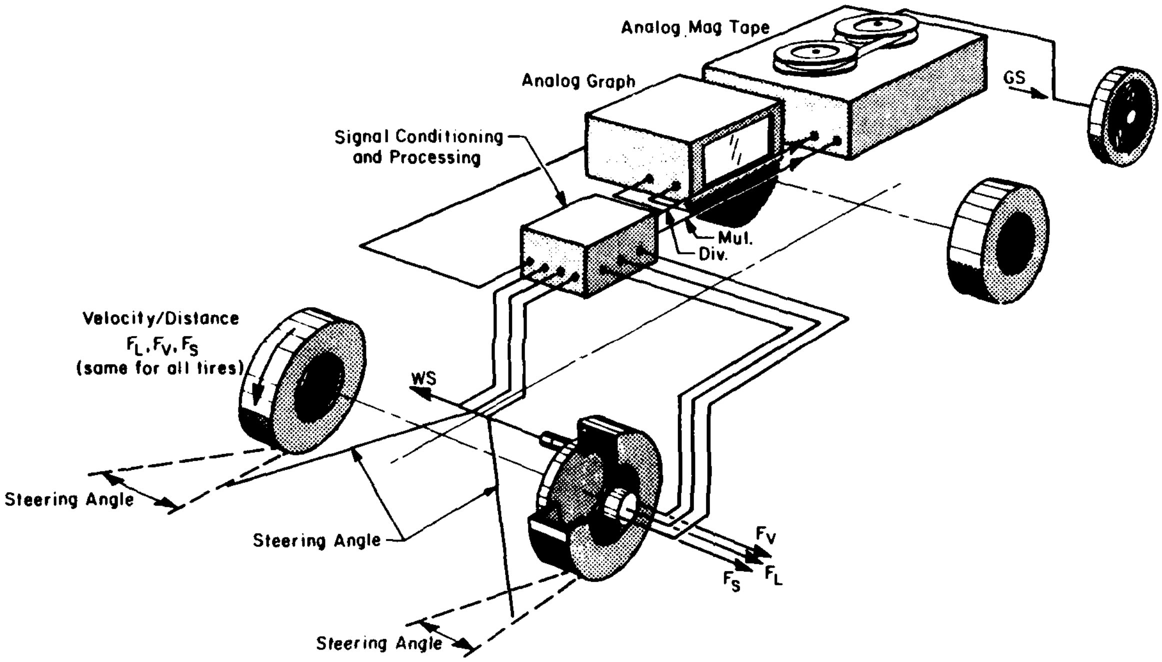

Figure 23. Four triaxial strain gauge type force transducers incorporated in the Dynamic Force Measurement Vehicle System.

characterized by Vertical Force (F_v), Longitudinal Force (F_ℓ), Side Force (F_s), Ground Velocity (V_g) and Wheel Velocity (V_w) at all points of interaction between the vehicle and the terrain over which it travels. For wheeled vehicle systems, steering angles (0) of the vehicles' front wheels are also measured.

The system calculates, records and displays Mu_ℓ, where $Mu_\ell = F_\ell/F_v$, Mu_s, where $Mu_s = F_s/F_v$ and Differential Interface Velocity (DIV) which is equivalent to ground speed less wheel speed. These calculations are performed independently on each of the points of interaction between the vehicle and the terrain.

The system incorporates four triaxial strain gauge type force transducers, providing outputs proportional to F_v, F_ℓ, F_s from each of the individual positions (Fig. 23).

Electronic counters measure and display revolutions of a fifth wheel attached to the test vehicle and of all wheels of the vehicle, thus providing correlation of distance traveled versus the number of wheel revolutions. Optical shaft encoders provide multiple pulses from the fifth wheel and the vehicle wheels to the counters. This pulse rate is inputted into frequency to voltage converters which provide an analog output equivalent to velocity.

Universal in nature, the system can record and/or display any of the thirty-six (36) functions available from the transducers and/or function modules incorporated into the system.

The vehicle on which the system is currently mounted incorporates a modified brake system that will allow any of the four wheels to be independently locked by the brake or to rotate free from any hydraulic pressure. This permits the vehicle to act as its own dynamometer if the front brakes are applied and the rear axle, free from braking force, supplies the driving forces.

The vehicle is equipped with locking hubs on both the front and rear axles. This allows the vehicle to be operated in front-wheel drive, rear-wheel drive or all-wheel drive modes.

A modified air-assisted shock absorber system was built into the vehicle so that the air pressure in each of the units can be independently regulated (up to a maximum pressure of 100 psig) from the driver's position. This provides a flexible system which permits changing the front and rear spring rates independently, and transferring the vertical load from one end or corner of the vehicle to another through a change in ridge height. It also allows the establishment of normal ride heights under unusual or heavy vehicle loads.

The vehicles also have a special transfer case which allows low-range or high-range operation in front-wheel drive, rear-wheel drive or all-wheel drive. The modes of operation can be selected from the driver's position.

VEHICLE DESIGN SPECIFICATION DFMVS-5

Vehicle design details, for a specific instrumented vehicle (DFMVS-5), include the following:

1976 AMC Jeep CJ-7 equipped with:

a. 304 CID V8 engine
b. Turbohydramatic 400 transmission
c. 4000-lb axles, 3.73:1 ratio
d. 4-wheel disc brakes
e. Dana Model 20 transfer case
f. Power steering
g. 4-wheel drive.

Special vehicle modifications made by HTI:

a. Steerable front-drive axle with 0-degree camber and 0-degree caster
b. Independent front-drive and rear-drive axles
c. Infinitely variable front axle toe-in controlled and monitored from within the vehicle; toe-in to 10 degrees total possible.

Instrumentation systems installed in vehicle:

a. Analog Data Acquisition System:
   1. One 18-channel visicorder oscillographic recorder
   2. Twelve strain gauge signal conditioning devices
   3. Four strain gauge control units
   4. Digital read-out of steer angle
   5. Digital velocity read-out from fifth wheel
   6. One 28-channel analog tape recorder
   7. RS 232 compatibility for digital interface through an A/D converter
b. NATC slip velocity integrator:
   1. Optical shaft encoders at all four wheels
   2. Frequency to voltage converter circuits (4)
   3. Velocity integrator (DIV = wheel speed minus ground speed)
   4. Visual slip velocity read-out (4)

NATC wheel force system:

a. 4000-lb wheel force transducers simultaneously measuring the dynamic vertical, longitudinal and lateral forces (4)
b. Integrated visual read-out (all channels)
c. Zero force DIV calibration.

FORCE FUNCTIONS

Each force function output of each triaxial load cell is conditioned by a strain gauge amplifier device (Fig. 24). The output of each amplifier is connected to a push button switch panel and then to a digital panel meter (DPM). The switch panel allows immediate display of any of

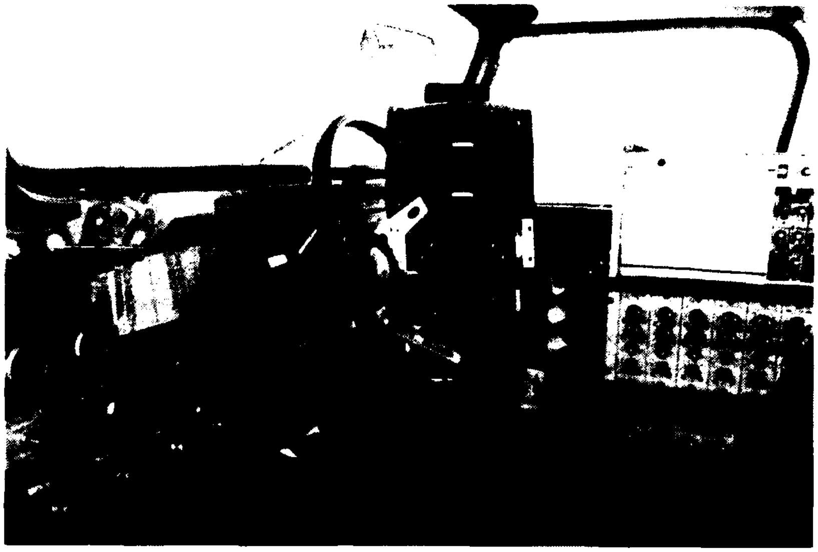

Figure 24. Strain gauge amplifier device.

Figure 25. Display of wheel forces, Mu levels or DIV values.

the wheel forces, Mu levels or DIV values (Fig. 25). The output of each amplifier and each function module is connected to a signal conditioning unit and each unit regulates the span and gain of the signals into the visicorder oscillograph or magnetic tape recorder. All values recorded are in analog format and are recorded in real time for each function.

WHEEL SPEED AND DISTANCE FUNCTIONS

Each wheel generates 300 pulses per revolution. Each of these are fed into a counter for driver readout and into a frequency-to-voltage converter circuit. The fifth wheel (for vehicle ground velocity and distance) has a similar counting and readout system, and the counts for all wheels and the fifth wheel can be displayed simultaneously. The output of each circuit is independent and can be displayed in feet per second or miles per hour. Individual wheel velocities or DIV can be recorded on the visicorder oscillograph or magnetic tape.

SYSTEM CALIBRATION

Calibration of the system's triaxial load cells was accomplished through the use of an air bearing plate. This unit consists of a force transducer resting on an air bearing and has National Bureau of Standards calibration traceability.

SUMMARY OF DATA ACQUISITION CAPABILITIES

(All recordable on photo-sensitive chart paper or magnetic tape)

1. Forces:
   a. vertical, longitudinal and side forces measured at all four wheel positions
   b. rates of force input from 0 to 10,000 lb/sec have been measured
   c. frequencies of force input ranging from 0.5 Hz to 5000 Hz have been recorded.
2. Energy Index:
   a. Mu values for all four wheel positions can be measured in the longitudinal and lateral directions
   b. values have been recorded from 0 to greater than 1.2 on dry pavement under braking or traction conditions.
3. Wheel Speed Minus Ground Speed (DIV):
   a. DIV values from 0 to 44 ft/sec have been recorded
   b. the pulse counter system is capable of measuring a rate of change of DIV instantaneously.
4. Front Wheel Steer Angle: The system displays steering angles from 0 to ± 30 degrees through all transition rates.
5. Vehicle Speed: Forward velocities from 0 to 140 mph have been accurately measured (± 2% of actual value).

CONCLUSION

In the energy-conscious 1980s, the need for quantification of the work done by a vehicle, and the efficiency with which this work is accomplished, have become necessities. Vehicle mobility and vehicle durability must be expressed in those energy terms which reflect the principles of propulsion common to all vehicles.[1]

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USE OF A SINGLE WHEEL TRACTION TRUCK FOR WINTER TRACTION TESTING

W.R. Janowski DataMotive, Inc., 14041 Mt. Bismark, Reno, Nevada, U.S.A. 89506

Passenger car and light truck tire traction testing in the winter environment has continued to increase in importance to tire manufacturers. This is due to the continued refinement of the all-season design, the consumer's demand for more effective performance, and the greater amounts of test documentation required for government agencies. Because the winter season is comparatively short and always unpredictable, it became apparent that a more efficient method of snow and ice driving traction testing was required in order to beneficially utilize the conditions when they occurred.

The single wheel traction test vehicle is an important tool for accomplishing as much testing as possible in the available time. Fast, consistent and repeatable data are produced. Following is information on the system DataMotive employs as well as a description of the special drawbar/traction truck demonstration that will be provided later in the program.

TEST VEHICLE

Chevrolet C-10 Half Ton Pickup Single Wheel Traction Truck for passenger and LT tires on 12.0- to 16.5-inch rims. The axle is limited to 2000 pounds maximum tire loading and approximately 650 pounds minimum tire loading. The minimum weight is obtained by removal of the rear body. The vehicle is equipped with a data acquisition and processing system consisting of a CRT terminal with thermal printer, desk top computer, strip chart, multiprogrammer and custom designed signal conditioning and amplifying systems. An automatic throttle applicator with variable rates for different surfaces is utilized to control the 350-in^3 engine which drives the right rear wheel through an automatic transmission in first gear during a spin-up. Brakes are applied to the front and left rear wheels only to hold vehicle speed to approximately five miles per hour during a spin-up. Tire chains are normally installed on LH side tires to prevent tire slippage during braking. Chains are not used on ice where only the left rear wheel is braked. A secondary high output alternator and separate battery provides the dedicated 12 VDC power to the inverter which in turn supplies a stable and regulated 115 VAC to the computer and data acquisition systems. Vehicle speed is obtained from a tach generator installed on the left front wheel. An analog speed meter positioned in front of the driver is utilized to monitor vehicle speed. Test tire speed is obtained from a pulse generator located at the right rear test wheel position. Special high pressure shock absorbers are mounted on the rear axle to permit height adjustment as monitored by a string potentiometer located between the frame and rear axle housing. This system is utilized in order to maintain correct geometry of the rear axle transducer with varying tire size and load. The specially modified rear axle is mounted with a dual trailing arm suspension to further assist in maintaining proper axle location and geometry. The right end of the rear axle has been modified with the addition of a biaxial strain gage force transducer which supplies an analog signal of dynamic tractive force and vertical tire load.

INSTRUMENTATION

The single wheel traction test vehicle is completely self contained with all instrumentation mounted convenient to the driver. The entire data acquisition, processing, displaying and printing activities are performed onboard simultaneously with the test activities.

A test sequence begins by driving the vehicle at 5 mph and pressing a "cal" button which instructs the computer to utilize the correct test wheel revolution speed as 5 mph. This permits the utilization of tires with various rolling radii (due to physical size and test load) with proper calibration. The driver then presses a "start" button which puts most of the spin-up function under computer control from throttle application to throttle shutoff after meeting time and speed requirements for both the SAE and GM tests. During this time the driver need only steer the vehicle and apply sufficient braking to maintain a constant 5 mph vehicle speed. At the end of a spin-up a horn sounds indicating spin-up completion and returns throttle control to the driver. Approximately 1-3/4 seconds later a complete run line is displayed on the terminal (the same as printed on interim data sheet). The driver can process data (calculate mean, standard deviation, etc.) at any time, or repeatedly, to assess the accuracy of the data to that point. After a minimum of 10 spin-ups final data processing is completed. An interim report is printed as the vehicle is driven back to the tire changing area. Following completion of the entire test sequence the computer calculates test ratings and the terminal prints out the results.

Analog dynamic and static traction forces and dynamic wheel loads filtered to 20 Hz are fed to the data acquisition system from the instrumented right rear wheel position. Analog test wheel and vehicle speed data filtered to 5 Hz are also accumulated during the test spin-up. A time base provides the fifth channel of input information. The data is digitized and recorded at the rate of 50 points/second/channel. Calibration resistors permit daily calibration of the force and speed amplifiers.

All data acquisition and processing is accomplished with a Hewlett Packard 6825T Desk Top Calculator, 6940B Multiprogrammer and 2621B Printing Terminal. A specially designed signal conditioning package with strain gage amplifiers interfaces with the computer equipment. A three-channel strip chart recorder is installed to provide a visual indication of input data. All equipment is mounted on vibration insulators.

The test program can be instructed to limit maximum slip to any range between 50 and 300% slip to accommodate special test requirements, i.e., hard surface or mud traction tests. The GM coefficients are only reported when 300% slip is selected. In addition, a beeper sounds any time the GM ending speed falls below the prescribed minimum of 10.0 mph. This alerts the test engineer and allows him to delete that run if GM data is of primary interest.

A special drawbar test will be set up for comparison with traction truck data. Dynamic tractive force loads are measured with an auxiliary strain gage load cell which is part of the drawbar assembly. This assembly is attached through freely rotating joints on the test vehicle's rear axle housing to eliminate the variable of weight transfer due to drawbar pickup position. The load cell is plugged into the data acquisition wiring system in place of the instrumented axle tractive force transducer. The computer takes the existing vertical load from the instrumented axle and doubles it to account for two driving tires. Vehicle ground speed continues to be measured from the left front wheel position. Wheel speed continues to be measured from the right rear wheel position. All data obtained during the drawbar test is processed exactly as for the single wheel test mode.

TEST DATA AND REPORTING

1. Dynamic traction

Tests on medium pack snow are normally conducted in accordance with the proposed SAE Recommended Practice, "Passenger Car and Light Truck Tire Dynamic Traction in Snow." A minimum of ten spin-ups are made and a report printed with the onboard printer immediately after completion of the spin-ups. This report is similar to that entitled "Interim Dynamic Traction Data Sheet" (Fig. 26). Information in the header defines test sequences by block number, tire identification, existing test conditions with temperatures updated with every control tire, etc. Each spin-up is identified by run number and the SAE Coefficient (area method over 1-15 mph [Differential Interface Velocity] DIV test wheel speed

Block #:	XXX	Customer:	XXXXXXXXXXXXXXXXXXXX
Time:	XXXXXX	Date:	XX/XX/XX
Tire Code:	XXXXXX	Surface:	XXXXXXXXXXXXXXXXXXXX
Tire I.D.:	XXXXXXXXXXXXXXXXXXXX	Tire Size:	XXXXXXXXXXXXXXXXXXXX
Amb Temp °F:	XXX	Test Load Lbs:	XXXX
Surf Temp °F:	XXX	Tire Infl PSI:	XXX
Surf Comp:	XXXXX	Operator:	XXX
		Location:	XXXXXXXXXXXXXXXXXXXX

INDIVIDUAL RUNS

Run	SAE Coef	Peak Coef	GM Coef	GM Speed	Avg G.S.	Run Time	Avg Load
1	X.XXX	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
2	X.XXX	X.XXX	X.XXX*	XX.X	XX.X	X.XX	XXXX
3	X.XXX	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
4	X.XXX*	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
5	X.XXX	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
6	X.XXX	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
7	X.XXX	X.XXX*	X.XXX	XX.X	XX.X	X.XX	XXXX
8	X.XXX	X.XXX	X.XXX*	XX.X	XX.X	X.XX	XXXX
9	X.XXX	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
10	X.XXX	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
11	X.XXX	X.XXX*	X.XXX	XX.X	XX.X	X.XX	XXXX
12	X.XXX	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
13	X.XXX	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
14	X.XXX	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
15	X.XXX	X.XXX	X.XXX	XX.X	XX.X	X.XX	XXXX
Mean	X.XXX	X.XXX	X.XXX				XXXX
S.D.	X.XXX	X.XXX	X.XXX				
R.U.	XX	XX	XX				
Adj Mean	X.XXX	X.XXX	X.XXX				
Adj S.D.	X.XXX	X.XXX	X.XXX				
C.V.	X.XXX	X.XXX	X.XXX				

SAE COEF @ MPH DIV

Run	1	2	3	5	7	11	15
1	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
2	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
3	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
4	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
5	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
6	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
13	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
14	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
15	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
Avg.	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX

Figure 26. Interim dynamic traction data sheet.

range), Peak Coefficient, and GM Coefficient (time integration for 1.5 seconds starting at 2 mph DIV) are calculated. The GM speed is the speed of the test tire in mph DIV at the end of 1.5 seconds of data. Average ground speed is the average vehicle speed in mph over the SAE area test. Each of the coefficient columns is then analyzed for the mean value and standard deviation for all runs. Any coefficient values outside ± 1.5 standard deviation are noted with an (*). The number of runs left is noted by R.U. (runs used) and a new adjusted mean and

Customer:	XXXXXXXXXXXXXXXXXXXX
Date:	XX/XX/XX
Surface:	XXXXXXXXXXXXXXXXXXXX
Blocks Summarized:	XXXXXXX

CONTROL TIRE ANALYSIS

Tire Code:	XXXXXX	Test Load Lbs:	XXXX
Tire I.D.:	XXXXXXXXXXXXXXXXXXXX	Tire Infl PSI:	XXXX
Tire Size:	XXXXXXXXXXXXXXXXXXXX		

							Temp	
Block #	SAE Coef	CV%	Peak Coef	CV%	GM Coef	CV%	Amb	Surf
XX	X.XXX	XX	X.XXX	XX	X.XXX	XX	XXX	XXX
XX	X.XXX	XX	X.XXX	XX	X.XXX	XX	XXX	XXX
XX	X.XXX	XX	X.XXX	XX	X.XXX	XX	XXX	XXX
XX	X.XXX	XX	X.XXX	XX	X.XXX	XX	XXX	XXX
XX	X.XXX	XX	X.XXX	XX	X.XXX	XX	XXX	XXX
XX	X.XXX	XX	X.XXX	XX	X.XXX	XX	XXX	XXX
XX	X.XXX	XX	X.XXX	XX	X.XXX	XX	XXX	XXX
Avg	X.XXX		X.XXX		X.XXX			

TEST TIRE SUMMARY

Block #:	XXX	Tire Code:	XXXXXX	Tire Load:	XXXX
		Tire ID:	XXXXXXXXXXXXXXXXXXXX	Tire Infl:	XXX
		Tire Size:	XXXXXXXXXXXXXXXXXXXX		

	SAE	CV%	Peak	CV%	GM	CV%
Coef	X.XXX	XX	X.XXX	XX	X.XXX	XX
Test Rating %	XXX		XXX		XXX	
Avg Rating %	XXX		XXX		XXX	

Block #:	XXX	Tire Code:	XXXXXX	Tire Load:	XXXX
		Tire ID:	XXXXXXXXXXXXXXXXXXXX	Tire Infl:	XXX
		Tire Size:	XXXXXXXXXXXXXXXXXXXX		

	SAE	CV%	Peak	CV%	GM	CV%
Coef	X.XXX	XX	X.XXX	XX	X.XXX	XX
Test Rating %	XXX		XXX		XXX	
Avg Rating %	XXX		XXX		XXX	

continued

Figure 27. Tire test summary sheet.

standard deviation are calculated along with a coefficient of variation. For those who might like to plot traction curves or statistically analyze data, al runs are detailed at the bottom of the sheet based upon SAE coefficients at var ious wheel speeds (DIV [20-300% slip]). The entire data sheet is also available on cassette tape for those who request i in advance. At the completion of a test sequence for a customer, a control tire analysis and test tire summary sheet with rating is produced and printed immediately on-site. This provides an analysis of all control tires run during the preceding sequence and summarizes results of each individual test tire reported in order of testing. The adjusted mean coefficients for each of these test methods is presented along with a "test rating" based upon comparisons with control tires run immediately before and after the test tire and an "AVG rating" based upon the overall average of the total control tire runs. The attached sample sheet (Fig. 27) continues on to cover all test tires run during any one sequence.

2. Static traction

Static traction is the maximum tractive coefficient of the test tire measured with the test vehicle held stationary. Individual maximum static spin-up coefficients are recorded and displayed on the CRT terminal immediately after each spin-up. A minimum of 10 individual spin-up results are tabulated and data averaged and adjusted in the same mathematical manner as described under dynamic traction testing. Comparative ratings with a control tire are manually calculated following completion of a test sequence.

CONCLUDING REMARKS

The single wheel traction truck represents a significant improvement in the technology of tire driving traction evaluations. The time-proven two-vehicle drawbar test method will continue as a viable method of mobility evaluations of whole wheeled and tracked vehicles. The biggest problem when using either system continues to be the preparation of consistent snow courses on which repeatable and reproducible test results can be obtained.

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SESSION II: PERFORMANCE REQUIREMENTS EVALUATION

The purpose of this session was to discuss current and proposed methods of evaluating tire performance on snow and ice. The effectiveness of tire design criteria was also discussed. As a necessary lead-in, characterization measurements of snow and ice were also covered.

Surprising similarity exists in the manner in which tire traction tests are performed by the various groups represented at the workshop. It can also be seen that, in principle, the philosophy employed for evaluating tire performance is quite similar among those performing tire tests. The unique features of each scheme appear to result from specific differences in the measurement device used or in the ultimate use of the performance ratings.

PASSENGER CAR AND LIGHT TRUCK TIRE DYNAMIC DRIVING TRACTION IN SNOW: SAE RECOMMENDED PRACTICE

SAE Snow Test Ad Hoc Committee

The procedure that follows is presently recommended by the SAE for determining the relative snow traction performance of tires. It is reprinted here in its entirety.

SCOPE

This SAE Recommended Practice defines the best known techniques for evaluating dynamic passenger car and light truck tire driving traction in snow.

OBJECT

The object of this SAE Recommended Practice is to provide a uniform test procedure for measuring the dynamic driving traction of passenger car and light truck tires in snow.

PREPARATION OF TIRE(S) FOR TEST

All tires to be tested shall be trimmed to remove protuberances in the tread and upper sidewall area caused by mold air vents or flashes at mold junctions. All tread labels shall also be removed at this time. Tires should not have evidence of force or runout grinding.* Test tires shall be mounted on rims† of a width approved by the Tire and Rim Association (T&RA) for the tire size being tested, inflated to the T&RA design inflation pressure, applied to an appropriate vehicle, loaded to 80-100% T&RA design load for recommended inflation, and run on a paved road for a minimum of 80 km (50 miles) at 80-88 km/h (50-55 mph). This break-in is run to remove mold lubricant and mold sheen from the tread surface. Excessive acceleration, braking and cornering, that might result in abnormal tread surface wear, are to be avoided. (NOTE: Tires that have been buffed to simulate wear must be run on a paved road until all evidence of buffing has been removed.)

EQUIPMENT

Test vehicles

Either a self-contained traction vehicle or a two-vehicle drawbar pull system designed to measure dynamic driving traction forces and meeting the requirements outlined in Appendix A or B is required.

Course preparation equipment

Snow handling equipment and a device designed for compacting the snow surface in a uniform manner is normally needed--see Appendix C.

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* Force or runout grinding may produce incorrect results due to surface texture changes in the tread rubber.

† For meaningful comparisons, tires of similar size should be run on compatable width rims.

Course measuring equipment

1. Snow Compaction Measuring Device - CTI Snow Penetrometer--see Appendix D.
2. Snow Monitoring Tire (SMT) - Industry Standard Tires for characterizing test surface--see Appendix E.
3. Calibrated thermometers or other temperature measuring devices used to measure ambient and snow temperatures.

TEST PROCEDURE

Test conditions

1. Load* -

   A. Passenger: 85% T&RA design load.
   B. Light truck: 5337 N (1200 lbs).

2. Inflation Pressure -

   A. Passenger: T&RA max. as stamped on the side of the tire.
   B. Light truck: Bias ply tires - 300 kPa (45 psi), Radial tires - 350 kPa (50 psi), but not to exceed maximum shown on tire sidewall.

3. Vehicle Test Speed -

   Vehicle 8 km/h ± 1.6 km/h (5 ± 1 mph). (NOTE: Change in speed for any test run should not exceed 0.8 km/h [0.5 mph]).

Test surface

The test surface shall be of a reasonable depth, 50-100 mm (2-4"), of prepared natural snow over a moderately packed snow base. This surface shall have a mean CTI Penetrometer reading between 70 and 80 (see Appendix D) and snow monitoring tire mean friction coefficient of 0.18-0.26 (see Appendix E). A sufficient number of individual measurements shall be taken in establishing the average to ensure course uniformity. The range of the individual measurements shall not exceed 8 points for Penetrometer readings or 0.05 coefficient for snow monitoring tire. The temperature of the prepared test course as measured one inch below the surface shall be in the range of -12°C (+10°F) to -4°C (+25°F). Snow course preparation is extremely critical for obtaining valid results. See Appendix C for additional details.

Testing procedure

Tests should be conducted as outlined in procedures shown in Appendix A or B.

DATA REDUCTION AND ANALYSIS

Data Reduction

The quantitative measure of tire performance shall be the average tractive force a tire produces during a test. This average may be determined by one or both of the following methods: 1) Digital or analog average determined between 2 and 24 km/h (1-15 mph) DIV of a tractive force - DIV curve. (NOTE: DIV-Differential interface velocity is the difference between the test tire speed and the test vehicle speed.) 2) Digital or analog average of 1.5 seconds of data from a tractive force-time plot. Data acquisition begins when DIV is 3 km/h (2 mph). Minimum ending DIV must be 16 km/h (10 mph).

To convert the average tractive force to a coefficient offriction, divide by the average test load (see Test Procedure). The average test load can be determined in the same manner as the average tractive force. If the average test load is not available, the nominal test load is an acceptable alternative value.

Data analysis

Determine mean and standard deviation of test sequence. Eliminate any individual test value more than 1.5 standard deviations different from the calculated mean. After eliminating such an individual test value, recalculate the mean and standard deviation of the test sequence.

Examine the data for variation by some means such as coefficient of variation (C.V. = Standard Deviation/Mean). If the data has extreme variations (i.e., C.V. greater than 0.20), the individual tire data should not be used and the test sequence repeated.

The SMT tire should be used to monitor changes in the testsite conditions so that test tire coefficients can be adjusted appropriately. A basic method to

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* These loads were selected to represent typical usage.

adjust test tire coefficients for SMT tire variations is as follows:

The SMT tire coefficients are averaged for a sequence of tests (usually one test day).

Each test tire coefficient is then adjusted by multiplying by the ratio of the overall SMT tire coefficient to the average coefficient of the individual SMT tires tested before and after that test tire. The standard deviation of each test tire is also adjusted by multiplying by the same ratio. The following example test sequence computations illustrate the method, using four test tires:

1) SMT Tire (SMT_1)
2) Test Tire (T_1) (SD_1)
3) Test Tire (T_2) (SD_2)
4) SMT Tire (SMT_2)
5) Test Tire (T_3) (SD_3)
6) Test Tire (T_4) (SD_4)
7) SMT tire (SMT_3)

Overall SMT average (SMT_{avg}) =

$$\frac{SMT_1 + SMT_2 + SMT_3}{3}$$

$$\text{SMT average } (SMT_{12}) = \frac{SMT_1 + SMT_2}{6}$$

$$\text{SMT average } (SMT_{23}) = \frac{SMT_2 + SMT_3}{2}$$

The means and standard deviations of the test tires T_1 and T_2 are adjusted by:

$$\left(\frac{SMT_{avg}}{SMT_{12}} \right) (T_1 \text{ or } T_2),$$

$$\left(\frac{SMT_{avg}}{SMT_{12}} \right) (SD_1 \text{ or } SD_2).$$

Test tires T_3 or T_4 are adjusted by:

$$\left(\frac{SMT_{avg}}{SMT_{23}}\right) (T_3 \text{ or } T_4),$$

$$\left(\frac{SMT_{avg}}{SMT_{23}}\right) (SD_3 \text{ or } SD_4).$$

Comparative test tire data is then determined by normalizing the test tire coefficients to a 0.22 coefficient surface on a proportionate basis of SMT values at the time of actual test.

The above procedure should be considered only as a fundamental outline for test tire adjustment to minimize error caused by changes in uncontrolled variables. Other, more complex, methods for test tire adjustment can be used. These methods generally incorporate test variability and sample size. If variations in SMT tire values were observed that cannot be accounted for, or if test tire data is corrected more than 5%, the entire test should be repeated.

An overall mean using a minimum of three (3) different tests (data obtained on different days) should be calculated. Testing error should be determined using appropriate techniques. Means obtained from more than one day of testing combined with testing error, best represent a given tire's performance. Differences between specific tires or among tire groups must be determined in a statistical manner. The Student's T test or Analysis of Variance techniques are appropriate for determining these differences. Individual tire performance values do not necessarily imply significant differences.

PRECISION AND ACCURACY

Precision

This precision statement is based on data obtained from five test laboratories and reflects the combined variability of both self-contained and drawbar pull driving traction tests. Two candidate tires and the recommended Snow Monitoring Tire (SMT) were tested:

Candidate 1 - P195/75R14 Large Lug Type M&S
Candidate 2 - P195/75R14 All Season Type M&S
SMT - P195/75R14 Uniroyal "Steeler" #32164-U

Performance for each tire was determined by averaging three test replications. All tests were conducted within the recommended SAE test conditions. The precision of results for tires of this type could be expected to fall within ± 0.04 spin coefficient.

Accuracy

No statement of accuracy can be prepared for this method since there is no absolute value for use as a comparison.

APPENDIX A: SELF-CONTAINED DRIVING TRACTION TEST PROCEDURE

Scope

This method covers the measurement of driving traction for passenger and light truck tires traveling straight ahead on prepared or selected test surfaces of uniform consistencies as measured using a single instrumented vehicle. This procedure and equipment described herein are intended for snow-covered surfaces.

Summary of test method

This test utilizes a four-wheel, rear-wheel drive test vehicle with one specially-instrumented drive wheel to measure the fore-aft and vertical forces on its tire and with the capability of deactivating the brake on this wheel. The test is conducted by gradually increasing the driving torque to the test wheel and maintaining test speed by modulating the brakes of the other nontest wheel positions. The test progresses with increasing throttle setting and brake application until the desired maximum tire test is achieved.

The nominal recommended vehicle test speed is 8.0 km/h (5 mph) and the actual vehicle speed must be within ± 1.6 km/h (1 mph) of nominal recommended. Speed variation during any individual test run must not exceed 0.8 km/h (0.5 mph).

Equipment

Test vehicle. The test vehicle shall be a rear-wheel drive, four-wheel vehicle specially fabricated and instrumented to measure the fore-aft and vertical forces at one wheel position at the tire/surface interface while driving torque is applied. Vehicle size and selection depends on the tire size and loading condition to be tested. Automatic transmission is recommended.

The test vehicle shall have the capability of maintaining a specified test vehicle speed to within 0.8 km/h (0.5 mph) even at maximum levels of application of driving torque.

The test vehicle shall be equipped with an automatic throttle applier to provide for a smooth increase of driving torque.

The brake system will be modified to deactivate the test wheel brake upon initiation of a tire test.

Predetermined test vehicle ride heights adjusted in conjunction with a position transducer to obtain proper transducer orientation.

Calibration instrumentation. Appropriate loading platform or load cells, air bearings, and other auxiliary equipment required for calibrating the vertical and fore-aft force transducer (ref. ASTM F377).

Required instrumentation for calibrating speed transducers, and adequate support equipment to calibrate and maintain all intermediate instrumentation (ref. ASTM F457).

Instrumentation. The test system instrumentation and transducer shall have specifications sufficient to meet accuracy, filtering, and digital requirements as outlined in ASTM F408.

A force transducer, to measure tractive force produced by the test tire and the vertical force on the test tire is required. This transducer is generally mounted at the axle tire-brake backing plate interface of the test wheel position.

It is important that the orthogonal measuring axes of the force transducer be properly oriented to theplane of the road surface. Improper orientation of the transducer can cause errors in the input force signal. Misalignment can result from initial setting of transducer angle, dynamic change due to suspension rotation or "wind-up," or dynamic change due to ride motion.

Prior to testing at different loads or changing test tire diameter, the force measuring transducer must be repositioned to null the vertical load component induced into the fore-aft channel. This is particularly important in dual-axis measuring devices because:

fore-aft force indicated = $T_A \cos\alpha \pm V_A \sin\alpha$ (Equation 1)

vertical force indicated = $V_A \cos\alpha \pm T_A \sin\alpha$ (Equation 2)

where T_A = actual fore-aft force
V_A = actual vertical force
α = angle of transducer positioning error.

If the fore-aft channel is zeroed with the static load applied to the transducer, the $\pm V_A \sin \alpha$ term of Equation 1 will be essentially nulled (neglecting the effect of dynamic vertical load change, which should be made very small). Because there is no practical way to zero the vertical channel with fore-aft force applied, the $\pm T_A \sin\alpha$ error of Equation 2 cannot be compensated for and increases in magnitude with increasing fore-aft force development.

Vehicle speed sensor, to determine vehicle speed accurately. This may be accomplished with a speed pickup from a front wheel of the test vehicle, a fifth wheel, or some other appropriate device.

Tachgenerator, to measure angular velocity of test wheel.

Data recorder, to provide a permanent record of transducer output signals prior to any data processing. This recorded data can be used for hand processing of data or to provide an information source for confirming outputs of any digital or analog data processors. A visual display of these data is appropriate as an aid to the operator, but is not required. Microprocessor, used for onboard data processing. This unit is not required, but simplifies data processing.

Preparation of equipment

All transducers and instrumentation should be calibrated using recognized procedures (see Calibration). The test vehicle front tires should be the same size and have the same inflation pressure as used in calibration to maintain the front axle heights. Mount test and SMT tires on appropriate rims to account for possible test vehicle transducer offset sensitivity.

Calibration

Calibrate the transducer for measuring driving forces as generally described in ASTM F377.

The vehicle transmission should be placed in "Park" (P) with the emergency brake off during fore-aft calibration. This allows calibration with all the components of the drive system involved, as in the actual test mode. The test wheel brake must be deactivated during calibration.

Calibrate vehicle speed sensor, test wheel speed tachgenerator, and all other intermediate instrumentation according to established procedures or manufacturer's specifications.

The ride height required for transducer alignment is determined during calibration, using specific test loads and tire size combinations to be tested. A position transducer is used in conjunction with height adjustment device to measure the distance between the vehicle frame and rear axle.

All instrumentation is to be calibrated prior to each test program.

General test conditions

Conduct the tests on a level surface meeting the requirements of manufacturer's calibration specifications.

Procedure

1. Warm up electronic test equipment as required for stabilization.
2. Test tires should be stabilized at ambient temperature and shielded from direct sunlight before testing.
3. Install test tire on test vehicle. A tire with a similar loaded radius and equipped with a tire chain or other traction device should be used on the nontest side to prevent this position from spinning.
4. Adjust the vehicle static weight on the test tire to the test load.
5. Check and adjust tire inflation pressure as required immediately before testing.
6. Adjust vehicle ride height to the predetermined output reading of the position transducer by using the leveling device. This positions the transducer to compensate for different test loads and changing test tire diameters.
7. Record tire identification and other data, including date, time, ambient temperature, and test surface information.
8. Conduct test at nominal 8 km/h (5 mph) test vehicle speed.
9. Activate the automatic throttle applicator to obtain a maximum 1780 N/sec (400 lb/sec) measured fore-aft force before spin and apply the brakes as required to maintain test vehicle speed. (NOTE: An invalid snow traction test run occurs when a tire digs through to either the base road material or to glare ice during tire acceleration or spin.)
10. Record test data. Data recorded shall include tractive force, vertical force, test tire speed, ground speed and a time reference.
11. Repeat steps 8-10 (a minimum of 8 times) to complete the tire test. (NOTE: Multiple tests should not be con-

ducted over the same surface without adequate surface reconditioning between tests.)

12. Run an SMT tire at the beginning and end of each test sequence and every third test in between (SMT-T-T-SMT-T-T-SMT, etc.).

13. Each test tire should be tested at least three times, preferably on different days.

APPENDIX B: DRAWBAR PULL TEST PROCEDURE

Scope

This method covers the measurement of driving traction of a pair of tires designed for and mounted on passenger cars or light trucks traveling straight ahead on a prepared snow surface using the two vehicle drawbar pull system.

Summary of method

The test is conducted by towing a hold-back vehicle (dynamometer) behind the test vehicle moving in a straight line. A constant speed is maintained by increasing the brake application of the dynamometer to compensate for increasing throttle setting of the test vehicle. The dynamometer braking is increased only as much as is necessary to maintain a constant test speed. The test progresses with increased throttle setting and dynamometer brake application until the test tires spin through the desired slip range.

The nominal recommended vehicle test speed is 8.0 km/h (5 mph). The actual vehicle speed must be within ± 1.6 km/h (1 mph) of nominal recommended. Speed variation during any individual test run must not exceed 0.8 km/h (0.5 mph).

Equipment

Test vehicle. The test vehicle shall normally be a rear-wheel drive, four-wheel passenger car or a light truck under 44,482 N (10,000 lbs) GVW (gross vehicle weight). A front-wheel drive vehicle is acceptable where test requirements dictate.

The test vehicle should be designed to carry the test load on the drive axle. The use of overload springs, air shocks or suspension blocks is acceptable.

The test vehicle should incorporate an automatic engine throttle applicator capable of providing a smooth increase of driving torque.

Towed hold back vehicle

The towed vehicle should have capability to develop a dynamic drawbar pull force and maintain test speed dictated by test tire size and load.

Calibration

Calibrate the force transducer, speed sensor, test wheel speed, tachgenerator, and all other intermediate instrumentation, in accordance with the manufacturer's recommended procedure. All instrumentation is to be calibrated prior to each test program, and provisions should be provided for daily field calibrations.

General test conditions

Conduct the tests on a level surface meeting the requirements met during calibration.

Procedure

1. Warm up electronic test equipment as required for stabilization.
2. Test tires should be stabilized at ambient temperature and shielded from direct sunlight before testing.
3. Apply test tires to the test positions.
4. Adjust the vehicle test wheel static weight by ballasting to match the static wheel load specified for test tires.
5. Check and adjust tire inflation pressure as required immediately before testing.
6. Record tire identification and other data, including date, time, ambient temperature, and test surface information.
7. Approach a test site moving in a straight line at a constant nominal speed of 8.0 km/h (5 mph) and adjust the hold back vehicle speed to obtain near zero drawbar pull force.
8. Turn on the recorder drive just prior to reaching the test site.
9. Activate the automatic throttle applicator to obtain a maximum 1780 N/sec (400 lb/sec) measured drawbar force before spin. (NOTE: An invalid snow traction test run occurs when a tire digs through to either the base road material or to glare ice during tire acceleration or spin.)

10. Record test data. Data plotted or recorded shall include drawbar force or traction coefficient vs DIV, ground speed, and a time reference.

11. Repeat steps 8-10 to obtain a minimum of 8 acceptable curves. (NOTE: Tests should not be conducted over the same surface without adequate surface reconditioning between tests.)

12. Run an SMT tire at the beginning and end of each test sequence and every third test in between (SMT-T-T-SMT-T-T-SMT, etc.).

13. Each test tire should be tested at least three times, preferably on different days.

14. Every effort should be made to have the same test drivers perform the same test functions through a sequence of tests.

Other equipment

Drawbar assembly. The drawbar assembly consists of a load transducer in series with a flexible (chain) or solid connection between the test vehicle and hold-back vehicle. The attachment of the drawbar to the rear-wheel drive test vehicle is directly to the test vehicle's frame or rear axle assembly through a freely rotating joint. Springs can be provided to counterbalance the static weight of the force transducers and drawbar assembly.

Intercom--An intercom should be used between the test and dynamometer vehicles for proper coordination of the test activities.

Instrumentation. The test system measuring instrumentation shall have specifications sufficient to meet accuracy, filtering, and digital requirements as outlined in ASTM F408.

Force transducer--to measure drawbar pull force. An analog or digital readout may be provided (optional) in the test vehicle for on-site calibration purposes.

Vehicle speed sensor--to determine vehicle speed accurately. This may be accomplished with a speed pickup from a front wheel of the test vehicle, a fifth wheel, or some other appropriate device.

Tachgenerator--to measure average angular velocity of two test wheels, installed on the test vehicle.

Multichannel Recorder or XXY or XYY Function Plotter--to provide a permanent record of transducer output signals prior to any data processing. This recorded data can be used for hand processing of data or to provide an information source for confirming outputs of any digital or analog data processors. A visual display of this data is appropriate as an aid to the operator, but is not required.

Microprocessor--used for on-board data processing. This unit is not required, but simplifies data processing.

Preparation of equipment

All transducers and instrumentation should be calibrated to recognized procedures. The same tires are to remain on the nontest wheel positions throughout the test.

APPENDIX C: SNOW TEST COURSE SITE SELECTION, PREPARATION, AND MAINTENANCE

There are three basic requirements for the selection of a test course site. First, the test area must be flat. A maximum of 1% grade, including crown is preferable. This ensures testing of the tire and not the grade requirements of the vehicle. Second, the test area should be limited access. Having only test vehicles on the test surface reduces maintenance requirements for the surface. Third, no vegetation should be exposed. If a field is used, all vegetation should be cut and/or covered such that it is never exposed during testing. This may also apply to private road areas when vegetation occurs in pavement cracks. Appropriate test sites include airport runways, private road systems, large, unused parking lots, and open, level fields.

Once a site has been selected, a course must be prepared. Developing a base is the most critical step in this preparation. A good base must adhere to the firm subsurface and be completely smooth and uniform in consistency. Without a good base, it is impossible to develop good test data.

Deep loose snow cannot generally be compacted into a satisfactory hard pack base. Therefore, it should be packed in layers. Excessive snow should be removed to a depth of two to four inches, depending on the compressibility of the snow before packing. After the first layer is packed, the snow that was previously removed can be brought in from the banks to a depth of two inches (provided the banked snow has not hardened into large chunks) and com[illegible]d again. This process is repeated until sufficient base depth is developed. Allowing a base to sit undisturbed overnight or longer will usually firm it up. Defining sufficient base depth is difficult.

The base must be of sufficient depth so that a spinning test tire does not dig down to anything but more base snow. Required depth changes depending on test tread designs, but usually a minimum of two inches is necessary. Throughout a test season, it will be necessary to groom the surface to keep it smooth and free from holes and undulations. Use of a road grader is the most ideal method; however, a standard snow plow, preferably with a long wheel base, can be used if a speed is selected to minimize suspension rocking which can result in increased undulations.

Once a base is established, the preferred method is to wait for natural snow to accumulate to a sufficient depth to allow appropriate testing conditions. When a large test area is available, various sections can be designated as virgin, soft, medium, and extra hard test areas. This allows testing on medium and extra hard surfaces while other sections are accumulating sufficient depth for soft and virgin snow conditions. The preferred snow condition for best discrimination among tire types is medium packed snow over a hard packed base. Medium packed snow corresponds to CTI penetrometer readings (Fig. 28) between 70 and 80 and Snow Monitoring Tire friction coefficients of 0.18 - 0.26 (see Appendices D and E). Test surfaces can be groomed to these levels. Test surfaces should always be quantified by averaging several locations along the test course. The range of these measurements should not exceed 8 points for penetrometer readings or 0.05 in friction coefficients for the Snow Monitoring Tire.

Each time a surface is used for testing, it gets packed down and consequently becomes harder. Therefore, the same test area cannot be used over and over for the same compaction range without reconditioning. Mechanical snow reconditioners to loosen hard packed snow can be used when fresh snow is not available. However, whenever a surface is reconditioned or regroomed, it should be rechecked to ensure that the penetrometer and the Snow Monitoring Tire measurements are correct.

It is also necessary to check a test surface periodically during a test day to ensure that it has not changed significantly. This may be accomplished by monitoring the SMT test results and rechecking with the penetrometer.

CTI INDEX	SURFACE DESCRIPTION
100	Steel
94-98	Ice
84-94	Extra Hard Pack
70-84	Standard Medium Pack
50-70	Soft Pack

Figure 28. CTI penetrometer readings.

APPENDIX D: SMITHERS/CTI* SNOW COMPACTION GAUGE

The compaction and shear strength of snow have a major effect on the snow traction performance of tires. These parameters cannot be isolated, but a rating can be placed on the results of both variables by making a combined vertical and horizontal compression test.

After considerable research on past methods of measuring snow compaction, it was found that these methods were too far removed from the actual action of a tire tread in snow to be meaningful. Smithers/CTI designed and built a "compaction tester" to measure the combined effect of the vertical compaction and the horizontal compressibility of snow.

The CTI Snow Compaction Gauge is shaped like a plumb bob (see illustration), except that the point is rounded with a 1.6 mm (1/16") radius. A measuring rod is fitted in the other end. Each gauge is adjusted in the laboratory to have a weight of 220 ± 1 grams, including the knurled nut on top of the drop rod. The drop height has been adjusted to 218.9 mm ± .25 mm (8.62 ± 0.01 in.).

In use, the mass of the projectile and the measuring rod is dropped a preset distance through a guide tube with a flanged end which rests on the test surface. The kinetic energy is expended in both vertical penetration and side compression. The penetration distance is converted by a hand-held scale to read the compaction numbers (50-100) directly.

*Smithers Scientific Services, Inc., Akron, Ohio.

To better understand the meaning of the readings, the following table is offered. It should be noted that numbers below sixty (60) are difficult to obtain in snow.

Surface Description Q_c	CTI Compaction Range
Steel	100
Ice	93 - 98
Extra hard pack snow	84 - 93
Standard medium hard pack snow	70 - 84
Soft pack or loose pack snow	50 - 70
Virgin snow - no rating: (Use depth and moisture content) Water	1

The recommended snow test conditions of 70-80 (see Appendix C) represent a range in which good discrimination among tire types can be obtained. The range obtained when measuring different locations on a test course should be no greater than eight to ensure course consistency.

When using the CTI Snow Compaction Gauge in the field, it should be kept on top of the snow to maintain the metal at approximately the same temperature as the snow. It is also necessary that the gauge does not accumulate an excessive amount of snow on the inside. This will not happen if the plunger is wiped after each drop. Should it occur through unforeseen circumstances, it is preferable to melt the snow from the inside, rather than disassemble the unit. If for some reason the unit must be disassembled, be sure to note the location of any washers used in the assembly. Also, note the position of the lead shot weights in the plunger opening for the drop rod.

Standard practice in the field is to drive the front wheels of the test vehicle equipped with highway tires over the test bed, then turn the vehicle to the right or left to expose a tire track. Place the gauge in the center of the tire track. With the plunger rod raised, rotate the gauge 45° and back to gently smooth the tread pattern left by the tire. Be sure the plunger is bottomed internally on the upper part of the drop tube. Keep a very light pressure on the aluminum foot to prevent it from changing position or lifting off the snow.

Release the drop rod assembly and immediately set the brass engraved measurement scale on top of the drop tube, close to the knurled nut. Read the CTI Compaction Number from the scale at the top outer edge of the knurled nut.

Calibration may be checked by placing the unit on a smooth, hard surface with the plunger in the down position. The gauge should now read 100 to the top of the knurled nut. If the unit should be disassembled for any reason, then the drop length should be checked for 218.9 mm ± .25 mm (8.62 ± 0.01 in.) and the plunger assembly weight adjusted for 220 ± 1 gram.

APPENDIX E: SNOW MONITORING TIRE

Test course surface quantification can be obtained by using an industry designated Snow Monitoring Tire or SMT. The current* industry SMT is the Uniroyal "Steeler" steel belted radial P195/75R14 TPC, spec number 1024 (Uniroyal development reference number 32164-H). This tire must not be subjected to uniformity or other grinding procedures and should be obtained from the Manager of Industry Standards, Uniroyal Tire Technical Center, P.O. Box 3940, Troy, Michigan 48084.

On an appropriately prepared surface (medium packed snow, see Appendix C), the average friction coefficient of this tire is 0.18-0.26. This performance represents a range in which good discrimination among tire types can be obtained. The range obtained when measuring different locations on a test course should not exceed 0.05 to ensure course consistency.

Use of the SMT concept allows for direct surface measurement comparisons of all test agencies' test sites. It also allows common base comparison of performance obtained by various agencies using the procedure outlined in this recommended practice.

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* If the tread design, tire construction, or rubber compounds in this SMT tire are changed, Uniroyal will notify the SAE Test Committee, who will review the changes and make recommendations if a new SMT tire should be considered.

WINTER TIRE TESTING AS SEEN BY THE INDEPENDENT TESTER*

Douglas C. Domeck Smithers Scientific Services, Inc., 1150 N. Freedom Street, P.O. box 351, Ravenna, Ohio, U.S.A. 44266

ABSTRACT

A review of tire testing in the winter environment is presented from the viewpoint of an independent tesing laboratory. The independent tester, by necessity, must satisfy the particular requirements of individual customers. A description of the drive traction truck which was designed to meet these individual client requirements is presented. Also, a comparison of results obtained by the various techniques of analysis is included.

INTRODUCTION

Independent testing laboratories exist to assist manufacturers in testing or certifying their products to various industry and government standards. Smithers Scientific Services, Inc., has been assisting the tire industry for over 55 years, and has been performing winter tire testing since 1971. Over the years, we have seen many changes occur in winter tire testing, not only in types of testing, but also in data analysis methods.

There was a time when customers routinely requested complete testing, including braking distance,† static traction and drive traction on two or three snow conditions. Unfortunately, the various tests sometimes provided conflicting results, meaning that the tire engineer had to make his choice of design on a compromise basis. Around the 1977-78 winter season, we saw a fall-off of both braking distance and static traction on snow in favor of dynamic traction only. However, we still had some problems.

The lack of standards resulted in as many dynamic traction data analysis methods as there were tire companies! Some wanted peak traction between 0 and 8 km/h slip; others wanted peak traction (μ peak) between 0 and 24 km/h slip; then there was the area under the 0- to 24-km/h curve (μ area), analysis according to General Motor's method of time averaging (μ average), and ratings based on 8-, 16-, and 24-km/h slip values. Needless to say, this complicated the job of the independent laboratory when preparing final reports.

SNOW TEST SURFACE

Snow surfaces have generally been characterized by four separate types: virgin snow, soft pack, medium pack, and hard pack. Although combinations of the above are often used verbally (such as medium hardpack and extra hard hardpack), it is difficult to envision being able to duplicate so many snow conditions in actual testing. Verbal definitions of these snow conditions are well-defined in the literature.[1] Smithers found from experience that verbal definitions do not always have the same meaning to all customers or even to test crews, and developed the CTI Snow Compaction Gauge (Appendix G) to better define a snow condition as "seen" by a tire (Fig. 29).

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† Appendix F contains definitions of all terms as they relate to winter testing.

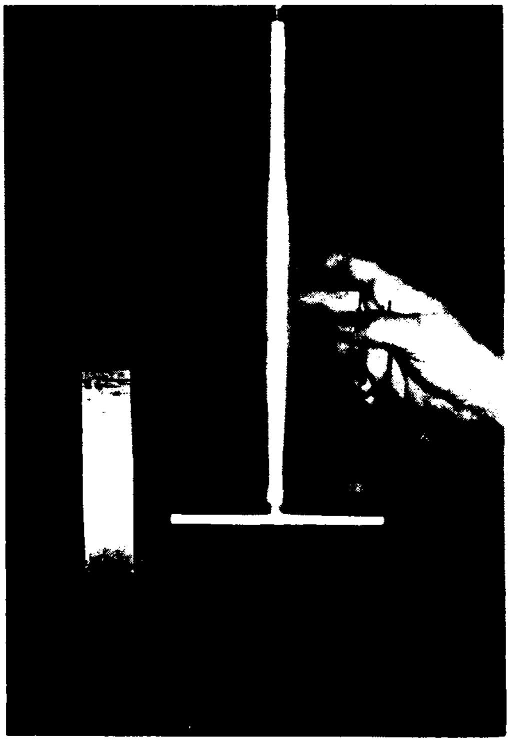

Figure 29. CTI compaction gauge.

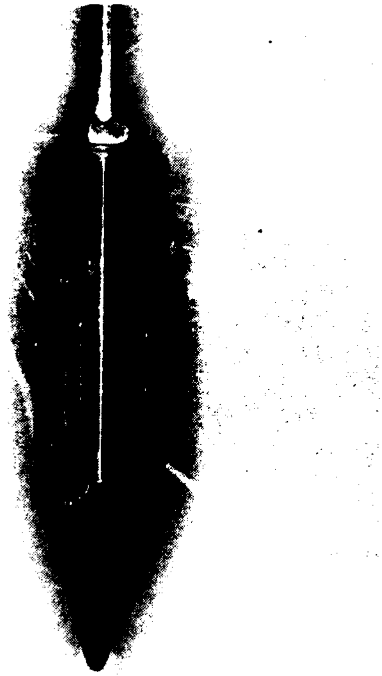

Figure 30. Business end of a CTI compaction gauge.

The CTI Compaction Gauge was developed because other compaction testers largely ignored the necessity of getting some kind of measurement of the ability of snow to be compacted laterally as well as vertically. This factor can best be spoken of as the "shear value" of snow. One might think of a snow traction tire as a device which has the ability to first construct walls, then to push them over in a cyclic energy translation system. Although this is a simplistic approach to a very complex problem, it does show the importance of the shear strength of snow. The CTI Compaction Gauge, by virtue of its conical end (Fig. 30), does establish a rating which considers the shear value of snow as seen by a tire, as well as tire penetration limitations. The use of this device allowed us to characterize snow by means other than verbal definitions, and without the necessity of testing an actual tire. For convenience, a number rating system based on depth of penetration was assigned to the various snow definitions. That system is shown in Figure 31. A rating of 100 was chosen for zero penetration and a low rating of 50 established for approximately two inches of penetration.

Smithers' original definitions do not correspond exactly with the four definitions given above. However, hardpack would be generally between 80 and 84; medium pack, 70-80; and soft pack, 60-70. Generally, numbers below 60 are meaningless, and virgin snow is still rated based on depth and moisture content.

CTI INDEX	SURFACE DESCRIPTION
100	Steel
94-98	Ice
84-94	Extra Hard Pack
70-84	Standard Medium Pack
50-70	Soft Pack

Figure 31. CTI number rating system for compaction gauge.

TEST EQUIPMENT

As tires have improved, so have the techniques for evaluating their performance in snow conditions. The two mainly accepted methods for developing driving traction are the two-vehicle drawbar method and the self-contained instrumented axle traction vehicle. Drawbar has the advantage of being relatively simple, requiring a minimum of investment, and still being able to distinguish between the performance of various tires. However, maintenance of stable ground speed is imperative in order to reduce the high inertial effects of the test vehicle itself.

For many years, Smithers used the drawbar technique with great success, but with advancing tire technology found the single vehicle method to be more attractive. This especially became true as the proposed SAE recommended practice[2] for measuring dynamic driving traction in snow took final form. It appeared that for once a standard practice in industry would be available. This is not to say that each client would not have his own preferred method of data analysis though. The basic design of the drive traction truck is well-defined in literature[3], and will not be repeated here.

The Smithers drive traction truck was built by modifying a 1980 Chevrolet model C10 half-ton pickup truck. The truck is equipped with a 350 CID engine and automatic transmission. The bed of the truck was removed to allow for a lower net test weight without off-loading (Fig. 32). As a result, the truck has an unloaded weight of 322 kg (710 lb). Off-loading can bring the weight even lower. A maximum test weight of 907 kg (2000 lb) is obtainable due to heavy duty springs and overload shock absorbers.

A two-axis transducer, which allows for continuous measurement of load and traction forces, is installed in the right rear drive position. The suspension was changed to a parallelogram configuration holding the transducer in proper orientation throughout suspension travel. A lower rear axle ratio (5.35) was installed to allow greater torque application to the drive wheel under heavy load test conditions.

Test wheel speed is sensed using a magnetic pickup mounted inside the brake drum. This eliminates wheel speed multiplication problems encountered by speedometer take-off speed sensors. Ground speed is measured with a D.C. tachometer mounted directly to the left front wheel, and is displayed on a 270° analog meter mounted in front of the driver (Fig. 33). Throttle application rate is controlled by a mechanical device which opens the throttle at a uniform rate.

Signals from the transducer are conditioned by ultrastable instrumentation amplifiers and limited to 20-Hz-bandwidth using active filters. Daily calibration of the transducer is performed using precision shunt calibration resistors. Ground speed and wheel speed signals are appropriately signal-conditioned and are also limited to 20-Hz bandwidth. Calibration signals are also provided to al-

Figure 32. Smithers drive traction test vehicle.

Figure 33a. Drive traction truck instrumentation.

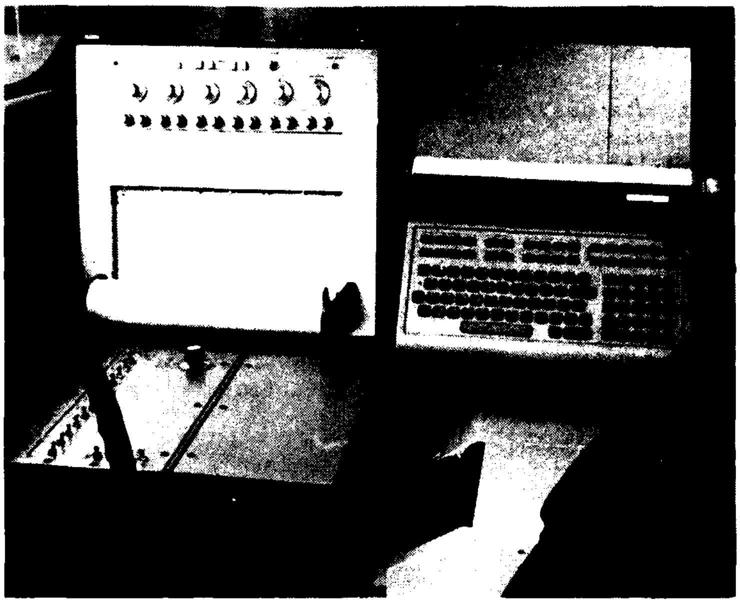

Figure 33b. Data acquisition equipment.

low daily calibration checks. Final calibration of the test tire speed is performed automatically in the computer to compensate for the rolling radii.

All analog signals are fed to an A/D converter and ultimately to a Hewlett-Packard 9825 desktop computer (Fig. 34). Once a test run begins, the entire process is under the control of the computer. The driver need only be concerned with maintaining the vehicle in a straight line and applying the brake as necessary to hold an 8 km/h ground speed. The computer turns on the strip chart recorder and throttle applicator, then waits to begin sampling at 0.8 km/h slip. Sampling continues until both the μ area and μ average methods are satisfied. The throttle and recorder are then turned off and the coefficients for the various analysis methods (discussed elsewhere in this paper) are calculated. The μ average is displayed to the driver for reference. This process continues until 10 satisfactory runs have been made. While the test tire is being changed, the com-

Figure 34. Hewlett-Packard desk-top computer.

puter prints the results of the test on the on-board thermal printer. Multiple copies of this data can be made immediately. The test results are also stored on magnetic tape for later processing through a final analysis program.

DATA PRESENTATION

Figure 35 is an example of the data sheet printed by the computer for each tire tested. Refer to Section 1 of the figure where the identifying information, including client's name, test date, etc., is printed at the top of the sheet. CTI snow compaction index and ambient and surface temperatures are measured and updated each time a control tire is tested.

The second section (labeled "Individual Run Analysis") of the data sheet is divided into nine columns, as follows:

Column 1 indicates the run number. In general, 10 runs (spinups) are made on each tire. This number can be changed based on program requirements.

Column 2, called "SS Avg" (Smithers Average), is an average coefficient determined in a manner similar to the μ average method of data analysis. This method begins averaging at 0.8 km/h DIV (10% slip), but does not require 1.5 seconds of data. Instead, the average is determined across the time required to develop 24 km/h DIV (300% slip). This average usually has the greatest standard deviation of any of the evaluation methods due to the instability of data developed at low values of DIV (less than 3 km/h).

Column 3, labeled "Area", is the average coefficient (μ area) under the coefficient DIV curve from 0.8 km/h DIV to 24 km/h DIV.

Column 4 is the time in seconds that it takes a tire to increase from 0.8 km/h DIV to 24 km/h DIV. This time is widely scattered, again due to the difficulty of measuring the 0.8 km/h DIV point. Column 4 is most interesting when compared to the Smithers Average (Col. 2). Generally, the greater the time, the lesser the Smithers Average, indicating a significant amount of time spent below the peak of the mu-slip curve.

Column 5 (GM Average) gives the average coefficient based on the μ average method of data analysis. This method begins averaging at 3.2 km/h DIV (40% slip) and continues for 1.5 seconds, irrespective of final test tire speed.

Column 6 shows the final test wheel speed in miles-per-hour DIV. If the μ average (Col. 5) is contained within the μ area, then this column would be less than 15 mph (24 km/h).

Column 7 is the average ground speed in miles-per-hour throughout a test run. Nominal final percent slip for the μ average can be found by dividing Col. 6 by Col. 7. The computer program internally casts out the data which does not meet the proposed SAE ground speed standard (8 ± 1.6 km/h), and forces the test operator to repeat a test run.

Column 8 shows the peak coefficient (μ peak) developed during a run.

Column 9 gives the average load in pounds throughout a test run. Generally, it is greater than the static load due to

SMITHERS SCIENTIFIC SERVICES INC

CTI DIVISION

DYNAMIC TRACTION DATA SHEET

Client:		Tire Name:	Highway Design
Test Date:	2/9/81	Tire Size:	P195/75R14
Test Surface:	MEDIUM PACK GM	Test Load Lbs.:	1030
Program Number:		Tire Inflation:	26
Test Number:	20	Ambient Temp:	20
CTI Index:	74	Surface Temp:	19

INDIVIDUAL RUN ANALYSIS

RUN	SS AVG	AREA	TIME	GM AVG	SPEED	AGS	PEAK	LOAD
1	0.1741	0.1723	1.28	0.1694	19.0	5.1	0.2726	1043
2	0.1719	0.1719	1.28	0.1575	19.2	5.3	0.2417	1052
3	0.1718	0.1736	1.18	0.1645	19.1	5.3	0.2189	1045
4	0.1761	0.1753	1.23	0.1667	19.1	4.9	0.2763	1024
5	0.1694	0.1702	1.20	0.1720	19.3	5.2	0.2460	1011
6	0.1896	0.1897	1.53	0.1828	17.0	5.5	0.2421	1034
7	0.1879	0.1882	1.33	0.1799	18.9	5.2	0.2601	1011
8	0.1871	0.1871	1.28	0.1732	19.0	4.7	0.2584	1023
9	0.1954	0.1943	1.28	0.1819	18.9	4.9	0.2800	1014
10	0.1962	0.1957	1.43	0.1897	17.6	5.2	0.2403	1049

SLIP SPEED DATA @ MPH DIV

RUN	.5	1	2	3	5	8	12	15
1	0.2726	0.2726	0.2386	0.1728	0.1899	0.1651	0.1540	0.1730
2	0.2188	0.2188	0.2005	0.2265	0.1936	0.1694	0.1560	0.1338
3	0.2017	0.2017	0.1684	0.1942	0.2070	0.1923	0.1449	0.1486
4	0.2461	0.2461	0.2643	0.2403	0.1431	0.2002	0.1101	0.1600
5	0.1970	0.1970	0.2278	0.1740	0.1831	0.1949	0.1324	0.1657
6	0.2035	0.2063	0.2210	0.1822	0.1771	0.1932	0.2053	0.1028
7	0.2601	0.2601	0.2150	0.2102	0.2314	0.1909	0.1917	0.1628
8	0.2576	0.2576	0.2249	0.2033	0.2002	0.1766	0.1924	0.1671
9	0.2800	0.2800	0.2045	0.2118	0.1725	0.2311	0.1785	0.1520
10	0.2272	0.2188	0.2284	0.2224	0.1712	0.2224	0.1601	0.1885
AVG	0.2365	0.2359	0.2193	0.2038	0.1869	0.1926	0.1625	0.1554

FINAL ANALYSIS

TYPE ANALYSIS	PULLS	CAST	OUT		MEAN1	STD DEV1	MEAN2	STD DEV2	C.V.2
GM AVERAGE	2	10	0	0	0.1738	0.0098	0.1738	0.0070	0.040
SSS AVERAGE	0	0	0	0	0.1820	0.0103	0.1820	0.0103	0.057
AREA 15MPH SLIP	0	0	0	0	0.1818	0.0101	0.1818	0.0101	0.055
PEAK	3	0	0	0	0.2536	0.0193	0.2575	0.0158	0.062

Figure 35. Sample of on-board data printout.

load transfer as a result of the forward-driving test tire.

Section 3 of the data sheet (labeled "Slip Speed Data @ MPH DIV"), contains the coefficients developed at various slip speeds. The average of each column is given to facilitate plotting a mu-slip curve, and for locating the approximate speed at which the peak occurs. This section can also be used to compare tires at various values of slip. No data is cast out in the average.

Section 4 is the final analysis for each of the four methods of data cap-

SMITHERS SCIENTIFIC SERVICES, INC.

CTI DIVISION

DYNAMIC TRACTION ANALYSIS

Client:
Test Date: 2/9/81
Test Surface: MEDIUM PACK GM
Program Number:
Test Numbers: 20- 38

CONTROL SUMMARY

Tire Name: STEELER CONTROL
Tire Size: P195/75R14
Test Load: 1030
Tire Inflation: 26

Test#	GM AVG	CV%	AREA	CV%	SS AVG	CV%	PEAK	CV%	TEMP: AMB	SNOW
20	0.1738	4	0.1818	6	0.1820	6	0.2575	6	20	19
23	0.1681	6	0.1734	4	0.1730	5	0.2435	10	17	19
26	0.1768	3	0.1830	3	0.1815	4	0.2732	12	16	18
29	0.1753	4	0.1820	3	0.1780	6	0.2882	12	16	18
32	0.1821	6	0.1879	4	0.1826	9	0.2757	18	15	18
35	0.1697	7	0.1800	4	0.1763	6	0.2385	10	15	18
38	0.1759	6	0.1821	5	0.1770	5	0.2557	14	15	18
Avg	0.1745		0.1815		0.1786		0.2618			

TEST TIRE SUMMARY

Test# 21 Tire Name: All Season Tire Tire Size: P195/75R14
Test Load: 1030 Inflation: 26

	GM AVG	CV%	AREA	CV%	SS AVG	CV%	PEAK	CV%
Coef	0.3208	4	0.3149	4	0.2896	12	0.3937	3
%Bound	188		177		163		157	
%Avg	184		173		162		150	

Test# 22 Tire Name: Snow Tire Tire Size: P195/75R14
Test Load: 1030 Inflation: 26

	GM AVG	CV%	AREA	CV%	SS AVG	CV%	PEAK	CV%
Coef	0.2700	8	0.2690	8	0.2405	9	0.3419	4
%Bound	158		151		135		137	
%Avg	155		148		135		131	

Figure 36. Sample test summary.

ture. Mean 1 and standard deviation 1 are calculated using all runs. Data that falls outside ± 1.5 standard deviation 1 from mean 1 is cast out and mean 2 and standard deviation 2 are calculated using the remaining points. "Pulls Cast Out" are indicated for each method. Zero's are used to fill blank spaces when there are less than four runs cast out. A coefficient of variation (CV2) is printed to aid in determining relative value of standard deviation. Generally, CV2 is less than 0.07 or 7%.

Upon completion of all tests within a test sequence, the data is analyzed to summarize and rank the tires tested in that sequence. Figures 36 and 37 are examples of this printout. The top section of Figure 36 identifies the client, test date, program number, and test numbers included in this analysis.

Section 2, labeled "Control Sum-

SMITHERS SCIENTIFIC SERVICES, INC.

CTI DIVISION

DYNAMIC TRACTION ANALYSIS

Client:
Test Date: 2/9/81
Test Surface: MEDIUM PACK GM
Program Number: 32800-IB-R1
Test Numbers: 20- 38

STATISTICAL ANALYSIS OF AREA

Tire Name	Test Number	%Avg	GM Avg Coef	90% Confidence Limits Upper	Lower
All Season	21	173	0.3149	0.3266	0.3031
Tire G	33	166	0.3005	0.3123	0.2887
Tire H	34	165	0.2987	0.3105	0.2869
Tire A	24	152	0.2756	0.2874	0.2639
Snow Tire	22	148	0.2690	0.2808	0.2572
Tire B	25	135	0.2447	0.2565	0.2329
Tire K	37	125	0.2276	0.2394	0.2158
Tire D	28	125	0.2266	0.2384	0.2148
Tire C	27	121	0.2191	0.2309	0.2074
Tire E	30	110	0.1993	0.2111	0.1875
Tire J	36	110	0.1988	0.2105	0.1870
Steeler - Control	CONTROL	100	0.1815	0.1933	0.1697
Tire F	31	98	0.1774	0.1892	0.1656

AOV TABLE

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Stat.
Treatments	18	0.359028	0.019946	117.02
Error	151	0.025739	0.000170	
Total	169	0.384767		

Duncans Multi-Range Test Rp=0.0118

Figure 37. Sample tire ranking.

mary," identifies the control tire and summarizes the results of the control tests. Each test is identified by number along with Mean 2 and a percent CV2 for each method of analysis. Ambient and surface temperatures are also included. The average of the control tire for each analysis method is printed under the last control tire.

Section 3, labeled "Tire Test Summary," begins a summary of each test tire according to the order in which the tires were tested. Each tire is identified by test number, name, size, load and inflation. The average coefficient (Mean 2) and a corresponding CV2, expressed as a percentage, is given for each method of analysis. Percent ratings are then given for each method. The first percent rating (labeled "% Bound"), is the percentage based on the average of the two nearest bounding control tires. The second (labeled "% Avg"), is the percent rating based on the average of all the control tires in a particular test matrix. Section 3 continues for as many pages as is necessary.

Figure 37 is a sample of the final printout that ranks the tires based on the μ area method of analysis. Rankings are also calculated using μ average and μ peak, but are not shown here. Again, identifying information is printed in Section 1 so that this page may be used alone. A one-way analysis of variance is performed on the data. Then, Duncan's multirange test[4] is used to develop a least significant range (Rp) for two means. Section 2 prints the various test tires in order beginning with the highest coefficient. Percentage ratings based on the control tire average are also printed. Control tire average is included as a test tire rated 100%. An upper and lower coefficient based on Duncan's range is printed for each test tire. Use this range to determine significantly different tires.

The "Analysis of Variance" table is printed in Section 2 of Figure 37, for those who are interested. Also, Duncan's multirange value is given as a coefficient.

COMPARISON OF ANALYSIS METHODS

Some of the information shown on the data sheet (Smithers Average, Time, and Final Speed), Figure 35, may prove to be useful in the future. However, this discussion will be limited to the three most promising and accepted analysis methods. The first two, μ area and μ average, are allowed under the proposed "SAE Recommended Practice for Testing Passenger and Light Truck Tires in Snow." The third method, μ peak, is still used by many organizations, and is of some interest.

Figures 38 and 39 summarize the results from two different dynamic traction tests on medium pack snow by comparing the resulting rank order for each of the three analysis techniques. Arrows have been used to point out the same test numbers. In Figure 38, the rank order is the same by all test methods. Notice, though, that the μ average method for test number 50 rates the tire 168%, the same tire is rated 153% by the μ area method, and 124% by the μ peak method. A quick inspection of the remaining tests shows that this relationship holds true there as well and, in fact, always holds true. That is, the μ average analysis method shows the greatest difference between tires, and the μ peak method, the least difference. To understand this phenomenon, we must examine the three methods of analysis more closely.

Figure 40 shows three typical traction mu-slip curves on medium pack snow. Curve 1 is a standard highway design tire; Curve 2 is an aggressive design snow tire; and Curve 3 is an all-season tread design. All tires are of radial construction. These three tires were chosen from among the hundreds of tests performed during the 1980-81 winter test season. The results of this one test are included to facilitate the discussion of analysis methods, not conclusions, con-

μ AVERAGE		μ AREA		μ PEAK	
SSS TIRE NUMBER	TRACTION PERCENT CONTROL	SSS TIRE NUMBER	TRACTION PERCENT CONTROL	SSS TIRE NUMBER	TRACTION PERCENT CONTROL
50	168	50	153	50	124
46	147	46	143	46	120
47	144	47	134	47	114
C	100	C	100	C	100
49	66	49	68	49	93

Figure 38. Sample ranking based on three data analysis methods. Note: Brackets indicate no statistical significance between tires.

μ AVERAGE		μ AREA		μ PEAK	
SSS TIRE NUMBER	TRACTION PERCENT CONTROL	SSS TIRE NUMBER	TRACTION PERCENT CONTROL	SSS TIRE NUMBER	TRACTION PERCENT CONTROL
155	143	155	136	152	132
148	133	148	129	155	129
152	129	152	127	148	125
144	121	144	123	144	120
147	113	147	108	151	115
151	105	151	106	147	108
C	100	C	100	145	102
145	82	145	84	C	100
157	81	157	82	157	96
154	60	154	61	154	68

Figure 39. Sample rank order based on three data analysis methods. Note: Brackets indicate no statistical significance between tires.

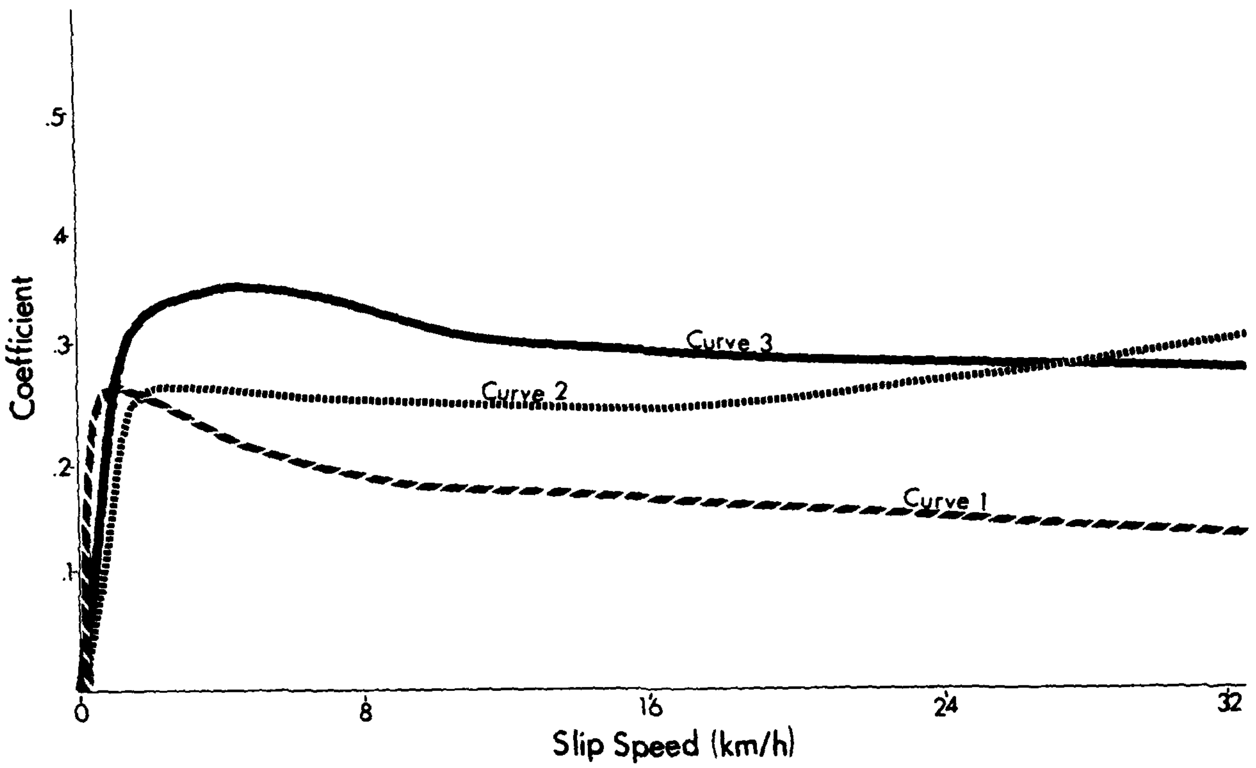

Figure 40. Three typical traction mu-slip curves on medium pack snow.

cerning the relative performance of tire designs. The resulting ratings are found in Table 2. All ratings are expressed as a percentage of Curve 1.

The standard highway design tire (Curve 1) and the all-season design (Curve 3) are characterized by a definite peak at low slip speed, and a fall-off of coefficient as slip speed increases. The snow tire (Curve 2), however, shows no real definite peak and a relatively flat coefficient at high slip speeds. Determination of the peak of each curve is self-evident. Notice, though, that for Curve 1, the ratio of μ peak to μ area is 1.35. In the case of Curve 2 it is 1.06, and for Curve 3 it is 1.11. We can conclude then that the ratio of μ peak to μ average is greater for highway tread design tires than for the more agressive designs. As a result, any percentage ratings based on μ peak show the least difference between tire designs.

Let's now examine the remaining two methods (μ area and μ average) that attempt to characterize a tire's performance over a range of slip speeds. The μ area method had its beginnings in drawbar testing where it was common to plot tractive force versus slip speed on an X-Y

Table 2. Comparison of analysis methods.

TIRE	μ AVERAGE	PERCENT RATING	μ AREA	PERCENT RATING	μ PEAK	PERCENT RATING	μAREA/μAVG.	μPEAK/μAVG.
Highway Design Curve 1	.174	100%	.182	100%	.235	100%	1.046	1.35
Snow Design Curve 2	.270	155%	.269	148%	.285	122%	.996	1.06
All-Season Curve 3	.321	184%	.315	173%	.355	151%	.981	1.11

recorder. We obtain μ area by computing the average coefficient between a lower (0.8 km/h) and an upper (24 km/h) slip speed. The μ average had its beginnings in drive traction where it was usual to plot tractive force versus time on a multichannel strip chart recorder. A μ average results by computing the average coefficient over a period of time (1.5 sec), beginning after the peak has occurred (3.2 km/h slip). These methods appear similar since slip speed generally increases with time. However, our previous work has shown that increasing slip speed is not necessarily a linear function of time.

There are three significant differences between these methods. First, the μ area method includes data between 0.8 and 3.2 km/h slip which is not included in the μ average method. The coefficient in this range is generally greater than the coefficient at higher slip speeds. This would partially explain why μ area is generally 5% greater than μ average. The second difference involves the test end point. For μ area, data is included up to 24 km/h slip speed, and the μ average incorporates data for 1.5 seconds irrespective of slip speed. Since slip speed increases more rapidly for low coefficient tires, the range of slip speed is different for different tire designs. In the example (Fig. 40), the corresponding maximum slip speed by the μ average method is 23.7 km/h for the snow tire (Curve 2), 25.5 km/h for the all-season tire (Curve 3), and 30 km/h for the highway design (Curve 1). The first two end points are approximately the same as in μ area, but the third is not. Notice that μ average and μ area differ the most in this case (Table 2, Curve 1).

Let's say for the moment that for the highway design tire, the throttle application rate was reduced such that μ average ended at 24 km/h. Inspection shows that the equivalent coefficient would increase to 0.178, reducing the difference between μ average and μ area for this tire. The third reason is probably the least significant of the three. It centers on the fact that increasing wheel slip is not a linear function of time; however, in most cases this nonlinearity can be ignored, especially after the peak traction has been developed.

Let's now examine each method's ability to distinguish significant differences between these tires. Those tires where peformance is statistically not significantly different are bracketed in Figures 38 and 39. Brackets occasionally overlap each other in Figure 39. In Figure 38, tires #46 and #47 are not significantly different by the μ average analysis method, where the μ area indicates they are different. When examining the peak method, tires #46, #47 and #50 are not significantly different from each other nor are the control tire and tire #49. From the tire engineer's standpoint, μ peak data makes it difficult to distinguish significant peformance differences between tires.

Figure 39 illustrates this even further. Ratings based upon μ average and μ area show a performance difference between most tires in this test group. Mu average does a better job of making that distinction by separating the 10 tires involved into seven distinct groups. Mu area does almost as good by separating them into five distinct groups. However, the analysis based on μ peak is much more confusing with many overlaping brackets, including a much lesser ability to statistically separate tires.

CONCLUSION

The real question now boils down to which method is the most realistic from the consumer's point of view: From the all-season design in Table 2, does he realize the 184% traction increase that the μ average method says he has?; or, does he realize the 178% from μ area, or just 151% from μ peak? We may never be able to completely answer this question, but I suspect very few drivers actually operate their tires near the peak traction coefficient point when they require maximum traction. Rather, they allow their wheels to spin considerably beyond the peak traction point, a point characterized by either the μ area or μ average methods. However, the μ area method has a better definition of performance range, having defined the ending slip speed. We have shown that the actual value of coefficients by the μ average method varies slightly based on final test wheel speed (throttle application rate). Whether this difference is truly significant will require further research.

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1. BRAKING DISTANCE: The distance required to stop a vehicle from some speed in the locked wheel mode.

2. COEFFICIENT (μ): Drive force divided by vehicle load.

3. DIFFERENTIAL INTERFACE VELOCITY (DIV): This is the difference between the test tire speed and the test vehicle speed.

4. DRIVE TRACTION: Drive traction, also referred to as dynamic traction, is the force developed by a spinning tire while the test vehicle is moving.

5. μ AREA: Digital or analog average determined between 2 km/h and 24 km/h DIV of a tractive force-DIV curve. It is expressed as a coefficient by dividing by the average vertical force.

6. μ AVERAGE: Digital or analog average of 1.5 seconds of data from a tractive force-time plot. Data acquisition begins when DIV is 3 km/h and is expressed as a coefficient by dividing by the average vertical load.

7. μ PEAK: The maximum force developed between 2 km/h and 24 km/h DIV, expressed as a coefficient by dividing by the average vertical load.

8. μ SLIP: The difference between test tire speed and test vehicle speed expressed as a percentage of vehicle speed. It is always positive for drive traction analysis.

9. STATIC TRACTION: The maximum force developed by a test tire just prior to breakaway with the test vehicle stationary.

10. TRACTION FORCE: Force applied to the test tire parallel to the test surface at the tire pavement contact patch.

CTI SNOW COMPACTION GAUGE

Instructions for use.

When using the CTI Snow Compaction Gauge in the field, it should be kept on top of the snow to maintain the metal at approximately the same temperature as the snow. It is also necessary that the gauge does not accumulate an accessive amount of snow on the inside. This will not happen if the plunger is wiped after each drop. Should it occur through unforeseen circumstances, it is preferable to melt the snow from the inside, rather than disassemble the unit. If for some reason the unit must be disassembled, be sure to note the location of any washers used in the assembly. Also note the position of the lead shot weights in the plunger opening for the drop rod.

Standard practice in the field is to drive the front wheels of the test vehicle equipped with highway tires over the test area. Place the gauge in the center of the tire track. With the plunger rod raised, rotate the gauge 45° and back to gently smooth the tread pattern left by the tire. Be sure the plunger is bottomed internally on the upper part of the drop tube. Keep a very light pressure on the aluminum foot to prevent it from changing position or lifting off the snow.

Release the drop rod assembly and immediately set the brass engraved measurement scale on top of the drop tube, close to the knurled nut. Read the CTI Compaction Number from the scale at the top outer edge of the knurled nut.

Calibration may be checked by placing the unit on a smooth, hard surface with the plunger in the down position. The gauge should now read 100 to the top of the knurled nut. If the unit should be disassembled for any reason, then the drop length should be checked for 8.62 ± 0.01-in. and the plunger assembly weight adjusted for 220 ± 1 gram.

TIRE PERFORMANCE EVALUATION FOR SHALLOW SNOW AND ICE

William L. Harrison Sno-Mech, Route 103A, New London, N.H. 03257

INTRODUCTION

There are several methods for predicting the performance of wheeled vehicles operating off-road. A number of these are listed in the accompanying bibliography. Most of the authors tend to rely on soil mechanics applications to achieve an estimate of performance, although soils and snows are quite dissimilar in their response to external loads.[1] Not only are soil failure models used but the instruments for sampling soil strength and strength indices are used as well. The results of using these applications in predicting the performance of wheeled vehicles operating in shallow snow are reflected in a study reported by Harrison,[2] which concluded that neither of the prediction methods used in the study offered a satisfactory solution.

With this experience in mind, alternative models were examined and the decision to attempt an energy-based prediction methodology began.[3]

Another problem in predicting wheel performance arises when tire design characteristics are not included in the prediction model. This earlier omission in performance predictions was recognized by Browne[4] who used such parameters as depth of tread element penetration, tread rubber hysteresis loss, tread rubber hardness, number of tread sipes per unit area, length of tread element, etc. in a prediction model for shallow snow; by Bekker and Semonin,[5] who used a measure of carcass strength in their proposed prediction model; and by Yong et al.,[6 7 8 9] who considered various tire design parameters in their prediction model, which will be discussed in greater detail later.

Of great importance to this work was the concept of an energy balance methodology proposed by Yong and Webb[10] to be applied to wheel-soil interaction problems. This work describes the energy-dissipating mechanisms of a wheel-soil system as a function of slip as follows:

$$T\omega = PV + RV + E_{FR} \qquad (1)$$

where T = torque
ω = radial velocity
V = linear velocity
P = drawbar pull
R = deformation energy loss
E_{FR} = rate of interfacial energy loss.

$T\omega$ is the input rate, PV the rate of useful energy developed, and RV the deformation energy rate (soil). This concept of slip energy dissipation is very useful in examining the performance of single wheels relative to tire design differences, and was maintained in later studies by Yong et al.[6 7 8 9] where further developments of the earlier work by Yong and Webb were used to examine the effects of various design properties.

In Yong et al.[8] an equation for performance efficiency is proposed, where

$$\eta = \frac{PV}{T\omega} \qquad (2)$$

with η being the performance efficiency and the other parameters as defined earlier.

In an earlier work by Leflaive[11] a torque energy coefficient η was proposed and was defined as the energy expended at the axle, per unit distance traveled by the wheel, and written as

$$\eta = \frac{M\omega}{WV} \qquad (2a)$$

where M is torque (N-m), W is load (N) and ω and V are as defined in eq 2. Equation 2 is the inverse of eq 2a. Leflaive further develops this expression in terms of differential slip g to

$$\eta = \frac{M}{WR}\ (1 + g) \qquad (2b)$$

where R is the rolling radius of the tire. It is encouraging to note that when eq 2b is written in terms of the parameters used in this report, i.e.

$$\eta = \frac{F_\ell R}{F_v R}\left(1 + \frac{d_w - d_v}{d_v}\right) = \frac{F_\ell}{F_v} \cdot \frac{d_w}{d_v}$$

it is rather similar to the expression for energy efficiency ε_t in eq 11.

This report discusses an effort to determine, quantitatively, the difference in tire performance over shallow snow and ice due to tire construction, tire compound, and tread design. Differences in tire compounds will only be discernible relative to the resulting tire hardness. Tire construction will be based on whether it qualifies as radial ply or bias ply, with or without belts.

SURFACE TRACTION

Tires generate traction through the development of adhesive and frictional forces in the tire/snow surface interface. Adhesive forces are dependent on snow properties and tread material compounds, while the frictional forces are a function of snow properties and the wheel load.

The total tractive force is represented by the following expression:

$$H = Ac_a + W \tan\delta \qquad (3)$$

where H = gross tractive effort
A = tire contact area
c_a = adhesion
W = vertical load
δ = angle of interface shearing resistance.

To complete the picture, there are losses due to snow compaction which also must be considered. These losses are identified as motion resistance and are dependent on snow depth and tire properties and the work of compaction, as expressed in the following equation:

$$R = 2bh\delta \qquad (4)$$

where b is tread width, h is snow depth and ω is the energy required to compact snow from its undisturbed density to its critical density[12]. The resistance due to tire properties is measured on a hard surface (rolling resistance), while snow resistance to motion, R, is determined by measurements obtained in the shallow snowpack of interest.

The net traction, which is most indicative of tire performance, is the difference between the total tractive force and the resistances:

$$F_\ell = H - R. \qquad (5)$$

The force F_ℓ is the traction characteristic available to compare the performance of tires having different design features while operating over snow and ice.

Performance is affected by contact area as well as the general orientation of the area (the more an area is oriented towards the direction of travel [long and narrow] the less resistance is developed.) Also, the uniformity of loading on the contact area will have an effect on the resulting performance. The tread is the final force-transmitting element to the interface material, and thus tread design will or can affect the performance. Tread material and carcass stiffness are other parameters which can affect performance. It is not suggested at this time that variations in performance can be directed to a particular design feature, but only that there are differences which can, individually and collectively, cause some tires to perform better than others.

DEFINITION OF SURFACE PROPERTIES

Webster defines snow as "precipitation in the form of small tabular and columnar white ice crystals formed directly from the water vapor of the air at temperature of less than 32°F." "Snow job" is defined as "an intensive effort at persuasion or deception." To assume that the first definition sufficiently describes "snow" is to be a victim of the second.

Locomotion over snow is concerned with the snowpack behaving as a pseudogranular medium. To observe the metamorphism of snow in the pack as a function of elapsed time, i.e. aging, is not a valid criterion for our purposes. The snowpack is an endochronic entity, and the strength properties and related phenomena reflect the snowpack history as such.

Snow properties are sensitive to many phenomena, such as wind and temperature gradients during precipitation, temperature gradient of the snowpack, the unfrozen water content of the grains within the pack, stress history of the snowpack, solar and radiational/cooling effects, etc. These effects or phenomena cannot all be observed or measured. But since we are aware of them, measurements can be made which reflect their influence on strength, which is, in fact, the characteristic of interest. These measurements are simply material responses to known force applications, and are the strength parameters required for eq 3 and 4.

TIRE PERFORMANCE EVALUATION

There are three easily identifiable tire design parameters which may affect tires' performance in shallow snow, ice, slush, etc., excluding width and diameter. When performance evaluations are made, it is assumed that proper tire loads and inflation pressures relative to the tire size will be maintained. The three variable parameters are tire construction, tread design, and tire compound. Although tire compound formulas are proprietary, there are standard tests to determine engineering properties, which are in fact more meaningful in this type of evaluation than chemical analyses.

When snow is compacted or sheared, a certain minimum amount of energy is required. Thus, we can visualize the quantities, compaction energy and shear energy, and determine their dissipation during vehicle motion. To change a unit volume of snow from its initial density to its critical density requires a specific amount of energy dissipation through the process of compaction. Furthermore, to shear the compacted snow in the tire/snow interface requires a certain amount of energy to overcome the interface shearing resistance. Any capability of energy dissipation developed over and above these basic requirements reflects the performance level of the traction-producing element.

Compaction energy dissipation is easily understood, whereas shear energy dissipation requires a bit more discussion. If it were possible to visualize the processes of shear which occur in the tire/snow surface interface, then one could observe the mobilization of resistant forces attempting to prevent surface failure through shear or slippage of the interface elements in contact. This process of "slip-shear" or shear energy dissipation can be useful in comparing tire traction performance. Several evaluation processes will be described and discussed.

Tractive force/vertical load (F_ℓ/F_v)

This is a well-known evaluation factor common to the literature on vehicle mobility akin to drawbar pull/vehicle weight. F_ℓ/F_v is more sensitive to tire response than drawbar pull in that it considers the interfacial forces of a single tire rather than the total vehicle output and total weight. The sampling process is designed so that all forces are monitored simultaneously. This allows a graphic output of F_ℓ/F_v, as shown in Figure 41. Any number above 0.0 indicates reserve traction usable for acceleration, deceleration (not skidding), slope climbing, deeper snow, etc. F_ℓ/F_v most probably reflects the effects of compounds, construction, and tread design, in the order given, for low traction surfaces. It is not a sensitive isolator of the effects of the various design elements.

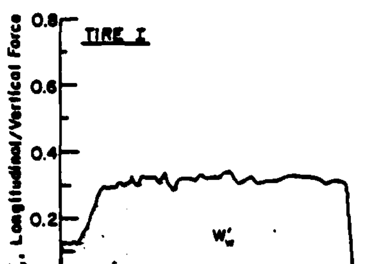

Figure 41. Eaton road traction test: tractive coefficient vs wheel distance.

Unit shear energy (ω_μ)

The unit shear energy dissipation parameter ω_μ is indicative of the work-producing capability of a tire. It is

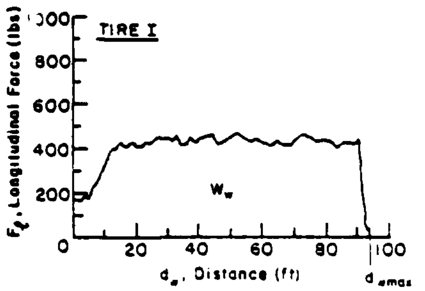

Figure 42. Eaton road traction test: longitudinal force vs wheel distance.

the total energy generated in developing traction divided by the circumferential distance traveled by the tire. From Figure 42:

$$W_w = \int_0^{d_{wmax}} F_\ell \, dd_w \qquad (6)$$

and

$$\omega_\mu = d_{wmax}^{-1} \cdot W_w \qquad (7)$$

wheel. The significance of ω_μ is discussed later.

Unit slip energy (ω_s)

While the parameter ω_μ reflects the capability of a tire to generate energy (or "work capability per unit distance") it does not indicate how far the payload was actually moved. The unit slip energy parameter ω_s considers both slip energy and slip distance. The difference between the distance the tire moved (circumferentially) and the distance the vehicle moved is obviously the slip distance. By plotting the force F_ℓ as a function of the distance traveled by the vehicle, d_{vmax} (Fig.

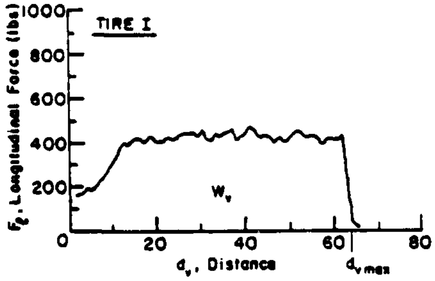

Figure 43. Eaton road traction test: longitudinal force vs vehicle distance.

43), the useful work can be expressed as:

$$W_v = \int_0^{d_{vmax}} F_\ell \, dd_v. \qquad (8)$$

The "slip energy" developed is $W_w - W_v$, and the slip distance is $d_{wmax} - d_{vmax}$. The unit slip energy developed is:

$$\omega_s = \frac{W_w - W_v}{d_{wmax}} - d_{vmax}. \qquad (9)$$

Domeck[13] discusses several performance rating coefficients used by the tire industry, two of which are somewhat similar to the unit slip energy parameter. The "Smithers coefficient," designated "ss," is explained using Figure 41. Assume that the graph in Figure 1 has the dimension of time in the abscissa instead of distance and vertical lines indicating the occurrence of differential interface velocity (DIV) of 0.7 ft/sec and 23 ft/sec. The area between the vertical lines representing the specified DIV's divided by the elapsed time bounding the area and the average vertical force gives the "ss" coefficient.

The so-called "area" coefficient is determined the same way, the exception being that DIV is plotted on the abscissa and the area beneath the curve is divided by the bounds ($V_{max} - V_{min}$ = 21.3 ft/sec). The "ss" coefficient has since been modified using the limits of DIV as 1.42 ft/sec and 22.0 ft/sec. Since the test vehicle speed is maintained at 7.35 ft/sec (5 mph), the limits bound a window between 17% and 75% normal slip or 20% and 300% differential slip. Of the two methods, i.e. the "ss" and "area," the units of the areas of integration are initially force-time and force-distance/time before dividing by the average vertical force. From this observation the "area" coefficient which is derived from an energy rate (power) quantity seems quite justifiable from an engineering viewpoint in lieu of the "ss" derivation.

Energy efficiency (ε_t)

ε_t is so defined (energy efficiency) for lack of a better term. The interesting aspect or validity of ε_t as a meaningful performance parameter is that it considers both the longitudinal force F_ℓ and the vertical force F_v in the calculation of an energy factor. In addition, it includes the tread width b, which brings the concept of the total area disturbed into consideration. ε_t is determined from the relationship shown in Figure 42:

$$W'_w = \int_0^{d_{wmax}} (F_\ell/F_v)\,ddw \qquad (10)$$

and

$$\varepsilon_t = \frac{W'_w}{b} \cdot \frac{d_{vmax}}{d_{wmax}} \qquad (11)$$

DISCUSSION

The parameter ε_t seems to be related to tire tread design. The aggressive patterns found on so-called mud and snow (M&S) tires, and some all-season tread designs (AS), tend to score better than highway tread designs and some "neutral" AS tread designs.

The unit slip energy ω_s[14] seems to reflect tire structure as well as tread design, seemingly being more influenced by structure than tread design. The parameter ω_μ considers only the work output of the tire without reference to the degree of slip or interface velocity involved. It appears that ω_μ is most sensitive to tire structure. The distance-normalizing factor in eq 7, i.e. d_{max}^{-1}, allows the comparison of test events having different wheel travel.

F_ℓ/F_v apparently is the least sensitive of the four parameters described earlier. It has the tendency of favoring both aggressive tread design and the radial carcass structure while penalizing the rib-type highway tread and the bias carcass structure.

These comments are based on the results of tests conducted on a 6-cm snow cover over rough "snow-ice" covered road. This type of surface will not delineate the differences in tire design as well as other winter surfaces. On the other hand, those differences which are detectable can be assumed as valid with a high confidence level. The results on which the discussion of performance parameters was based are shown in Table 3.

The assessment of performance of a number of tires on ice is shown in Table 4. As shown, all tires for the ice performance tests were radial ply. c_a and δ were measured with the CRREL-instrumented vehicle[14]. As a matter of interest, the ranking of the tires used and the cumulative scores from the four performance parameters (with $F_\ell/F_v \times 100$) are also shown.

Figure 44 contains the surface properties as measured for both the snow and the ice tests.

These parameters will be carefully examined over a large range of winter surface conditions to validate the influence of the design parameters as well as to determine the range of each parameter in the various surfaces.

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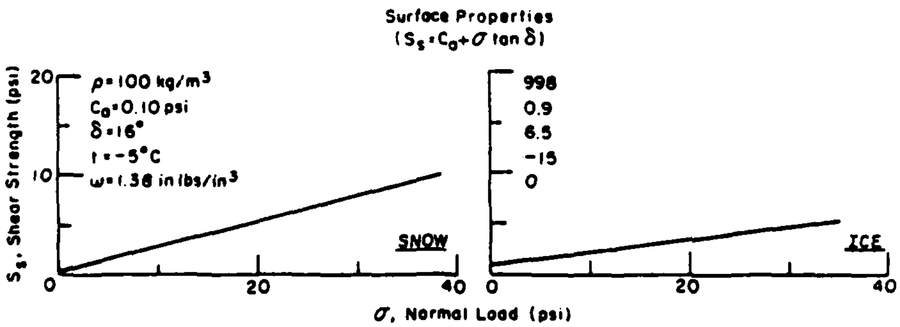

Figure 44. Measurement of snow strength parameters C_a and δ.

Table 3. Tire performance--snow.

Tire code	Structure	Tread	Tread characteristic	ϵ_t	ω_s	ω_μ	F_t/F_v
M	Bias	Highway	Ribbed	23.2	320	310	0.25
K	Radial	Highway	Rib-lug	35.8	393	336	0.28
L	Radial	Highway	Mod-rib lug	36.6	417	412	0.31
D	Radial	All season	Neutral	35.5	437	421	0.33
I	Radial	All season	Aggressive	41.9	430	391	0.32
F	Radial	M&S	Aggressive	39.0	436	406	0.32
O	Bias	M&S	Aggressive	37.8	430	373	0.31

Performance parameter	Ranking 1	2	3	4	5	6	7
ϵ_t	I	F	O	L	K	D	M
ω_s	D	F	I	O	L	K	M
ω_μ	D	L	F	I	O	K	M
F_t/F_v	D	F/I	F/I	L/O	L/O	K	M

Tire code	Score
D	927
F	913
L	897
I	895
O	872
K	793
M	678

Table 4. Tire performance--ice.

Tire code	Structure	Tread	Tread characteristic	ϵ_t	ω_s	ω_μ	F_t/F_v
D	Radial	AS	Neutral lug	23	140	140	0.14
S	Radial	M&S	Agressive	19	121	121	0.12
T	Radial	M&S	Agressive	10	135	137	0.15
U	Radial	M&S	Agressive	15	113	135	0.12
V	Radial	AS	Moderate lug	25	169	175	0.16
W	Radial	AS	Aggressive	21	146	176	0.16
X	Radial	AS	Moderate	20	116	118	0.12

Performance parameter	Ranking 1	2	3	4	5	6	7
ϵ_t	V	D	W	X	S	V	T
ω_s	V	W	D	T	S	X	U
ω_μ	W	V	D	T	U	S	X
F_t/F_v	V/W	T	D	S/U/W			

Tire code	Score
V	383
W	358
D	319
T	296
U	274
S	272
X	264

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EVALUATION OF EMPIRICAL TREAD DESIGN PREDICTIONS OF SNOW TRACTION AS MEASURED WITH A SELF-CONTAINED TRACTION VEHICLE*

G.P. Buchner
R.W. Centner
T.M. Knowles

Uniroyal Tire Company, Uniroyal Tire Technical Center, P.O. Box 3940, Troy Michigan, U.S.A. 48007-3940

ABSTRACT

This paper discusses snow testing of passenger and light truck tires, utilizing a self-contained instrumented driving traction test truck. It comparesthe test results of snow traction performance to empirical predictions. Tire test design parameters of lateral density, sipe density, tread depth and tread width are examined. It is recognized that additional work is required to further establish these relationships.

INTRODUCTION

Automobile manufacturers place stringent performance criteria on original equipment tires[1]. One of the areas of tire performance is snow traction. New tire designs are routinely evaluated with actual snow traction tests. This testing process is costly, time-consuming, and sensitive to the availability of suitable facilities with proper environmental conditions. The difficulties of providing such test data provide the stimulus for the development of mathematical methods of predicting snow traction performance.

In a 1980 study, T.R. Nesbitt and D.J. Barron[2] designed an experiment to develop empirical equations to predict snow traction performance. It involved hand-carved tires and testing on snow using a self-contained traction measuring vehicle. Such predictions were based on geometric properties of tire tread patterns. This technique had the potential to provide realistic estimates of snow traction capability in the "paper design" stage of the tire development. However, it was understood that further validations of this technique were required. Such a follow-up investigation is presented in this paper.

EQUIPMENT

In 1968 a milestone in snow traction methodology occurred in the form of a self-contained traction measuring truck[3]. This device brought with it significant improvements in test accuracy, manpower needs, and test surface requirements. This type of vehicle was used in early 1981 to generate the data discussed herein.

TEST METHODOLOGY

Test methodology for this program was developed by the SAE Snow Traction Task Force of the SAE Highway Tire Committee. The intent is to have the methodology published in a future SAE Handbook. The method utilizes a rear-wheel drive test vehicle with one drive wheel specially instrumented to measure its fore-aft and vertical forces. The tests are conducted by gradually increasing the driving torque at the instrumented wheel with an automatic throttle application device while maintaining an 8.0-km/h (5-mph) test speed by modulating the brakes of the non-test wheel positions. The vehicle's ground speed, the traction coefficient (definitions of all terms are contained in Appendix H), and the speed of the test tire constitute the output data of the test. The duration of the measurement interval is 1.5 seconds immediately following the instant when the test tire's speed exceeds vehicle ground speed by 3 km/h (2 mph). The average of each 1.5-second signal represents a single run. This procedure is repeated eight times. The corresponding eight 1.5-second signal averages are again averaged to form a test data set.

The test tires were assigned percentage ratings consisting of their traction coefficients divided by the average control tire coefficient for the day's test matrix. Such ratings were generated on three separate days to check the repeatability and the validity of the rating. The average of the three ratings represents the final tire rating.

All data were assigned ratings based on a P195/75R14 control tire. This tire is described in Appendix I. Four sizes of control tires were used: P195/75R14, P205/75R15, P215/75R15, P235/75R15. All were of similar design. The predominate volume of testing was monitored by the P195/75R14 control tire. Tires monitored by the other sizes of control tires were normalized accordingly.

The variability of traction ratings for the same tire was estimated to be 11.4% (of control tire). These variances represent measurement errors that a regression equation could not be expected to explain.

TEST SURFACE

Tests were performed on a surface prepared by compacting a natural snow base, using a special multi-wheel compactor, until this base surface could be traveled without leaving a tire tread imprint and with sufficient depth to preclude a spinning tire from cutting through to the pavement below.

In a second stage an additional layer of snow was added to the base. This snow was obtained mainly from a natural fall, but on occasion was bladed on from piles of natural snow set aside for the purpose. This additional snow was compacted uniformly to a consistent depth between 40 and 100 mm (2-4 inches), having a mean CTI Penetrometer reading[4] between 70 and 80.

The properties of this test surface reflected goals agreed upon by the SAE Snow Traction Task Force. CTI Penetrometer readings and SMT traction coefficients were measured randomly across the prepared test surface, from which mean values were calculated. In order to assure surface uniformity, it was required that the range of the individual Penetrometer readings not exceed 8 points and that the range of the individual SMT traction coefficients not exceed 0.05.

In the tests run, trouble was encountered in maintaining a mean SMT traction coefficient above 0.18. Mean values of 0.15 were at times the best obtainable. However, the range requirement of 0.05 was met, indicating a uniform surface. The significance of those low SMT values is not fully understood. Nevertheless, since rank orders and meaningful significant differences occurred for repetitive tests, the data are considered to be valid.

TIRES AND PARAMETERS

In the previous study[2] of snow traction predictions, tread design properties of lateral density, lateral angle, cross groove width, tread depth, sipe density, and sipe angle were investigated. The tire variables of size, tread compound, construction, and sipe width were controlled by using blank radial tires of a common compound from a single build. The tread designs were hand-carved, using a single sipe width of 1.0 mm. Our study was broadened to incorporate numerous and varied samples of size, construction, tread compound and sipe width. These tires were molded, rather than hand-carved. Tire tread width and overall diameter were also studied. These terms are listed and defined in Appendix H.

Shown in Table 5 of Appendix J are the tread element features of the 38 tires. Where several sizes and tire I.D. numbers are shown adjacent to a single illustration, specific tread element dimensions and related features will vary among the tires listed. The illustration simply serves as a "guide" to the design for that particular "family" of tires.

To develop the equations predicting traction values, it is necessary to distinguish tread "grooves" from tread "sipes". In the previous study, this was straightforward, since all "sipes" were fixed at 1.0 mm. However, since the tires used in this study had tread voids with a wide range of widths, such a differentiation between "grooves" and "sipes" was not straightforward.

Table 5. W_O = 1.5 mm correlations/regressions analysis.

	T	ρ_g	ρ_s	D_g	D_s	W_g	W_s	A_g	A_s	TW	OD
T	1.000										
ρ_g	0.816	1.000									
ρ_s	-0.195	-0.433	1.000								
D_g	0.123	-0.105	-0.283	1.000							
D_s	-0.098	-0.041	0.132	-0.168	1.000						
W_g	-0.398	-0.466	-0.026	0.346	-0.022	1.000					
W_s	-0.172	-0.245	0.411	-0.111	0.655	0.143	1.000				
A_g	-0.259	-0.389	-0.141	0.629	-0.076	0.944	0.072	1.000			
A_s	-0.170	-0.137	0.173	-0.019	0.900	0.076	0.825	0.049	1.000		
TW	0.138	-0.003	-0.220	0.466	0.016	-0.001	-0.048	0.161	0.098	1.000	
OD	0.135	-0.039	-0.239	-0.538	-0.088	0.006	-0.133	0.179	0.009	0.840	1.000

TIRE DESIGN EQUATIONS

	Equation	R	R^2(%)	$\bar{R}^2$(%)	SE
1.	$T = 96.4 + (1816)\rho_g$	0.816	66.6	66.6	17.5
2.	$T = 78.0 + (2004)\rho_g + (405)\rho_s$	0.835	69.7	68.9	17.0
3.	$T = -6.8 + (2202)\rho_g + (672)\rho_s + (7.6)D_g$	0.885	78.3	77.1	14.5
4.	$T = -31.6 + (2211)\rho_g + (698)\rho_s + (6.2)D_g + (0.05)\,OD$	0.890	79.2	77.4	14.4
5.	$T = -27.4 + (2177)\rho_g + (686)\rho_s + (6.5)D_g + (0.05)\,OD - (0.5)W_g$	0.890	79.2	76.7	14.6

Figure 45 shows the distribution of the narrowest tread void for each tire among the population of the tires analyzed.

The existence of such a distribution can be expected to complicate any application of the results of the earlier study. Moreover, since many tire designs incorporate a distribution of many void widths in a single tire, further complications can be expected. Figure 46 illustrates the total distribution of the widths of all "sipes" and "grooves" for the test sample. The decision as to what constitutes a "sipe" and what constitutes a "groove" has bearing on the capabilities of the equations to predict traction levels.

REGRESSION ANALYSIS METHODOLOGY

The regression models were built up a single variable (parameter) at a time.

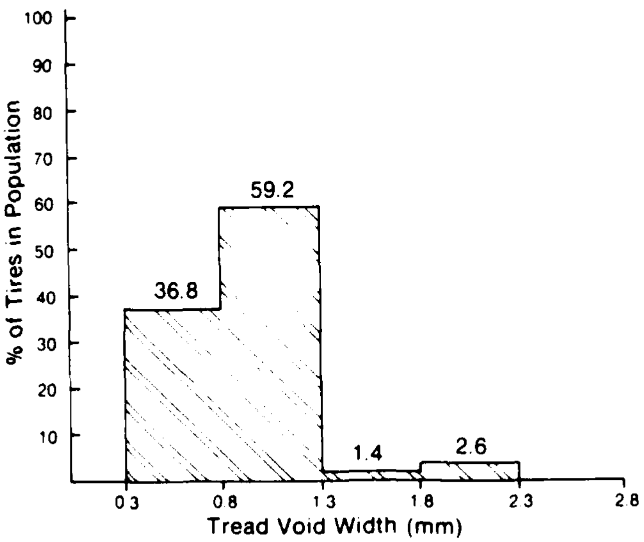

Figure 45. Distribution of smallest void (sipe) by void width.

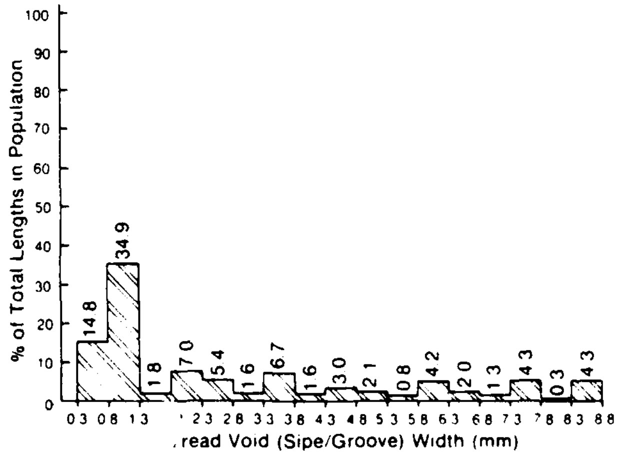

Figure 46. Distribution of projected lateral lengths by void width.

Terms were included in the regression equation according to their ability to reduce the amount of unexplained variances. The effectiveness of a variable in reducing variance is measured by the coefficient of determination, $\bar{R}^2$, the adjusted coefficient of determination[5], R^2, and the standard error (SE) of fit for each regression equation. This forward step-wise fitting procedure requires a review of each of those three goodness of fit estimators at each step.

The value of R^2 varies from 0 to 1.0 and is equal to the fraction of response (snow traction) variance explained by the current set of variables included in the fitted equation. R^2 continues to increase (until it reaches 1.0) as extra explanatory variables are added to the equation, regardless of the significance of those extra explanatory variables. This continually increasing feature of R^2 occurs because degrees of freedom are ignored; hence, $\bar{R}^2$, (R^2 adjusted for degrees of freedom), was chosen for this study to be a key indicator of goodness of fit.

SIPE/GROOVE DEFINITION

The issue of sipe/groove demarcation was explored by a search technique. A decision variable, W_o, was defined as the width, at and above which a void is classified as a "groove" and below which it was classified as a "sipe." Each void was either a sipe or groove; the two classifications were mutually exclusive and together formed the complete set of tread voids.

W_o was varied in increasing steps of 0.25 mm. With the demarcation width, W_o, determined, each tire's lateral density ar : sipe density was calculated. This produced a complete regression analysis data set for each value of W_o.

DEVELOPMENT OF PERFORMANCE EQUATIONS

Table 5 shows correlation coefficient and regression models for W_o= 1.5 mm. The correlation coefficients shown in this table were used to develop equation 1. The largest coefficient in the column under "T" (traction) is lateral density (ρ_g). For equation 2, the correlation coefficients (not shown) revealed the next dominant variable to be sipe density (ρ_s). These preliminary regression analyses led to the identification of three dominant variables: lateral density (ρ_g), sipe density (ρ_s), and groove depth (Dg). Equation 4 shows very little improvement (increase in $\bar{R}^2$).

Linear regression models of these three variables were fitted to each data set and the resulting R^2 values were plotted to find the maximum (best fit) value. Tables 6 and 7 show the coefficients and models for W_o = 1.0 mm (the sipe width used im the 1980 study) and W_o = 2.0 mm respectively. Similar exercises were performed for each value of W_o in steps of 0.25 mm.

Figure 47 illustrates the results of this search. A maximum value for $\bar{R}^2$ exists at the W_o = 1.5 mm point. This value therefore was taken as the optimal value for W_o, and is the recommended value for the 38 tire population used in this study.

Accordingly, equations 1 through 5 are the preferred set of equations.

Equation 3 seems to be the best choice as a model for predicting snow traction performance. Little is gained with additional parameters, as shown with equations 4 and 5.

A non-optimal choice of W_o would alter the amount of covariance in the data set (ref. tables 6 and 7) and could even alter the choice of variables which enter the fitted model. Hence, if any choice of Wo is to be made, it should be the optimal value, obtained by a search technique similar to that used for this study.

Moreover, comparison of Figure 47 with Figures 45 and 46 reveals similarity in structure. It is felt that perhaps a natural optimum value for Wo exists for

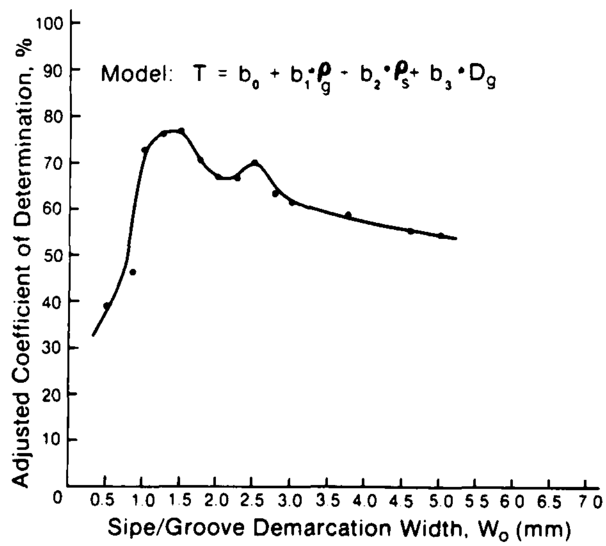

Figure 47. Adjusted coefficient of determination.

Table 6. W_o = 1.0 mm correlation/regression analysis.

	T	ρ_g	ρ_s	D_g	D_s	W_g	A_g	A_s	TW	OD	
T	1.000										
ρ_g	0.731	1.000									
ρ_s	-0.192	-0.616	1.000								
D_g	0.071	-0.232	-0.011	1.000							
D_s	-0.186	-0.427	0.526	0.020	1.000						
W_g	-0.408	-0.604	0.181	0.475	0.113	1.000					
W_s	-0.353	-0.581	0.713	-0.080	0.726	0.150	1.000				
A_g	-0.276	-0.519	0.081	0.715	0.054	0.941	0.045	1.000			
A_s	-0.418	-0.603	0.663	-0.085	0.842	0.163	0.911	0.059	1.000		
TW	0.138	0.264	-0.416	0.316	-0.184	-0.159	-0.333	0.034	-0.295	1.000	
OD	0.135	0.321	-0.511	0.417	-0.302	-0.153	-0.411	0.083	-0.413	0.840	1.000

TIRE DESIGN EQUATIONS

	Equation	R	R^2(%)	$\bar{R}^2$(%)	SE
6.	$T = 100.7 + (1380)\rho_g$	0.731	53.4	53.4	20.7
7.	$T = 65.7 + (1862)\rho_g + (699)\rho_s$	0.801	64.2	63.2	18.4
8.	$T = -0.3 + (2105)\rho_g + (838)\rho_s + (6.0)D_g$	0.863	74.5	74.3	15.8
9.	$T = 49.4 + (2174)\rho_g + (708)\rho_s + (7.7)D_g - (0.09)\,OD$	0.875	76.6	74.5	15.3
10.	$T = 58.0 + (2119)\rho_g + (679)\rho_s + (8.1)D_g\ (-0.10)\,OD - (0.9)W_g$	0.876	76.7	73.9	15.6

Table 7. W_o = 2.0 mm correlation/regression analysis.

	T	ρ_g	ρ_s	D_g	D_s	W_g	W_s	A_g	A_s	TW	OD
T	1.000										
ρ_g	0.702	1.000									
ρ_s	-0.017	-0.262	1.000								
D_g	0.242	-0.118	-0.296	1.000							
D_s	0.004	-0.001	-0.356	0.485	1.000						
W_g	-0.294	-0.389	-0.219	0.371	0.134	1.000					
W_s	0.120	-0.202	-0.223	0.744	0.321	0.342	1.000				
A_g	-0.100	-0.318	-0.307	0.697	0.290	0.919	0.569	1.000			
A_s	0.101	-0.133	-0.331	0.767	0.668	0.292	0.912	0.534	1.000		
TW	0.138	-0.130	-0.132	0.529	0.394	0.159	0.511	0.337	0.545	1.000	
OD	0.135	-0.186	-0.139	0.625	0.491	0.183	0.660	0.395	0.697	0.840	1.000

TIRE DESIGN EQUATIONS

	Equation	R	R^2(%)	$\bar{R}^2$(%)	SE
11.	$T = 103.6 + (1757)\rho_g$	0.702	49.3	49.2	21.6
12.	$T = 85.5 + (1875)\rho_g + (429)\rho_s$	0.723	52.3	50.9	21.3
13.	$T = -20.8 + (2107)\rho_g + (800)\rho_s + (9.1)D_g$	0.831	69.1	67.3	17.4
14.	$T = -42.2 + (2136)\rho_g + (796)\rho_s + (7.8)D_g + (0.05)\,OD$	0.835	69.7	67.1	17.4
15.	$T = -32.9 + (2057)\rho_g + (752)\rho_s + (8.2)D_g + (0.04)\,OD - (1.2)W_g$	0.837	70.1	66.4	17.6

each tire data set. While 1.5 mm was the best choice for this 38 tire sample, it may or may not be the best choice for a different sample of tires. This underscores the importance of defining "sipes" and "grooves" for each sample of tires to be examined.

COMPARISON OF MODELS

In the 1980 study[2], eight "Tire Design Equations" were reported. Two of these equations contain non-linear cross-terms. Such cross-terms can be considered undesirable if extrapolations are to be permitted in the day-to-day use of such equations. Four other equations included a groove width variable, which was not found to be significant in this study. Accordingly two of the eight equations (referred to in this study as NB-1 and NB-2) are compared to equations 2 and 3 of this report. NB-1 and NB-2 are shown for W_o values of 1.0 mm and 1.5 mm. Equations 3 and 4 are shown for W_o = 1.5 mm (the optimal value). Table 8 lists the projected values for these equations, along with the test data. The equations are displayed in Table 9.

Standard Errors (SE) of fit and Spearman rank correlation coefficients are shown for each equation. The Spearman rank correlation, r_s, is commonly used to demonstrate degree of ranking concordance and discordance, having values from -1 (complete discordance) to +1 (complete concordance). These values are excellent for all equations shown in Table 5.

Figures 48 and 49 demonstrate a near perfect 1.000 slope for predicted T values versus measured T values when equation 3 is used to obtain T. A slope of 1.052 for the analogous graph was obtained from the NB-2 equation. Both values are excellent.

SUMMARY

The previously published[2] simplified tire design snow traction prediction equations have been applied to a data set of tires external to the original "designed experiment" used to develop them. These equations have been demonstrated to be remarkably effective for predicting snow traction values. Difficulties resultant from a distribution of sipe and groove widths (rather than a single designed sipe width) were discussed.

It was shown that an optimal value for the demarcation (by width) of sipes and grooves is required when samples of commercially available tires are studied. This optimal value can be located by a search technique. Care must be taken

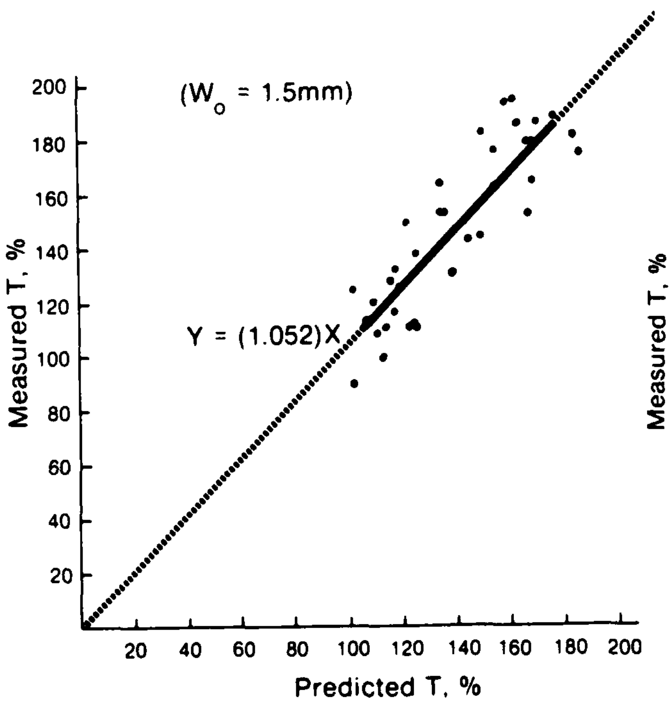

Figure 48. NB-2: $T = 20 + (1603)\rho_g + (392)\rho_s + (3.4)Dg$.

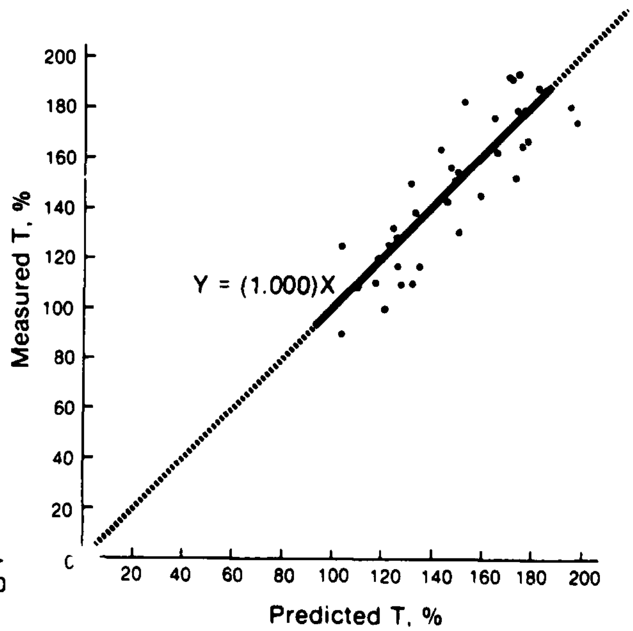

Figure 49. Equation 3: $T = -6.8 + (2202)\rho_g + (672)\rho_s + (7.6)Dg$.

Table 8. Predicted traction ratings for selected models.

Tire No.	Actual Data	Wo = 1.0 mm		Wo = 1.5 mm		Wo = 1.5 mm	
		NB-1	NB-2	NB-1	NB-2	3	4
1	138.7	151.3	148.3	124.6	125.7	131.6	130.6
2	111.0	114.7	114.3	116.7	114.3	116.9	112.7
3	120.3	155.1	113.9	115.1	113.9	118.3	115.6
4	179.3	178.1	172.8	171.6	169.5	177.4	177.3
5	164.3	124.1	134.4	124.0	134.3	142.9	138.1
6	90.7	103.7	101.6	103.7	101.6	103.7	103.0
7	167.6	162.8	166.1	162.8	166.1	177.3	177.8
8	125.0	121.0	119.9	121.0	119.9	123.8	123.4
9	132.0	114.9	117.4	114.9	117.4	124.0	124.7
10	143.6	153.2	145.7	153.2	145.7	145.0	148.6
11	114.0	105.0	107.9	105.0	107.9	113.5	113.5
12	150.7	162.4	151.9	162.4	151.9	149.2	147.3
13	186.7	165.9	163.9	165.9	163.9	170.2	169.9
14	128.0	113.6	117.6	113.6	117.6	125.4	127.8
15	179.7	168.2	167.5	168.2	167.4	174.4	173.6
16	150.0	117.5	121.9	117.5	121.9	131.2	131.9
17	100.0	109.8	113.5	109.8	113.5	120.8	118.4
18	111.3	118.9	122.6	118.9	122.6	131.6	130.3
19	117.0	120.5	124.2	120.5	124.2	133.5	131.3
20	116.7	113.3	116.9	113.3	116.9	124.9	121.9
21	113.3	125.0	124.5	125.0	124.5	126.5	124.8
22	131.7	150.1	155.4	126.8	139.6	151.3	146.5
23	156.0	190.4	163.4	129.7	136.6	147.1	144.1
24	181.0	188.0	188.9	183.6	184.4	194.6	193.8
25	188.3	176.5	177.7	176.5	177.5	182.8	181.3
26	175.7	182.8	186.1	182.8	186.1	197.0	194.9
27	187.3	172.3	172.9	172.3	172.9	184.4	183.6
28	176.3	155.5	155.0	155.5	155.0	164.0	163.3
29	145.9	137.4	149.2	137.4	149.2	158.8	160.3
30	153.6	140.4	155.2	120.5	135.1	148.9	151.7
31	163.8	143.9	154.0	143.9	154.0	164.5	166.7
32	194.6	187.8	200.1	147.3	159.2	173.3	177.2
33	194.6	194.0	199.8	151.4	160.9	173.6	176.5
34	125.4	162.2	155.6	104.7	101.2	103.7	110.6
35	108.8	158.4	153.8	109.7	109.8	114.5	121.9
36	152.3	170.8	175.2	162.2	166.6	173.2	177.2
37	165.1	169.7	168.1	168.8	168.1	175.9	178.3
38	183.0	151.1	149.6	155.0	149.9	153.8	153.3

Table 9. 38 tire population: projections/interpolation goodness-of-fits.

Model	Wo (mm)	Fitted Model	SE	r_s
NB-1	1.5	$T = 50.0 + (1593)\rho_g + (394)\rho_s$	19.8	0.825
NB-1	1.0	$T = 50.0 + (1593)\rho_g + (394)\rho_s$	19.3	0.786
NB-2	1.5	$T = 20.0 + (1603)\rho_g + (392)\rho_s + (3.4)\ Dg$	16.9	0.863
NB-2	1.0	$T = 20.0 + (1603)\rho_g + (392)\rho_s + (3.4)\ Dg$	17.0	0.824
3	1.5	$T = -6.8 + (2202)\rho_g + (672)\rho_s + (7.6)\ Dg$	14.5	0.870
4	1.5	$T = -31.6 + (2211)\rho_g + (698)\rho_s + (6.2) Dg + (0.05)\ OD$	14.4	0.877

when applying the NB equations to data sets external to the "designed experiment" which produced them. The sipe/groove geometric parameters must be optimized prior to use in a NB equation. The goodness of fit and reliability of predictions are sensitive to the distribution of sipe widths, which has bearing on the optimal sipe/groove demarcation.

However, once sufficient care is taken to properly match data set with fitted model, it appears that the NB technique of using tread measurements to predict snow traction performance is a sound, pre-test, tire design tool.

It is recommended that further independent snow traction data sets be evaluated using this technique to confirm these promising conclusions. Moreover, further study should be expanded to include other parameters such as tread compounds and tread contact pressure distribution.

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2. T.R. Nesbitt and D.J. Barron (1980), Prediction of Driving Traction Performance on Snow. Paper 800836 presented at the SAE Passenger Car Meeting, Hyatt Regency, Dearborn, Michigan, June.

3. National Safety Council. 1969-70 Winter Test Report. Committee on Winter Driving - Traffic Conference.

4. D.C. Domeck (1982), Winter Tire Testing as Seen by the Independent Tire Tester. SAE Paper 820344.

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APPENDIX H: DEFINITION OF TERMS

Symbol	Term	Units	Description
T	Traction Rating	%	Traction as % of P195/75R14 control tire.
ρ_g	Lateral Density	mm/mm^2	Sum of projected lateral groove lengths in a tire divided by total surface area of the tread.
ρ_s	Sipe Density	mm/mm^2	Sum of projected lateral sipe lengths in a tire divided by total surface area of the tread.
W_o	Groove/Sipe	mm	The minimum width, at and above which an incision into the tread surface is classified as a groove and below which the incision is termed a sipe.
Dg	Average Groove Depth	mm	Average depth of a "groove" classified tread voids.
Wg	Average Groove Width	mm	Average width, perpendicular to sides of voids which are classified as grooves.
Ws	Average Sipe Width	mm	Average width, perpendicular to sides of voids which are classified as sipes.
Ag	Average Groove Void Cross-Sectional Area	mm^2	Wg·Dg
As	Average Sipe Void Cross-Sectional Area	mm^2	Ws·Ds
Tw	Tread Width	mm	Tire Tread Width (Mold)
OD	Outside Diameter	mm	Tire Outside Diameter (Mold)
Tc	Traction Coefficient	N/N	Average Coefficient of Friction (drive force divided by vertical load)

APPENDIX I: SNOW MONITORING TIRE

Test course surface quantification can be obtained by using an industry designated Snow Monitoring Tire or SMT. The current* industry SMT is the Uniroyal "Steeler" steel belted radial P195/75R14, TPC spec number 1024 (Uniroyal development reference number 32164-H). This tire must not be subjected to uniformity or other grinding procedures and should be obtained from the Manager of Industry Standards, Uniroyal Tire Technical Center, P.O. Box 3940, Troy, Michigan 48084.

On an appropriately prepared surface (medium packed snow) the average friction coefficient of this tire is 0.18 to 0.26. This performance represents a range in which good discrimination among tire types can be obtained. The range obtained when measuring different locations on a test course should not exceed 0.05 to ensure course consistency.

Use of the SMT concept allows for direct surface measurement comparisons of all test agencies' test sites.

* If the tread design, tire construction, or rubber compounds in this SMT tire are changed, Uniroyal will notify the SAE Test Committee, who will review the changes and make recommendations if a new SMT tire should be considered.

SESSION III: TIRE SELECTION

The intent of this session was to discuss the user methodology, rationale and criteria for tire selection for specific applications. The methods used for specification are, obviously, tailored to ensure that the users' needs are met. Thus, the systems used to select a tire vary with the nature of the customer and the value and importance of the mission.

The differences between selection considerations for military and public tires became immediately apparent during this session. For instance, the military's primary concern is with off-road operation while commercial manufacturers are principally interested in on-road driving. This leads to widely different speed, hazard, obstacle and surface material considerations. The methodology (and some of the categories) for tire specification, however, can be similar in philosophy.

It was also apparent from this session that the military has just realized the need to be more critical of its tire selection and has begun to develop a system for ensuring user satisfaction. The commercial tire market, on the other hand, has available a system which, for on-road passenger car/light truck application, has proven to be valuable.

GENERAL MOTORS TIRE PERFORMANCE CRITERIA (TPC) SPECIFICATION SYSTEM*

Kenneth G. Peterson
Fraser D. Smithson
Fredric: W. Hill, Jr.

General Motors Corporation, General Motors Proving Ground, Milford, Michigan 48042

ABSTRACT

Over the years, General Motors has expended considerable effort in the selection of tires for use on its vehicles. In the early days, tires were evaluated within GM by vehicle development engineers and selected primarily on subjective ride and handlingevaluations. The tire manufacturer was responsible for certifying his tire's performance in the other areas, such as traction and durability. With this type of tire procurement system, each manufacturer's tire was a design created on criteria judged by that manufacturer to be satisfactory. As General Motors tire testing technology increased, the objective evaluation of our supplier's products indicated variations in other areas of performance among our suppliers.

Variation in tire performance from different sources supplying the same size original equipment tire for a specific usage was only one of several reasons why General Motors Management initiated a GM Tire System Improvement Program. Field surveys were conducted which indicated that customers desired improved original equipment tires in areas of performance, warranty, and service. Further, analyses of aftermarket tire performance characteristics indicated that if replacement tires from various sources, while nominally of the same size and type, were intermixed on a vehicle, there could be a resulting change in the vehicle's handling qualities. For GM owners who choose traction and durability. With this type of tire procurement system, each manufacturer's tire was a design created on criteria judged by that manufacturer to be satisfactory. As General Motors tire testing technology increased, the objective evaluation of our supplier's products indicated variations in other areas of performance among our suppliers.

Variation in tire performance from different sources supplying the same size original equipment tire for a specific usage was only one of several reasons why General Motors Management initiated a GM Tire System Improvement Program. Field surveys were conducted which indicated that customers desired improved original equipment tires in areas of performance, warranty, and service. Further, analyses of aftermarket tire performance characteristics indicated that if replacement tires from various sources, while nominally of the same size and type, were intermixed on a vehicle, there could be a resulting change in the vehicle's handling qualities. For GM owners who choose to purchase "TPC" specification tires, the "TPC" system enables them to avoid variations in their vehicle handling due to tires.

In 1971, a Central Tire Group was established to direct the GM Tire System Improvement Program with headquarters located at General Motors Proving Ground. This group was assigned the tire responsibilities to provide: future planning; liaison with tire companies, GM divisions, and the government; evaluation and development of tires; tire specifications; tire quality assurance--service and tire warranty program coordination.

Each of these activities then formulated plans to resolve the particular problems related to their areas of concern.

INTRODUCTION

The part of the GM Tire Program to be outlined in this paper describes the reasoning behind the establishment of the General Motors Tire Performance Criteria (TPC) Specification System and the system itself. (All TPC specifications are included in Appendix K.) The specific objectives of this system were to provide the General Motors Corporation with improved specifications for original equipment tires to assure that all the suppliers' tires are equal to or above the specified minimum performance levels, and to provide the customer with a system by which he could obtain replacement tires designed to provide the same performance characteristics as the OE tires originally installed on his vehicle.

Until the development of the Tire Performance Criteria (TPC) specification system there was no method of providing a customer with information that a particular tire possessed certain performance characteristics. Therefore, this "TPC" specification number, when used for field application, is beneficial to the customer as it will identify the tire as one that meets a set of engineering requirements in the areas of handling, endurance, uniformity, noise, dimensions, and traction performance for his vehicle.

Car owners replacing their tires with tires having the same "TPC" specification number as those provided originally with the vehicle will be assured that the tires have equivalent dimensions and performance characteristics. This is important as it offers the customer an opportunity to more nearly maintain the design characteristics of his vehicle and should eliminate much of the confusion that occurs during purchase of replacement tires. A special tire Owner's Guide supplied with GM cars equipped with these tires will acquaint our customers with the value of the "TPC" specification number.

GM also furnishes "TPC" specifications to all replacement tire manufacturers which describe the tire characteristics which best meet the needs of GM vehicles. In addition, a service has also been established to make available to replacement tire manufacturers information which will enable them to provide equivalent replacement tires for General Motors vehicles.

Any manufacturer is welcome and encouraged to produce a tire to meet the "TPC" requirements. Each tire manufacturer is responsible for evaluating its tire to these "TPC" requirements and judging if the design complies with the "TPC" spec number for that size.

Although the original equipment "TPC" tires supplied to General Motors have one common tread design irrespective of supplier, this is not a requirement of the "TPC" system. The "TPC" system is tire performance oriented and not design restrictive. Tires bearing different design characteristics (tread configurations, belt and carcass materials, etc.) may meet the performance requirements of the "TPC" system.

The "TPC" system includes a much larger number of tire performance categories than the current NHTSA uniform tire quality grading proposal and we do not feel the eventual adoption of a quality grading system will reduce the usefulness of the "TPC" system.

The tire performance characteristics finally specified in the General Motors "TPC" specification system evolved from many years of tire performance evaluation. The evaluations in turn led to sets of tire performance guidelines. From these guidelines, specific performance categories were chosen for further development into "TPC" specifications. The final "TPC" categories were selected based on the importance of their relationship to the tire/vehicle, the existence of a test procedure, a significant data base having reasonable test repeatability and sufficient meaning relative to actual tire performance. The "TPC" specification tests were designed such that they could be conducted by individual tire companies or by other groups outside of General Motors.

GENERAL MOTORS TPC SPECIFICATION SYSTEM

The "TPC", or Tire Performance Criteria, specification system covers the following dimensional and peformance areas:

Tire Performance Criteria (TPC) Specifications

- Dimensions
  - Maximum size
  - Static loaded radius
  - Revolutions per mile
- Endurance
- High Speed

Traction
  Wet
  Dry
  Snow
Passby Noise
Force & Moment Characteristics
  Cornering coefficient
  Aligning torque coefficient
  Load sensitivity
  Load transfer sensitivity
Uniformity
  Radial force variation
  Lateral force variation
  Conicity
  Plysteer
Balance

Figure 50. Laboratory tire profiler.

Taking each of these performance categories in the order listed, we will now describe the basic performance requirement and the reason behind its inclusion in the "TPC" specifications.

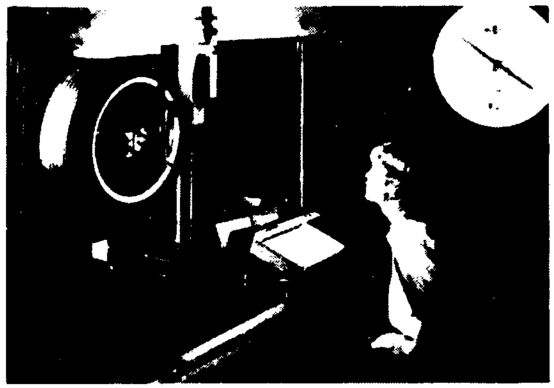

Figure 51. Facility for measuring static vertical spring rate and static loaded radius.

DIMENSIONS

The tire maximum cross section dimensional requirements are given in Table K-2 (all tables are in Appendix K) which shows the maximum profile box in which the tires must fit. As shown in the table, a unique "TPC" number is assigned to each tire size. The dimensional envelope indicated is smaller than the rather broad envelope allowed by T&RA for each given tire size. It reflects the envelope in which GM specifies its tires in order that tire-to-vehicle clearances are adequate on the GM vehicles on which the tires are installed. Consequently, this tire specification includes consideration of the specific vehicles that will use each tire size (Fig. 50).

In addition to meeting the above clearance profile, "TPC" tires meet additional dimensional requirements (Table K-1). These include specifications on maximum diameter and tire revolutions per mile which allow more accurate speedometer/odometer control and specifications on static loaded radius to allow more precise control over vehicle bumper height, etc. (Fig. 51).

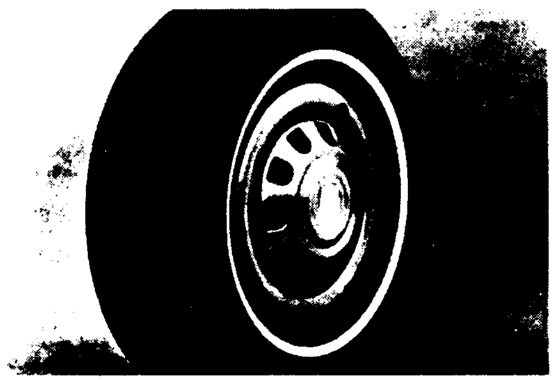

Figure 52. GM-2B tread pattern.

Tires purchased by GM for OE installation have a further requirement in that they must conform to a tire drawing which specifies a unique tread design and sidewall treatment. As stated earlier, aftermarket or replacement tires would not necessarily have to conform to this tread design drawing to meet the "TPC" specification requirements, as long as they were equivalent to the "TPC" tires in dimensional and performance specifications (Fig. 52).

ENDURANCE

General Motors developed the performance specification of the "TPC" tires in the area of structural integrity when driven at speeds up to the legal maximum

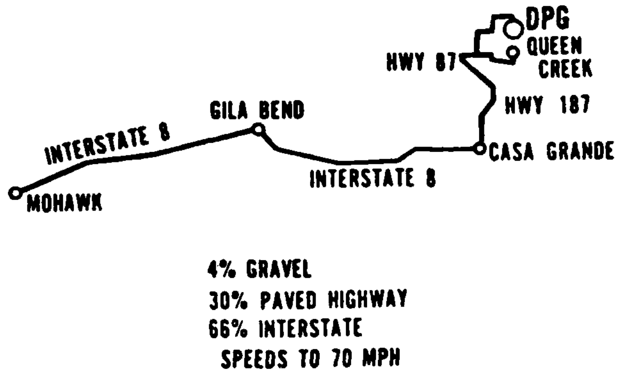

Figure 53. Accelerated tire endurance test route.

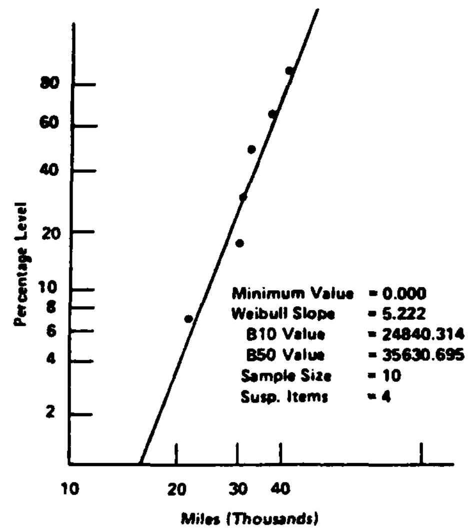

Figure 54. Typical A.T.E. data analysis.

near Phoenix, Arizona, and on specific public highways in that area. Higher speed performance was tested on the high speed test track at the General Motors Desert Proving Ground and is discussed in the following section (Fig. 53).

It would certainly be desirable (from an economic and time viewpoint) to evaluate long term tire structural integrity using an accelerated laboratory test procedure. However, GM has not yet been able to accurately evaluate, in the laboratory, the tire endurance performance obtained under real world operating conditions involving all the various speeds, road surfaces, road hazard exposure, lateral acceleration conditions, suspension dynamic loadings, etc., that the tire can be expected to see in service. Consequently, we are using a public highway test procedure, but have accelerated the test duration by running the tires continuously at 100% of their maximum rated loads--24 psi load and pressure front and 32 psi load and pressure rear. This test loading tends to expose any areas of potential structural weakness and also serves to accelerate the test time.

A tire's performance on this test is determined by its mileage until removal. The test is run until the tire must be removed for wear, road hazard, or lack of structural integrity. The primary purpose of the test is to determine the structural integrity of each tire construction, so the distribution of structural removal mileages for a sample of eight tires of a given construction is determined. The usual statistical analysis technique used involves fitting a Weibull distribution curve to the structural removal mileages. Wearout and road hazard removals are considered as suspended items rather than removals in this analysis (Fig. 54). Such analysis techniques are described in references 1, 2, and 3. If there is not a sufficient number of structural removals to define a structural removal distribution, a Weibull distribution is fitted to all the pertinent removal mileages. In this case, the mileage values of an actual structural removal Weibull distribution are assumed to be at least as great as the values determined by the removal distribution.

The OE tire suppliers to GM have test procedures that incorporate the same tire loading, speed content, etc., as the GM Accelerated Tire Endurance (ATE) procedure. Each of the suppliers evaluates their GM Specification Number tires on their own schedule simultaneously with our own evaluation.

Based on an evaluation of the performance of bias belted and radial tires, and a desired improvement in structural endurance mileage of radial tires over bias belted tires to accommodate their increased tread wear life, the "TPC" structural endurance specification based on the above test procedure is:

B_{10} Mileage $\geq$ 15,000 miles (i.e., at least 90% of the tires should exceed 15,000 miles on this accelerated test).

B_{50} Mileage $\geq$ 25,000 miles (i.e. at least 50% of the tire should exceed 25,000 miles on this accelerated test).

HIGH SPEED

The test procedure GM used for the "TPC" high speed performance specification is conducted on a vehicle on the high speed track at the General Motors Desert Proving Ground. The development of a laboratory high speed test that can simulate results obtained on the high speed track has been undertaken. A laboratory test procedure involving a specific set of test conditions has been developed that correlates well with road tests for bias belted tires. However, the same set of lab conditions, when used for radial tires, does not produce correlation with a road test. Different radial tire constructions appear to require different lab test conditions in order to produce reasonable correlation with road test results.

The road test procedure is carried out using specifically prepared, high-speed test vehicles run in a neutral lateral acceleration lane on the General Motors Desert Proving Ground high speed track. Tire test conditions are 100% of the 24 psi T&RA load and 28 psi cold inflation pressure to accommodate the 4 psi pressure increase recommended for high speed driving. The test is conducted on an eight tire sample run at a temperature corrected speed of 100 mph for 125 miles, or until structural degradation is detected. Previous high speed tire testing to determine the effect of ambient temperature on high speed performance conducted at the General Motors Desert Proving Ground has indicated that equivalent high speed performance can be obtained at different ambient temperatures by running at test speeds that are adjusted according to a relationship of approximately a 1 mph increase in test speed per 10°F decrease in ambient temperature. Consequently, high speed test mileage results obtained at different ambient temperatures can be compared on an equivalent basis by using the actual test speed that corresponds to 100 mph at 75°F.

The test results for a sample of eight tires run according to the above test procedure are analyzed using Weibull techniques. The performance specification is that the sample B_{20} life must be at least 100 miles at 100 mph. If there are any structural removals, the mileage distribution and its B_{20} life is determined, i.e. the mileage that at least 80% of the tires should go under these test conditions. If no structural removals occur in the sample by 125 miles, Weibull statistical analysis based on past high speed testing indicates we can have very high statistical confidence that the sample B_{20} is at least 100 miles.

TRACTION

Wet traction

Development of improved wet traction was one of the major goals of the GM tire improvement program. The performance of the General Motors tread design was used as a basis for establishing the wet traction specification.

The specification is written as a percentage of performance of a control tire, in this case the ASTM E501-73 tire. Major wet traction improvements are specified at higher speeds with a requirement of 20% improvement over the control tire at 60 mph.

This comparison is to be performed on a trailer test similar to SAE J345A. And, it is felt that a minimum performance difference can be effectively substantiated in sound statistical terms (Fig. 55).

Figure 55. GMPG Model II friction test vehicle.

Dry traction

A similar traction test which evaluates performance relative to the same control tire is used to substantiate dry traction performance. The purpose was to maintain dry traction near current levels of performance.

Snow traction

The current interim specification for snow traction requires that a vehicle equipped with candidate tires have a locked wheel stopping distance from 20 mph on soft packed snow equal to that of a vehicle equipped with "TPC" qualified tires of corresponding size produced by one of General Motors original equipment suppliers. This specification will be revised as soon as baseline data is established using the ASTM E501-73 as a control tire.

PASSBY NOISE

There is increasing concern over environmental noise. While passenger car tire noise is not a major contributor to overall environmental noise, it is the major source of automobile noise at speeds above 50 mph. In terms of environmental noise, the "TPC" requirement limits the passby noise level to that of the typical straight ribbed highway tire (Fig. 56).

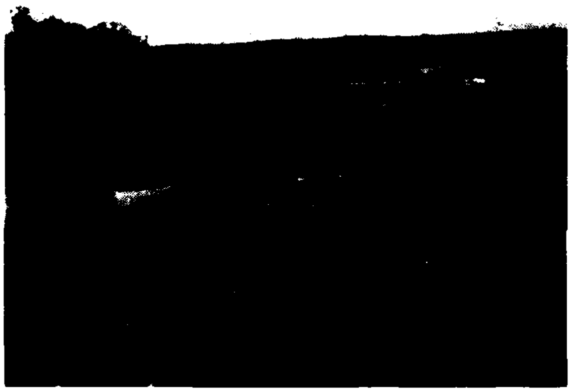

Figure 56. Passby noise test.

By meeting this goal, customer interior noise complaints due to tires can be virtually eliminated. Subjective interior noise evaluations conducted by acoustics engineers are also conducted on the "TPC" tires purchased by GM for OE installation.

FORCE AND MOMENT PROPERTIES

Tires generate the forces at the vehicle/road interface that play a major role in establishing the vehicle's directional control characteristics. The forces and moments specified in the "TPC" specifications are intrinsic properties of the tire itself. GM measured them on a laboratory test machine designed and built by General Motors[4]. This link belt tire test machine allows the tire-

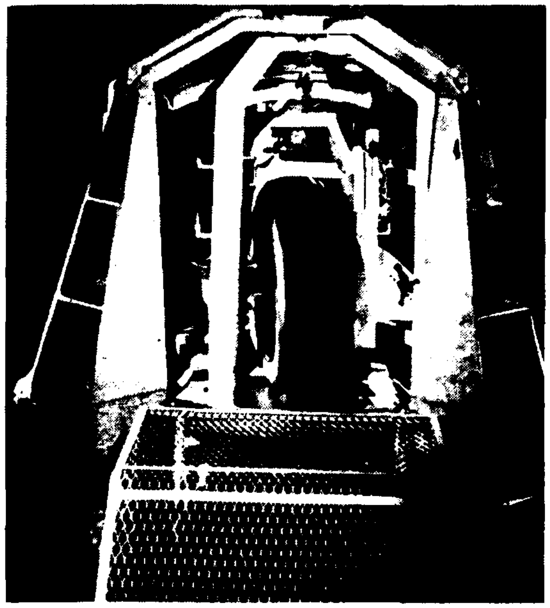

Figure 57. Tire force and moment test fixture.

generated forces and moments to be measured while it is operated at preset slip and inclination (camber) angles (Fig. 57). The vertical load on the tire is slowly increased from 0 to 1.6 times the T&RA load for the tire to provide a full range of generated forces at any desired *combinations of slip and inclination* angle. A weighing system is incorporated in the machine which measures the three forces and three moments generated by the tire. These forces and moments are depicted in Figure 58. The continuous analog force measurements are digitized, processed, and plotted using a digital computer system. While all six forces and moments influence vehicle behavior, the most important (relative to vehicle directional control) are lateral force and aligning torque. Figure 59 shows carpet plots of lateral force and aligning torque as functions of load and slip angle, as generated by a typical force and moment measurement test.

The performance parameters, which are the basis of the force and moment specification, are cornering coefficient, aligning torque coefficient, load sensitivity (h), and load transfer sensitivity (g). The tire's cornering coefficient is defined as the lateral force produced at one-degree slip angle and 100% of the 24 psi rated load, divided by the rated load (Fig. 60). This tire parameter is probably the most influential tire parameter affecting the linear directional control performance of the tire/vehicle system.

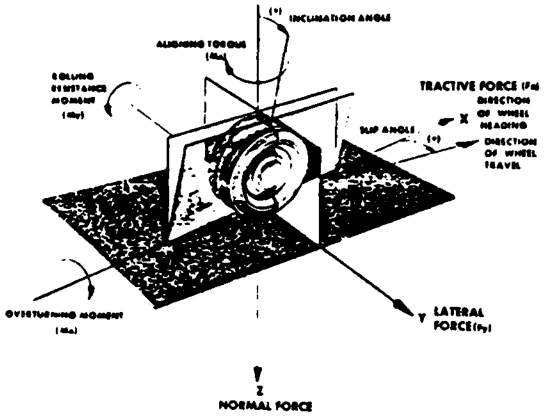

Figure 58. Forces and moments developed on rolling tires.

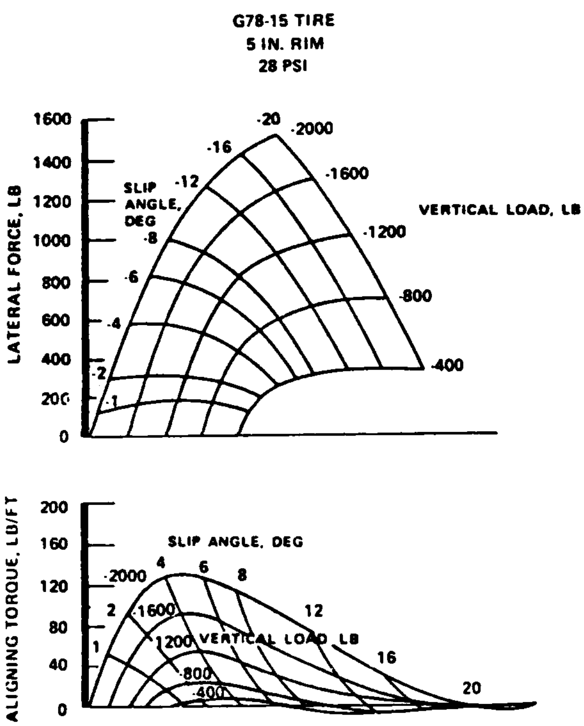

Figure 59. Lateral force and aligning torque as function of slip angle and vertical load.

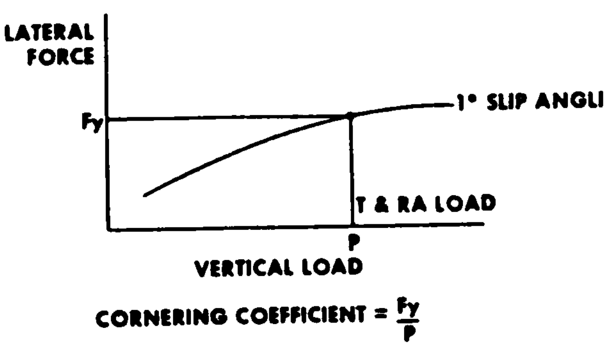

Figure 60. Cornering coefficient.

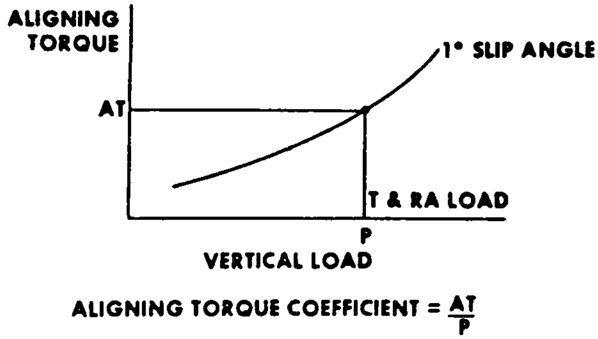

Figure 61. Aligning torque coefficient.

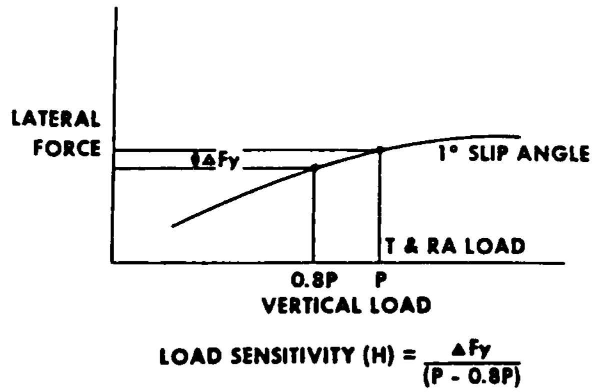

Figure 62. Load sensitivity.

Similarly, the aligning torque coefficient is defined as the aligning torque produced at one-degree slip and 100% of the 24 psi rated load, divided by the rated load (Fig. 61). The amount of aligning torque generated by the tire, in conjunction with the desired amount of vehicle front suspension aligning torque compliance designed into the vehicle by the chassis designer, significantly influences the vehicle directional control behavior. In addition, the aligning torque generated is very important in determining the force feedback through the steering wheel to the driver during any vehicle maneuvering.

The load sensitivity (or h function) is basically a measure of how much the tire is able to increase the lateral force produced at one-degree slip as the load is increased. It is evaluated between 0.8 and 1.0 times the rated load (Fig. 62). This parameter is important as it helps to define how consistently a vehicle's directional control properties can be maintained for various static loading conditions. This is most important in vehicles which can be expected to operate under various loading conditions.

The load transfer sensitivity (or g function) is basically a measure of how much total lateral force is lost by a

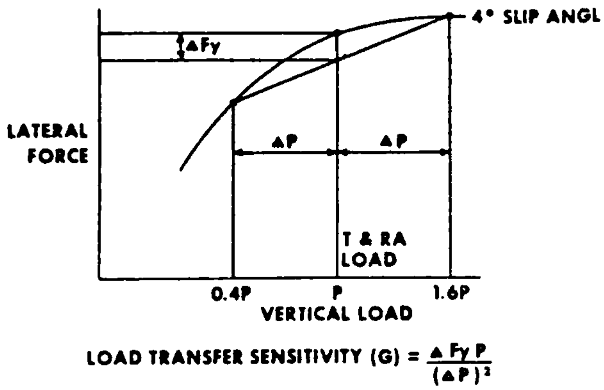

Figure 63. Load transfer sensitivity.

pair of tires when one is reduced in load by a certain amount from a base load value and the other is increased in load by that same amount. This situation is representative of a pair of front or rear wheels on a vehicle operating at a high lateral acceleration, with the resultant lateral load transfer.

Since the tire behaves non-linearly with load in this range, the sum of the lateral force produced by the loaded and unloaded tire is less than the total lateral force that would be produced by two tires both operating at the average loading condition and the same slip angle. This function is correspondingly evaluated at four degrees slip angle and between 0.4 and 1.6 times the tire rated load (Fig. 63). The parameter is important since it allows the vehicle designed flexibility in tailoring the higher lateral acceleration behavior of a vehicle. For example, it allows him to set the front and rear vehicle roll stiffnesses to produce a desired front-to-rear roll rate distribution. Too much tire load transfer sensitivity, however, would significantly limit the maximum lateral acceleration capability of the vehicle. A more complete description of these tire force and moment parameters and their application is found in references 5 and 6.

The specified values for these parameters are given in Table K-3. Note that there are different values specified for different tire sizes (and their corresponding different "TPC" specification numbers). In the development of these specifications the handling performance of the overall tire/vehicle system was evaluated for each tire size application. Those vehicles on which a certain size tire was to be installed did not necessarily require the same set of tire parameters as vehicles on which another size tire was to be installed. Consequently, the desired tire/vehicle handling performance was obtained over the range of different sizes of GM vehicles by specifying tire force and moment parameters consistent with the needs of the various vehicles.

The directional control properties of the various vehicle/tire combinations involved were investigated using the analysis techniques described in reference (7). By analyzing various tire/vehicle combinations in this manner, ranges of tire performance parameters were developed for each size tire that would produce the desired system handling performance characteristics. The principle reason for the width of the ranges of the specification parameters that were finally specified is to assure that an intermix of any of the tire brands meeting the specification range in a given size would still produce reasonable handling performance. A full set of four tires at one end of the specification range would also provide reasonable performance, as would another set of four tires at the other end of the range. Consequently, a customer purchasing replacement tires which are known to meet the specification can be confident that those tires will provide reasonable handling characteristics in his car.

Two of the vehicle directional control response parameters considered when evaluating the effect of different tires on a vehicle are vehicle lateral acceleration gain (a_y/δ_{sw}) and lateral acceleration response time (τ_{a_y}). Lateral acceleration gain is a steady state parameter and is defined as the rate of change of steady state lateral acceleration with steering wheel angle, expressed as G's per 100 degrees of steering wheel angle. Lateral acceleration response time is a transient response parameter and is defined as the time in seconds required for the lateral acceleration to initially reach 90% of its steady state value, with the steering input being a step or rapid ramp input. A tabulation of these response parameters generated for a typical intermediate size vehicle at full rated load using tires at both extremes of the cornering coefficient specification range and with a representative aligning torque coefficient is shown on the next page. These values indicate that configurations A, B and C provide somewhat similar response characteristics, and intermix situation D provides somewhat different, but still acceptable performance. However, if the tires used to generate these four possible intermix combinations were such

	Configuration	τ_{a_y} Sec	a_y/δ_{sw} G's/100 Degrees)
A	Four tires near high end of spec	0.44	0.77
B	Four tires near low end of spec	0.49	0.74
C	Front near low end of spec, rear near high end of spec	0.42	0.67
D	Front near high end of spec, rear near low end of spec	0.53	0.87

that they represented a larger spread in cornering coefficients than that allowed by the specification range, i.e. one set of tires with cornering coefficients above the specification range and another with coefficients below the range, the resulting performance could be marginal. This would be most likely to occur for intermix configuration D.

UNIFORMITY AND BALANCE

The "TPC" specification system is based primarily on measurable performance which must be incorporated into the overall basic design of a tire. The exception to this is the uniformity and balance requirements which must be measured on every tire produced to substantiate conformance.

Tire uniformity is a measurement of forces produced by a rolling tire which cause various forms of vehicle vibrations. The tire non-uniformities which create these forces are caused by inaccuracies in the build process. The simplest of these to visualize is radial runout which creates a once per revolution disturbance similar to tire imbalance. This is referred to as first harmonic radial force variation. The others of concern are total radial force variation, which is a measure of all harmonics of radial force and which can cause higher order vibrations, first harmonic lateral force variation which is a radial tire phenomena that causes a low speed first harmonic lateral vehicle mode known as "waddle;" and conicity, which is a lateral force offset that can cause vehicle lead and steering wheel pull similar to certain improper wheel alignment conditions, road crown situations, or steering gear asymmetries.

Setting the specification for each of these areas is a very difficult task in that the values selected must produce reasonably vibration-free cars, but still be within the manufacturing capability of the tire companies. The process used to develop a specification was to first analyze vehicle sensitivities by making subjective evaluations of vibration performance with known levels of tire non-uniformities. This is complicated by the fact that there are four wheels on a car and simple summation of forces does not necessarily apply.

Having determined vehicle sensitivities, we used statistical techniques to predict the levels of performance that would be achieved for a car population but curtailed at various specification limits. It was then a matter of whether a high percentage of satisfactory vehicles can be achieved at a specification level that produces a reasonable tire company yield. In the case of the "TPC" specification as shown in Table K-4 we feel we have achieved a reasonable level.

Tire balance is a slightly different proposition in that a large amount of imbalance may indicate a tire has a major flaw which could be detrimental to tire performance. The values selected for the "TPC" Spec are those below which there is any significant probability of faults in the tire. In the case of General Motors, original equipment suppliers correct balance to lower levels to be compatible with vehicle assembly plant balance equipment.

SUMMARY

In summary, the actual tire specifications covered in the GM "TPC" specifications are solely the product of General Motors engineering personnel, but are based on the analysis of test data from both General Motors and our suppliers.

This then describes how and why the specifications were developed. These specifications are available for use by any manufacturer on any tire configuration which can meet the specified performance levels.

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APPENDIX: GM TIRE PERFORMANCE CRITERIA SPECIFICATION

General

These specifications cover "new" TPC passenger tires intended for use on passenger cars and light trucks manufactured by General Motors. They outline, in terms of laboratory and simulated service test results, what performance values are required to qualify a tire under this specification.

Physical and performance characteristics

Tires to meet these specifications shall be designed to conform to the properties outlined in "General Information" Section as determined by the test methods indicated. A tire whose design has been demonstrated to conform with these specifications may bear the appropriate TPC Spec. No.

Tests

Tests referenced under "General Information" are outlined in the appendix of these specifications.

Markings

All tires will be marked as specified below:

Tire Size Designation	TPC Spec No.
BR78-13 Load Range B	1008
BR78-13 Load Range C	1014
FR78-14 Load Range B	1004
FR78-15 Load Range B	1010
GR78-15 Load Range B	1003
GR70-15 Load Range B	1007
HR78-15 Load Range B	2001
HR70-15 Load Range B	1011
JR78-15 Load Range B	1002
LR78-15 Load Range B	1005
LR78-15 Load Range C	1006
LR78-15 Load Range D	1009
NR78-15 Load Range D	1012

Physical and performance characteristics	Requirements
Dimensional requirements	See Tables K-1 and K-2
Accelerated tire endurance	The sample B_{50} life shall exceed 25,000 miles and the sample B_{10} life shall exceed 15,000 miles.
High speed	When run at a temperature-corrected speed of 100 mph, the sample B_{20} life shall exceed 100 miles.
Traction	
Wet	The average of peak and sliding wet braking traction coefficients shall be at least the following percentages of the control tire. 100% at 20 mph 120% at 60 mph
Dry	The average of 40-mph peak and sliding dry braking traction coefficients shall not be less than 95% of the control tire performance.
Snow	Interim specification. In soft pack snow at 20°F or warmer, the 20 mph locked wheel stopping distance of a vehicle equipped with four test tires shall be no greater than the stopping distance of that car when equipped with four TPC approved tires from one of General Motors' suppliers (Firestone, General, Goodrich, Goodyear or Uniroyal).
Force & moment	See Table K-3
Noise - passby	The average levels measured from a four tire care set shall not exceed those of the control tires by more than 4DbA at 50 mph.
Uniformity & balance	See Table K-4

Table K-1. New Tire Dimensional Specifications

TPC Spec. No.	Tire Size	Suggested Maximum Section Width*	Suggested Maximum Overall Diameter	Static Loaded Radius @24 psi Inflation 70% T&RA Load	Static Loaded Radius @24 psi Inflation 100% T&RA Load	Revolutions Per Mile (@45 mph)	Design Rim Width
1008	(BR78-13/B)	7.20	23.99	10.94 ± .20	10.61 ± .20	878 ± 7	4.50
1014	(BR78-13/C)	7.20	23.99	10.94 ± .20	10.61 ± .20	878 ± 7	4.50
1004	(FR78-14/B)	8.24	26.35	11.98 ± .20	11.60 ± .20	797 ± 7	5.50
1010	(FR78-15/B)	8.08	26.99	12.34 ± .20	11.97 ± .20	779 ± 7	5.50
1003	(GR78-15/B)	8.56	27.58	12.60 ± .20	12.19 ± .20	763 ± 7	6.00
1007	(GR70-15/B)	9.08	27.58	12.60 ± .20	12.19 ± .20	763 ± 7	6.00
1001	(HR78-15/B)	8.87	28.23	12.86 ± .20	12.42 ± .20	744 ± 7	6.00
1011	(HR70-15/B)	9.66	28.23	12.86 ± .20	12.42 ± .20	744 ± 7	6.50
1002	(JR78-15/B)	9.24	28.59	13.01 ± .20	12.55 ± .20	734 ± 7	6.50
1005	(LR78-15/B)	9.45	29.15	13.23 ± .20	12.76 ± .20	719 ± 7	6.50
1006	(LR78-15/C)	9.45	29.15	13.23 ± .20	12.76 ± .20	719 ± 7	6.50
1009	(LR78-15/D)	9.45	29.15	13.23 ± .20	12.76 ± .20	719 ± 7	6.50
1012	(NR78-15/D)	9.85	30.35	13.69 ± .20	13.20 ± .20	693 ± 7	7.00

*Maximum Tire Section Width increases .20 inch for each .5 inch increase in measuring rim width and decreases .20 inch for each .5 inch decrease in measuring rim width.

Table K-2. Growth Dimensional Specifications

TPC Spec. No.	Tire Size	A	B	C	D	E	F	J	Max. Growth Width	Design Rim Width
1008	(BR78-13/B)	1.47	3.64	5.17	5.64	2.43	3.09	5.88	7.36	4.50
1014	(BR78-13/C)	1.47	3.64	5.17	5.64	2.43	3.09	5.88	7.36	4.50
1004	(FR78-14/B)	1.66	4.12	5.84	6.37	2.77	3.53	6.64	8.40	5.50
1010	(FR78-15/B)	1.61	4.00	5.68	6.19	2.72	3.46	6.45	8.24	5.50
1003	(GR78-15/B)	1.69	4.19	5.95	6.49	2.88	3.66	6.76	8.72	6.00
1007	(GR70-15/B)	1.68	4.15	5.90	6.43	3.06	3.89	6.70	9.26	6.00
1001	(HR78-15/B)	1.78	4.41	6.26	6.84	2.98	3.80	7.12	9.04	6.00
1011	(HR70-15/B)	1.76	4.36	6.20	6.76	3.25	4.13	7.04	9.84	6.50
1002	(JR78-15/B)	1.83	4.54	6.45	7.04	3.11	3.96	7.33	9.42	6.50
1005	(LR78-15/B)	1.90	4.71	6.69	7.30	3.18	4.04	7.60	9.63	6.50
1006	(LR78-15/C)	1.90	4.71	6.69	7.30	3.18	4.04	7.60	9.63	6.50
1009	(LR78-15/D)	1.90	4.71	6.69	7.30	3.18	4.04	7.60	9.63	6.50
1012	(NR78-15/D)	2.01	5.00	7.09	7.73	3.33	4.24	8.06	10.09	7.00

*Maximum Growth Width increases .20 inch for each .5 inch increase in measuring rim width and decreases .20 inch for each .5 inch decrease in measuring rim width.

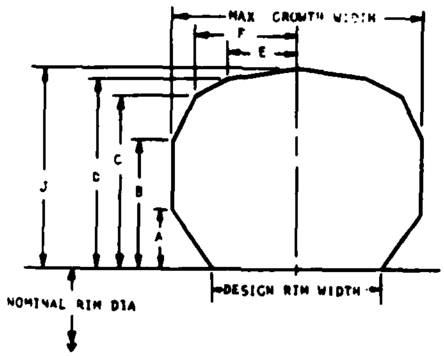

Table K-3. Force & Moment Requirements (Procedure TWDE2-20

1008 (BR78-13/B)

TPC Spec No.	Tire Size	Cornering Coefficient (1^o) Min.	Cornering Coefficient (1^o) Nom.	Cornering Coefficient (1^o) Max.	Aligning Torque Coefficient Min.	Load Sensitivity Min.	Load Transfer Sensitivity Min.	Load Transfer Sensitivity Max.
1008	(BR78-13/B)	0.175	0.185	0.200	0.020	0.03	0.18	0.35
1014	(BR78-13/C)	0.175	0.185	0.200	0.020	0.03	0.18	0.35
1004	(FR78-14/B)	0.155	0.165	0.180	0.024	0.03	0.20	0.35
1010	(FR78-15/B)	0.160	0.170	0.185	0.024	0.03	0.20	0.35
1003	(GR78-15/B)	0.150	0.160	0.175	0.025	0.03	0.20	0.35
1007	(GR70-15/B)	0.185	0.195	0.210	0.028	0.04	0.20	0.35
1001	(HR78-15/B)	0.150	0.160	0.175	0.026	0.04	0.20	0.35
1011	(HR70-15/B)	0.185	0.195	0.210	0.030	0.04	0.20	0.35
1002	(JR78-15/B)	0.145	0.155	0.170	0.027	0.04	0.20	0.35
1005	(LR78-15/B)	0.145	0.155	0.170	0.028	0.04	0.20	0.35
1006	(LR78-15C)	0.145	0.155	0.170	0.028	0.04	0.20	0.35
1009	(LR78-15/D)	0.145	0.155	0.170	0.028	0.04	0.20	0.35
1012	(NR78-15/D)	0.140	0.150	0.165	0.030	0.04	0.25	0.40

The force and moment properties are measured on a sample of four tires inflated to 28 psi on six inch rims for 78 series tires and seven inch rims for 70 series tires. The 90% confidence intervals on the mean for each measured property must be between the minimum and maximum specified values.

In addition, the cornering coefficients shall have the 90% population limits at a 90% level not less than 0.0007 below the minimum specifications nor greater than 0.0007 above the maximum specification.

Table K-4. Uniformity & Balance

CRITERIA	ACCEPTANCE LEVEL	CORRECTION
UNIFORMITY	ACCEPTANCE	
(Uniformity Procedures per SAE J332		
Radial Force Variation		
1st Harmonic	22 lb Maximum	Correction permissible, with appearance as acceptance criteria
Total (or Composite)	35 lb Maximum	
Lateral Force Variation		
1st Harmonic	25 lb Maximum	
Conitity (or pseudo camber) ± from zero	25 lb Maximum	
BALANCE		
Tire Size		In.-Oz. Maximum
15" (Exc. TPC No. 1010 & 1003)		50
15" (TPC No. 1010 & 1003 only)		46
14"		42
13"		38
PLYSTEER		
All sizes	Positive	

ARMY BASIC CRITERIA FOR TIRES

LTC. Nicholas Collins U.S. Army Transportation School, P.O. Box 4178, Ft. Eustis, Virginia, U.S.A. 23604

The nondirectional cross-country tire, hereinafter referred to as the NDCC tire, was one of the world's first all-season tires. It has been with the U.S. Army, in one form or another, for more than 40 years. In many instances and for certain particular applications, the tire was acceptable. Depending on the specification for it and the quality put into it, the NDCC fulfilled the Army's requirement from the beginning of World War II until about 1958.

During this time frame, the Ordnance Advisory Pneumatic Tire Committee recommended specific design and performance criteria for military tires to the Tire and Rim Association. This committee accomplished many significant improvements and innovations which contributed to enhanced mobility. Its recommendations included variable tire-ground contact pressure, a central tire inflation system, ozone inhibiters to extend storage and operational tire life, single-tire application for wheeledvehicles used in tactical environments, bead-positioning devices for run-flat or highly deflected tire operations, and many others.

For reasons that are unknown, the Ordnance Advisory Pneumatic Tire Committee was terminated in 1958. At that time, the U.S. Army was in somewhat of a holding pattern on new wheeled vehicle developments, and tires just didn't seem to be important as the age of missiles came up over the horizon.

Low-bid procurement procedures without Army performance verification, along with termination of military tire performance criteria, produced some deficiencies. Tire life was reduced because of decreased off-road failure resistance, accelerated on-road tread wear, and decreased on-road ton-mile-per-hour rating at off-highway military tire pressure requirements. By the mid-1960s, the low-cost tire without requirement for performance testing was the order of the day.

In one study done by the U.S. Army Materiel Development and Readiness Command in the early 1970s, it was discovered that a complete tire change was being made on 2-1/2-ton trucks four times in slightly over 17,000 miles. Forty tires for a ten-wheeled truck to go 17,000 miles--with nearly 80% of the travel on highways or secondary roads--was certainly grounds for concern. No self-respecting trucker would accept such performance.

In combat line-haul operations in the late 1960s, tractor-trailer combination drivers were hard put to avoid a single day without changing a tire. In numerous examples, it was found that tires would not last 1,500 miles. New replacement tires, shipped from the manufacturer through depots to the using unit, were no better. Though the Army was buying a low-cost tire, it was absorbing huge losses in tire repairs and replacements as well as in administrative, shipping, and labor costs. And, all this was in addition to the poor mobility performance of these tires in general usage. The poor performance of the NDCC tire in mud, snow, sand, and freezing/thawing soils in comparison to tires being designed and produced today is well known.

There is general agreement that the Army needs to require more in its tires than simply a torus of particular size and nondirectional, cross-country tread pattern, with a valve stem and water-proof valve cap. The low ratio of net tread contact area to gross projected contact area in the NDCC tire was, essentially, designed for off-road interchangeability rather than hard-surface use. This limitation coupled with questionable construction quality has resulted in numerous problems. These include irregular tread wear, fast tread wear, poor hard-surface horizontal slip efficiency, excessive cutting and chipping, excessive hard-surface tread noise, poor tread cleaning in certain saturated soils, and poor interfacial (tire/surface) contact. Another significant problem with NDCC tires is they don't all have similar load deflection characteristics at equal inflation pressures.

Can the U.S. Army then just go out and select a commerical off-highway tire and adapt it to military service? Probably not--for several reasons. Commercial off-highway tires are designed for tire loads which differ significantly in many cases from those required in military applications. Most of these tires are designed for higher pressures than those currently recommended by the Army for critical off-highway mobility in sand, snow, and mud. This drawback is in addition to their overall insufficient cross-country mobility. Another problem is their insufficient cut, chip, and rock resistance. Further, most commerical standard truck rims are rated for highway loads--not necessarily for military off-highway maximum dynamic loads. Finally, there is a severe degradation in performance when commerical off-highway tires are used 70% of the time on the highways.

Where does the U.S. Army go from here? How does it determine which tires will enhance mobility? How does it procure them?

It is a fact that the NDCC tire is outdated and obsolete. It served well in the past and filled the requirement in its day. But, it is generally accepted that a replacement is long overdue. Does the U.S. Army then want a single tire to call its own, manufactured with some type of unique construction and tread which will meet its across-the-board requirements?

It depends on the requirement. The answer might be "yes" for those tactical vehicles primarily used by maneuver battalions or combat and combat support units in the field. But it would definitely be "no" for those vehicles used by combat service support units behind the division rear boundary--where most of the Army's wheeled vehicles will be found.

In either case, the Army needs a tire that will accomplish the mission. This tire must provide the greatest range of optimum mobility, have a reasonable minimum wear life, and be cost effective. Unquestionably, some compromises will be necessary to obtain such a tire.

Users of wheeled military vehicles do not believe that the U.S. Army should attempt to obtain a new tire <u>exclusively</u> for its own use. However, they do want a good operational tire, and they want an effort made toward the optimum tire for every vehicle. Should the U.S. Army specify the design or the performance for this tire or a combination of both? There is considerable belief today that military proponents must primarily specify performance with some minimum specifications for the tire itself.

The major issue is how best to resolve the problem of the NDCC replacement. Over the past 15 years, many studies, forums, discussions, and other interactions have taken place. But the days of meetings without results are fast coming to an end. Costs and other restrictions and the need for performance now require positive action.

Three years ago, a workshop was held on "The Optimum Tire Design Parameters for Military Vehicles." Members of this workshop included representatives from the U.S. Army Training and Doctrine Command, U.S. Army Materiel Development Command, Waterways Experiment Station, Cold Regions Research and Engineering Laboratory, and the U.S. Army Transportation School, as well as test/research organization representatives. For five days, this group hammered out every known facet of tire criteria and performance--and, some that were not known. This group initially established what has come to be known as the Army Basic Criteria for Tires, or ABCT.

One of the additional issues that the workshop tackled was a critical review of the Army Mobility Model, its significance and its shortcomings. It is important to point out a conclusion reached at that workshop: The U.S. Army needs to realistically acknowledge that the Army Mobility Model is not currently viable as a means for ultimate selection of tires for mobility.

Several iterations of the ABCT have been ongoing in the three years since that workshop. Major efforts in tire research and testing have been undertaken, some of which have been reviewed with various members of the International Society for Terrain Vehicle Systems

(ISTVS). Many of these efforts have either confirmed previous enhancements in mobility or have shown the way to new and better enhancements.

The primary results of the workshop on optimum tire design parameters have since been reviewed, restudied, and, finally, reduced to paper form. They are now being presented to the ISTVS Committee on Snow and to representatives of the tire and automotive industry. It is hoped that they will be considered as a proposed method of selecting tires for the U.S. Army.

This method--the Army Basic Criteria for Tires--is a basic program that can be refined over a period of time and intense usage. Original as well as replacement tires could be procured with greater reliability and assurance. Instances of relatively poor performance tires would be negligible while instances of relatively good performers should be the rule. The program requires some basic verification testing and evaluation as well as a verification test whenever a tire characteristic is suspect. However, the lower overall cost to the U.S. Army could be quite nominal while the results should definitely enhance tire reliability and U.S. Army mobility by a significant percentage.

This methodology is a means of selecting commercially available tires suitable for a specific vehicle. It encompasses mission profiles that range from line-haul applications to variable on/off road use, including cross-country and off-road travel in various multi-seasonal regions.

The ABCT is broken down into five distinct areas, or phases, each of which supports the end results as well as complements each of the other four in arriving at the selection basis.

Phase I--Market Survey. A market survey* is conducted based on the following criteria:

a. Tire geometry and size.
b. Load range (specified by the user and approved by the manufacturer).
c. Tread design (nearly all treads could be considered except those obviously created for cosmetic or other unique purposes).

*NOTE: Before conducting the survey, or in conjunction with such survey, a mission profile would be provided for the particular vehicle in question.

Phase II--Manufacturer's Data. This data, based on standard tests, is readily available from the manufacturer and includes:

a. Rim recommendations. (Do the manufacturer's recommendations fill the U.S. Army's requirement for wheels?)
b. Load/deflection/inflation relationships (load-carrying characteristics of a tire related to contact area at various inflation and load levels).
c. Thermal profile (ton-miles/hour) (heat buildup locations and characteristics; design/climate operations).
d. Durability (DOT MVSS 109, 119) or capacity (DOT MVSS 110, 120) test results, depending on tire size (miles, shelf life, ability to cope with operation in non-design environment).
e. Noise (decibel) level (DOT standard)(noise properties).
f. Plunger energy data (static puncture resistance with a standard object).
g. Tube and flap recommendations (that is, if the tire is not tubeless). (While there is a general consensus that bias-ply tires are obsolete, no tire is outside consideration.)

If the manufacturer's data meets the basic minimum requirement established by the U.S. Army (candidate tires would require the manufacturer's certification that they do, in fact, meet the level of data provided), proceed to the next phase.

Phase III--Basic Tire Criteria. Basic tire criteria include the dynamic engineering properties of a tire. Criteria will be based on tests as well as on a tire's compatibility with other tires and with the vehicle's design. Basic criteria will include:

a. Wet pavement mu-slip (tractive force, wet and dry pavement).
b. Cornering power versus slip velocity versus steering demand.
c. Resonant frequency band(s) (the tire's natural frequency of vibration).
d. Dynamic spring rate (engineering response to force application of tire under driving conditions).
e. Damping coefficient (tire's damping response to forces imposed on it which would set up cyclic deformations).
f. Reserve load (ability to handle overloads--similar to a factor of safety).

g. Tire cutting.

h. Tire chipping.

i. Temperature resistance (ability to dissipate heat built up during tire operation).

j. Dynamic road plunger energy (moving variation of static plunger energy).

k. Spin-up velocity.

l. Shore "A" hardness (tread compound hardness).

m. Force variation, radial and lateral (response of tire to single and combined forces and movements).

n. Ozone and storage deterioration resistance.

o. Irregular wear resistance (resistance to irregular wear, including per-tire irregular wear around circumference and from tire to tire within the group of tires manufactured "the same").

p. Dimensional stability (stability against changes in tire's geometry and dimensions during operations).

q. Air migration resistance (loss in air pressure).

After determining that minimums have been met and that there are no associated discrepancies among the various criteria, go to the next phase.

<u>Phase IV--Tire System Mobility Test</u>. Here traction and motion resistance will be measured in the longitudinal axis. All tests are to be conducted in terms of energy-based parameters. The following conditions should govern the test procedures and scope:

a. <u>Tire Conditions</u>.
   1) Manufacturer's recommended deflection (user's specified load).
   2) Thirty-five percent deflection.
   3) Course reference tire comparison required. More than one may be used. The standard NDCC could be used if there is one available in the size being considered. Once a tire has been selected, it could become a course reference tire for future criteria comparisons.

b. <u>Surface Conditions</u>
   1) Road ice.
      a) 23°F ± 5° (at near freezing).
      b) 0°F ± 5° (lower than near freezing).
      c) -25°F ± 5° (optional).

(Item (c) is considered optional because current research indicates that a higher performer in (a) and (b) will follow through at the same comparative level or higher.)

   2) Packed snow.
      a) 28°F ± 5° (slightly below freezing).
      b) 0°F ± 5° (lower than just below freezing).
      c) -25°F ± 5° (optional, for same reasons as previously explained for road ice).
   3) Sand (standard coarse sand).
   4) Mud (saturated clay, for consistent comparison).
   5) Undisturbed snow (Tests would be conducted in four to ten inches of snow. All candidates will be in the same snow depth, under the same conditions, on a firm packed base, and at the same temperatures specified for packed snow. Test areas will be in temperate regions).
   6) Thawing soil layers

(strength properties and documentary data of sand and clay to be measured by standard U.S. Army practices; like properties for snow surfaces to be measured by standard U.S. Army practices).

Upon completion and comparative analysis of this phase, proceed to the fifth and final phase.

<u>Phase V--Accelerated Tire Performance Verification in a Controlled Mission Environment</u>. This phase will provide a final basis for judgment and selection; it will be a basic comparison on a like or similar vehicle under the following parameters:

a. A 5,000-mile "equal energy input" method (same conditions, same surfaces, etc. against the stated mission profile).

b. Waterways Experiment Station (WES) Ride Index Test.

At the completion of each step, candidate tires which show sub-performance may be eliminated. In some tests, tires which were nominated for elimination in the early stages of performance may be included in follow-on phases to have or maintain a comparability relationship and to validate the elimination procedure.

Everyone in the wheeled vehicle business knows that a collection of an engine, transmission, frame, axles, and a body of some type is not a wheeled vehicle without wheels and tires. Tires do make a significant difference. What that difference is and how it affects mobility, reliability, and productivity need positive solution--today.

COMPARISON TEST OF M151A2 TRUCK TIRES

Cpt. Jean W. Lane U.S. Army Cold Regions Test Center, Fort Greely, Alaska,
Presented by: APO Seattle, Washington, U.S.A. 98733
Arthur W. Trantham

ABSTRACT

The Cold Regions Test Center conducted a test comparing four types of tires with the standard military nondirectional cross-country tire currently used on M151A2 1/4-ton trucks. Testing was conducted at Fort Greely, Alaska, from 5 January through 30 May 1981 in temperatures ranging from -13°F to 68°F (-25°C to 20°C). The four alternative types of tires were standard tires recapped with a mud/snow tread, commercial mud/snow tires, and each of the above with studs. None of the four alternative types of tires appeared to have any meaningful advantage in performance over the standard military tire for use on ice, snow, or mud. However, the standard military tires weremore difficult to control on rough, heavily-rutted roads and were not acceptable to drivers, who preferred the commercial mud/snow tires.

SUMMARY

Results

1. Four types of tires were compared with the standard military nondirectional cross-country (NDCC) tire currently used on M151A2 1/4-ton trucks. One type was the standard tire recapped with a mud/snow tread. The second type was a commercial mud/snow tire of the same nominal size as the standard tire. Studded versions of the recapped and commercial tires constituted the third and fourth types. The tires were compared for their performance on road tests, an obstacle course, on measured grades up to 47%, and traversal ofsnow drifts during winter and spring conditions at Fort Greely,Alaska, from 5 January to 30 May 1981.

2. The results are summarized below where the types of tires are ranked

Type of Tire	Overall Ranking: Troop Accept.	Overall Ranking: Handling on Obstacle Course	Overall Ranking: Braking	Specific Ranking: Handling on Ice	Handling on Snow	Braking on Ice	Braking on Snow	Grades	Snow Drifts
Standard military	5	3	2	3	3	1	5	1	5
Military recap	4	1	3	1	2	3	4	3	1
Commerical	1	4	5	5	1	5	3	5	2
Recap with studs	3	2	1	2	4	2	1	2	3
Commercial with studs	2	5	4	4	5	4	2	4	2

from highest to lowest (1 to 5) for troop acceptance on road tests, handling on the obstacle course, braking, climbing grades, and traversal of snow drifts. Differences in performance were small and were consistent with the similar physical characteristics of the various types of tires. However, it was clear that the standard military tires were not considered acceptable by the 172d Infantry Brigade (AK) drivers. Even under controlled conditions, (an experienced NCO regulated vehicle speed according to conditions, ensured the correct use of chains and four-wheel drive, and enforced correct inflation of tires) three serious accidents, much like the accident that led to this test,and 51 other incidents that could have led to accidents, occurred. These incidents were not attributable to any one type of tire.

Conclusions

1. None of the four types of tires compared with the standard tire have any meaningful advantage over the standard tires for use on ice, snow, and mud.

2. Operation of an M151A2, 1/4-ton truck with any of the types of tires evaluated is potentially hazardous when the roads are covered by ice, snow, or mud.

3. The thoroughness of a driver's training and experience appear to have more influence on safety than the type of tire used.

ACKNOWLEDGMENT

The Cold Regions Test Center was responsible for test planning, execution, and reporting. The test team consisted of the following personnel:

CPT Jean W. Lane — Test Officer, CRTC
SFC Larry T. Largent — Test NCOIC, CRTC

Military TDY personnel from 172d Infantry Brigade (AK) are listed below:

SECTION 1 - INTRODUCTION

1.1 Background

a. In the spring of 1980, in the wake of a serious traffic accident, a Quality Deficiency Report (ref 1, Appendix P) prepared by the 172d Infantry Brigade (AK) implied that the standard tire used on M151A2 1/4-ton trucks (jeeps) does not provide the driver with adequate control on icy roads.

b. Road conditions in Alaska during September through May are characterized by accumulations of ice and snow or by muddy conditions due to thawing. Generally low temperatures, high winds, and rugged terrain further complicate the problem of handling a jeep during this period. Therefore, tire performance is of importance for a jeep operated in the cold regions environment.

c. The 172d Infantry Brigade (AK) requested the Cold Regions Test Center (CRTC) to conduct a test comparing the performance of commercial mud/snow tires and military tires recapped with snow treads to the standard tire when used on jeeps operated in the cold regions environment during winter and spring.

d. Authority to conduct this test is contained in a TECOM Test Directive (ref 2, Appendix P).

1.2 Description of material

Five sets of seven tires each were tested. Each of the five tire types (Fig. 64 and 65) is described below:

1) Standard NDCC (A): Military bias ply tire with a nondirectional cross-country tread. Size 7.00-16.

2) Standard NDCC recap w/snow tread(B): Military bias ply tire recapped with a nondirectional cross-country tread modified for snow. It was an A tire with a recap mold. Size 7.00-16.

3) Commercial mud/snow (C): Commerical brand bias ply tire (several types: Dunlop light truck 6.50 × 16, 6

Personnel	Unit	MOS
SP4 David M. Sobol	28th Eng Det	51B10
SP4 Michael J. Evans	DS Det, 172d SPT BN	64C10
PV2 David L. Edging,	Co D, 172d SPT BN,	64C10
PV2 Joel R. Gibson,	Co D, 172d SPT BN,	64C10
PV2 Duane H. Snider,	HHC, Fort Wainwright	64C10

Figure 63. Tire types showing treads. A-standard military tire; B-standard military tire recapped with mud/snow tread; C-commercial mud/snow tire; D-same as B with studs; E-same as C with studs.

ply; BF Goodrich; Mohawk) with a mud/snow tread. Size 7.00-16.

4) <u>Studded standard NDCC recap w/ snow tread (D)</u>: The B tire after modification to accept studs. Size 7.00-16.

5) <u>Studded commercial mud/snow (E)</u>: The C tire with studs. Size 7.00-16.

1.3 Test Objective

Provide performance data comparing the B, C, D, and E tires to the A tires on jeeps operated in winter and spring in cold regions.

1.4 Scope

a. Testing was conducted at Fort Greely, Alaska, during the period 5 January through 30 May 1981.

b. The test team consisted of a test officer, a test NCO in grade E-7, and five soldiers in grades E4/2 (drivers) provided by the 172d Infantry Brigade (AK). In addition, one soldier in grade E4 acted as a substitute driver.

c. Existing roads (primary, improved secondary, and unimproved secondary) were used. In addition, the surface of a frozen lake and the shore of another was used. (Refer to Table N-1, Appendix N for a complete description.)

d. Testing emphasized evaluation of comparative handling characteristics of the different types of tires; however, comparative durability was not evaluated.

e. All participants in the test wore the appropriate components of the cold-dry uniform (Appendix M) and crash helmets.

f. Prior to testing, each jeep was modified by installing roll bars and safety belts with shoulder straps and was technically inspected in accordance with the applicable technical manual (ref 3, Appendix P). Each jeep and trailer were required to meet all equipment serviceability criteria before it was used in testing.

g. At the end of testing, each jeep and each trailer were technically inspected in accordance with the applicable technical manual (ref 3, Appendix P) and all differences between the conditions found and those found prior to testing were documented.

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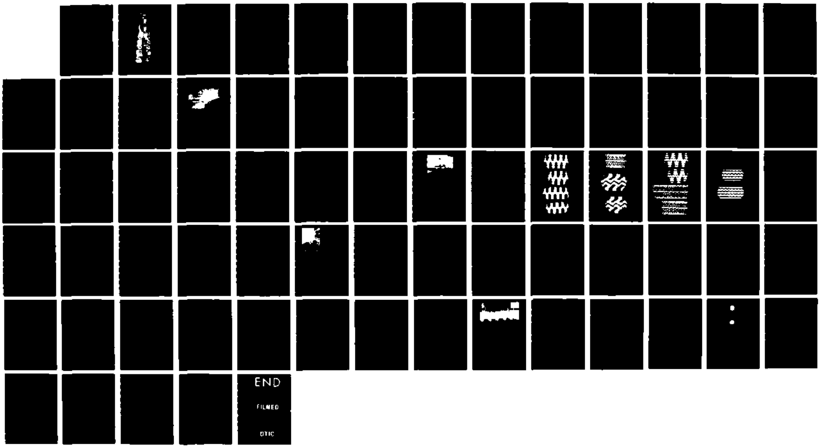
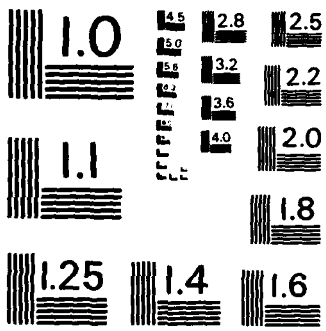




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Figure 65. M151A2 1/4-ton trucks and 1/4-ton trailers with five tire types. From left to right: Types A, B, C, D and E on vehicles numbered 1, 2, 3, 4 and 4, respectively.

h. If any jeep, trailer, or tire appeared to have developed a condition not in accordance with equipment serviceability criteria at any time during testing, the test was stopped until the condition was evaluated, documented, and corrected.

i. Each jeep was operated as indicated in each subtest with one of the loads described below:

(1) Minimum load (MIN): The equivalent of two passengers and gear, not exceeding 500 lb nor less than 400 lb, and no trailer.

(2) Medium load (MED): The equivalent of two passengers and gear, not exceeding 500 lb nor less than 400 lb, and a 1/4-ton trailer with 500 lb load.

j. Each tire was inflated to the pressure as specified by the applicable documents for the specific position of each tire on the vehicle or trailer, the ambient temperature, and the road surface (ref 3, 4, and 5, Appendix P).

k. The Truck, M151A2 (Tire Comparison) Test qualifies for categorical exclusion under Categorical Exclusion Number 6 of DOD Directive 6050.1 and therefore was not required to have an environmental assessment or statement.

l. The 29 road exercises conducted were adequate for analysis.

m. In the spring (after 30 April 1981), only three jeeps and the three unstudded types of tires were used in road exercises due to restrictions by the state of Alaska on the use of studded tires.

n. Each driver was assigned a vehicle and trailer for which he was responsible. Except as noted, a driver did not drive any vehicle or trailer other than that assigned to him. The substitute driver drove the vehicle assigned to the absent driver he replaced.

o. Throughout testing, the following definitions were used and all situations meeting any of these definitions were documented on Driver Data Sheet No. 2 (Fig. N-2, Appendix N).

(1) Handling incident: any event that involved loss of control of a jeep or a trailer during any exercise. The loss of control did not need to be serious or caused by tire performance.

(2) Safety incident: any handling incident that required the filing of an accident report.

(3) Maintenance incident: any event in which a tire was found to require maintenance to include all repairs and a loss of inflation pressure in excess of 5 psi.

(4) Neutral incident: any event that disrupted the flow of testing but was not a handling, safety, or maintenance incident (i.e., the break-down of a vehicle during an exercise due to wear of a part).

p. Documentation of maintenance incidents included tire identification (by type and position on the vehicle or trailer) and a description of the repair.

q. All temperatures encountered, -13°F to 68°F (-25°C to 20°C), were used for testing and those in climatic design C1 of AR70-38. Road conditions were those commonly encountered by the 172d Infantry Brigade (AK) during maneuvers in the winter and spring.

r. Ambient air temperature, road surface temperature, windspeed, and wind direction were measured during testing using the following instruments:

(1) Dial thermometer.

(2) Wind measuring set AN/PMQ-3A.

s. Precipitation measurements were obtained from the ASL Alaska Meteorological Team and compared with recorded subjective descriptions of precipitation.

t. At the beginning of testing, each tire of a set was assigned to one of seven positions on a vehicle/trailer - left front, right front, left rear, right rear, left trailer, right trailer, and spare. Throughout testing, when tires were exchanged between vehicles, they were exchanged as sets so that the tire in a given position on one vehicle/trailer was always moved to the same position on the second vehicle/trailer - left front to left front, right front to right front, etc.

u. The test items will be returned to the 172d Infantry Brigade (AK).

v. MTP 2-2-704 (ref 5, Appendix P), was used as a guide in testing procedures.

w. Eleven of the scheduled road exercises were not performed due to the conclusion of state troopers and test personnel investigating safety incidents that they would be too hazardous for the drivers and the public.

x. Three of the scheduled traction exercises were not performed due to lack of suitable snow drifts.

SECTION 2 - DETAILS OF TEST

2.1 Preoperational inspection

2.1.1 Objective

Determine the condition of all tires prior to the beginning of testing.

2.1.2 Criteria

None.

2.1.3 Data acquisition procedure

a. Upon receipt, all tires were inspected in accordance with paragraph 6.1 of MTP 2-2-704 (ref 5, Appendix P).

b. The tire condition was determined in accordance with TM 9-2610-201-14 (ref 6, Appendix P) and one tire condition sheet (Fig. N-8, Appendix N) was completed for each tire.

c. Since each tire was to be used in one position on a vehicle or trailer throughout testing, tires were identified by type and fixed position by painting a three letter code for the type and position on each tire. (The five possible types and their codes are defined in paragraph 1.2. The seven possible positions and their codes are noted in paragraph 1.4t. Type A mounted in the right front position on a jeep was labeled "ARF").

d. Identification photographs were taken of each tire. One photograph showed the tire alone and a second photograph showed the tire as mounted on the vehicle or trailer. Additionally, an identification photograph was taken showing the typical operational configuration; this photograph showed the vehicle and trailer with test tires and a MED load.

e. Defects in tire condition were documented by photographing the specific conditions found and entering a description on the tire condition sheet.

2.1.4 Results

a. Detailed measurements are given in Table L-1, Appendix L. The definitions of tire width, diameter, and perimeter are those provided by MTP 2-2-704 (ref 5, Appendix P).

b. It was found that the most important differences between type A tires and the comparison tires were in physical characteristics. In particular, types B, C, D, and E had contact areas per tire within 4 square inches of each other, but were all greater than that of type A by 8 to 12 square inches, with type E having the greatest difference.

c. The only defects found were superficial abrasions in the sidewalls of the type B tires.

2.1.5 Analysis

a. All tires were judged to be in satisfactory condition for testing as only superficial defects were found.

b. The physical differences between type A tires and the comparison tires could be expected to result in a maximum of 5 percent better traction for tires of type A as compared to tires of type E on smooth surfaces, and a maximum of 5 percent better flotation for tires of type E as compared to tires of type A on soft surfaces such as fresh snow or mud. (Refer to calculation of differences in the pressure exerted by a tire on a surface as a function of weight and contact area of the tire, paragraph 2, Appendix O.)

2.2 Handling

2.2.1 Objective

Compare effects of each type of tire on the maneuverability of a jeep.

2.2.2 Criteria

None.

2.2.3 Data acquisition procedure

a. Twenty-nine road exercises and two obstacle course exercises were performed.

b. A road exercise consisted of all vehicles driving (in convoy) a road selected from the nine roads listed in Table N-1, Appendix N.

(1) Each exercise was conducted on one of three road types: primary (9 exercises), improved secondary (10 exercises), or unimproved secondary (10 exercises). Route selections were made by considering conditions likely to be encountered on each possible road. Tires were exchanged between vehicles as a set (each tire retaining its position) in accordance with Table 10 for the next available exercise corresponding to the road type selected.

(2) The order of vehicles in convoy remained fixed throughout the test.

(3) Each exercise began with the completion of relevant portions of Driver Data Sheet No. 1 by each driver and Master Data Sheet No. 1 by the test NCO (Fig. N-1 and N-4, respectively, Appendix N).

(4) During each exercise the vehicle speed and distance traveled were controlled by the test NCO and recorded by a tachograph installed in the lead vehicle. All incidents (as defined by paragraph 1.4o) were recorded on Driver Data Sheet No. 2 (Fig. N-2, Appendix N).

(5) In accordance with the safety SOP, the test NCO determined when tire chains, changes in tire inflation pressure, or four-wheel drive were used. Only those vehicles that required the use of tire chains or four-wheel drive used

TABLE 10. Tires Assigned to Vehicles for Road Exercises[1]

Exercise Number	Type of Tire[2] on Vehicle No. 1	2	3	4	5	Exercise Number	Type of Tire[2] on Vehicle No. 1	2	3	4	5
1	E	A	C	B	D[3]	16	N	A	B	N	C
2	D	E	B	A	C	17	N	B	C	N	A
3	C	D	A	E	B	18	N	C	A	N	B
4	A	B	D	C	E	19	N	B	C	N	A
5	B	C	E	D	A	20	B	A	D	E	C
6	B	E	A	C	D	21	A	E	C	D[3]	B
7	E	C	D	A	B	22	D	C	A	B	E
8	C	A	B	D	E	23	E	D	B	C	A
9	A	D	E	B	C	24	C	B	E	A	D
10	E	B	A	D	C	25	N	B	A	N	C
11	D	A	E	C	B	26	N	C	B	N	A
12	C	E	D	B	A	27	N	A	C	N	B
13	B	D	C	A	E	28	N	B	A	N	C
14	A	C	B	E	D	29	N	C	B	N	A
15	D	E	B	A	C						

[1]Exercises 1 through 9 were performed on primary roads; exercises 10 through 19 were performed on improved secondary roads; and exercises 20 through 29 were performed on unimproved secondary roads. For each type of road, exercises were conducted in numerical order.

[2]Tire types are given as defined in paragraph 1.2. Thus "A" is the set of standard NDCC tires, etc., and "N" indicates vehicle not driven due to restrictions on use of studded tires in spring.

[3]Neutral incidents involving vehicle malfunction prevented type D from being evaluated in exercises 1 and 21.

them and these requirements were recorded as handling incidents on Driver Data Sheet No. 2 (Fig. N-2, Appendix N).

(6) At the midpoint of each exercise, the relevant portions of Driver Data Sheet No. 3 (Fig. N-3, Appendix N) was completed by the drivers and the test NCO continued to complete Master Data Sheet No. 1 (Fig. N-4, Appendix N).

(7) At the end of each exercise, each driver completed relevant portions of Driver Data Sheets No. 1 and 3 (Fig. N-1 and N-3, Appendix N); the test NCO collected and inspected all Driver Data Sheets and completed the rest of Master Data Sheet No. 1 (Fig. N-4, Appendix N). The most important item was the driver's rating of tire overall performance and for each of eight maneuvers (turning, climbing, descending, driving on straight flat areas, driving over bumps, driving over soft spots, and driving over slick spots) on a scale of 1 to 6 where 6 was the highest possible rating. (Ratings from 1 to 6 by the drivers compared one specific type of tire to the driver's personal standard for tire performance and are not to be confused with rankings from 1 to 5 of the five types of tires derived by comparing the performances or ratings of each tire with those of the other tires.)

(8) MED vehicle loads were used for primary and improved secondary roads and MIN vehicle loads were used for unimproved secondary roads.

c. An obstacle course exercise consisted of five vehicles, each with a different type of tire, being driven by the test NCO over the obstacle course (shown in Fig. 66) at 5, 10, 15, 20, and 25 miles per hour.

(1) One exercise was conducted on an ice surface and the other on a packed snow surface (roads no. 10 and 11, respectively, Table N-1, Appendix N). There was no precipitation, windspeeds were less than 5 knots, it was bright daylight, and the road surface temperature did not change more than 4°F (2°C).

(2) For each exercise, the relevant portions of Master Data Sheets No.

Total length from start to end was 0.56 mile; the nine obstacles were, in order driven:

Type Turn	Turn Radius (Meters)	Turn Direction
Quarter	35	Left
Quarter	35	Right
Quarter	30	Left
Quarter	30	Right
Quarter	25	Left
Quarter	25	Right
Quarter	20	Left
Quarter	20	Right
Circular	35	Right

Connecting lengths are 131 feet (4 meters)
Roadway is 13 feet wide (40 meters)

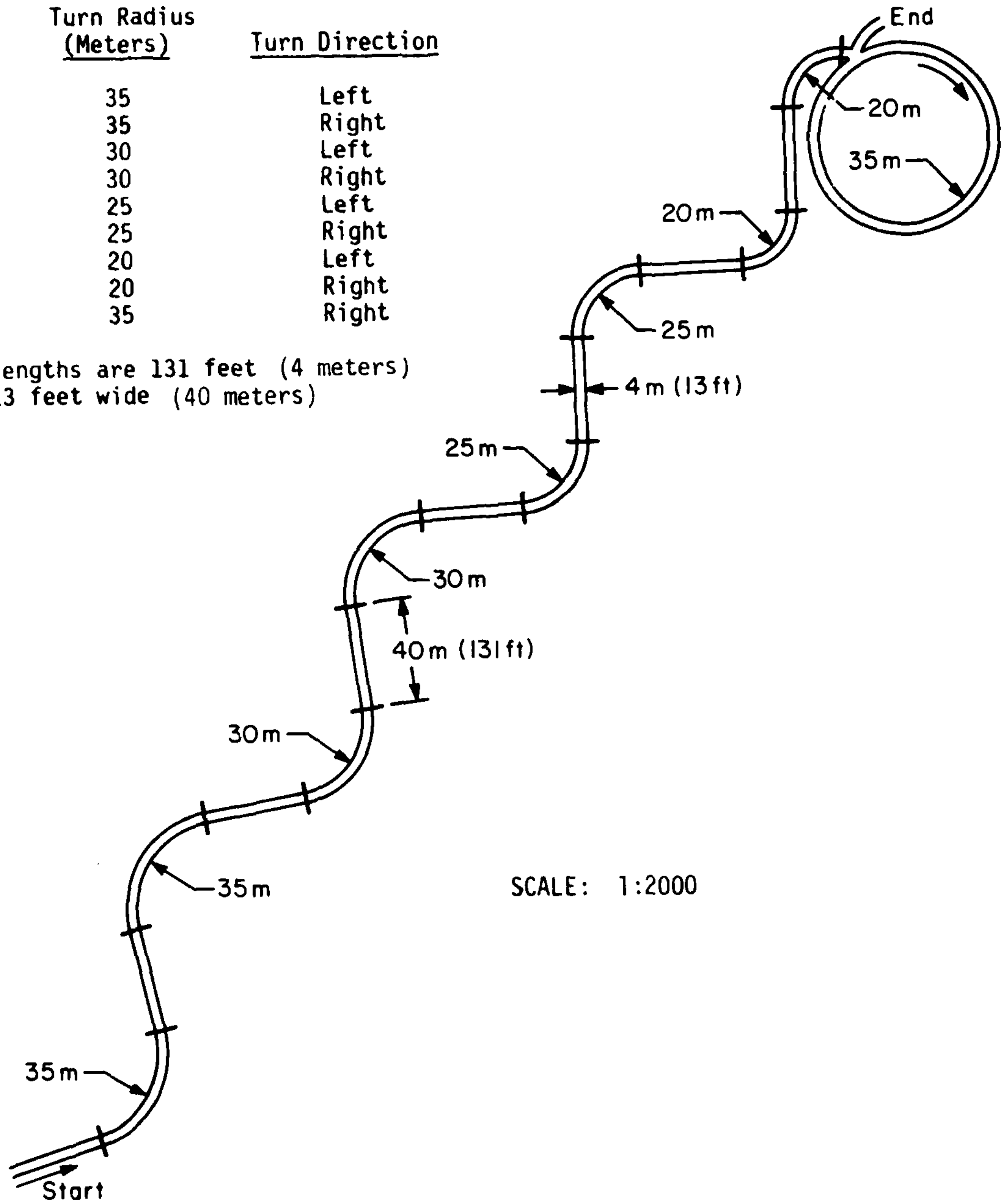


Figure 66. Obstacle course configuration.

1 and 2 were completed (Fig. N-1 and N-2, Appendix N).

(3) Chains were not used.

(4) The MIN vehicle load was used.

(5) Each type of tire was driven through the obstacle course beginning with the lowest speed and using two-wheel drive until any two of the vehicle's wheels left the roadway. The driver stopped at this point and the percentage of the course completed for the particular speed was noted. The course was attempted again at the same speed with the same tires but using four-wheel drive and the results noted. At this point, a different set of tires was selected and the procedure repeated.

(6) An evaluator riding in the passenger's seat of the vehicle and an evaluator observing from outside the vehicle scored the performance in navigat-

ing each obstacle at each speed by noting whether maneuvering problems--skids, fishtailing, or minor contact with roadway markers--occurred.

(a) A skid was defined as when the vehicle slid in one direction against the desire of the driver but did not leave the roadway.

(b) Fishtailing was defined as the vehicle swerving back and forth briefly across the roadway but not leaving the roadway.

(c) Minor contact with markers was defined as the vehicle contacting a marker, but not leaving the roadway.

(d) Whenever two or more wheels left the roadway, the vehicle was considered to have left the roadway.

(7) The vehicle speed was controlled by placing a block under the accelerator pedal and setting the throttle adjustment on the carburetor for the necessary engine speed. The vehicle speed did not vary more than 2 miles per hour (3 kph) from the set speed.

2.2.4 Results

a. The data collected for the road exercises is summarized in Tables 11, 12, and 13.

b. The seven drivers (including the substitute driver and the test NCO who drove when the regular drivers were not available) tended to rate tire performance differently. Some drivers gave higher ratings than others. (Note the overall ratings shown in Table 12 for the five regular driver.) To adjust for these rating differences, in the way drivers rated, the mean rating given by each driver was subtracted from each individual rating* before the ratings were compared.

c. For each of the 29 road exercises, the adjusted ratings were ranked from 1 to 5 (highest to lowest). Figure 67 shows the average ranks for each type of tire by maneuver and the point in the exercise (mid or end) when an evaluation was made by the drivers. (Figure L-1, Appendix L shows the distribution of the

Table 11. Mileages for road exercises by type of tire and road conditions.

Tire Type	Total Miles Driven in Convoy	Total Miles Driven in Convoy on Given Surface		
		Dry Road	Fresh Snow/Mud	Packed Snow/Mud
A	1313	419.5	500	393.5
B	1263	369.5	500	393.5
C	1313	419.5	500	393.5
D	1041	326.5	334	380.5
E	1155	326.5	435	393.5

Table 12. Average overall ratings by driver (only regular drivers considered) for each type of tire. Rating scale 1 to 6 (lowest to highest performance.

Tire Type	Average Rating Given by Driver Number				
	1	2	3	4	5
A	4.0	4.0	4.1	3.6	3.9
B	5.25	5.3	4.0	3.7	3.8
C	5.0	5.4	5.7	5.0	4.9
D	5.0	5.3	3.7	4.3	4.0
E	5.7	4.8	5.0	5.0	5.0

*A more detailed method of adjustment led to the same ranks as the method used.

Table 13. Incidents by type of tire and classification of incident.

Tire Type	Number of Incidents of Classification: Handling[1] All Types Of Tires Tested	Handling[1] Only Unstudded Types of Tires Tested	Safety[2]	Maintenance[3]	Neutral[4]
A	12	4	1	1	0
B	9	8	1	2	1
C	7	2	1	0	0
D	7	---	0	0	2
E	5	---	0	1	0

[1]Temporary loss of control of vehicle or trailer.
[2]A handling incident that ended in a reportable accident.
[3]An incident requiring maintenance on a tire.
[4]An incident that interrupted testing but was not a handling, safety, or maintenance incident.

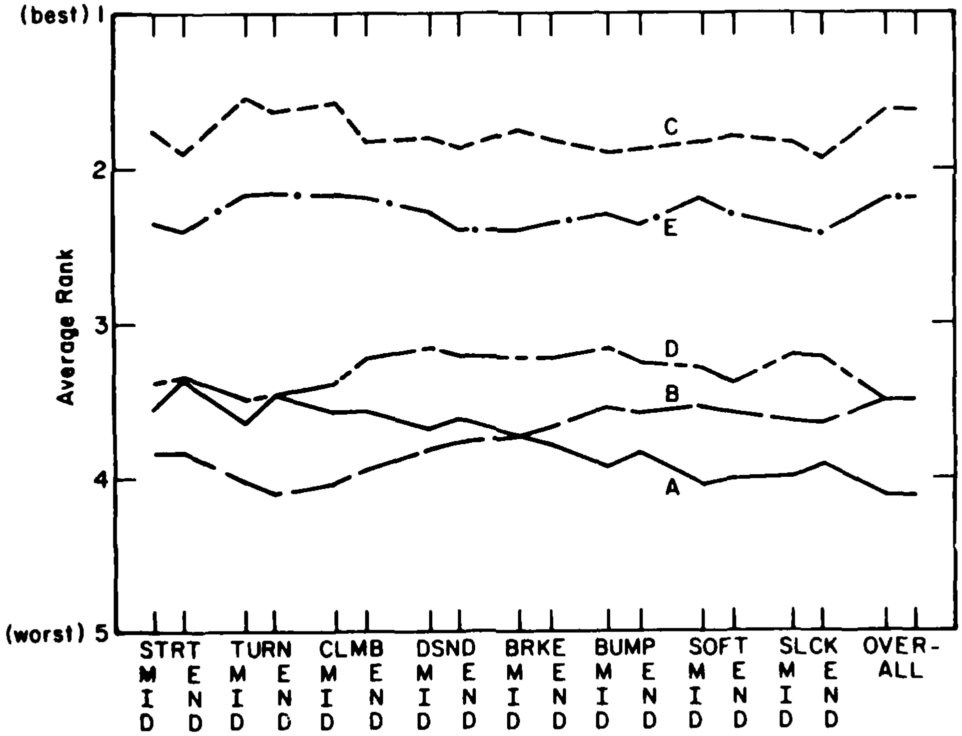


Figure 67. Average rank for each type of tire by maneuver and point in exercise when evaluation was made by drivers. Rank gives relative performance rating of the five types of tires with 1 to 5 (highest to lowest). Maneuvers were: driving on straight flat area (STRT), turning (TURN), climbing (CLMB), descending (DSND), braking (BRKE), driving over bumps (BUMP), driving over soft spots (SOFT), and driving over slick spots (SLCK).

ranks for the overall ratings by exercise and is similar to the distributions for each of the maneuvers.)

d. The data collected for the obstacle course exercise is summarized in Tables 14 and 15. For each type of tire and each exercise, tire performance was scored in two different ways. The first method was by the percentage of the course completed at each speed. The second method subtracted up to half the distance of travel for each obstacle where the vehicle was observed to have maneuvering problems--skids, fishtailing, or contact with the markers. Since there were nine obstacles and it was possible to complete the course and have all three maneuvering problems in each obstacle, the total number of maneuvering problems possible for a run was 27; thus the percentage score was defined as follows for each run through the obstacle course:

Percent Score =
Percent Completion $-[(50/27) \times$ (Total Number of Maneuver Problems)].

In the tables, the percent of completion and the score (percent) are shown for each run and averaged for each tire.

2.2.5 Analysis

a. For the road exercises, it was concluded that the drivers strongly preferred either of the commercial types of tires to any of the military types of tires.

(1) Ranks for overall performance as shown in Figure 67 were analyzed using a multiple comparison test based on Friedman rank sums. Details are given in Table L-3, Appendix L.

(2) It was determined that while the differences in ranking between types C and E and types A, B, or D were statistically significant, neither the difference between type C and type E nor any of the differences between types A, B, and D were statistically significant.

b. The apparent difference in number of handling incidents for each type of tire in Table 13 is misleading. Statistical analysis indicated that these differences can be explained by differences in drivers and numbers of exercises in which a type of tire was evaluated. Once these factors were taken into account, the differences in number of handling incidents between the tire types was not statistically significant. A detailed breakdown of handling incidents by driver and road conditions is given in Table L-4, Appendix L and details of the statistical analysis are given in Table L-5, Appendix L.

c. The data for the obstacle course exercises (Tables 14 and 15) may be used to rank the performance of the types of tires by average percentage of completion and the average score; that is, the ability of the driver to drive through the course with a certain type of tire without leaving the roadway and without skidding, fishtailing, or coming into contact with the roadway markers. These rankings are shown in Table 16.

(1) Except for type A on snow, a tendency to have maneuvering problems led to failure to complete the course. Tires of type A, because of their smaller contact area and narrower width, tended to interact strongly with minor irregularities in the road surface. They were associated with the only instance in which a maneuvering problem occurred at the lowest speed on the easiest obstacle (Table 15, type A, 5 mph, 35 meter right-hand turn). The vehicle skidded when the front tires encountered ruts in the snow that could not be felt when riding on the other types of tires.

(2) No improvement in maneuverability when using studs was observed in this test.

(3) When performance on both ice and snow is averaged for an overall winter performance ranking, the three military types of tires (A, B, and D) outrank both the commercial types of tires (C and E), but the differences in performance are not sufficient to justify the conclusion that military tires are superior.

e. It is clear that the three tire types ranking highest in obstacle course exercises are the same tires that ranked lowest in the evaluations made by the drivers, and for which the most handling incidents occurred. This apparent lack of agreement will be discussed further in paragraph 2.4.

2.3 Traction

2.3.1 Objective

Compare the effects of each type of tire on a jeep's ability to traverse undisturbed snow, braking distance for a jeep being driven on packed snow or ice, and a jeep's ability to climb grades on wet, packed dirt.

2.3.2 Criteria

None.

Table 14. Data for obstacle course exercise on ice.*

		Number of Observed Maneuver Problems for Obstacle (Skids, Fishtailing, and/or Marker Contact)											Average	
Tire Type	Speed (mph)	35M Left	35M Right	30M Left	30M Right	25M Left	25M Right	20M Left	20M Right	Circle	Percent Completed	Percent Score	Percent Completed	Percent Score
A	5	0	0	0	0	0	0	0	0	0	100	100		
	10	0	0	0	0	0	0	0	0	0	100	100		
	15	0	0	0	0	0	0	0	0	0	100	100	73	69.7
	20	0	0	0	1	1	-	-	-	-	48	44		
	20**	0	0	0	0	2	2	1	1	3	91	74		
	25	-	-	-	-	-	-	-	-	-	0	0		
B	5	0	0	0	0	0	0	0	0	0	100	100		
	10	0	1	0	0	1	0	0	0	0	100	96		
	15	0	1	0	0	2	0	1	1	0	100	91	82	72.3
	20	1	1	1	1	1	2	2	1	3	95	71		
	20**	1	1	0	0	2	1	1	2	2	95	76		
	25	-	-	-	-	-	-	-	-	-	0	0		
C	5	0	0	0	0	0	0	0	0	0	100	100		
	10	0	0	0	0	0	0	0	0	0	100	100		
	15	0	0	0	0	0	0	0	1	2	100	94	64	61
	20	0	1	1	1	-	-	-	-	-	38.5	33		
	20**	0	1	1	1	2	-	-	-	-	48	39		
	25	-	-	-	-	-	-	-	-	-	0	0		
D	5	0	0	0	0	0	0	0	0	0	100	100		
	10	0	0	0	0	0	0	0	0	0	100	100		
	15	0	0	0	1	0	1	0	0	0	100	96	77	71.5
	20	0	1	1	0	1	1	1	1	2	81	66		
	20**	0	0	1	0	1	1	0	2	2	80	67		
	25	-	-	-	-	-	-	-	-	-	0	0		
E	5	0	0	0	0	0	0	0	0	0	100	100		
	10	0	0	0	0	0	0	0	0	0	100	100		
	15	0	1	0	0	0	1	0	1	1	100	92.5	76.5	68
	20	1	0	1	1	1	3	2	2	2	77	53		
	20**	0	1	0	0	1	2	2	1	2	82	65		
	25	-	-	-	-	-	-	-	-	-	0	0		

*Course surface consisted of the surface of a frozen lake covered by a 0.25-inch layer of rough ice formed by spraying water over the surface and allowing it to freeze. Surface temperature was 20°F (-7°C).
**Driven in four-wheel drive; all others driven in two-wheel drive.

Table 15. Data for obstacle course exercise on snow.*

Tire Type	Speed (mph)	Number of Observed Maneuver Problems for Obstacle (Skids, Fishtailing, and/or Marker Contact) 35M Left	35M Right	30M Left	30M Right	25M Left	25M Right	20M Left	20M Right	Circle	Percent Completed	Percent Score	Average Percent Completed	Average Percent Score
A	5	0	1	0	0	1	0	1	0	0	100	94		
	10	0	0	1	0	0	0	0	0	0	100	98		
	15	0	0	1	1	2	0	1	0	0	100	91	89	81.2
	20	0	0	0	0	1	0	0	0	1	100	96		
	25	0	1	1	1	1	3	-	-	-	55	42		
	25**	0	1	1	0	1	2	0	0	3	81	66		
B	5	0	0	0	0	0	0	0	0	0	100	100		
	10	0	0	0	0	0	0	0	0	0	100	100		
	15	0	0	1	0	1	0	0	0	0	100	96	87	84
	20	0	1	0	0	1	0	0	1	0	100	94		
	25	0	0	0	0	0	0	0	0	3	78	72		
	25**	0	0	0	0	2	-	-	-	-	46	42		
C	5	0	0	0	0	0	0	0	0	0	100	100		
	10	0	0	0	0	0	0	0	0	0	100	100		
	15	0	0	0	0	0	0	0	0	0	100	100	90.5	86
	20	0	0	0	1	1	0	0	0	1	100	94		
	25	0	1	0	1	1	1	2	-	-	65	54		
	25**	0	1	0	0	1	0	0	1	2	78	69		
D	5	0	0	0	0	0	0	0	0	0	100	100		
	10	0	0	0	0	0	0	0	0	0	100	100		
	15	0	0	0	0	0	0	0	0	0	100	100	83	80.9
	20	0	0	0	1	0	0	0	0	0	100	98		
	25	0	1	0	1	1	1	-	-	-	54	46.5		
	25**	0	0	0	0	2	-	-	-	-	45	41		
E	5	0	0	0	0	0	0	0	0	0	100	100		
	10	0	0	0	0	0	0	0	0	0	100	100		
	15	0	0	0	0	0	1	1	0	0	100	96	76	73
	20	0	0	1	1	1	2	-	-	-	55	46		
	20**	0	0	0	0	0	0	-	1	1	100	96		
	25	-	-	-	-	-	-	-	-	-	0	0		

*Course surface consisted of the surface of a frozen lake covered by 2 inches of old packed and loose snow. Surface temperatures were 0°F to -4°F (-18°C to -20°C).

**Driven in four-wheel drive; all others driven in two-wheel drive.

Table 16. Ranking of tire performance on obstacle course exercises by average percent score* and average percent course completion.

Comparative Ranking	Ice: By Percent Score	Ice: By Percent Completion	Snow: By Percent Score	Snow: By Percent Completion
1	B = 72	B = 82	C = 86	C = 90.5
2	D = 71.5	D = 77	B = 84	A = 89
3	A = 70	E = 76.5	A = 81.2	B = 87
4	E = 68	A = 73	D = 80.9	D = 83
5	C = 61	C = 64	E = 73	E = 76

Comparative Ranking	Overall Winter Performance: By Percent Score	Overall Winter Performance: By Percent Completion
.	B = 78	B = 84.5
2	D = 76.2	A = 81
3	A = 75.6	D = 80
4	C = 73.5	C = 77.25
5	E = 70.5	E = 76.25

*Percent Score = (Percent Completion) - ((50/27) x (No. Maneuver Problems)).

2.3.3 Data acquisition procedure

a. Two traction exercises, two braking exercises, and one grade exercise were performed.

b. A traction exercise consisted of all vehicles traversing a straight path through undisturbed snow until they were unable to proceed further (road no. 12, Table N-1, Appendix N).

(1) Chains were not used.

(2) The MIN vehicle load was used.

(3) Each vehicle began from a stationary position with the engine at correct operating temperatures and pressures.

(4) All five vehicles were driven by the same driver (the test NCO).

(5) The relevant portions of Master Data Sheets No. 1 and 3 (Fig. N-4 and N-6, Appendix N) were completed.

c. A braking exercise consisted of a vehicle (using each of the five tire types) accelerating to a speed of 15 miles per hour while driving on one of two roads (roads no. 10 and 11, Table N-1, Appendix N), the driver firmly braking on command, and the vehicle coming to a full stop. Each braking exercise was conducted four times for a total of 40 trials.

(1) Chains were not used.

(2) The MIN vehicle load was used.

(3) Vehicle speed was controlled and recorded as for the obstacle course.

(4) The braking distance was measured by marking the braking point and measuring with a steel tape measure. The braking distance was considered as the distance between the marker and the final position of the vehicle's rear tires.

(5) The relevant portions of Driver Data Sheet No. 1 and Master Data Sheets No. 1 and 3 (Fig. N-1, N-4, and N-6, Appendix N) were completed.

c. A grade exercise consisted of all vehicles, each with a different type of tire and each driven by the test NCO attempting to climb, successively, grades of 31, 38, and 47 percent slope.

(1) Chains were not used.

(2) The MIN vehicle load was used.

(3) The vehicle began climbing

from a level space at the foot of each grade in first gear and never exceeded a speed of 15 miles per hour.

(4) Each grade was attempted in two-wheel drive. If a grade could not be climbed in two-wheel drive, the percent of the grade completed was noted and another attempt was made in four-wheel drive. At this point, the next vehicle and type of tire was tested.

(5) The vehicle and first type of tire tested was retested at the midpoint of the exercise and again after all vehicles and types of tires had been tested to ensure that the surfaces of the grades had not sufficiently changed by successive trials to alter the results.

(6) The surfaces of the grades were compacted fine-grained silt with small amounts of clay and little or no organic content at or above optimum moisture content for compaction as defined in FM 5-34 (ref 7, Appendix P).

2.3.4 Results

Data are given in Tables 17, 18, and 19.

2.3.5 Analysis

a. On the basis of contact area (Table L-1, Appendix L), the types of tires would have been expected to have ranked in inverse order of their contact area for braking and climbing grades and in order of their contact area for traversing snow drifts (Appendix O). The degree to which this was observed indicates the relative effects of the contact area and other physical characteristics such as tread design. The actual rankings observed are compared with those to be expected from contact area below:

	Task	Actual rank (12345)	Expected rank from contact area (12345)
(1)	Braking	DABEC	ADBCE
(2)	Climbing grades	ADBEC	ADBCE
(3)	Snow drifts	BCEDA (C=E)	ECBDA

b. For unstudded tires (types A, B, and C) the contact area appeared to determine the results for braking and climbing while other characteristics determined the results for traversing snow drifts. Studded tires (types D and E compared to types B and C) appear to of-

Table 17. Data from traction exercise.*

Tire Type	Rank	Average Maximum Depth of Snow Traversed (Inches)
A	5	9.6
B	1	12.75
C	2	12.0
D	3	10.5
E	2	12.0

*The test tracks were parallel incursions into a wedge shaped snow drift. The snow drift varied in depth from 0 to 17 inches and consisted of a single layer of old, dry snow.

Table 18. Data from braking exercise.

	Winter		Ice*		Snow**	
Tire Type	Rank	Average Braking Distance (Feet)	Rank	Average Braking Distance (Feet)	Rank	Average Braking Distance (Feet)
A	2	56.05	1	63.6	5	48.5
B	3	56.95	3	67.1	4	46.8
C	5	60.95	5	75.7	3	46.2
D	1	49.75	2	65.4	1	34.1
E	4	57.8	4	70.1	2	45.5

*Surface consisted of a frozen lake at a surface temperature of 20°F (-7°C).
**Surface consisted of 2 inches of old packed and loose snow over ice at temperatures of 0°F to -4°F (-18°C to -20°C).

Table 19. Data from grade exercise.[1]

Tire Type	Percent Slope	Percent Completion
A[2]	31	100
	38	100
	47	71
Four-Wheel[3]	47	100
B	31	100
	38	100
	47	64
Four-Wheel	47	100
C	31	100
	38	81
Four-Wheel	38	100
	38	0
D	31	100
	38	100
	47	65
Four-Wheel	47	100
E	31	100
	38	90
	38	100
Four-Wheel	47	0

[1]Surface of grades consisted of compacted fine-grained silt with a small amount of clay and no detectable organic content at or above optimum moisture content for compaction.
[2]The exercise was repeated three times with type A with the same results.
[3]Two-wheel drive was used except where noted.

fer an advantage for braking and climbing but not for traversing snow drifts.

2.4 Subjective evaluation

2.4.1 Objective

Determine comparative degree of drivers' acceptance of each type of tire.

2.4.2 Criteria

None.

2.4.3 Data acquistion procedure

a. Each driver received 24 hours of instruction before participating in testing. This instruction consisted of:

(1) Data acquisition procedure - 8 hours.

(2) Maintenance, safety, and testing SOP - 8 hours.

(3) Practical exercise - 8 hours.

b. Each driver maintained a daily log recording his portion of the relevant data to include results of operator's maintenance checks and subjective evaluations of road conditions and tire performance. (Driver Data Sheets No. 1, 2, and 3, Fig. N-1, N-2, and N-3, respectively, Appendix N).

c. Each driver was encouraged to concentrate on evaluating the performance of the particular type of tires installed on his vehicle at any given time. By the end of every 5 days of testing, each driver had driven his assigned vehicle with each type of tire. Each driver kept a record of his continuing subjective evaluation of each type of tire. (Driver Data Sheet No. 3, Fig. N-3, Appendix N).

d. At the end of testing, each regular driver spent a 4-hour period completing the Human Factors Evaluation Booklet (Fig. N-7, Appendix N). He was to compute the average of all the ratings he had given each type of tire during road exercises, rank the types of tires by this result, and then compute the number of handling incidents he had experienced with each type of tire. In addition, he was to consider the type of weather and road conditions encountered with each type of tire. He was then asked to make a final ranking that reflected his best judgment as to the relative performance of the tire types.

Table 20. Driver's final evaluation compared to their evaluation during road exercises by type of tire.

Driver Number*	Rank from Road Exercises/Rank in Final Evaluation For Tire Types: A	B	C	D	E
1	5/5	2/3	4/2	3/1	1/4
2	5/5	2/3	1/1	3/4	4/2
3	3/5	2/4	1/2	5/3	2/1
4	5/3	2/5	1/1	3/2	2/4
5	4/5	5/4	2/2	3/3	1/1
All	5/5	3/4	1/1	4/3	2/2

*Only the five regular drivers are included.

Table 21. Comparison of number of incidents experienced by each driver with the rank the driver gave the type of tire in his final evaluation.

Driver	Handling Incidents While Driving With Type					Type With Incidents		Type Rank	
Number**	A	B	C	D	E	Least	Most	Highest	Lowest
1	4*	1	1*	2	0	E	A	D	A
2	2	2	2	0	2	D	ABCE	C	A
3	5	11	3	2	1	E	B	E	A
4	4	1*	0	3	2	C	A	C	B
5	0	2	3	0	0	ADE	C	E	A

*Includes one safety incident.
**Only five regular drivers are included.

2.4.4 Results

a. The comparison between the drivers' average ratings on road exercises and how they finally judged and ranked the tire types is given in Table 20.

b. Before final ranking judgments were made on the tire types, the drivers considered the number of incidents they had experienced with each type of tires. Table 21 compares the number of incidents with the final rank of each type of tire for each driver.

c. The drivers complained the most about tires of type A, which were described by all drivers as having a tendency to skid on ruts and become stuck in soft spots. The most common complaint about tires of types C and E was that they "threw rocks."

2.4.5 Analysis

a. The subjective evaluations of the five regular drivers appear to disagree with the evaluations of the relative performance of the types of tires in exercises other than the road exercises. Despite the fact that tires of types A, B, and D appear to be at least as good or better performers than tires of types C and E, the perception of the drivers is that types C and E out perform types A, B, and D.

b. From the comments of each driver, it appears that each felt less confident of his ability to handle his vehicle with tires of type A than any of the other types of tires. There is evidence from the obstacle course exercises (paragraph 2.2.5c(1)) to support the drivers' perceptions of type A. The very characteristic that gives these tires increased traction also makes them interact strongly with irregularities (such as ruts or soft spots) in the surface of the road. An inexperienced driver could find this interaction difficult to control and feel less confident of his ability to drive with these tires than those of larger contact area and less open tread design. Since the differences in contact area between the tires could have been expected to account for no more than a 5 percent difference in traction or flotation, the difference in detailed control of the tire's interaction with irregularities in the surface could easily have outweighed any perception of a difference in traction.

c. Although not tested, the use of radial tires might be expected to enhance smooth tracking, give drivers a more secure "feel" of the road, and overcome some of the objections to the standard military tire.

d. There is statistical evidence that differences between the drivers were more important in producing the differences in handling incidents among the types of tires than the actual characteristics of the tires (paragraph 2.2.5b). This, together with the discussion in the preceding paragraphs, implies that, while none of the types of tires evaluated is sufficiently different from type A to be considered a decisive improvement, type A is not accepted as an adequate tire by the soldiers who drove the jeeps.

2.5 Safety evaluation

2.5.1 Objective

Determine if any of the types of tires are hazardous to use under road and weather conditions common to cold regions (winter and spring seasons).

2.5.2 Criteria

None.

2.5.3 Data acquisition procedure

a. Before testing, each driver was familiarized with safety equipment and safety requirements.

b. Each driver recorded in a daily log all incidents that were relevant to the safety of operation of the tires on his vehicle and the road conditions related to the incidents (Driver Data Sheets No. 1, 2, and 3, Fig. N-1, N-2, and N-3, respectively, Appendix N).

c. All driving was done in convoy or under specific controlled conditions. All drivers participated in all tests and exercises as a group and were under the continuous supervision of the test NCO. A safety SOP developed by CRTC to cover conduct of all test exercises was followed.

d. Each driver was tested on an obstacle course (Fig. 66) at a speed of 15 miles per hour to determine the relative ability of each driver. The obstacle course was the same as that for the obstacle course exercise on ice (paragraph 2.2.4 and Table 14). The performance of each driver was compared to that of the test NCO who drove the obstacle course exercises.

2.5.4 Results

a. Three serious safety incidents, one for each type of unstudded tire (A, B, and C), occurred during testing. Each of these incidents was sufficiently serious as to have endangered the life of the driver if special safety equipment not normally used in military jeeps had not been employed (Fig. 68). Two involved MED vehicle loads and were on primary roads. The other involved a MIN load and was on an unimproved secondary road. In each case, conditions were those frequently encountered by the 172d Infantry Brigade (AK) during the winter--heavily rutted packed snow.

b. Investigation of tread marks and other physical evidence by state troopers and test team personnel revealed that the accidents were the result of errors in controlling minor skids, which caused the vehicle to go out of control and cross the center line of the highway. The most serious incident involved a MED vehicle load, and the physical evidence indicated that the driver failed to consider the motion of the trailer while trying to slow down during a skid. As a result, 11 of the exercises originally scheduled for primary highway were canceled as too hazardous.

c. In addition to the three handling incidents that were serious enough to be classified as safety incidents, 51 other handling incidents occurred for a total of 54. These incidents varied from getting stuck in the mud or snow to skidding 360 degrees in the middle of the highway, and any of them could have ended in an accident had there been other traffic on the road at the time. The number of handling incidents for each driver is shown in the top of Table L-4, Appendix L.

d. None of the drivers could complete the obstacle course at 15 miles per hour and two of them (drivers number 1 and 3) could only maneuver through the four easiest obstacles. This may be compared with the test NCO's performance--he completed the course with every vehicle and every type of tire at 15 miles per hour.

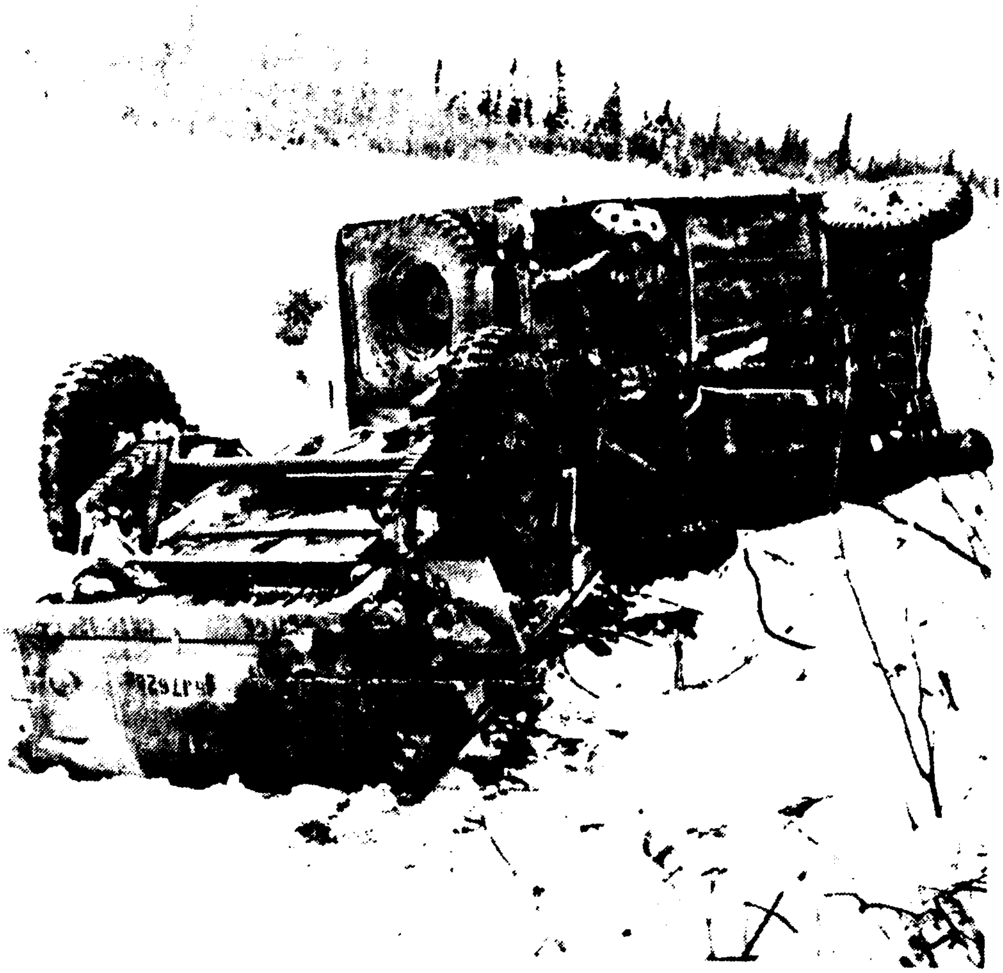


Figure 68. Safety incident. This involved vehicle number 4 and tire type B.

2.5.5 Analysis

a. The two regular drivers scoring lowest on the obstacle course accounted for 67 percent of the handling incidents and two of the three safety incidents (Table L-4, Appendix L).

b. Even under controlled conditions in which an experienced NCO regulated vehicle speed according to conditions, ensured the correct use of chains and four-wheel drive, and enforced correct inflation of tires; three serious accidents, much like the accident that led to this test, and 51 incidents that could have led to accidents, occurred. As this degree of control is unlikely to be duplicated in a field environment, the safety record for jeeps being driven on field maneuvers in Alaska during the winter and spring cannot be expected to be better than that observed during testing.

c. It appears that all of the types of tires evaluated are hazardous for inexperienced drivers to use on a jeep on wet snow and ice in cold regions (winter and spring season).

2.6 Post operational inspection

2.6.1 Objective

Determine the condition of all tires and vehicles at the end of testing.

2.6.2 Criteria

None.

2.6.3 Data acquisition procedure

a. At the end of testing, all tires were inspected in accordance with paragraph 6.1 of MTP 2-2-704 (ref 1, Appendix E).

b. Defects in tire condition were documented by photographing the specific conditions found.

c. The tire condition was determined in accordance with TM9-2610-201-14 (ref 6, Appendix P) and a tire condition sheet (Fig. N-8, Appendix N) was completed for each tire.

2.6.4 Results

a. The physical characteristics of the tires after testing were as given in Table L-2, Appendix L.

b. All tires showed minor cuts and were missing chunks of rubber in the tread. Tires of type D showed the most wear.

c. Vehicle number 2 was found to have worn spindle bearings.

d. During the course of testing, four flat tires were repaired for nail punctures. Two of these flat tires were for the same tire (type B). No maintenance was required for tires of types C and D.

e. There was no indication that any of the alternative tires required more or less maintenance than standard military tires or that any of them were incompatible with the vehicles.

2.6.5 Analysis

a. All tires were in satisfactory condition at the end of testing.

b. The worn spindle bearing found on vehicle number 2 does not account for the difference in tread wear observed for tires of type D since both tires of types B and D were driven for similar distances on vehicle number 2 and tires of type B showed less wear.

c. Much of the wear observed on tires of type D was centered around the area where the studs were installed. Studding a tire of type B may shorten the life of the tire.

d. The temperature range during testing did not allow evaluation of the recap mold of types B and D for its ability to withstand temperatures below -13°F (-25°C), which are common in Alaska in the winter.

e. No discernible damage to any of the vehicles was observed due to having been driven with nonstandard tires of types C and E.

APPENDIX L - TEST DATA

TABLE L-1.--Results of Preoperational Inspection and Physical Characteristics* of Tires by Type

Tire Type	Tread Depth (Inches)	Weight (Lbs)	Perimeter (Feet)	Width (Inches)	Diameter (Feet)	Contact Area (Inches^2)	Defects Observed	Inflation** Pressure (psi)
A	17/32	30	7.86	7.0	5.66	42	None	25
B	17/32	33.5	7.96	7.2	5.795	52	Abrasions on Sidewall	25
C	19/32	39	8.13	7.75	6.02	53	None	35
D	17/32	34	8.00	7.1	5.84	50	None	25
E	19/32	39	8.17	7.7	6.02	54	None	35

*Measured in accordance with MTP 2-2-704 (ref 6, appendix P). "Perimeter" is the outside circumference of the tire. "Width" is the width at the widest portion of the tire's cross-section. "Diameter" is measured by wrapping a tape measure around the tire so that the tape crosses the center of the tire on both sides and measuring the distance from a starting point on the sidewall back to the starting point.

**This was the correct inflation pressure for travel on dry pavement, which was the road condition at the time of the preoperational inspection.

TABLE L-2.--Results of Postoperational Inspection, Physical Characteristics of Tires, and Total Miles Driven by Type

Tire Type	Tread Depth (Inches)	Weight (Lbs)	Perimeter (Feet)	Width (Inches)	Diameter (Feet)	Contact Area (Inches)	Defects Observed	Inflation** Pressure (psi)
A	14/32	29	7.89	7.1	5.67	42	Dent in ring ¼ inch of rubber missing from tread	21
B	14/32	33	7.97	7.2	5.82	52	Dry rot, tears in bead, ¼ inch rubber missing from tread	18
C	17/32	38	8.19	7.8	6.04	53	¼ to 3/8 inch rubber missing from tread, cuts in tread	27
D	14/32	33	7.96	7.2	5.82	50	Tears in bead, dry rot, wear on one tire uneven and 1/32 inch below the average of the others	21
E	17/32	38	8.15	7.8	6.03	54	Cuts in tread, tread torn and gashed near studs	27.5

*Inflation pressure was that appropriate for the exercises on muddy roads, which were performed immediately before the postoperational inspection.

Tire Type	Total Miles Driven	Miles Driven on Vehicle Number					Average Tread Depth Loss (Inches)
		1	2	3	4	5	
A	3092	759	431	515	1004	383	2/32
B	3422.5	400	1264.5	655	713	390	2/32
C	2269	353	502	425	269	720	2/32
D	2622.5	315	1259.5	336	200	512	2/32
E	2803	353.5	474.5	1323	258	394	2/32

TABLE L-3.--Multiple Comparison Test of Overall Tire Performance Based on Friedman Rank System

To investigate which differences in overall tire performance ranks between tires were statistically significant, the test on page 151 of reference 11, appendix E, was used. To apply this test, the 18 exercises for which overall ratings were obtained for all five tire types were used. The sum of ranks for each type tire were obtained as 79, 61, 30, 62, and 38 for tire types A, B, C, D, and E, respectively. The average ranks (1=highest to 5=lowest) were 1.7, 2.1, 3.4, 3.4, and 4.4 for tires C, E, D, B, and A, respectively. For experiment wise error rate of α, it can be concluded that the observed difference between two tire types is statistically significant if the magnitude of the difference between the corresponding rank sums exceeds the critical value computed from equation (15), page 151 of reference 11, appendix E. It was found that differences between either tire type C or E and any of tire types A, B, or D were statistically significant at the following approximate levels.

Difference Between	Level of Significance
C and B	0.01
C and D	0.005
C and A	0.0001
E and B	0.11
E and D	0.10
E and A	0.0005

None of the other observed differences between rank sums was statistically significant.

TABLE L-4.--Handling Incidents by Group of Exercise, Type of Tire, and Driver

Group Road Exercises	Tire Type	Number of Incidents/Number of Exercises Driven By Driver Number** 1	2	3	4	5	6	7	All
	A	4*/4	2/5	5/7	4/5	0/7	1/1	0/0	16/29
	B	1/4	2/6	11/8	1*/4	2/6	0/0	0/1	17/29
	C	1*/4	2/5	3/6	0/4	3/8	0/2	0/0	9/29
	D	2/3	0/3	2/3	3/4	0/4	0/1	0/2	7/20
	E	0/3	2/5	1/4	2/3	0/4	0/0	0/1	5/20
	All	8/18	8/24	22/28	10/20	5/29	1/4	0/4	54/127
Mud on Unimproved Secondary Roads With Three Types of Tires	A		1/1	3/2		0/2			4/5
	B		2/2	6/2		0/1			8/5
	C		0/2	2/1		0/2			2/5
	All		3/5	11/5		0/5			14/15
Improved Secondary Roads With Three Types of Tires	A		0/1	0/1		0/2			0/4
	B		0/2	0/1		0/1			0/4
	C		0/1	0/2		0/1			0/4
	All		0/4	0/4		0/4			0/12
With Five Types of Tires	A	4*/4	1/3	2/4	4/5	0/3	1/1	0/0	12/20
	B	1/4	0/2	5/5	1*/4	2/4	0/0	0/1	9/20
	C	1*/4	2/2	1/3	0/4	3/5	0/2	0/0	7/20
	D	2/3	0/3	2/3	3/4	0/4	0/1	0/2	7/20
	E	0/3	2/5	1/4	2/3	0/4	0/0	0/1	5/20
	All	8/18	5/15	11/19	10/20	5/20	1/4	0/4	40/100

*Includes one safety incident.
**Drivers number 1 through 5 were the regular drivers; driver number 6 was the test NCO; driver number 7 was the substitute driver.

TABLE L-5.--Contingency Table Analyses of Handling Incidents

1. Of the 54 handling incidents (including the 3 safety incidents) which occurred in 127 runs (100 runs from the 20 exercises involving all five types of tires and 27 runs from the 9 exercises involving only three types of tires), 14 incidents occurred during the 15 runs conducted on muddy trails in exercises involving only three types of tires (these were the only runs conducted on muddy trails and the only runs on trails in exercises involving only three types of tires). No handling incidents occurred during the 12 runs conducted on secondary roads in exercises involving only three types of tires.

2. The 40 handling incidents (including the 3 safety incidents which occurred during exercises involving all five types of tires) were fairly evenly distributed over types of tires: 12, 9, 7, 7, and 5 incidents on type A, B, C, D, and E respectively. The value of the usual chi-square statistic for testing the null hypothesis of no difference between types of tires is 3.50 which is only significant at level 0.48.

3. Of the 14 incidents which occurred during the 15 runs on muddy trails, 11 occurred with one driver. That driver drove tire A and tire B twice each but drove tire C only once, while each of the other two drivers drove tire C twice. Once the differences in numbers of times each driver drove each tire is taken into account, the difference between tires is not statistically significant, but the difference between drivers (or perhaps driver/vehicle combinations) is highly statistically significant.

a. Given 3, 11, and 0 handling incidents with drivers 2, 3, and 5 respectively, and the given five runs for each driver, the expected numbers of incidents per run are 0.6, 1.2, and 0.0 for drivers 2, 3, and ,5 respectively. Thus, given the differences in number of handling incidents among drivers, the expected numbers of handling incidents by type of tire are:

	Driver 2	Driver 3	Driver 5	Total
Tire A	0.6	4.4	0.0	5.0
Tire B	1.2	4.4	0.0	5.6
Tire C	1.2	2.2	0.0	3.4

Since four, eight, and two handling incidents occurred on tires A, B, and C respectively, the chi-square value with 2 degrees of freedom for testing the null hypothesis of no tire differences is:

$$\chi^2_2 = (1.0)^2/5.0 + (2.4)^2/5.6 = (1/4)^2/3.4 = 1.80$$

which is only significant at level 0.41.

b. Given four, eight, and two handling incidents on tires A, B, and C, respectively, and given five runs on each tire, the expected number of incidents per run are 0.8, 1.6, and 0.4 for tires A, B, and C respectivelv. Thus, given the differences in handling incidents between tires, the expected number of handling incidents by driver are:

	Tire A	Tire B	Tire C	Total
Driver 2	0.8	3.2	0.8	4.8
Driver 3	1.6	3.2	0.4	4.0
Driver 5	1.6	1.6	0.8	4.0

Since 3, 11, and 0 handling incidents occurred with drivers 2, 3, and 5 respectively, the chi-square value with 2 degrees of freedom for testing the null hypothesis of no driver differences is:

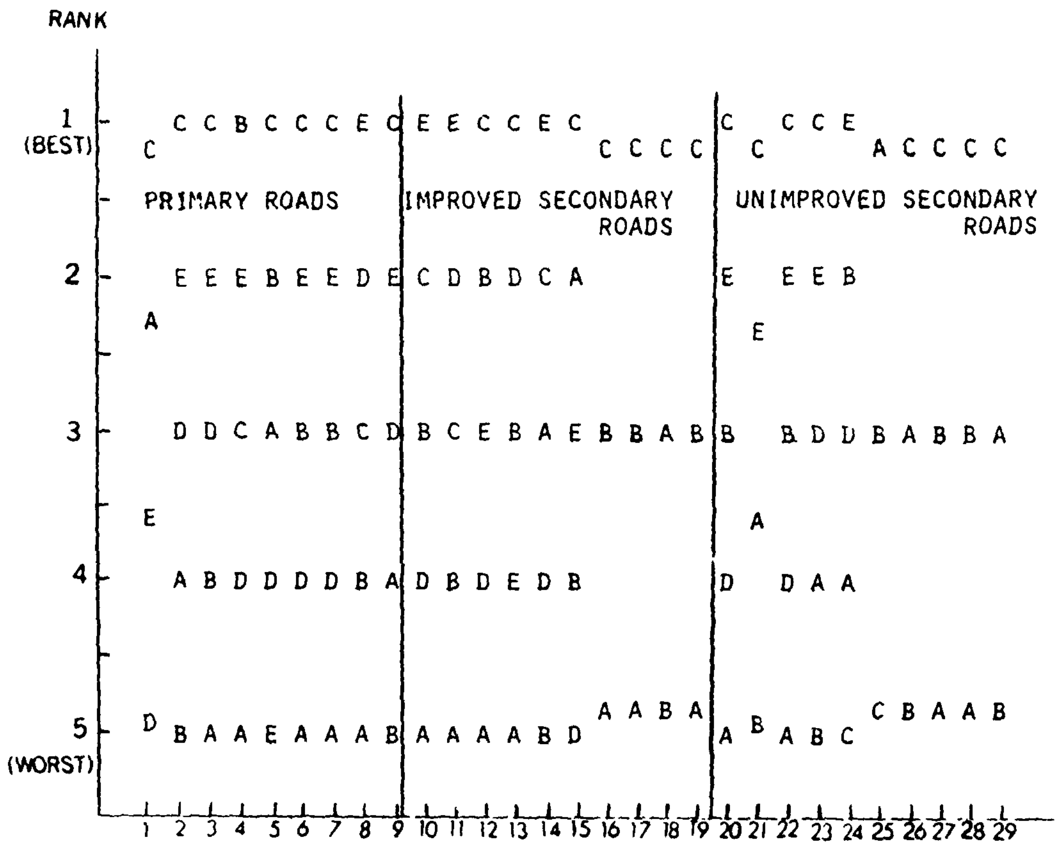
$$\chi^2_2 = (1.8)^2/4.8 + (5.8)^2/5.2 + (4.0)^2/4.0 = 11.14$$

which is significant at level 0.0005. (If possible differences between tires were ignored, the expected number of handling incidents for each driver would be 14/3 so the chi-square value would be:

$$\chi^2_2 = [(5/3)^2 + (19/3)^2 + (14/3)^2]/(14/3) = 13.86$$

which is also significant at level 0.0005.)

FIGURE L-1.--Overall Performance[1] Ranks for Comparison Tires[2] On 29 Road Exercises[3]



[1]Rank is the order of relative performance of the five types of tires indicated by the average of the drivers' ratings as adjusted for individual driver differences in rating scales. A rank of 5 is lowest and 1 is highest performance.

[2]A, B, C, D, and E represent the five types of tires compared. A is the standard military tire, B the military recap tire, C the commercial mud/snow tire, D the studded version of B, and E the studded version of C.

[3]Exercises 1 through 9 were performed on primary roads, 10 through 19 on improved secondary roads, and 20 through 29 on unimproved secondary roads. On some exercises, some drivers declined to rate their tires for maneuvers they felt had not been required by them during the exercise. On other exercises, only three types of tires were compared due to a prohibition against using studded tires in the spring. In these cases, the ranks were adjusted to compensate for fewer than five types of tires being compared.

APPENDIX M - COLD-DRY UNIFORM

The year-round temperature variation peculiar to the cold regions prohibits the prescribing of a particular uniform for any season. The clothing which is comfortable at approximately -50°F (-45°C) becomes uncomfortable at approximately -15°F (-25°C), and vice versa. Since a large fluctuation is experienced on an hour-by-hour, day-by-day basis, some degree of flexibility in uniform requirements is necessary.

The cold-wet uniform is designed to afford maximum protection against the hazards of changing temperatures, rain, wet snow, mud, and slush of a cold-wet environment.

The cold-dry uniform is designed to provide protection against the hazards of extreme temperatures, high winds, and snow of a cold-dry environment. As indicated below, the cold-wet uniform is part of the cold-dry uniform. The cold-wet uniform provides the inner insulating components of the cold-dry uniform. Progressing from cold-wet to cold-dry is accomplished by adding more insulation in the form of additional outer garments.

The necessary clothing components of the cold weather uniforms are worn as defined in TM 10-275, DA, Cold Weather Clothing and Sleeping Equipment, dated April 1968 as ammended by current Supply Bulletins and 172d Infantry Brigade (Arctic) Directives.

Item	Cold-Wet	Cold-Dry
a. Undershirt man, 50% cotton, 50% wool, full sleeve.	X	X
b. Drawers cold weather man, 50% cotton, 50% wool, knit, ankle length.	X	X
c. Socks mans, wool, cushion sole, OG 408, stretch type.	X	X
d. Suspenders trousers, scissor back type.	X	X
e. Shirt cold weather, wool, nylon, flannel, OG 108.	X	X
f. Trousers, cold weather wool serge, OG 108.	X	X
g. Trousers, utility cotton sateen, OG 107.	X	X
h. Trousers, camouflage cotton nylon, water repellent white.	X	X
i. Liner cold weather trousers, nylon rip-stop quilted white.	X	X
j. Liner, snow trousers, camouflage, nylon ripstop quilted white.		X
k. Boot extreme cold weather, mens rubber white w/release valve.		X
*l. Boot, cold weather, mens rubber, black, w/release valve.	X	
m. Coat cold weather mans, cotton and nylon wind resistant sateen.	X	X
n. Liner cold weather coat, nylon quilted, 6.2 oz, OG 106.	X	X
o. Parka, extreme cold weather, mans cotton/nylon oxford OG 107, wo/hood.		X
p. Liner extreme cold weather parka mans, nylon quilted, OG 106.		X
q. Cap, cold weather, cotton nylon oxford OG 107.	X	X
r. Hood extreme cold weather, cotton, nylon OG 107, w/fur ruff.		X
s. Handwear:		
(1) Mitten set arctic: Gauntlet style shell w/leather palm.	X	X

Item	Cold-Wet	Cold-Dry
**(2) Mitten shell, trigger finger, leather palm and thumb; mitten inserts, wool and nylon knit, OG, trigger finger.	X	X
**(3) Glove shells, work, leather; glove inserts, wool and nylon knit, OG 208.	X	X
(4) Gloves cloth, work type (anticontact).	X	X
t. Special purpose clothing items:		
(1) Parka snow camouflage, white.	X	X
(2) Trousers camouflage.	X	X
(3) Mask: Extreme cold weather.	X	X
(4) Dickey, rayon, OD (local item of issue).	X	X
(5) Balaclava, wool, navy blue (local item of issue).	X	X

*Not available to CRTC.
**Items not worn at same time.

APPENDIX N - SPECIAL ROADS AND DATA SHEETS

1. The special roads are identified by type, number, and general description in table N-1. The number is one arbitrarily assigned for the purposes of testing.

2. Two kinds of data sheets were used during testing:

a. Driver Data Sheets were of size 5¼ x 8 inches suitable for binding into individual field data books for the use of individual drivers. The formats of Driver Data Sheets No. 1, 2, and 3 are shown in figures N-1, N2, and N-3, respectively.

b. Master Data Sheets were of size 8½ x 11 inches suitable for storage in loose leaf notebooks for the use of data analysts. Format of Master Data Sheets No. 1, 2, and 3 are shown in figures N-4, N-5, and N-6, respectively.

3. Figure N-7 shows the Human Factors Evaluation Booklet to be completed by each driver at the end of testing.

4. Tire data collected during preoperational and postoperational inspections and maintenance incidents was recorded on the tire condition sheet shown in figure N-8.

TABLE N-1 - SPECIAL ROADS

Road No. and Type	Miles Length	Description of Route Based on Mt. Hayes D-4 Map*
1 Primary	120	From intersection of Meadows Road with Richardson Highway South for 60 miles and return.
2 Primary	120	From intersection of Meadows Road with Richardson Highway on Richardson Highway North for 60 miles and return.
3 Primary	120	From intersection of Meadows Road with Richardson Highway South to Alcan Highway East for 60 miles and return.
4 Improved Secondary	20.5	Bolio Lake Test Facility to Meadows Road North to 33-mile Loop North at (613885) to 11-mile Loop East at (616914) to 11-mile Loop North at (645915) to Ft. Greely reservoir and south to 33-mile Loop South at (616914) to Meadows Road South at (613885) to Bolio Lake Test Facility.
5 Improved Secondary	51	Bolio Lake Test Facility to Meadows Road North to 33-mile Loop South at (613885) to Richardson Highway South at (622812) to Old Airfield Road South at (621790) to tank stand at (632768) and West to Richardson Highway at (619768) across Richardson Highway to BM2735 to tower and return.
6 Improved Secondary	21	Bolio Lake Test Facility to Meadows Road South to (535800) and East to (583787) and North to Richardson Highway North to Meadows Road South to Bolio Lake Test Facility.
7 Unimproved Secondary	10.5	(617892) east to (644885) and north to (647907) and east to (667908) and south to (659888) and west to (644885) and north to (647907) and west to (616906) and south to (617892).
8 Unimproved Secondary	13.5	(616865) east to (635862) and north to (645885) and east to (659888) and south to (642844) and west to (630844) and north to (635862) and north to (645885) and west to (617892).
9 Unimproved Secondary	20	(616865) east to (635863) and south to (630844) and east to (642844) and north to (667908) and west to (617907) and south to (617892).
10 Ice Track	0.25 or 0.56	Bolio Lake graded to remove snow.
11 Packed Snow Track	0.25 or 0.56	Bolio Lake.
12	0.25	Shore of Big Lake. Snow was undisturbed and was 0 to 17 inches (0 to 43 cm) deep.

*(Reference 8, appendix P).

FIGURE N-1

DRIVER DATA SHEET NO. 1

DATE: __________ TIME: __________

EXERCISE NO.: __________ TYPE: __________

VEHICLE NO.: __________ TIRE: __________

ROAD TYPE: __________ NO.: __________

OPERATOR MAINTENANCE CHECKS:

____

____

TIRE INFLATION: __________ PSI. ADJUSTED TO: __________ PSI.

WHAT	START	FINISH
MILEAGE		
FUEL LEVEL		
SKY CONDITION		
LIGHT LEVEL		
TIME		

START POINT EVALUATION:

DRIVER CONDITION: __________

____

WEATHER CONDITIONS: __________

____

COMMENTS: __________

____

____

FIGURE N-2

DRIVER DATA SHEET NO. 2

EXERCISE NO. __________ CONTINUED . . . .

INCIDENTS:

1) TIME: __________ LOCATION: __________

MANEUVER: __________

DESCRIPTION: __________

____

2) TIME: __________ LOCATION: __________

MANEUVER: __________

DESCRIPTION: __________

____

3) TIME: __________ LOCATION: __________

MANEUVER: __________

DESCRIPTION: __________

____

4) TIME: __________ LOCATION: __________

MANEUVER: __________

DESCRIPTION: __________

____

5) TIME: __________ LOCATION: __________

MANEUVER: __________

DESCRIPTION: __________

____

FIGURE N-3

DRIVER DATA SHEET NO. 3

EXERCISE NO. ____________ CONTINUED . . . .

MIDPOINT EVALUATION:

LOCATION: ____________

ROAD CONDITIONS: ____________

WEATHER CONDITIONS: ____________

TIRE PERFORMANCE DURING EXERCISE: (Use scale of 1 to 6)

MANEUVER	SCORE (Mid/End)	MANEUVER	SCORE (Mid/End)
STRAIGHT	/	BRAKING	/
TURNING	/	ON BUMPS	/
CLIMBING	/	ON SOFT SPOTS	/
DESCENDING	/	ON SLICK SPOTS	/

ENDPOINT EVALUATION:

ROAD CONDITIONS: ____________

WEATHER CONDITIONS: ____________

OVERALL PERFORMANCE DURING EXERCISE: (Use scale of 1 to 6) ____________

EXPLAIN: ____________

FIGURE N-4

MASTER DATA SHEET NO. 1

EXERCISE NO. ______ EXERCISE TYPE ______ ROAD NO. ______ ROAD TYPE ______
TOTAL TIME ______ HOURS. TOTAL SOLAR RADIATION ______ LANGLEYS
TOTAL *PRECIPITATION* ______ *INCHES OF* ______

METEOROLOGICAL PARAMETERS	START POINT	MIDPOINT	ENDPOINT	CHANGE
Ambient Temperature	°F	°F	°F	°F
Humidity	%	%	%	%
Windspeed	kts	kts	kts	kts
Wind Direction	°	°	°	°
Light Level, subjective				
Sky Condition, subjective				
Weather, subjective				

ROAD CONDITIONS MIDPOINT ____________

ROAD CONDITIONS *ENDPOINT* ____________

TIRE SET	VEH NO.	MILEAGE	FUEL GAL	SPEED MPH AV	MAX	MIN	LOAD	NO. INCIDENTS HAND	SAF	MAINT
A										
B										
C										
D										
E										

TIRE SET	ENDPOINT TIRE PERFORMANCE EVALUATION STRAIGHT	TURN	CLIMB	DESCEND	BRAKE	BUMPS	SOFT	SLICK	OVERALL
A									
B									
C									
D									
E									

FIGURE II-5

MASTER DATA SHEET NO. 2

EXERCISE NO. ______ CONTINUED . . . .

TIRE TYPE	VEH. NO.	DRIVER NAME	SPEED MPH	DISTANCE % COURSE	NO. OBSTACLES SURMOUNTED BY RADIUS 20M	25M	30M	35M	35M CIRCULAR

SURFACE TEMPERATURE OF ROAD __________ °F

FIGURE II-6

MASTER DATA SHEET NO. 3

EXERCISE NO. __________ CONTINUED . . . .

TIRE TYPE	VEHICLE NO	MIN DEPTH CM	MAX DEPTH CM	LAYERS OF DRY/WET	OLD/NEW	DISTANCE MILES	CHANGE Y/N

TIRE TYPE	BRAKING DISTANCE IN FEET FOR TRIAL NO. 1	2	3	4	CHN Y/N

SURFACE TEMPERATURE __________ °F

FIGURE II-7

Human Factors Evaluation Booklet

NAME OF DRIVER ______________________________

DATE OF EVALUATION ___________________________

DIRECTIONS: You must complete the entire evaluation booklet correctly. If mistakes are found in your arithmetic or you have not taken the information correctly from your data book, you will be asked to do the work over again. If you did not bring a calculator, you may ask for one. You must do the work yourself and must not ask for help from other drivers. If you need help, ask the monitor. You have two 4-hour periods to complete the work but may leave when you have correctly completed the booklet. When you think you have finished, you must bring the completed work to the monitor, who will decide whether or not you may leave. Use a pencil so you can erase.

1. Overall, rate the different types of tires by filling in Table 1. When you have completed this, ask the monitor for your data book.

2. Look through your data book and fill in Tables 2, 3, 4, 5, and 6. Be sure to keep track of which exercises were for which types of tires and put them in the correct tables.

3. Using the averages that you have calculated in Tables 2, 3, 4, 5, and 6, fill in Table 7. For example, put the tire type with the highest overall rating in the "BEST" block of Table 7. You now have the rating that you actually gave the tires while you were driving on them.

4. Does your rating in Table 7 agree with your rating in Table 1? If not, explain why. ______________________________

____

5. Check the weather and road conditions that were present when you were testing each of the tire types by filling in Table 8 using the information you wrote in your data book.

6. From Table 8, which type of tire did your drive under the worst weather and road conditions? ______________________________

7. According to your data book, which types of tires did you test while not feeling your best?

____

____

8. Check the incidents that happened while you were testing each type of tire by filling in Table 9.

9. From Table 9, which type of tire do your think caused the most incidents? ______________________________

10. Read your answers to all the questions. What is your final rating of the types of tires? (Put this in Table 10. What you put in Table 10 does not have to agree with either Table 1 or Table 7.)

TABLE 1 First Attempt to Rate Tires

RATING	TYPE OF TIRE
BEST	
SECOND BEST	
AVERAGE	
SECOND WORST	
WORST	

TABLE 2

TIRE TYPE A

EX. NO.	TIRE PERFORMANCE RATING FROM YOUR DATA BOOK FOR STD TIRES OVERALL	STRAIGHT	TURN	CLIMB	DESCEND	BRAKE	BUMP	SOFT	SLICK
SUM									
AV.									

NOTE: Add each column to get sums and then divide each sum by 8 to get averages.

*Tables 3 through 6 were identical except for type of tire and so are omitted.

TABLE 7

Overall Tire Rating from Daily Rating Averages

RATING	TYPE OF TIRE
BEST	
SECOND BEST	
AVERAGE	
SECOND WORST	
WORST	

TABLE 8

WEATHER AND ROAD CONDITIONS

TIRE TYPE	For how many exercises was the tire type driven in weather that was: SNOW/RAIN	COLD/FOGGY	NORMAL	For how many exercises was the tire type driven on roads that were: ICY	SNOWY	MUDDY	WET	DRY
A								
B								
C								
D								
E								

TABLE 9

INCIDENTS

TIRE TYPE	Total number of incidents that happened while driving the tire type:	Number of incidents that you think were due to the tire type:
A		
B		
C		
D		
E		

NOTE: Only incidents that are recorded in your data book should be counted. Your opinion of what caused the incident in each case is what you should count, not someone else's. The weather must be as you recorded in your data book for each exercise and the same is true for the road conditions.

TABLE 10

Final Overall Rating of Tires

RATING	TYPE OF TIRE
BEST	
SECOND BEST	
AVERAGE	
SECOND WORST	
WORST	

FIGURE H -8

TIRE CONDITION SHEET

SERIAL NO. ______________TYPE*______POSITION ON VEHICLE*________________

1. Perform visual inspection on deflated tire and tube, record results below, and photograph defects found.**

SPLICE SEPARATION ____

LOOSE CORDS ____

EXTREME OVERLAP OF PLIES ____

DAMAGED BEADS ____

SURFACE IMPERFECTIONS
CAUSED BY DIRTY MOLDS ____

TUBE CONDITION ____

VALVE STEM CONDITION ____

OTHER ____

2. Measure while tire is deflated but with tube inserted:

WEIGHT _________ lbs

TREAD DEPTH: ______in. ______in. ______in. ______in. ______in.

BEAD WIDTH: ______in. ______in. ______in. ______in. ______in.

3. Inflate tire to rated pressure for type, position, normal temperatures, and dry pavement and measure:

INFLATION PRESSURE _________psi. PERIMETER ________ft. WIDTH _________in.

DIAMETER: ______ft. ______ft. ______ft. ______ft. ______ft.

4. Install in selected position on vehicle and measure:

CONTACT AREA W/ROAD _________in. BULGE WIDTH _________in.

5. Rate overall condition of tire: ____SATISFACTORY ____UNSATISFACTORY

*Paint an ID mark on side of tire consisting of the code for the type followed by "LF", "RF", "LR", "RR", "LT", "RT", or "S" as applicable to identify the tire position when "L" is left, "R" is right or rear, "T" is trailer, and "S" is spare.
**Standards will be in accordance with TM 9-2610-201-14.

APPENDIX O - RELATIVE EFFECTS OF PHYSICAL CHARACTERISTICS OF TIRES

1. It is well known that the forces of friction between two surfaces is directly proportional to the pressure exerted by one surface on the other (page 96, ref ~~9~~ 10, appendix P)

2. If the pressure exerted by a tire on a road surface is approximated by computing the total weight of the vehicle, its load, and its tires and dividing the result by the total contact area of the four tires with the road, differences in the weight of the tires and the contact area per tire compared to a given type of tire would change the pressure exerted by the amount:

$$\frac{dP}{P} = \frac{4\ d(\text{weight})}{\text{total weight}} - \frac{d(\text{contact area})}{4 \times (\text{Contact area})}$$

where dP is the change in pressure, d(weight) is the difference in the weight due to different tires, d(contact area) is the difference in contact area per tire due to the different tires, and P is the pressure.

3. As the total weight of a jeep, its load, and its tires is at least three orders of magnitude greater than any difference in the weight of a set of tires, the first term of the equation in paragraph 2 above is negligible. However, the second term is approximately 5 percent for the values of contact area given in table B.1, appendix B if the given tire is taken to be of type A:

$$\frac{dP}{P} \cong - \frac{d(\text{contact area})}{4 \times (\text{Contact area})} = \frac{12\ in^2}{4 \times 54\ in^2} = -0.05.$$

which indicates that the pressure exerted by tires of type E should be 5 percent less than that exerted by tires of type A.

APPENDIX P - REFERENCES

1. Quality Deficiency Report, Control No. RM 0092-1, dated 2 April 1980, from Cdr, Co D, 172d Spt Bn, Fort Richardson, AK to Cdr, TECOM, Warren, Michigan.

2. Letter, DRSTE-CM-R, dated 17 December 1980, subject: Test Execution Directive for Truck, M151A2, TECOM Project No. 1-VG-120-151-091.

3. TM 9-2320-218-10, Operator's Manual Truck Utility, 1/4-Ton, 4X4, dated September-1971, with Change 1, dated 1 May 1973.

4. Manufacturer's tire inflation guide.

5. FM 9-207, Operation and Maintenance of Ordnance Materiel in Cold Weather (0°F to--65°F), dated January 1978.

6. MTP 2-2-704, USA TECOM Common Engineering Test Procedure Tires, dated 24 November 1965.

7. TM 9-2610-201-14, Standards and Criteria for Technical Inspection and Classification of Tires, dated August 1975.

8. FM5-34, Engineer Field Data, dated 24 September 1976.

9. Mount Hayes D-4 Map.

10. R. Resnick and D. Halliday, Physics for Students of Science and Engineering, Part I, 5th printing, December 1962 (John Wiley and Sons).

11. Hollander, Myles and Douglas A. Wolfe, Nonparametric Statistical Methods, 1973 (John Wiley and Sons, New York).

WINTER TIRE TESTS: 1980-81

G.L. Blaisdell U.S. Army Cold Regions Research and Engineering Laboratory
W.L. Harrison Hanover, New Hampshire, U.S.A. 03755-1290

INTRODUCTION

Mobility prediction models for wheeled vehicles are lacking in the differentiation between performance levels due to tire design. Currently, tires are identified by their diameter and section width, and sometimes inflation pressure and/or deflection. No consideration is given for tread design, carcass construction, or material properties. While it may prove to be impractical to include all of these factors in prediction models, those that are in sufficient evidence relative to their influence on performance must be included.

In addressing the subject of mobility under winter battlefield conditions, it is not unlikely that tire design has more of an influence on mobility than in non-winter environments. The object of this research effort is, therefore, the assessment of tire design on mobility in winter environments.

Tests are being conducted to obtain a quantitative assessment of tire design parameters and performance on winter surface conditions. The surfaces of interest are shallow snow in packed and virgin states, road ice, and thawing soils. Ranges in temperature, depth, and material properties are also of interest.

This report describes an initial series of tests conducted during the late winter weeks of 1981. Several tires having different tread designs, carcass construction, and material properties (although not identifiable) were tested on ice and packed snow.

TIRES

The tires used in the tests were a U.S. Military NDCC tire, modified Military NDCC tire, a commerical Mud and Snow (M&S) bias ply tire, a FRG (West Germany) Military off-road tire, and a FRG Military highway tire. A U.S. commerical radial all-season tire was used for measuring snow properties and also as a control tire. A description of the tires is contained in Table 22.

The control tire, whose primary function was measurement of snow properties, was chosen specifically for its "neutral" design, representing a compromise in performance for all conditions.

CRREL INSTRUMENTED VEHICLE (CIV)

The CRREL instrumented vehicle (Fig. 69) is equipped with moment compensated triaxial load cells[1], which are mounted in the two front wheel assemblies. The load cells measure the forces which are present at the tire material contact patch. Three force directions are defined for each wheel: vertical, longitudinal and side (Fig. 70). Additional measurement instrumentation includes a torque cell and pulse pick-up speed indicator mounted on the rear propeller shaft, a pulse pick-up device on each front wheel, and a 5th wheel assembly for accurate vehicle speed and distance values. The signals generated by the force and speed measuring devices are converted to digital form and collected by an on-board minicomputer. The com-

Figure 69. The CRREL Instrumented Vehicle.

Table 22. Test tire description.

	Tire	Section Width	Diameter	Belt	Carcass
	P225/75R15 All season	8 1/4	28 1/2"	2 polyester-2 steel plys	2 polyester radial plys
7.00x16	USA Mil NDCC	7 1/4"	30"	NA	6 ply nylon
7.00x16	USA Mil NDCC Mod.	7 3/4"	30"	NA	6 ply nylon
7.00x16	USA Com. mud/snow	8"	31"	NA	4 ply nylon
7.00x16	FRG Mil OFF road	7 1/2"	30"	NA	6 ply nylon
7.00x16	FRG Mil Highway	7 1/2"	30 1/4"	5 ply steel	1 radial ply-steel

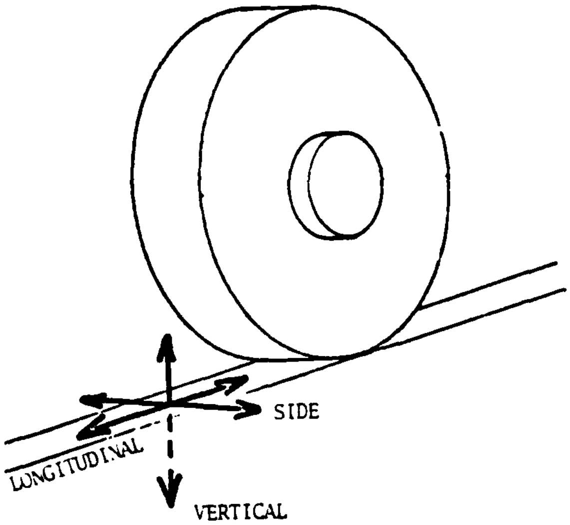


Figure 70. Axes convention for the triaxial load cells.

puter also acts as a controller for much of the instrumentation and, through software, stores and manipulates test data.

The vehicle is equipped with lockout hubs on each of the 4 axles permitting front-wheel, rear-wheel, or 4-wheel-drive and individual brake valves for front, rear, or 4-wheel braking. A complete description of the CIV is given by Blaisdell[2].

SURFACE PROPERTIES

The documentary properties of the surface materials measured before, during, and after testing are listed in Table 23.

TEST PROCEDURES

A control tire was included with the five tire types to be tested. This tire,

Table 23. Documentary test data.

TEST AREA	SURFACE MATERIAL	BEARING SURFACE	DATE	TIME	TEMPERATURE AIR	SURFACE	DENSITY	THICKNESS	SOLAR INPUT
CRREL Dock Area	Ice	Asphalt	5 Mar	0615	-12°C	-12°C	NA G/cc	1 cm	0%
Garipay Field	Wet Snow	Silt	13 Mar	1030	7	0	0.46	7	100
				1110	6	0	0.46	7	0
				1200	6	0	0.46	7	10
Bretton Woods	Packed Snow	Asphalt	14 Mar	0800	0	-1	0.54	13	0
				0920	5	0	0.54	13	50
				1110	9	0	0.54	13	50
		Asphalt	25 Mar	0900	3	0	0.54	14.5	100
				1010	5	0	0.54	14.5	100
				1140	9	0	0.54	14.5	100
				1220	9	0	0.54	14.5	50
		Asphalt	26 Mar	0750	-4	-3	0.55	13	100
				0830	0	-3	0.55	13	100
				0930	4	-2	0.55	13	100
				1010	5	-1	0.55	13	100
				1050	7	0	0.55	13	100

a commercial all-season radial, will be included in all tire tests performed with the CIV as an indicator of the variability of test course materials.

Each of the five military tires was footprinted at tire pressures of 34 and 20 psi. These tire pressures represent the recommended inflation pressure for highway and off-road operation, respectively. The control tire was footprinted at 26 psi (standard inflation pressure) and at 16 and 8 psi for purposes of snow strength measurement. The prints allow a determination of the actual tire contact area and such tread design factors as void ratio and tread angle. Photocopies (reductions) of the footprints and some of the data for each are presented in Figures 71-83.

The rolling circumference was measured for each tire at the stated inflation pressures. Table 24 lists this data and depicts the difference in the effect of changing inflation pressure on bias and radial ply tires. Of this group, only tires D and Z are radials and they, characteristically, show no change in rolling circumference with changing inflation pressure. The bias tires, on the other hand, all show between 2 and 3 percent change when deflating from 34 to 20 psi.

The tests performed with the CIV are designed to measure two quantities--resistance to motion and traction force generated during driving. Motion resistance measurements are taken with the front wheels in a free-wheeling mode and the rear wheels driving. At a speed of 5 mph, longitudinal force readings (motion resistance) are taken over a level 30-foot section of the test course. Resistance was measured at each inflation pressure on a hard surface and on the test course.

Traction tests are conducted with the vehicle in a front-wheel-drive mode (rear wheels disengaged) and brakes are applied to only the rear wheels. These tests are conducted with the vehicle speed initially set to 5 mph. Pressure is applied to the rear wheel brakes to hold vehicle speed at 5 mph while gradually increasing the speed of the front wheels. This produces a force-slip curve.

TEST RESULTS AND DISCUSSION

Rolling resistance tests were performed for all six tires on a level, dry asphalt surface at a vehicle speed of 5 mph. A typical plot of the longitudinal force as it varies along the 30-ft test course is shown in Figure 84. Variability in the force is due to small bumps in the test course and slight fluctuations in vehicle speed. (The longitudinal force registers negative since it is a resistive force.) The steady-state motion resistance value is found by averaging all of the force data points (10 per second). When performed on a snow course, the resistance force shows greater variability than on a hard surface (Fig. 85). This is a result of the roughness of the test course surface.

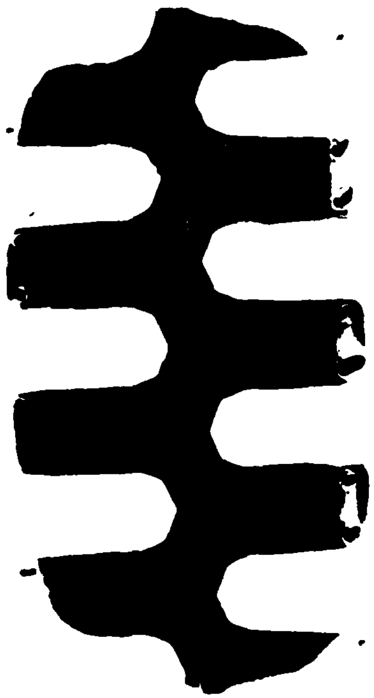


Figure 71. Footprint, tire A, 34 psi.
NDCC Standard; Bias·

Contact area 36.9 sq. in.
Contact width 4.7 in.
Void ratio 0.44

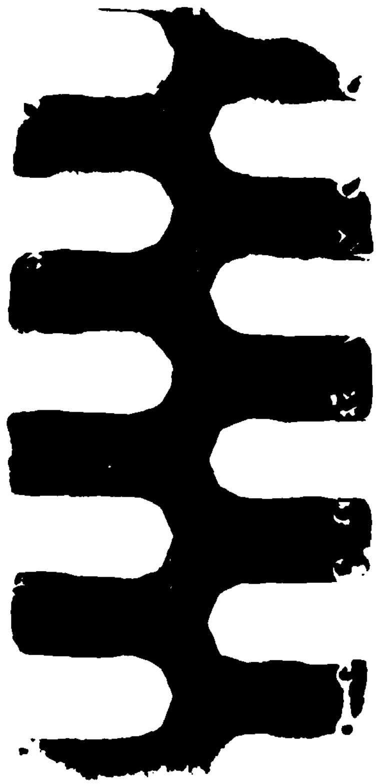


Figure 72. Footprint, tire A, 20 psi.
NDCC Standard; Bias.
Contact area 45.0 sq. in.
Contact width 4.8 in.
Void ratio 0.44

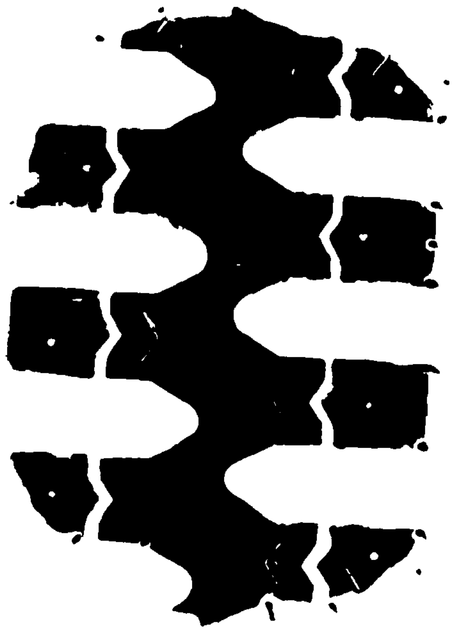


Figure 73. Footprint, tire B, 34 psi.
NDCC Modified Recap; Bias.
Contact area 38.8 sq. in.
Contact width 5.5 in.
Void ratio 0.46

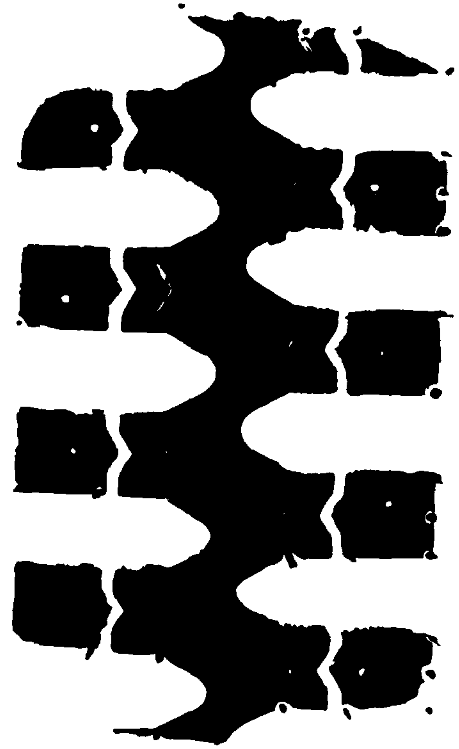


Figure 74. Footprint, tire B, 20 psi.
NDCC Modified Recap; Bias.
Contact area 49.1 sq. in.
Contact width 5.5 in.
Void ratio 0.46.

Figure 75. Footprint, tire C, 34 psi.
7.00-16LT General Super Grip.
Bias M/S.
Contact area 46.8 sq. in.
Contact width 6.7 in.
Void ratio 0.45.

Figure 76. Footprint, tire C, 20 psi.
7.00-16LT General Super Grip.
Bias M/S.
Contact area 60.6 sq. in.
Contact width 6.8 in.
Void ratio 0.45.

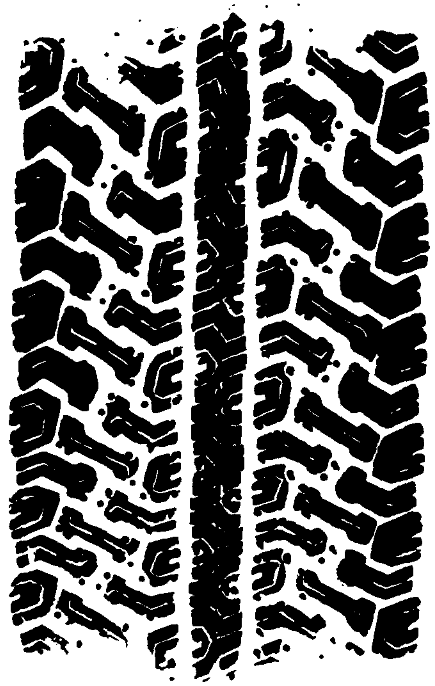


Figure 77. Footpring, tire D, 26 psi.
P225/75R15 Goodyear Tiempo.
Radial All-Season.
Contact area 43.3 sp. in.
Contact width 5.3 in.
Void ratio 0.43.

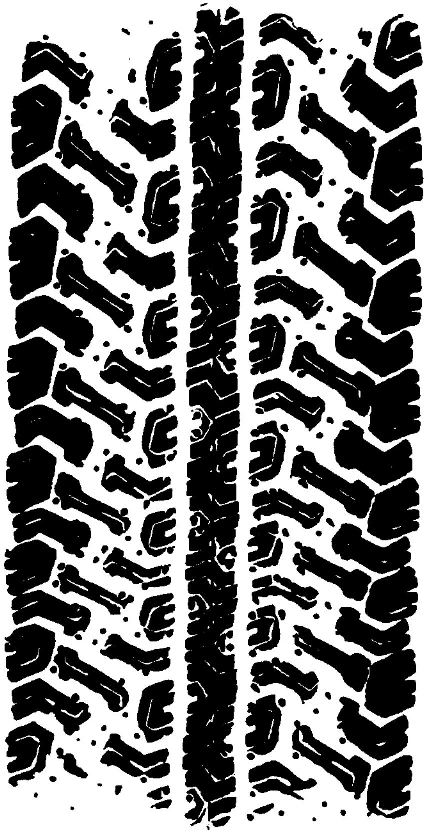


Figure 78. Footprint, tire D, 16 psi. Radial All-Season. P225/75R15 Goodyear Tiempo.
Contact area 53.5 sq. in.
Contact width 5.3 in.
Void ratio 0.43

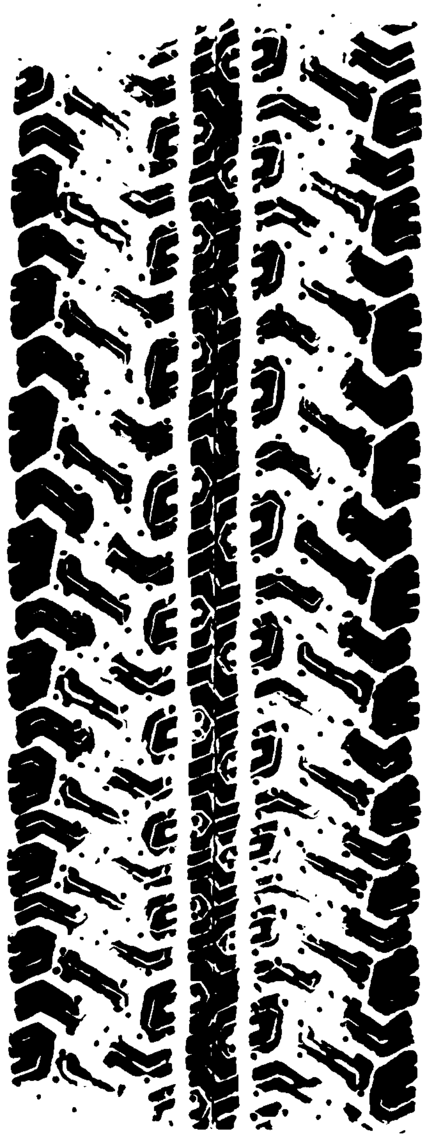


Figure 79. Footprint, tire D, 8 psi. Radial All-Season. P225/74T15 Goodyear Tiempo.
Contact area 73.9 sq. in.
Contact width 5.3 in.
Void ratio 0.43

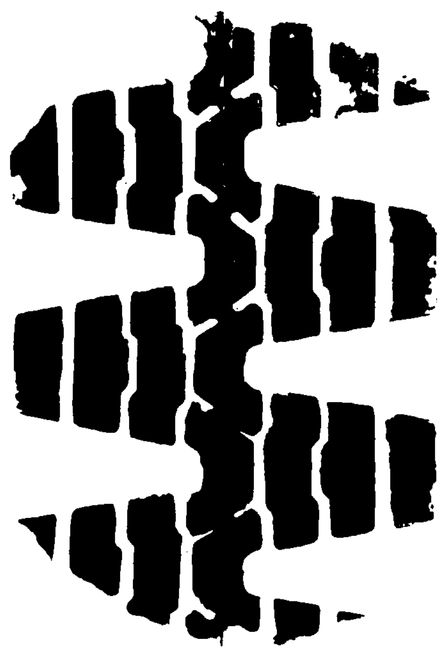


Figure 80. Footprint, tire Y, 34 psi. 7.00-16C Veith Mil. Bias.
Contact area 40.1 sq. in.
Contact width 5.5 in.
Void ratio 0.46.

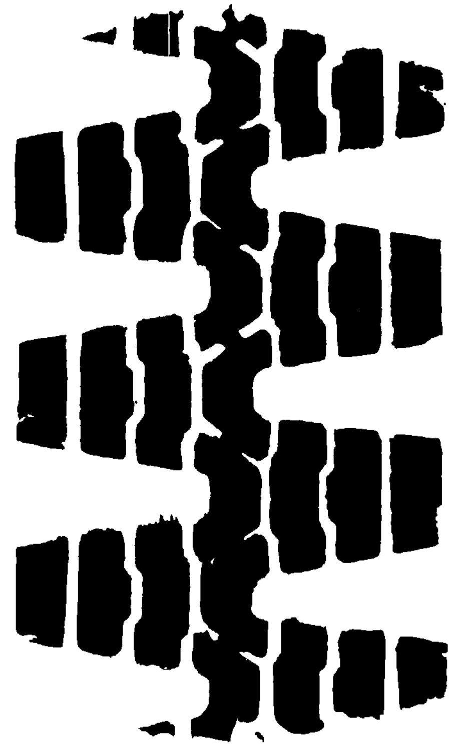


Figure 81. Footprint, tire Y, 20 psi. 7.00-16C Veith Mil. Bias.
Contact area 50.0 sq. in.
Contact width 5.5 in.
Void ratio 0.46.

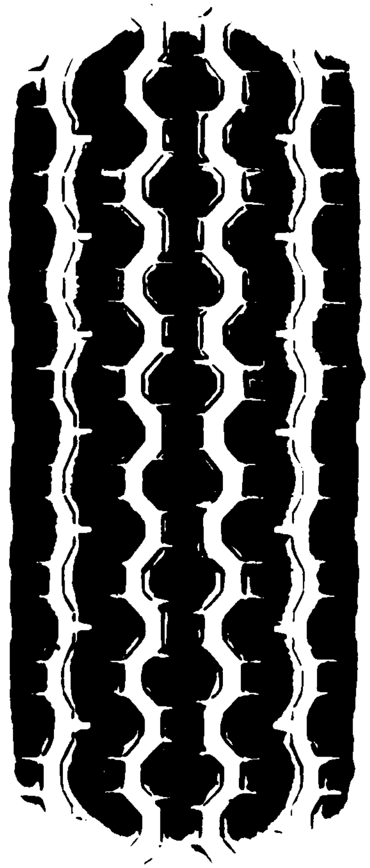


Figure 82. Footprint, tire Z, 34 psi. Radial Highway. 7.00 R16C Continental RS2. Contact area 39.3 sq. in. Contact width 4.5 in. Void ratio 0.29

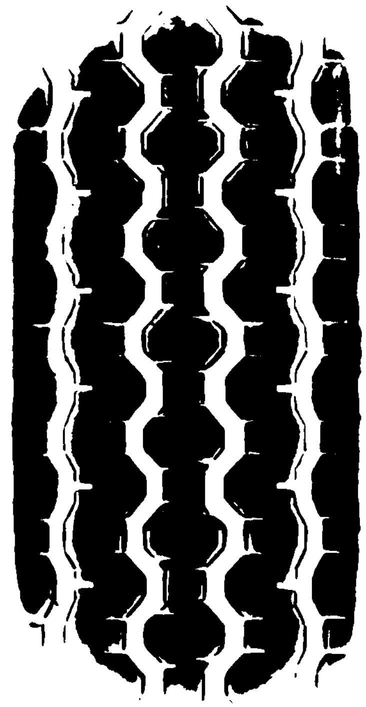


Figure 83. Footprint, tire Z, 20 psi. Radial Highway. 7.00 R16C Continental RS2. Contact area 47.8 sq. in. Contact width 4.5 in. Void ratio 0.29.

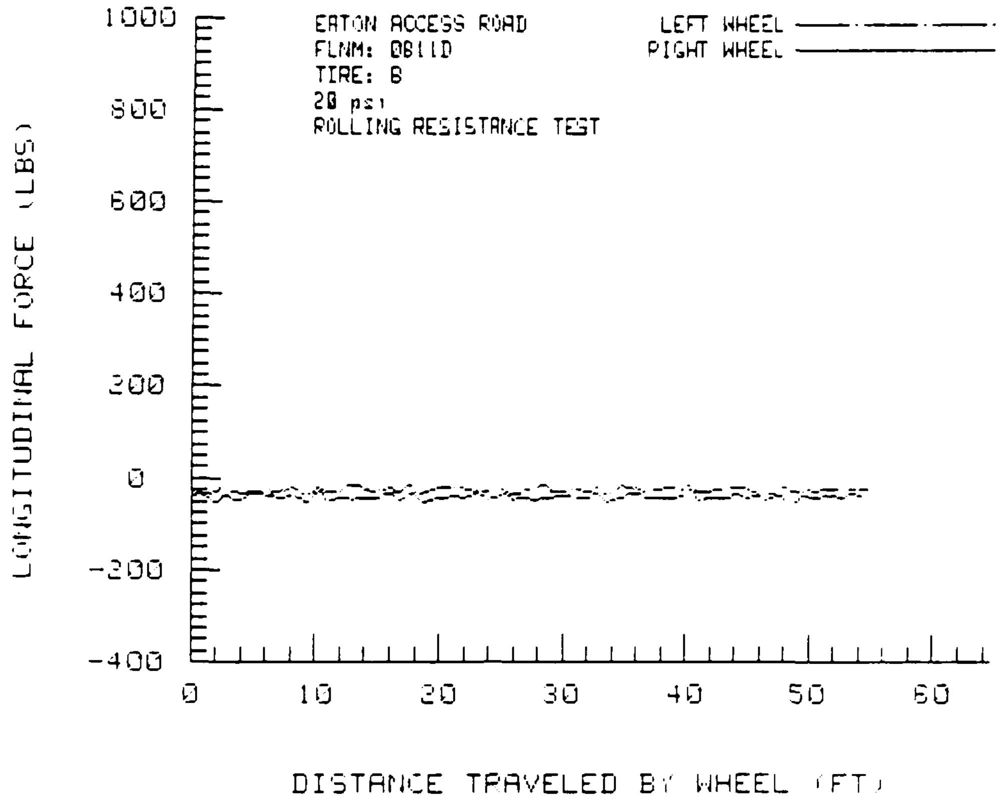


Figure 84. Longitudinal force plot for hard surface motion resistance test.

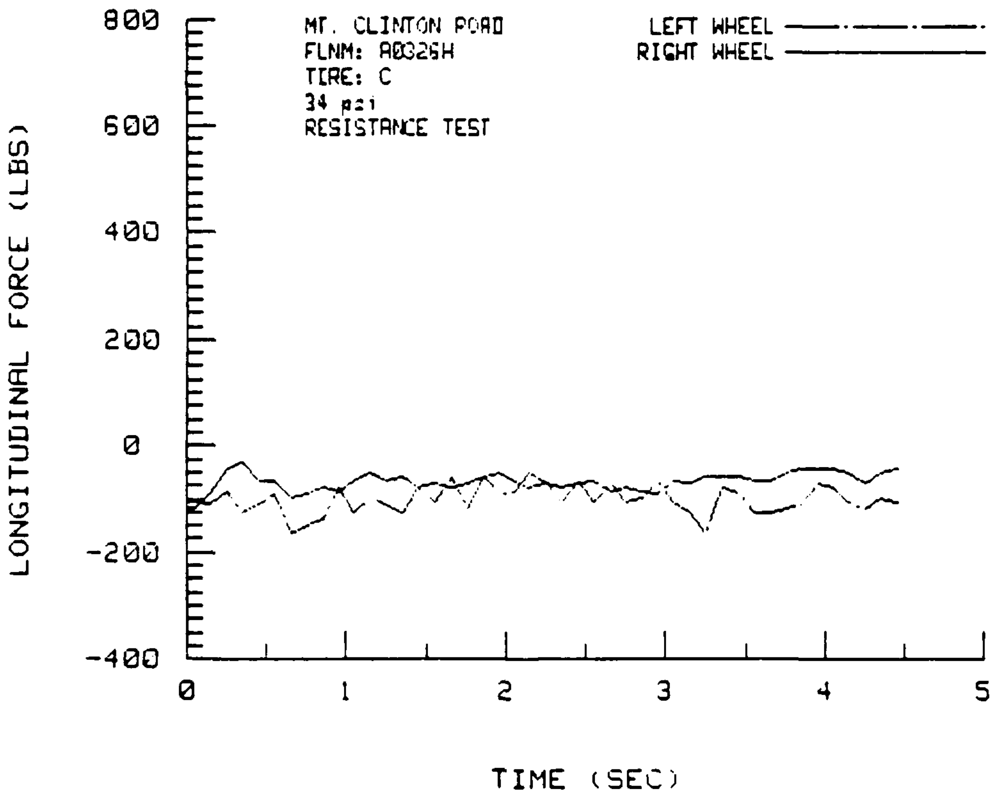


Figure 85. Longitudinal force plot for packed snow motion resistance test.

Table 24. Rolling circumference (in inches.)

Tire	34 psi	26 psi	20 psi	16 psi	8 psi
A	89.3		87.0		
B	90.7		88.9		
C	83.0		91.0		
D		84.5		84.5	84.4
Y	90.7		38.7		
Z	93.3		93.3		

Again, all of the data are averaged to arrive at a motion resistance value. Table 25 presents all of the motion resistance values.

Some of the traction data are shown plotted in Figures 86–91. These plots were chosen to illustrate the differences in tire behavior on the packed snow test course.

All of the aggressive tire designs, A, B, C and Y, dug a rut in the snow as slip occurred. This had the effect of increasing motion resistance and is commonly referred to as "slip sinkage," although the sinkage in this case is caused by excavation. This is illustrated in Figure 92, which shows an increase in rut depth with increasing slip. The effect of this on the longitudinal force plot (Fig. 86) is a decrease in force with increasing rut depth. This plot also indicates that there is only a small range of slip values at which the maximum tractive force can be sustained. Tires C and Y

Table 25. Motion resistance values (pounds).

Tire Code	Pressure	Date/Material		Resistance Left	Resistance Right
A	34	13 Mar	W. Snow	103	168
		25 Mar	P. Snow	29	197
		26 Mar	P. Snow	89	42
		17 Jul	H. Surface	23	35
	20	5 Mar	Ice		
		5 Mar	Ice		
		13 Mar	W. Snow	116	184
		25 Mar	P. Snow	47	248
		26 Mar	P. Snow	84	55
		17 Jul	H. Surface	32	47
B	34	5 Mar	Ice		
		13 Mar	W. Snow	169	195
		25 Mar	P. Snow	76	87
		26 Mar	P. Snow	80	122
		17 Jul	H. Surface	17	28
	20	5 Mar	Ice		
		13 Mar	W. Snow	164	170
		25 Mar	P. Snow	123	28
		26 Mar	P. Snow	97	94
		17 Jul	H. Surface	25	41
C	34	5 Mar	Ice		
		13 Mar	W. Snow	201	154
		25 Mar	P. Snow	25	47
		26 Mar	P. Snow	101	67
		17 Jul	H. Surface	10	14
	20	5 Mar	Ice		
		13 Mar	W. Snow	47	39
		25 Mar	P. Snow	37	33
		26 Mar	P. Snow	113	73
		17 Jul	H. Surface	15	26

Table 25 (cont'd). Motion resistance values (pounds).

Tire Code	Pressure	Date	Material	Resistance Left	Resistance Right
D	26	5 Mar	Ice		
		5 Mar	Ice		
		13 Mar	W. Snow	64	20
		25 Mar	P. Snow	17	38
		25 Mar	P. Snow	29	38
		26 Mar	P. Snow	32	70
		26 Mar	P. Snow	80	51
		17 Jul	H. Surface	11	15
	16	5 Mar	Ice		
		5 Mar	Ice		
		13 Mar	W. Snow	58	53
		25 Mar	P. Snow	51	28
		25 Mar	P. Snow	29	38
		26 Mar	P. Snow	46	70
		26 Mar	P. Snow	79	47
		17 Jul	H. Surface	30	42
	8	5 Mar	Ice		
		5 Mar	Ice		
		13 Mar		101	20
		25 Mar	P. Snow	26	26
		25 Mar	P. Snow	26	72
		26 Mar	p. Snow	69	106
		26 Mar	P. Snow	118	80
		17 Jul	H. Surface	47	70
Y	34	25 Mar	P. Snow	74	94
		26 Mar	P. Snow	49	39
		17 Jul	H. Surface	20	23
	20	25 Mar	P. Snow	79	49
		26 Mar	P. Snow	55	51
		17 Jul	H. Surface	23	34
Z	34	25 Mar	P. Snow	38	81
		26 Mar	P. Snow	44	24
		17 Jul	H. Surface	16	20
	20	25 Mar	P. Snow	51	22
		26 Mar	P. Snow		
		17 Jul	H. Surface	27	32

also showed rather narrow bands of maximum longitudinal force (Fig. 88 and 90). This is probably true for tire B as well, although it is not evident in Figure 87.

Tires D and Z, with non-agressive tread designs, were found to dig ruts of between zero and approximately one inch in depth. With increasing degrees of slip, these tires created an iced layer on the snow surface, which in turn resulted in a lower tractive force. Tire Z, with its principally ribbed design and 5 ply tread, was particularly susceptible to this behavior. Figure 91 is an example of the icing effect.

Tire D showed less sensitivity to the degree of slip (Fig. 89), however, it was also prone to icing. Since tire D was, in fact, more aggressive in tread design than tire Z, the icing effect occurred at a much higher rate of slip.

Traction test data were averaged by using the upper 30 percent of the longitudinal force values. The 30 percent cut-off was chosen to represent a range of slip values that could reasonably be maintained by a vehicle operator. Each traction value (10 per second) was divided by its corresponding vertical force value measured concurrently during the test run. The resulting dimensionless number is the net traction per unit vehicle weight, similar in concept to the well-known drawbar pull/weight factor, differing in that there is no drawbar effect included.

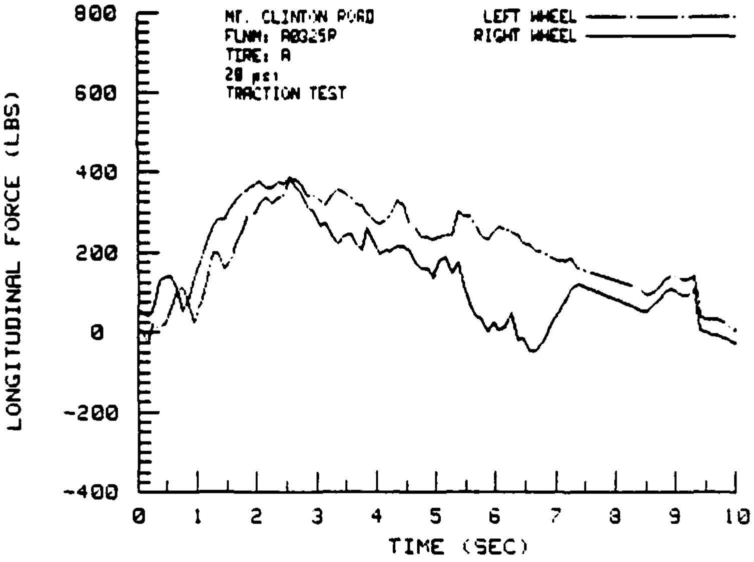


Figure 86. Longitudinal force plot for packed snow traction test, tire A.

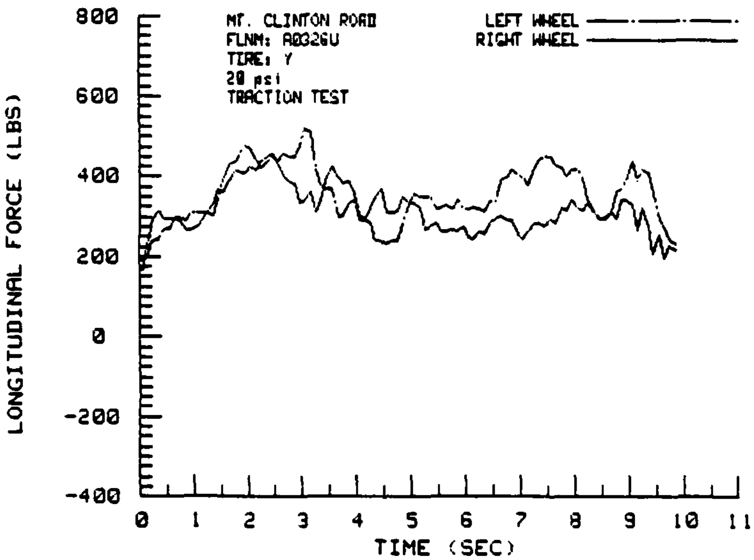


Figure 87. Longitudinal force plot for packed snow traction test, tire B.

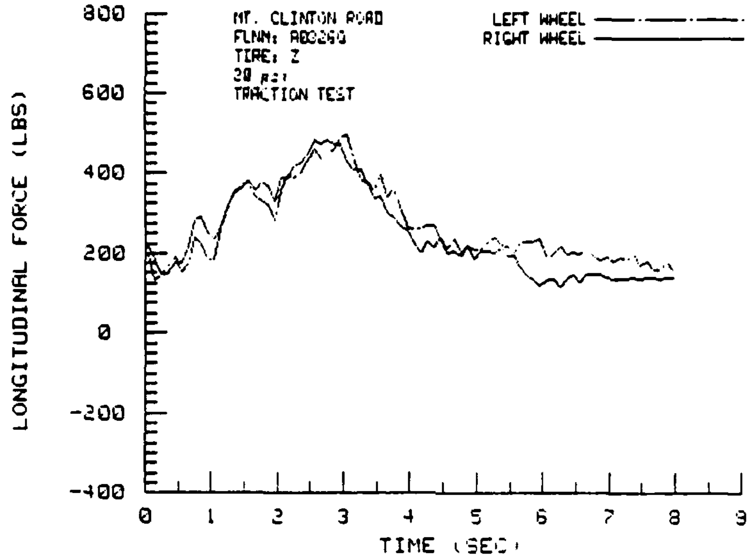


Figure 88. Longitudinal force plot for packed snow traction test, tire C.

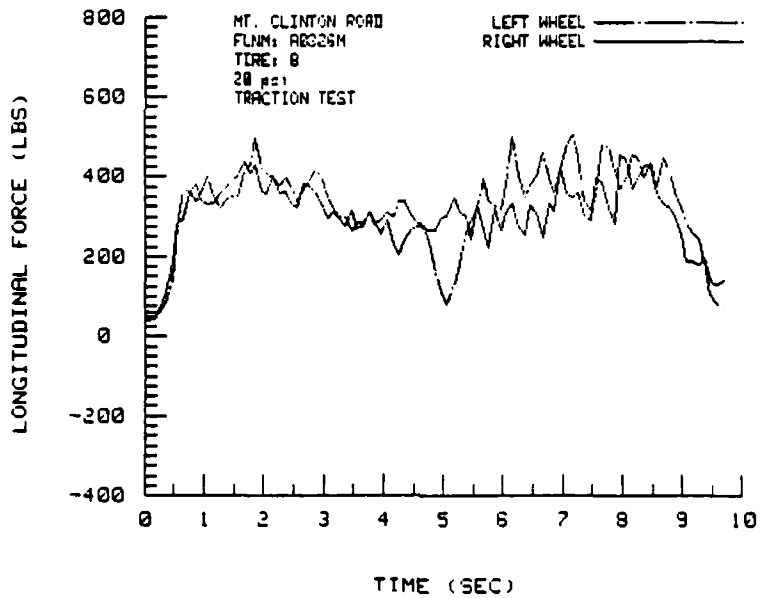


Figure 89. Longitudinal force plot for packed snow traction test, tire D.

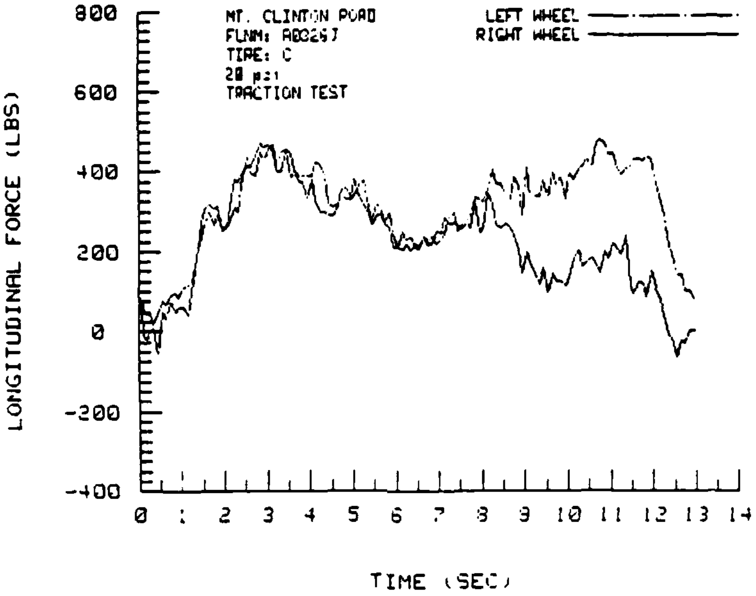


Figure 90. Longitudinal force plot forpacked snow traction test, tire Y.

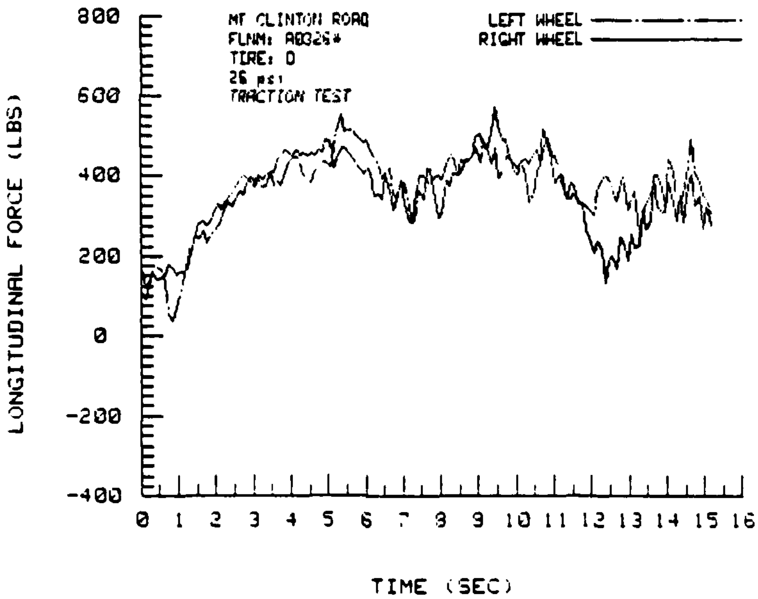


Figure 91. Longitudinal force plot for packed snow traction test, tire Z.

Figure 92. Increasing rut depth developed with increasing tire slip.

Traction test data for ice (CRREL dock area), wet snow (Garipay field, Hanover, New Hampshire) and packed snow (Bretton Woods, New Hampshire) are presented in Figures 93-97. Tests proceed chronologically during the day across the figures from left to right.

Ice tests were performed in a large asphalt-covered area on the CRREL grounds. The ice was made by towing a water tank equipped with a sprinkler bar over the area. The water was applied to the pavement in late evening and allowed to freeze overnight.

Venturing some discussion on the ice data (Fig. 93), it appears that reduced inflation pressures result in a lower tractive coefficient. In each case (tire A being the exception) a reduction in inflation pressure decreased the maximum longitudinal force developed.

In terms of ranking, it appears from Figure 93 that the three military tires (tires Y and Z were not available until 25 March 1981) were able to generate a slightly higher tractive force than the commercial tire D. It also appears that tires B and C outperformed tire A. Quite possibly the aggressive "thicker tread tires" (higher inflation pressures also) were able to scrape away the thin ice

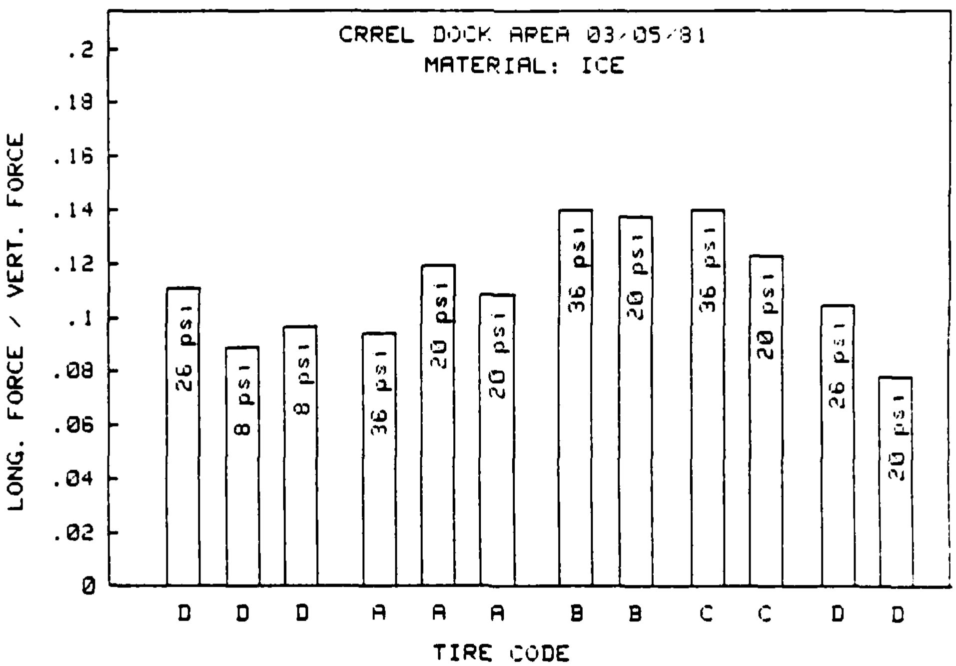


Figure 93. Traction test data, 5 March, ice.

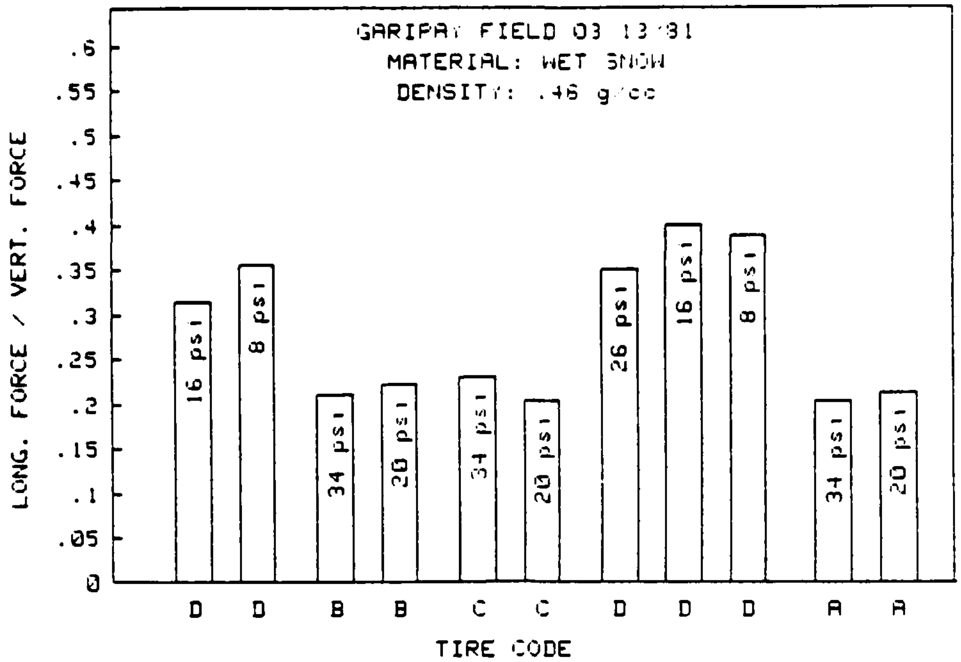


Figure 94. Traction test data, 13 March, wet snow.

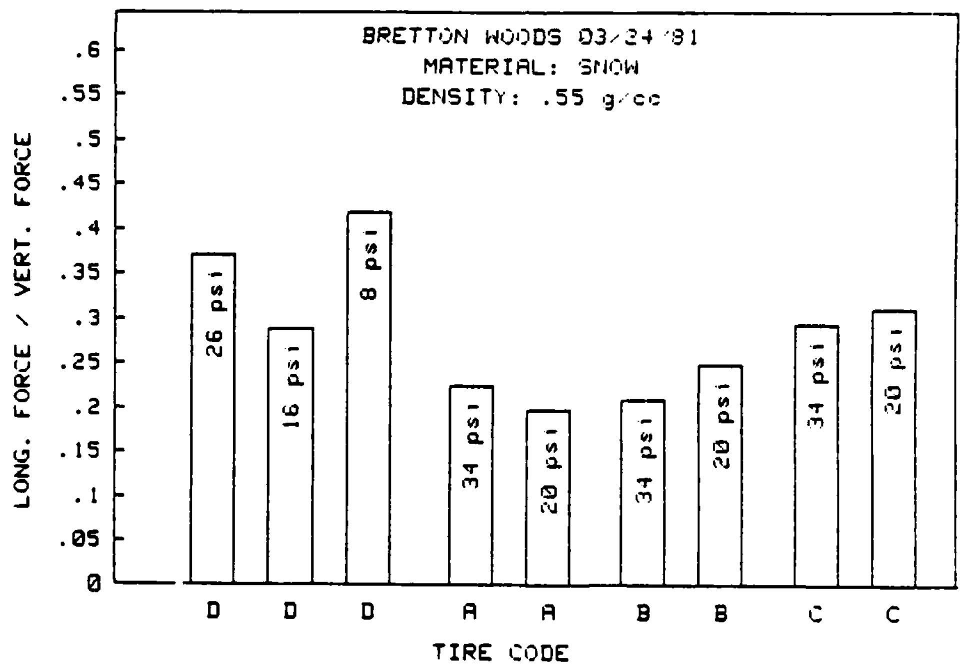


Figure 95. Traction test data, 24 March, packed snow.

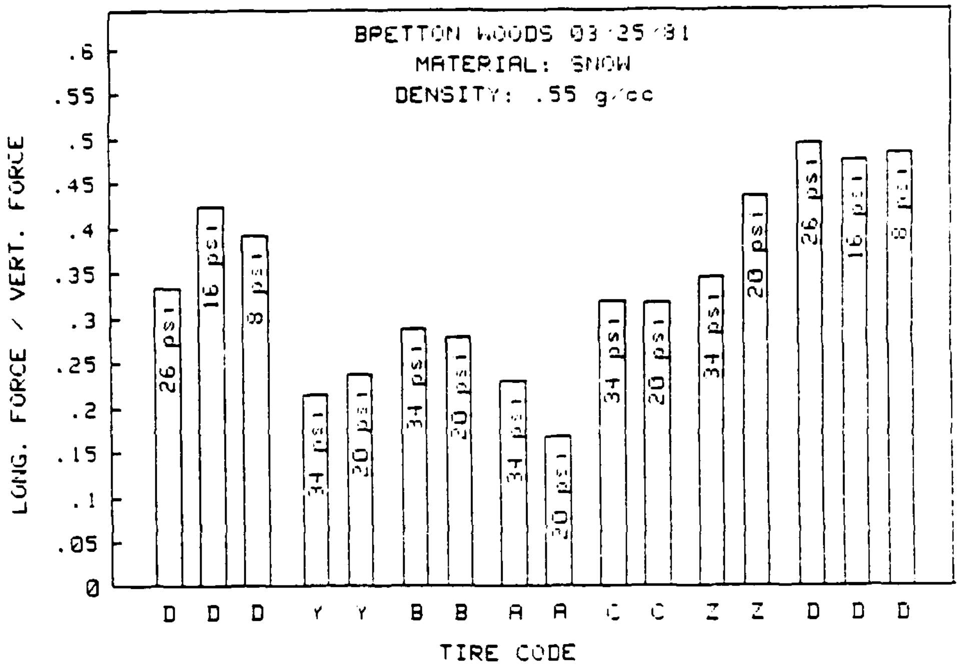


Figure 96. Traction test data, 25 March, packed snow.

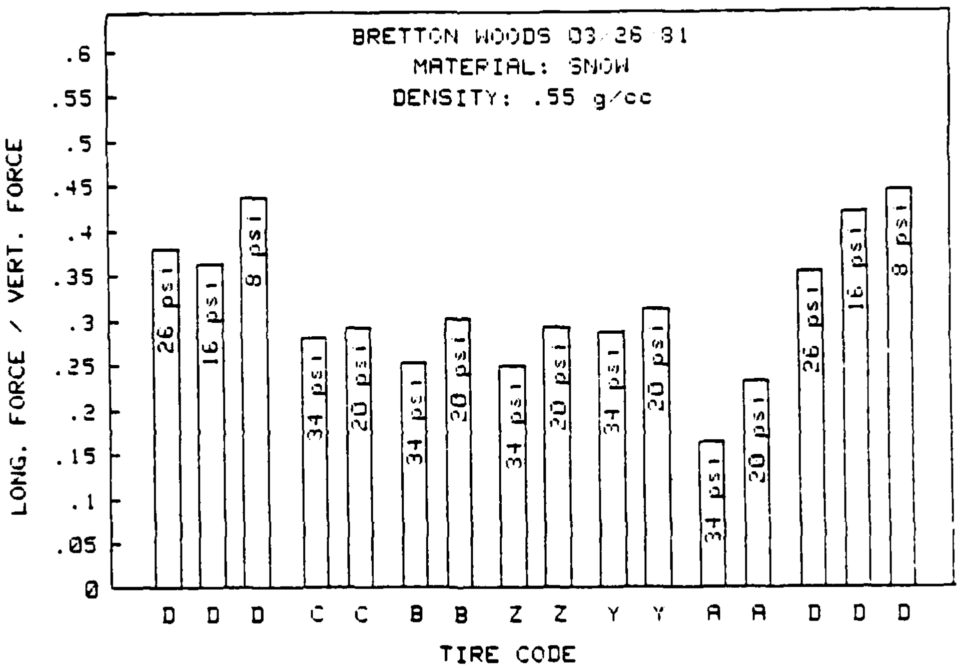


Figure 97. Traction test data, 26 March, packed snow.

layer to a degree, resulting in some tractive advantage. More comprehensive tests are planned for the coming winter (1981-82) when temperatures are sufficiently low enough to maintain a reasonable depth of road ice.

Traction tests on wet snow were performed in Hanover, New Hampshire, on a snow-covered grass field. Air temperatures were near 0°C during and prior to the testing period which resulted in saturated snow with a 0.46-g/cc density. The test course was prepared by multiple passes with a snow machine pulling a wire mesh drag.

Wet snow traction test data (Fig. 94), contrary to the ice data, generally shows an increase in the longitudinal force with decreasing tire inflation pressure.

Performance ranking was reversed, relative to the ice tests, in wet snow. Tire D show the ability to generate a significantly higher tractive force. Tires A, B and C all appear to perform nearly equal.

Data collected on packed snow is illustrated in Figures 95-97. The test course was a country highway which was closed to traffic during the winter season. The road was maintained with a snow grooming machine for cross country skiers and snow machines. The snow was dry but packed by traffic and grooming to a 0.55-g/cc density and had a 13-cm thickness.

The packed snow data support the data of increased traction with reduced tire pressure which was noted in wet snow. Tests from 26 March (Fig. 97) all show this trend. The packed snow data indicates that tire D was able to generate the greatest tractive forces while tire A was consistently the poorest performer. The 26 March data (Fig. 97) suggests that tires B, C, Y and Z all perform at about the same level. This was noted in the wet snow data (Fig. 94) for tires B and C and in the 24 March data (Fig. 95) as well. The 25 March data (Fig. 96) shows tires C and Z developing notably higher traction coefficients. This may be the effect of changing test course conditions (as the day became warmer) rather than actual differences between tires. Evidence for this is shown by the fact that the tests run with tire D at the end of the test day resulted in better tractive coefficients than at the beginning of the day.

Summarizing the traction test results, reduced inflation pressures give increased tractive coefficients in snows with densities greater than 0.46 g/cc. Comparative tire performance results indicates that tire A is a poor choice for both ice and snow conditions. Tires B and C perform quite similarly on both ice and snow. Tires Y and Z yield results comparable with tires B and C in snow. (No ice tests were performed for tires Y and Z.) Tire type D shows superior performance in snow but only average or "tire A-level" results for ice. Aggressive tread tires (A, B, C, Z) show considerable rut formation during slip when performing traction tests, which leads to lower traction force values. The non-aggressive tread patterns (D, Y) showed little or no rut formation but tended to generate an ice patch when the degree of wheel slip became high.

The obvious limitation of these tests is the lack of sufficient tests to make definitive statements about each tire's relative performance. This is especially true for ice. In addition, a broader range of snow and ice types need to be addressed as well as the aforementioned thawing soil regime.

A complete series of tests, which will include the six tires used in this initial study, will be conducted during the coming winter test season (1981-82). The CIV hardware and software have been modified and completed, in order to overcome some of the limitation in recording and data analysis experienced in the initial tests. Specifically, the inclusion of wheel speed/distance and vehicle speed/distance signals directly into the data logger will allow for more comprehensive comparisons.

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SOME OBSERVATIONS ON TIRE TECHNOLOGY FROM THE ITALIAN ARMY

General Valentino Romano Corpo Tecnico Esercito Italiano, Via Antonio Scarpa 18, 00161 Roma, ITALY

I perceive some problems that have surfaced from the comments at the end of the very interesting presentation of tire testing methods. These problems pertain to the characteristics and properties we expect or desire to provide improvement in tire performance under winter conditions. The problems have their origin in the past differences in the conditions referring to predicted use. Furthermore, for many types of special tires, in addition to usage in off-road missions, we intend them to be used over usual road conditions.

Based on these expectations, we can make two observations: the first concerns the structure and the second the design of the tread.

Modifications of the structure of tires can offer different resultant possibilities. As an example, I refer to the radial tires the Italian Army adopted 15 years ago. It is well known that radial tires appeared as a type of tire with a lower rolling resistance, a longer life and reduced fuel consumption requirements. These qualities are much appreciated in civilian practice both for motor cars and, in general, for most road transportation vehicles. Nevertheless, Italian military technicians have been primarily interested in some qualities such as: a) a more uniform specific pressure distribution on the ground, b) a better deflection response of the tire on the soil, and c) increased tire durability with lower-than-normal tire inflation pressures. As one knows, these are the characteristics peculiar to radial tires. The good results of tests performed have produced the almost generalized adoption of this type of tire in the Italian Army transport vehicles, and it is pertinent to note that we have no report of troubles to date. I mentioned the above as an example of innovation in the construction of tires, which seems to have produced good results; also in reference to different applications (civilian and military). Some years ago I sent a report on this subject to the USA TACOM.

As for the tread for commercial highway tires, the little modifications made have also produced psychological, advertising and "fashion" effects.

With reference to experience in military testing, the Italian Army believes that, in the case of usual road tires, great differences are not expected in connection with different tread designs. However, in the field of special tires, as off-road tires for military purposes or snow tires or agricultural tires, differences in tread design offer great improvements. However, they obviously decrease the qualities of the tire in usual use on roads (life of tire decreases and fuel consumption goes up).

There are also great differences between off-road tires for military transport vehicles and special tires for snow environments. For instance, in commercial snow tires, we see also in Italy, in accordance with land locomotion, a much smaller spacing between tread elements than in the tread elements of military off-road tires. Theidea of the "optimum" compromise is an illusion.

In conclusion, I suppose it is very unlikely that a suitable compromise in the tread design of commercial tires can be achieved in order to improve their off-road performance.

SESSION IV: PREDICTIVE PERFORMANCE MODELING

The purpose of this session was to discuss the current analytical empirical and correlative methods used to predict performance levels of tires as influenced by the properties of snow and ice. It became apparent, however, that within the commercial tire industry and market, either little actual prediction of tire performance is done or tire performance modeling and prediction is shrouded in secrecy. Some mention is made in paper 4 of Session II (Evaluation of empirical tread design predictions of snow tractionas measured with a self-contained traction vehicle) of predicting performance levels, but it appears that testing and its evaluation certainly overshadowed modeling.

For the military, however, to succeed in its task of providing national defense, it is vital to be able to predict performance for *many different vehicle, terrain and weather scenarios. Though still* at the beginning stages of understanding tire performance on ice and snow for modeling and predicting purposes, the Army is taking steps (as reported in the last session) to include tire behavior in its mobility assessments. Eventually, tire performance prediction techniques for cold regions materials will be obtained and fully incorporated into Army mobility modeling.

In lieu of the panel discussion originally planned for this session, a brief description of the NATO Reference Mobility Model (NRMM, an extensive program which utilizes as many vehicle and terrain parameters as possible for mobility prediction) was presented. Also, since informal discussions among several workshop attendees indicated interest in the Waterways Experiment Station dimensional analysis (numeric) approach to describing in-soil tire performance, some key results obtained by this method were also presented.

THE NATO REFERENCE MOBILITY MODEL AND THE WES DIMENSIONAL ANALYSIS METHOD OF DESCRIBING TIRE PERFORMANCE

Mr. Gerald Turnage U.S. Army Engineer Waterways Experiment Station, Mobility Research Section, P.O. Box 631, Vicksburg, Mississippi, U.S.A. 39180

As we near the close of this workshop, it is clear that the most important general benefits to all workshop participants have been the mutual understanding and appreciation of recent work by a number of agencies in measuring and evaluating tire performance under winter conditions. From the military perspective, certainly the most important single benefit--and hopefully a breakthrough--has been the unanimous endorsement by the workshop's participants of the Army Basic Criteria for Tires (ABCT) to serve not as a final document, but as a reasonable strawman to promote close cooperation between the U.S. Government and the U.S. tire/vehicle manufacturing communities in producing the best possible tires for our military needs.

In addressing those of you representing the U.S. tire/vehicle manufacturing community, I can assure you that in producing tires which will best satisfy our wheeled vehicle military performance requirements, you will have to consider a very broad range of operational environments and scenarios. You will come to appreciate very quickly, I believe, that in addition to your extensive efforts, many man-years of effort by other investigators have also been expended to develop objective, detailed, mathematicalmodels of the performance characteristicsof military wheeled vehicles operating both on- and off-road. Probably the mostcomprehensive and almost certainly the best field-validated and most internationally accepted among these models is the NATO Reference Mobility Model (NRMM),which I will now briefly describe.

The NRMM is the product of research and field validation efforts conducted by a number of agencies over many years. Figure 98 illustrates a few of the many steps involved in this development process during "modern" times; i.e., during about the last 20 years.

In 1964, representatives of the U.S. Army Tank-Automotive Command (TACOM, somewhat differently named then), WES, the U.S. Army Materiel Command (AMC, now DARCOM), the Office, Chief of Engineers (OCE), the Office, Chief of Research and Development (OCRD), and Wilson, Nuttall, Raimond, Engineers, Inc. (WNRE, a private consulting firm) met largely at the insistence of Mr. R.R. Philippe, AMC, to conduct what came to be called Mobility Exercise A (MEXA). The primary purpose of MEXA was to "design a number of vehicle test bed concepts that could operate in remote areas of the world where extremely soft soil conditions predominate...."[1] Three vehicles (two wheeled and one tracked) were designed, built, and tested which a) validated the state of the art in terms of producing vehicles to negotiate extremely soft soils, and, just as important, b) included in their design the best features of what at that time were considered by many to be two largely incompatible research approaches--the TACOM Land Locomotion Laboratory's largely theoretically-oriented approach and WES's primarily semiempirically-oriented approach. Objectives a) and b) both were achieved, and Mr. Bob Philippe deserves considerable credit for bringing together two largely divergent philosophies of soil/vehicle mechanics to bear on an important real-world vehicle

1964:	MEXA (Mobility Exercise A)
1966-68:	MERS (Mobility Environmental Research Study)
1971:	ANAMOB (Analysis of Ground Mobility Models)
1971:	AMC 71
1974:	AMC 74 Versions of AMM
1975 to Now:	AMC 74X
June 1977:	AMM Conditionally Accepted as NRMM, Edition 1
May 1978:	(1) AMM Officially Accepted as NRMM, Edition 1
	(2) Technical Management Committee (TMC) of NRMM Formed (Haley, TACOM)
October 1979:	NRMM, Edition 1 published (Users Guide, Computer Programs, Obstacle-Crossing Module)

Figure 98. The NATO Reference Mobility Model (NRMM)--a little history.

design problem. TACOM/WES cooperation in vehicle mobility research showed immediate and dramatic improvement and remains excellent today.

During 1966-68, the WES eight-volume series of reports developed under the Mobility Environmental Research Study (MERS) produced field-validated, quantitative methods of describing terrain in terms applicable to the prediction of off-road vehicle mobility performance. In 1971 (Rula and Nuttall), the WES Analysis of Ground Mobility Models (ANAMOB) report,[3] made a comprehensive survey and analysis of then-existent vehicle mobility prediction models to determine the best features of available models and to develop guidelines for future development of ground mobility models.

Largely as a result of the ANAMOB study, the first version of the vehicle mobility model that has evolved today into NRMM was developed in 1971: AMC 71 (named after the principal financial supporter of WES vehicle mobility research work up to 1971). Steady improvements have been made in the model over the years, primarily in terms of a) expanding the capabilities of the model to handle additional vehicle/terrain and vehicle/road conditions, and b) modifying the model to reflect the real-world results of ad hoc model applications and of special field validation tests. These improvements produced, in turn, AMC 74 and AMC 74X. AMC 71, AMC 74, and AMC 74X are each versions of the Army Mobility Model (AMM), the name by which the model is called today.

In June 1977, AMM was conditionally accepted as the initial model of NRMM, pending improvements in certain of AMM's submodels. In May 1978, AMM was officially accepted as the "Initial NATO Reference Mobility Model," and the Technical Management Committee (TMC) of NRMM was formed. Mr. Peter W. Haley, TACOM, was named TMC manager of the model to serve as "the focal point for the uniform maintenance of the model and as custodian of the official version."

In October 1979, the "NATO Reference Mobility Model, Edition I, Users Guide, Volumes I and II,"[4] was published. This report provided a) narrative descriptions and equations defining the predictive relations in NRMM, b) a listing of the instructions for all computer programs in NRMM, and c) a description of the NRMM obstacle module (which mathematically defines the mechanics of wheeled and tracked vehicle override of discrete obstacles).

For those unfamiliar with the general characteristics of NRMM, Figures 99 and 100 describe in qualitative terms some of NRMM's properties--some of the things that NRMM is and some of the things it is not. Generally, Figures 99 and 100 say that NRMM is a detailed, com-

- It is a comprehensive mathematical model of a complex system--it describes major aspects of mobility performance for essentially any wheeled and/or tracked vehicle operating in nearly any on- or off-road environment.

- It is a mix of analytical, empirical, and correlative methods, nearly all of them validated by field testing over a wide range of conditions.

- It is capable of describing vehicle mobility performance at the nuts-and-bolts level for design purposes (influence of tire size, track width, etc.) up to the overall vehicle level (vehicle GO/NOGO, tractive force, speed-made-good, etc.).

- It is extensive and complex. The Users Manual is 174 pages long and the computer programs that implement NRMM are longer still, over 200 pages. (To place this in perspective, the Users Manual uses slightly less than two pages to describe wheeled and tracked vehicle performance in shallow snow.)

Figure 99. NRMM--some things that it is.

- It is not perfect (and never will be).

- It is not complete--i.e., it won't predict every type of vehicle performance in every environment (and it never will).

- It is not judged in a restricted arena--i.e., its predictive relations are scrutinized by a number of participating user agencies (in the U. S., Canada, France, the Federal Republic of Germany, the Netherlands, and the United Kingdom) as well as by customers for whom the model is applied (well over 200 projects involving several hundred vehicles since AMM was accepted as NRMM).

Figure 100. NRMM--some things that it is not.

prehensive, computerized mathematical model that incorporates relations backed by a broad range of real-world validation studies and successful ad hoc applications involving a large number of NRMM users and customers. Today's NRMM, while not perfect and not all-inclusive, can describe many important aspects of vehicle on- and off-road mobility performance accurately and in detail from the nuts-and-bolts level up to the overall vehicle level.

To set in perspective the comprehensiveness of NRMM, particularly in relation to the purpose of this workshop session, note the observation at the bottom of Figure 101. The NRMM Users Guide is 174 pages long, and NRMM mobility prediction relations for wheeled and tracked vehicles operating in shallow snow are described within that manual in slightly less than two pages. The somewhat limited description on those two pages does not reflect that NRMM considers vehicle performance in snow and ice relatively unimportant--in fact, the accurate prediction of such performance is recognized to be vitally important for many large areas around the world. What is reflected primarily by the short NRMM description of in-snow vehicle performance is dearth of real-world vehicle in-snow test

Gross traction coefficient (from Coulomb equation):

$$\frac{H_i}{W_i} = \tan \phi + \frac{CA_{ij}\ n_i}{W_i}$$

where H_i = gross traction force on wheel assembly i

ϕ = apparent angle of internal friction

c = apparent cohesion

A_{ij} = individual tire ground contact area on assembly i at inflation j

n_i = number of wheels on assembly i

W_i = weight supported by assembly i

Resistance to motion coefficient (based on a dimensional analysis of the force required for bulk movement of snow):

$$\frac{R_i}{W_i} = \frac{10}{N} \cdot \frac{n_i\ b_i}{d_i} \cdot \frac{\gamma z_s}{\ell_{ij}}$$

where R_i = resistance to motion of wheel assembly i

N = total number of wheel axles on vehicle

b_i = section width of each tire on assembly i

d_i = diameter of each tire on assembly i

γ = specific weight of snow

z_s = depth of snow

ℓ_{ij} = characteristic (chord) length of tire on assembly i at inflation $j = 2\sqrt{\delta_{ij}\ d_i - \delta_{ij}^2}$

δ_{ij} = deflection of tire on assembly i at inflation j

Pull coefficient

$$\frac{DP_i}{W_i} = \frac{H_i}{W_i} - \frac{R_i}{W_i}$$

where DP_i = pull developed by wheel assembly i

Figure 101. NRMM description of tire performance in shallow snow.

- All input data required by NRMM to describe the vehicle, terrain, and driver are read in.
- Appropriate input scenario and field operational conditions are specified.
- Terrain in the area of interest is mapped in the computer in terms of class values of each of the input terrain variables. Then, the area is divided into terrain units (TU's), each one of which is different from its neighboring TU's in terms of having one or more of its terrain class values different from each of its neighbors.
- Vehicle performance is predicted for each TU, and performance across TU's is computed according to logic built into the areal (off-road) module or the road module.
- Vehicle GO/NOGO, and, if GO, vehicle speed, are usually the primary performance measures to be predicted. (In arriving at these predictions, NRMM computes a number of other useful measures of performance--available vehicle tractive force, vehicle obstacle override force, etc.)

Figure 102. Some general characteristics of how NRMM works.

data that have been reported in quanitative vehicle and snow property terms that lend themselves to validating a vehicle mobility predictive system.

Figure 103 illustrates the predictive relations that NRMM presently uses to describe tire performance in shallow snow. In NRMM, wheeled vehicle performance is predicted in terms of "pull and resistance coefficients for each suspension assembly (which are later summed for the vehicle as a whole) when the scenario variables indicate that the terrain unit is covered by a shallow layer of snow." Shallow snow as considered by NRMM is snow covering frozen ground to a depth less than the characteristic length of the tire defined as ℓ_{ij} under "Resistance to motion coefficient" in Figure 103). In typical applications of the predictive relations in Figure 103, snow is described as belonging to one of five classes (new, old, wet, dry, or packed), and tabled values of c, ϕ, and γ (the three snow properties included in the predictive relations of Figure 101 are applied according to snow class.

The predictive relations in Figure 101 were developed by MR. C.J. Nuttall, Jr., of WES, and are based largely on his extensive experience in vehicle mobility research. While reasonable results have been obtained in each application of these relations in many ad hoc studies, the range of conditions that the relations treat is admittedly somewhat limited, as is the quantity of field validation data backing the relations. Expansion and improvement of the relations in Figure 101 are welcomed, with the major test of acceptable changes being proof of improvement in terms of better correlation with field-validated, in-snow tire (and wheeled vehicle) test data.

To this point, we have considered only some rather general characeristics of NRMM as a whole and some fairly detailed characteristics of NRMM's description of wheeled vehicle performance in shallow snow. To be somewhat more specific about how NRMM predicts vehicle mobility performance in nearly any type of on- or off-road environment, we might ask, "So how does NRMM work?" This question is answered starting in Figure 102.

NRMM requires in its input data base detailed, quantitative, standardized descriptions of those vehicle, terrain, and driver attributes shown in Table 26. To expand slightly on the Table 26 descrip-

Table 26. Vehicle, terrain, and driver attributes characterized in the NRMM data base.

Vehicle	Terrain
Geometric characteristics	Surface composition
Inertial characteristics	Type
Mechanical characteristics	Strength
	Surface geometry
	Slope
	Discrete obstacles
	Roughness
	Vegetation
	Stem size and spacing
	Visibility
	Linear geometry
	Stream cross section
	Water velocity and depth

Driver
Reaction time
Recognition distance
Vertical acceleration limit
Horizontal acceleration limit

tion and to set in some perspective the detail required by the NRMM data base, note first that NRMM presently processes up to 104 vehicle input variables, each one of which is defined in considerable detail. Some 90 input variables are required to define a wheeled vehicle, 87 to define a tracked vehicle, and the full 104 to define a combination wheeled/tracked vehicle. Second, note that terrain in NRMM is described as being either off-road or on-road, with off-road terrain being further delineated as either areal terrain (terrain with a potentially wide variety of physical impediments to vehicle motion that are spread over a relatively broad land area) or linear features (terrain with geometrical and sometimes water-carrying impediments to vehicle motion that are concentrated in land features of relatively narrow cross section and considerable length--rivers, streams, dikes, etc.). NRMM on-road terrain (superhighways, primary roads, and trails) is described by soil type and strength (for trails), urban code, slope, (driver) recognition distance for the four seasons of the year, surface roughness, AASHO curvature speed limit, and road segment length. Third, note that NRMM input values of driver reaction time, recognition distance, and acceleration limits (vertical and horizontal) are accurate approximations based primarily on extensive real-world validation testing of drivers under a very broad range of field conditions and operational scenarios.

Figure 102 shows that the user of NRMM, having input the required descriptions of the vehicle(s), terrain, and driver(s) involved, next completes the description of the operational situation at hand by inputting those scenario and field conditions which cause NRMM's implementation to most closely fit the real-world conditions being approximated. Included among these use-controlled operational conditions are driver visibility limits, on-road vehicle speed limits, tire pressure selection to match on- and off-road conditions, driver (ride) roughness acceptance level(s), etc.

Having received its full complement of input data, NRMM next maps the input terrain data into digitally defined geographical areas called terrain units (TU's). Each TU has a particular set of off-road or on-road terrain factor class values (see Table 27) that differs from those of each neighboring TU in terms of

Table 27. Terrain data required for NRMM.

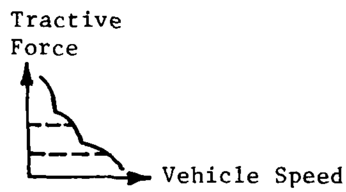
Terrain or Road Factor	Description*	Range	No. of Factor Classes
	Off-Road		
1. Surface material			
a. Type	USCS/other	NA	4
b. Mass strength	CI or RCI	0 to >280	11
c. Wetness	NA	NA	4
2. Slope	Percent	0 to >70	8
3. Obstacle			
a. Approach angle	Degrees	90 to 270	14
b. Vertical magnitude	cm	0 to >85	7
c. Length	m	0 to >150	7
d. Width	cm	0 to >120	5
e. Spacing	m	0 to >60	8
f. Spacing type	NA	NA	2
4. Surface roughness (× 10)	rms, cm	0 to >7.5	9
5. Stem diameter	cm	0 to >25	8
6. Stem spacing	m	0 to >20	8
7. Visibility	m	0 to >50	9
8. Left approach angle (LA)	Degrees	90 to 270	20
9. Right approach angle (RA)	Degrees	90 to 270	20
10. Differential bank height or differential vertical magnitude (Δ)	m	0 to >4	9
11. Base width or top width	m	0 to >70	21
12. Low bank height or least vertical magnitude (LBH)	m	0 to >6	8
13. Water depth (D)	m	0 to >5	6
14. Water velocity	mps	0 to >3.5	6
	On-Road		
15. Surface material			
a. Type	NA	NA	4
b. Surface strength	CI or RCI	0 to >280	11
16. Slope	Percent	0 to 50	8
17. Surface roughness (× 10)	rms, cm	0 to 4	9
18. Curvature	Degrees	<140 to 180	9
19. Visibility	m	0 to 91.4	9

* NRMM can accept terrain and other data in either English or metric units of measurement. Data preprocessors in NRMM convert values of all input data to the inch-pound system before calculations involving these data occur.

Vehicle GO/NOGO for operation in fine-grained soil or in coarse-grained soil or in muskeg is computed from Vehicle Cone Index (VCI) relations.

Vehicle speed in areal (off-road) terrain is predicted by 21 NRMM subroutines, each of which either:

- Degrades vehicle speed indirectly by subtracting from available tractive force the tractive force required for a given vehicle operation (traveling through soft, fine-grained soil, overriding an obstacle, traveling over rough ground, etc.).



OR

- Degrades vehicle speed directly by imposing speed restraints due to other causes (visibility limitation, driver-dependent vehicle vegetation override check, etc.).

Figure 103. General characteristics of how NRMM predicts vehicle GO/NOGO and speed.

one or more class values. NRMM first predicts vehicle mobility performance within each TU, and then predicts performance across TU's using logic built into the NRMM off-road and on-road vehicle performance prediction modules.

The primary vehicle performance measures of usual interest in NRMM applications are vehicle GO/NOGO and, if GO, vehicle speed. In the process of predicting these types of performance, however, NRMM also computes a number of other useful measures of vehicle performance, a partial listing of which is illustrated in Table 28 for the NRMM areal (off-road) module, for example.

As shown in Figure 103, GO/NOGO for vehicle operation in fine-grained soil, in coarse-grained soil or in muskeg is predicted by NRMM using Vehicle Cone Index (VCI) relations. For example, $VCI_{1(fg)}$--the soil strength in terms of cone index* that is just sufficient for one vehicle pass in a fine-grained soil--is mathematically defined by relations that include nine factors. The definition of $VCI_{1(fg)}$ was developed from the results of field tests of literally hundreds of wheeled vehicles conducted over a number of years, and accounts for the influence on vehicle GO/NOGO performance of vehicle contact pres-

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* Cone index (CI) is the force per unit cone base area required to penetrate a soil vertically to a specified depth (often taken as 6 in.) at 72 in/min with a right circular cone of 0.5-sq-in^2 base area. CI has implied units of psi. The equivalent of CI in metric units is soil penetration resistance (C), in units of kPa.

Table 28. Some of the measures of vehicle performance predicted by the areal module of NRMM.

Speed Reduction Factor Due Vegetation Avoidance

Effective Obstacle Spacing

Tree Density for all Stem Classes

Speed Reduction Factor Due obstacle and Vegetation Avoidance

Obstacle Override/Avoidance Strategy Indicator:
1. Choose to Override
2. Never Override Due Belly/Axle Interference with Stumps and Boulders
3. Never Override Due Lack of Penalty for Avoidance

Water Depth Go-No-Go Indicato

Vehicle Floating/Fording Indicator

Vehicle Buoyancy Weight

Water Drag Resistance

Selected Floating Vehicle Speed in Marsh

Assembly Soil Drawbar Pull and Motion Resistance Coefficients
A. Soil
   1. Fine grained
   2. Coarse grained
   3. Muskeg
   4. Snow

B. Coefficients
   1. Powered or Braked Pull
   2. Powered or Braked Resistance
   3. Towed Resistance

Summed Vehicle Assemblies' Pull and Resistance Coefficient
1. Powered Pull
2. Powered Resistance
3. Braked Pull
4. Braked Resistance
5. Non-powered Resistance
6. Non-braked Resistance

Soil Limited Maximum Tractive Effort

Net Force/Weight Slip Adjustment Factor

Soil Running Gear Slip at Net Force/Weight Ratio

Tractive Effort Modified for Slope/Soil Running Gear Slip
1. Gear by Gear Velocities Modified for Slip
2. Gear by Gear Tractive Effort - Up, level, Down slope
3. Maximum Tractive Effort - Up, Level, Down slope
4. Speed at Maximum Tractive Effort
5. Coefficients for Curves Fitted to Tractive Effort vs. Speed Curve

Vegetation Resistances for Overridden Stem Classes
1. Single Tree
2. Maximum Due Impact
3. Average Multiple Trees

Driver Limited Stem Class for Override

Total Resistance on Slope Overriding Multiple Trees
Total Resistance on Slope Override Single Tree

Maximum Velocities Limited by Soil/Slope/Vegetation
1. Three slopes: up, level, down
2. Nine stem classes
3. Total - 27 Velocities Between Obstacles

Speed Limited by Surface Roughness

Total Soil/Up, level, down slope/Vehicle Braking Force

Braking Force Go-No-Go Indicator

Driver Limited Braking Force - Up, level, down slope

Speed Limited by Visibility - Up, level, down slope

Selected Speeds Between Obstacles Overriding vegetation

Up, level, down slope
Total - 27, limited by:
1. Tires
2. Soil/Slope
3. Visibility
4. Ride

Maximum Selected Speeds Between Obstacles Overriding and Avoiding Vegetation, total - 27

Maximum Selected Speeds Avoiding Obstacles but Overriding Vegetation, Total - 27

Average Force to Override Obstacle

Maximum Force to Override Obstacle

Override/Avoidance Strategy Indicator Addition:

Never Override Due to Determined

Obstacle Interference

Driver Limited Speed Contacting Obstacle

Obstacle Approach Velocities Up, Level, Down, Overriding and Avoiding Vegetation, Total - 27

Obstacle Exiting Velocities Up, Level, Down, Overriding and Avoiding Vegetation, Total - 27

Average Speed Up, Level, Down Slope, Overriding and Accelerating/Decelerating Between Obstacles, Overriding and Avoidin Vegetation, Total - 27

Possible New Obstacle/Vegetation Override and Obstacle Avoidance/Vegetation Override Speeds Due Kinematic Force Vegetation Override Check, Total - 54

Final Selected Average Patch Speed Based on Decision Strategy:
Override Obstacles
Avoid Obstacles

sure, vehicle weight, tire size, grousers (chains), wheel load, vehicle clearance, engine (hp/ton), transmission type, and tire deflection (which is related to tire inflation pressure).

If the cone index (soil strength) of a given areal off-road terrain unit is greater than VCI_1, then vehicle speed within that terrain unit is predicted as a function of 21 subroutines within NRMM's areal module. The titles of these 21 subroutines, listed in Table 29, give an indication of the range of off-road impediments to vehicle mobility that are modeled by NRMM. As illustrated in Figure 103, these subroutines either a) degrade available vehicle tractive force by subtracting the tractive force required for a given in-soil vehicle operation, thus reducing the vehicle speed that can be achieved, or b) degrade vehicle speed directly by imposing driver-controlled

Table 29. Vehicle performance prediction subroutines of the NRMM areal module.

1. Obstacle Spacing and Area Denied
2. Land/Marsh Operating Factors
3. Pull and Resistance Coefficients
   a. Fine-Grained Soil
   b. Coarse-Grained Soil
   c. Muskeg
   d. Shallow Snow
4. Summed Pull and Resistance Coefficients
5. Slip-Modified Tractive Effort
6. Resistance Due to Vegetation
7. Driver-Dependent Vehicle Vegetation Override Check
8. Total Resistance Between Obstacles
9. Speed Limited by Resistance Between Obstacles
10. Speed Limited by Surface Roughness
11. Total Braking Force--Soil/Slope/Vehicle
12. Maximum Braking Force--Soil/Slope/Vehicle/Driver
13. Speed Limited by Visibility
14. Selected Speed Between Obstacles
15. Maximum Speed Between and Around Obstacles
16. Obstacle Override Interference and Resistance
17. Driver-Dependent Vehicle Speed Over Obstacles
18. Speed Onto and Off Obstacles
19. Average Terrain Unit Speed While Accelerating/Decelerating Between Obstacles
20. Kinematic Vegetation Override Check
21. Maximum Average Speed

vehicle speed restraints (caused by visibility limitations, vegetation override considerations, etc.).

Overall, NRMM describes nearly all terrain, either natural or modified by man, and predicts vehicle mobility performance quantitatively in this terrain by using relations that, in nearly every case, are backed by extensive field validation. Furthermore, NRMM describes vehicle mobility performance both on- and off-road in considerable detail, as indicated, for example, by the listing in Table 28 for areal (off-road) terrain.

It is emphasized, however, that in the proposed cooperative effort between the military and tire/vehicle manufacturer communities to provide the best possible military tires, the NRMM is <u>not</u> envisioned as competing with the tire/vehicle manufacturing community in providing tire design expertise. NRMM can serve as a very useful, in fact an almost indispensable, first filter to determine the <u>general</u> tire design characteristics (tire size, geometry, deflection, etc.) that are required to satisfy a particular military vehicle mission profile. Such a profile, often provided in rather nonterrain-specific terms (percent travel on-road, off-road, and on-trails, for example), can be made much more specific by NRMM (Mid-East, Federal Republic of Germany, South Korea, etc.) as appropriate for the mission profile. Using such a terrain-specific profile, and the vehicle performance requirements set by the military user, NRMM can be exercised in iterative fashion to define, within reasonably narrow limits, the general charac-

Relative to NRMM, WES has:

- Had major input to nearly all parts of the formulation of relations included in the model (though probably best known for VCI).
- Conducted field validation tests of many (if not most) of the NRMM relations.
- Been one of the primary users of the model, applying it to a wide variety of ad hoc problems (vehicle selection, performance prediction, etc.).

Relative to tire and wheeled vehicle research, WES:

- From the World War II era to 1972: Had one group, VCI or field oriented.
- From 1959 to 1972: Had a second group, numeric or laboratory oriented.
- In 1972: Caused the two groups to merge.
- In 1976: Stopped laboratory testing and concentrated on NRMM applications and full-scale vehicle testing.

Figure 104. Some WES history relevant to NRMM and to tire performance research.

teristics of the appropriate tire(s). NRMM then would give way to the expertise of the tire industry's design professionals to determine particular recommended tire and rim designs. Finally, testing of the tires recommended and of the wheeled vehicles involved could be done in a cooperative effort including both the government and the tire/vehicle manufacturer communities to determine which tires in fact do satisfy best the military's stated tire and wheeled vehicle performance requirements.

In bridging the gap between the rather broad considerations of NRMM examined to this point and some rather specific in-soil tire performance characteristics that will be described next, it is useful to consider some past WES mobility research relevant both to NRMM in particular and to tire performance research in general.

As indicated in Figure 104, WES has had a continuous, close involvement with NRMM in several respects, beginning with NRMM's initial development and continuing today. Though probably best known for development of the VCI relations that now are an important part of NRMM's off-road mobility predictive relations, WES in fact has had major input in the formulation of most of NRMM's vehicle performance predictive relations. Also, WES has conducted extensive vehicle field testing leading both to the development of new NRMM predictive relations and to the validation of relations already in NRMM. Finally, from NRMM's inception, WES has been one of the principal users of the model, having applied NRMM (or AMM) in well over 100 ad hoc studies involving vehicle selection and/or vehicle performance prediction for a wide range of real-world environments and operational scenarios. In this hands-on involvement with NRMM, WES has cooperated closely with many customers of NRMM, as well as with a number of users of NRMM in the

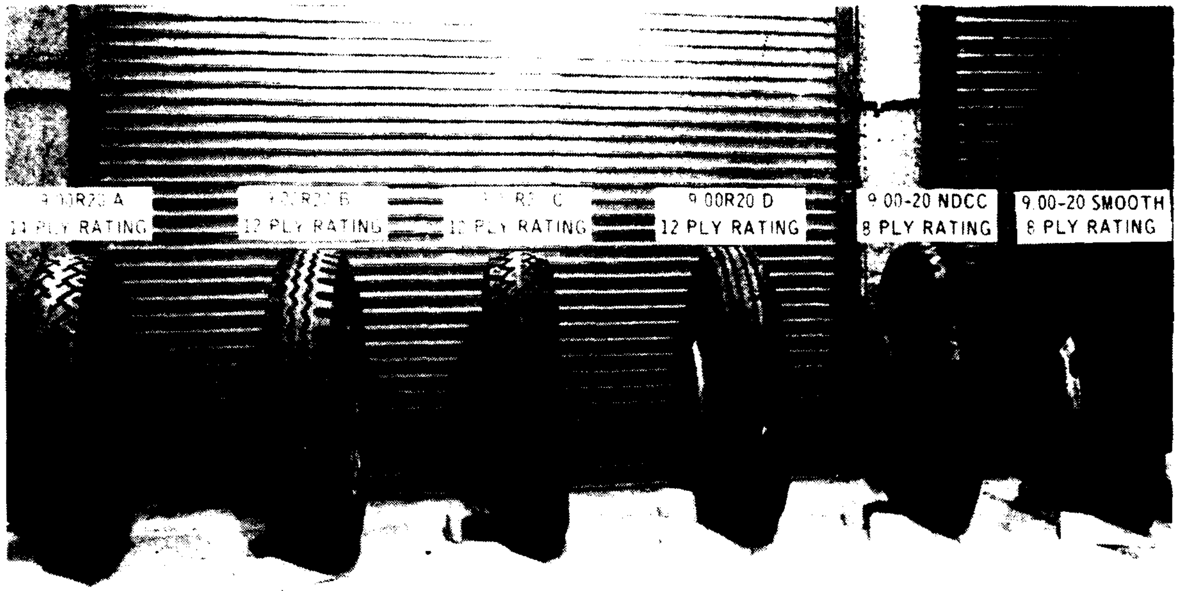


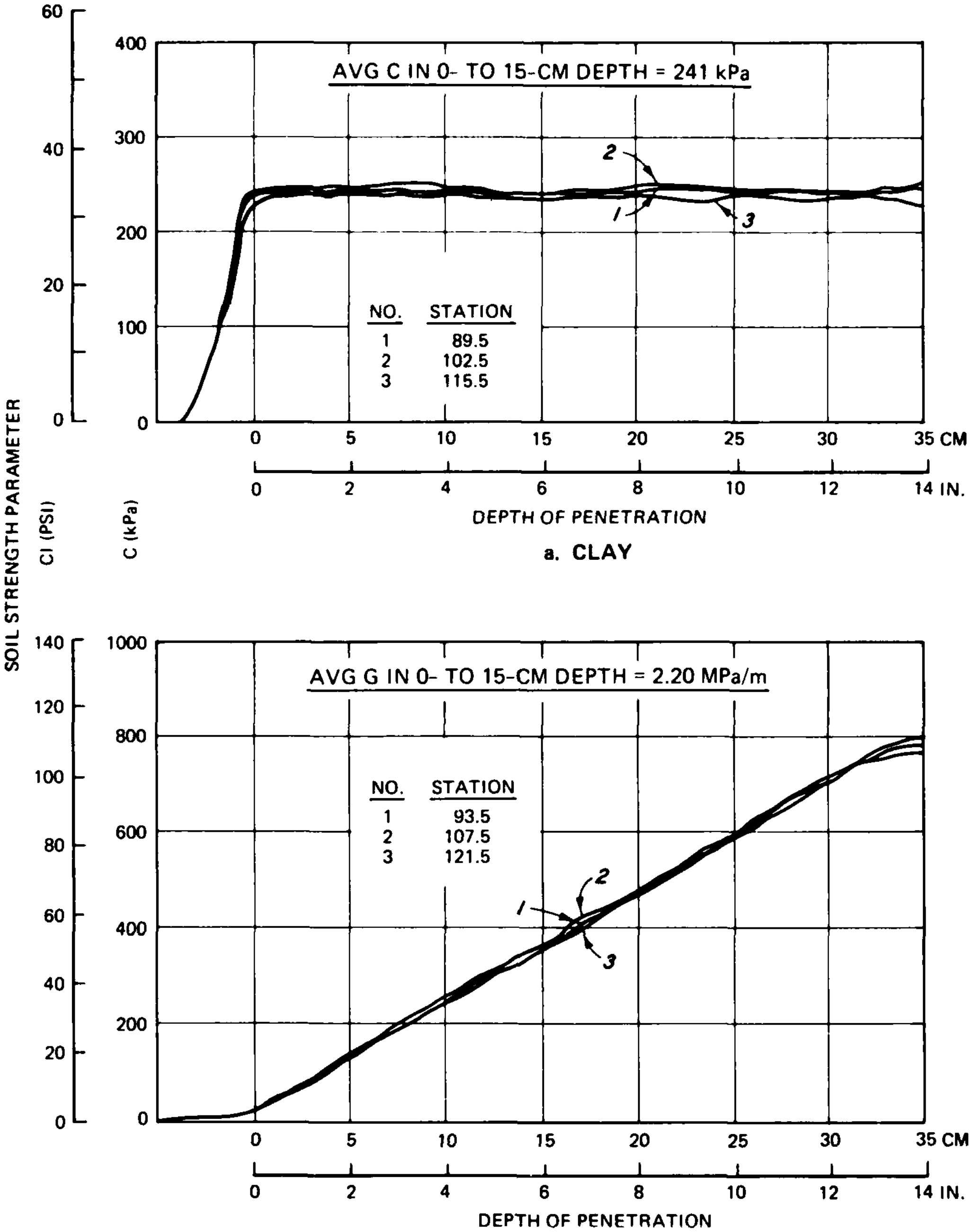
Figure 105. Four 9.00R20 radial-ply test tires and two 9.00-20 bias-ply reference tires.

U.S. (TACOM, CRREL, others), in Canada, and in Europe.

Regarding WES's research in tire and wheeled vehicle performance, the lower part of Figure 104 shows that beginning in the World War II era and continuing to 1972, one WES organizational group conducted wheeled vehicle performance research primarily under field conditions, its most notable achievement being development of the VCI description of in-soil vehicle performance. From 1959 to 1972, a second WES group conducted single-tire testing research using dynamometer/soil container arrangements under laboratory conditions, its most notable achievement being the development of a dimensional analysis (numeric) description of in-soil tire performance. In 1972, the two groups merged. By 1976, however, WES laboratory tire testing was stopped as sponsor interest in ad hoc applications of AMM accelerated and interest in "basic" in-soil tire performance research relative to NRMM diminished. The relations described in the remaining figures of this presentation grew out of a laboratory single-tire test study conducted at WES in 1975.

The primary purposes of the study were to evaluate the effects on in-soil tire tractive performance caused by a) radial versus bias ply carcass construction, b) a wide range of tire deflections, and c) inherent tire stiffness. Six tires were tested, all 9.00 × 20's as shown in Figure 105. The four tires on the left were radial ply, and the two on the right were bias ply. The radials had ply ratings of 12 and 14, and the bias ply tires had an 8-ply rating. One bias ply tire was buffed smooth, and the other five tires each had a different lug pattern. Each tire was mounted singly in the WES large-scale dynamometer and loaded to 8230 N (1850 lb), the approximate average single-tire load on a 2-1/2-ton, six-wheeled truck. Each tire was tested at zero inflation pressure and at inflation pressures that produced tire deflection ratios of 15, 35, and 60 percent. (Tire deflection ratio in percent is defined as 100 (δ/h), where δ is the difference between the unloaded tire section height (h) and the loaded tire section height, with the tire inflated to test pressure and resting on a flat, level, unyielding surface.)

Tests were conducted in laboratory pits filled either with saturated, fat clay (a cohesive, fine-grained soil) or with air-dry desert sand (a frictional, coarse-grained soil). Each test pit of soil was prepared to a uniform strength level over the full length of the subsequent tire test run. For this study,



b. SAND

Figure 106. Sample recordings of cone penetration tests in clay and sand.

clay test sections were prepared to a C value of about 240 kPa (35 CI), and sand test sections to a G value of about 2.2 MPa/m (8 psi/in.).* Figure 106 shows representative curves of C (and CI) versus depth of penetration in clay and in sand.

For this study, tire performance was described by two dimensionless terms, pull coefficient (μ = pull/load or P/W) and tractive efficiency (η = output power/input power or $PV_a/M\omega$ where P = pull, V_a = translational velocity of the dynamometer carriage, M = torque input to the wheel axle, and ω = angular velocity of the wheel axle). The test data were sampled at 20 percent slip, producing values of μ_{20} and η_{20} that correspond, at least nominally, to the

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* For sand, the soil strength parameter used is soil penetration resistance gradient G, defined as the average slope of the curve of C (or CI) versus cone penetration depth to a specified depth, often taken as 15 cm (6 in). Units of G are MPa/m in metric and psi/in in English.

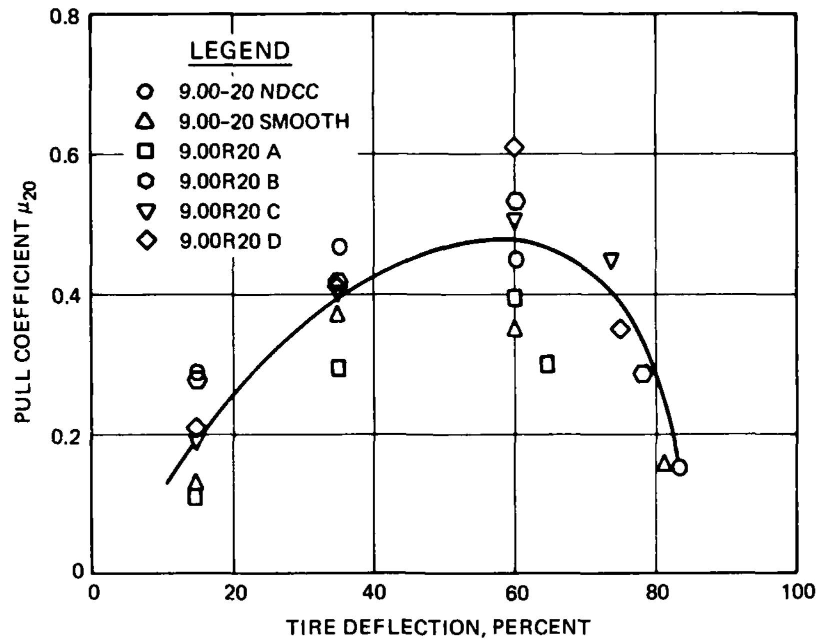

Figure 107. Relation of in-clay tire pull coefficient at 20 percent slip to percent tire deflection.

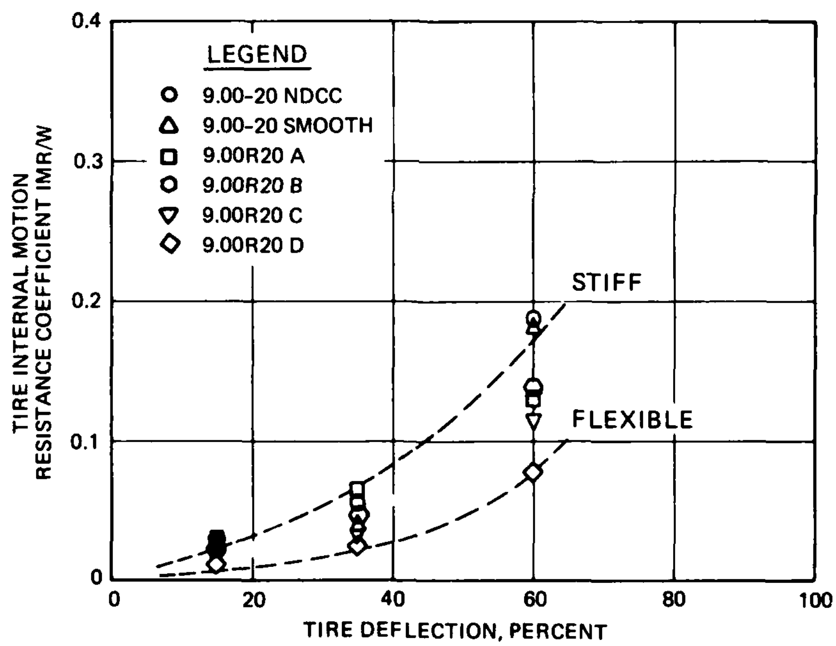

Figure 108. Relation of tire internal motion resistance coefficient to percent tire deflection (for tire tests on a flat, level, unyielding surface).

maximum values of pull coefficient and tractive efficiency obtainable in clay and in sand.

Figure 107 shows the relation of in-clay pull coefficient μ_{20} to tire deflection for the six 9.00 × 20 tires over the full range of deflections tested. (A curve of shape similar to that in Figure 109 was obtained for the relation of η_{20} to tire deflection for tests in clay and for the relations of μ_{20} and η_{20} to deflection for tests in sand.) In Figure 109, note that μ_{20} increases until tire deflection reaches about 60 percent and then decreases rapidly. The major part of the increase in μ_{20} occurs between 15 and 35 percent tire deflection (from about 0.2 to about 0.4), and a smaller part between 35 and 60 percent deflection (from about 0.4 to about 0.47). The immediate and important conclusion is that in-soil pull coefficient and tractive efficiency performance can be improved dramatically if today's usual in-soil tire operational deflection of about 20 percent could be increased significantly--to, say, at least 30 or 35 percent.

Because tire μ_{20} and η_{20} performance in clay and in sand decreased as tire deflection increased beyond about 60 percent, test results from the remainder of the study were examined only for deflections of 15, 35, and 60 percent. Figure 108 illustrates that values of tire internal motion resistance coefficient, IMR/W, increased significantly as tire deflection increased from 15 to 60 percent, the major part of the IMR/W increase occurring between tire deflections of 35 and 60 percent.* Dashed upper and lower boundary lines in Figure 108 describe stiff and flexible tires, respectively, for deflections from 15 to 60 percent and the remainder of the test conditions examined. For this range of conditions, values of IMR/W were large enough that they could not be neglected in describing in-soil tire performance.

The major in-soil tire test results were normalized by means of two dimensionless prediction terms (or numerics) developed at WES.[5 6] One numeric described basic conditions of the tire tests in clay:

$$N_c = \frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$$

and the other described tire test conditions in sand:

$$N_s = \frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$$

where b, d, and h are the section width, diameter, and section height, respectively, of the inflated, but unloaded, tire (Fig. 109); W is the load on the single tire; δ is the deflection of the inflated, loaded tire resting on a flat, level, unyielding surface (the difference between h and the deflected section height); and C and G have been defined previously.

Numerics N_c and N_s have two important, basic properties. First, each is uniquely related to a number of dimensionless tire performance terms (including μ_{20} and η_{20}). And second, in these numeric versus tire performance term relations, the numerics effectively describe the influence on tire performance of wheel load, soil strength, and tire size, shape, and deflection for broad ranges of values of each of these variables.

Figures 110a and 110b show the normalized relations for the pull coefficient test results in clay and in sand, respectively. (Turnage's normalized relations of tractive efficiency in clay and in sand also collapsed to equally well-defined central relations.[7]) Note in Figures 110a and 110b that the dimensionless pull term, which in conjunction with numerics N_c and N_s, successfully normalized the test data for the broad ranges of deflections and IMR's considered was not P_{20}/W, but

$$\frac{P_{20} + IMR}{W}$$

(termed μ_I, or intermediate pull coefficient).

To illustrate the major importance of tire deflection and accompanying tire internal motion resistance on in-soil tire pull performance for deflections up to 60 percent, pull coefficient μ_{20} was computed as $(P_{20} + IMR)/W$ (from the single curves in Figures 110a and 110b minus IMR/W (from the upper dashed curve in Figure 110 for a stiff tire, the lower curve for a flexible tire). One tire size was used, b = 26.4 cm (10.39 in) and d = 100 cm (39.37 in) (the average dimensions of the six 9.00 × 20 tires tested), one load (8230 N or 1850 lb), three tire deflection ratios (15, 30, and 60 percent), and a broad range of soil strengths (in terms of C or CI for clay, G for sand). Figures 111a and 111b show the families of curves thus developed for μ_{20} versus C (or CI) and μ_{20} versus G, respectively. (Relations qualitatively similar to those in Figure 110 were obtained for η_{20} versus C (or CI) and μ_{20} versus G for the conditions stated above.)

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* IMR is motion resistance of the tire measured as the tire is towed slowly, under test load, in a straight line over a flat, level, unyielding surface. In subsequent relations herein involving IMR and in-soil tire performance, IMR is used to approximate the motion resistance that the tire experiences in soil.

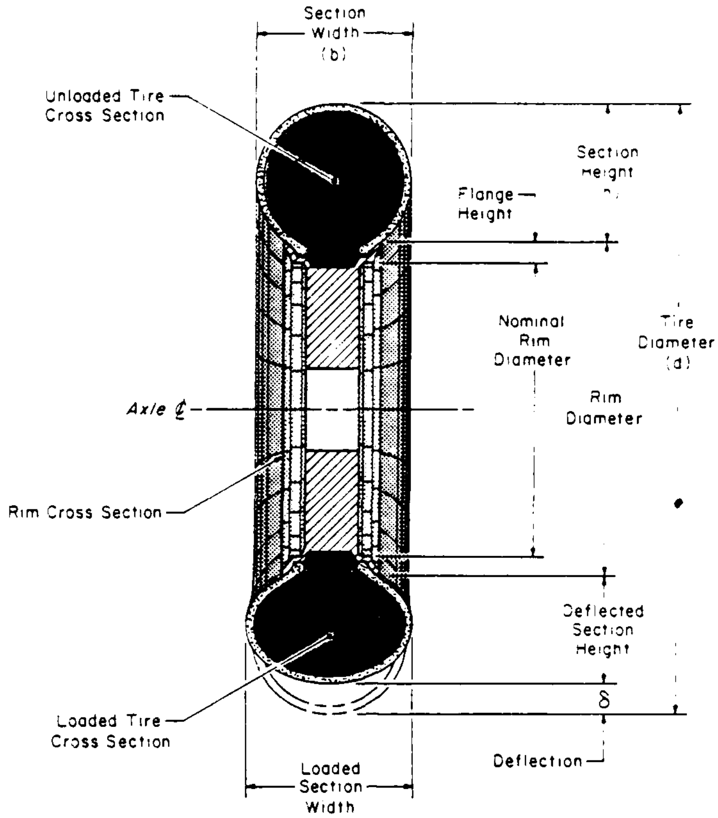
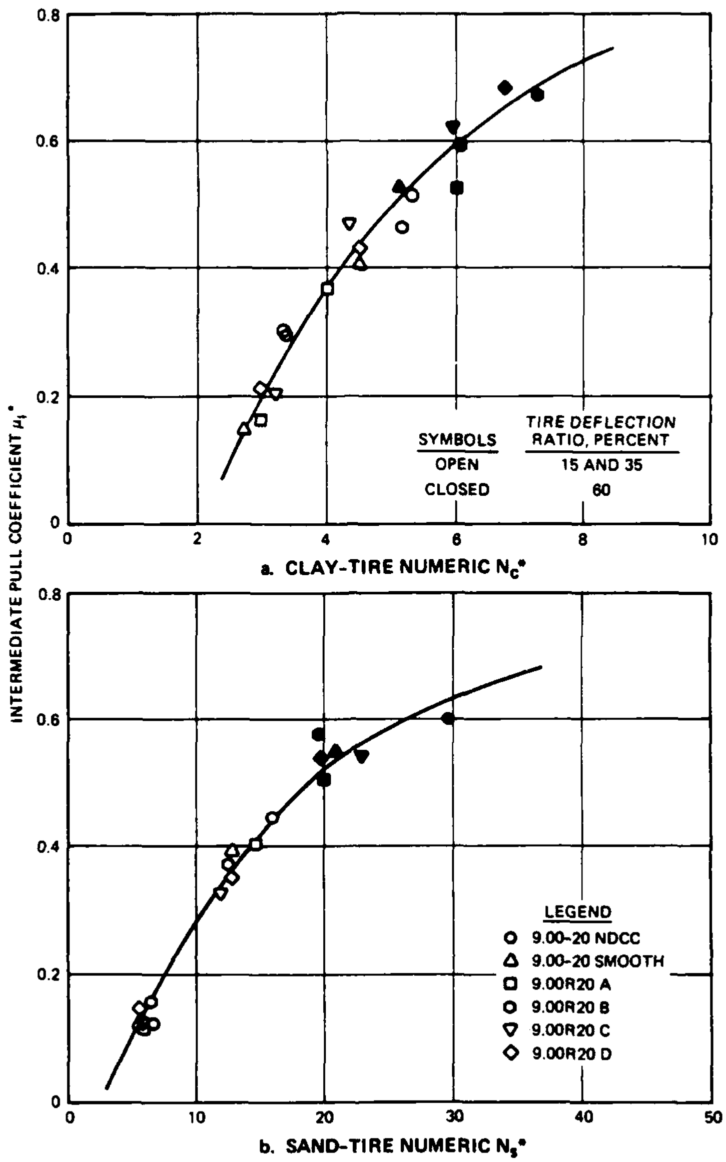


Figure 109. Some pneumatic tire terms.

Note, first, in both Figures 111a and 111b that increasing tire deflection from 15 to 30 percent increases tire pull coefficient performance drastically, and that a further increase in deflection from 30 to 60 percent adds a somewhat lesser, but still significant, amount to pull coefficient. Second, note that a secondary gain in performance results from using a flexible rather than a stiff tire, and that this gain becomes increasingly large as tire deflection increases (i.e., the widths of bands in Figures 111a and 111b for a stiff versus a flexible tire increase as tire deflection increases).

The general observations made above concerning the large variations in tire performance shown in Figure 111 can be illustrated by many detailed examples. For instance, in Figure 111a the C (or CI) value at pull coefficient = 0 is the smallest strength value of clay that will allow a tire to just propel itself at 20 percent slip. A stiff 9.00 × 20 tire at 15 percent deflection requires a C value of almost 200 (29 CI), while a flexible tire of the same size at 30 percent deflection requires a C of only about 130 (19 CI), and the same flexible tire at 60 percent deflection requires a C of only about 105 (15 CI). In Figure 111b, for a G value of 6 MPa/m (22 psi/in), the 9.00 × 20 tire at 15 percent deflection can develop a pull coefficient of only about 0.2. But if the same tire is flexible and operated at 30 percent deflection, pull coefficient increases to well over 0.4, and at 60 percent deflection to about 0.6.

Figure 112 illustrates the major recommendation for improved in-soil tire performance that resulted from the just-described laboratory tire study, plus two suggested means for accomplishing this recommendation. For wheeled vehicle operation in soft to medium hard soils, pull and tractive efficiency performance can be improved markedly by using flexible tires at relatively large deflections (up to 60 percent deflection). This improvement will be achieved only after the tire industry has responded to the challenge of producing such tires. When such tires are made available, they can be utilized best on our military trucks that operate a significant portion of time off-road by equipping these trucks with effective, reliable central inflation-deflation systems. These systems must



$$*\mu_i = \frac{P_{20} + IMR}{W};\ N_c = \frac{Cbd}{W} \cdot \frac{\delta}{h}^{1/2};\ N_s = \frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$$

Figure 110. Relations of intermediate pull coefficient at 20% slip to clay-tire and sand-tire numerics.

allow rapid, timely, in-the-field, driver-controlled "tuning" of the military truck tires' deflation and internal motion resistance characteristics to meet the multitude of soil conditions presented by off-road travel.

Finally, Figure 113 illustrates two major associated considerations concerning today's military needs for improved tires. First, the ABCT (described in detail in Session III of this workshop) is a reasonable strawman for opening serious discussions between the U.S. Government/military and U.S. tire/vehicle manufacturing communities aimed at producing the best tires possible for the military. Second, these discussions need to begin now since production of the U.S. Defense Department's new tactical truck fleet has already begun (with, for example, approximately 156,000 vehicles to be procured for the Army through FY 90 at a projected cost of about $ billion). Improvements in tire performance capabilities for the fleet would affect our military wheeled vehicle performance capabilities for many years to come.

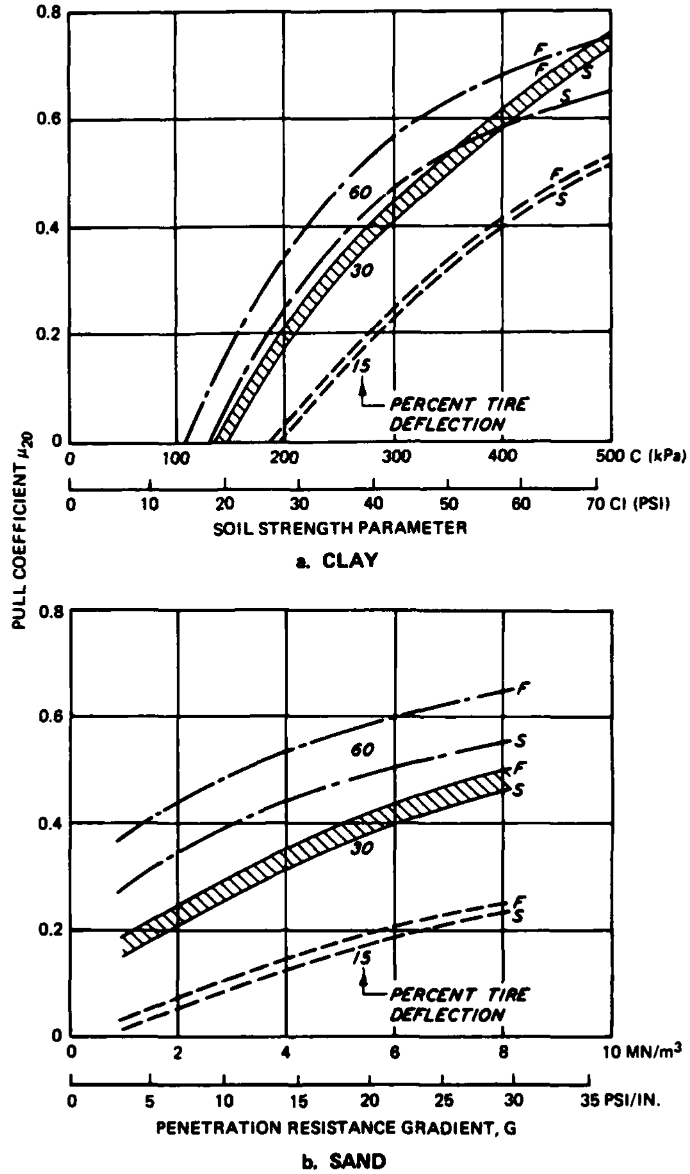


Figure 111. Relations of pull coefficient at 20% slip to soil strength for flexible and stiff 9.00-20 tires at a range of tire deflections in clay and in sand.

Recommendation:

Take maximum advantage of the improved pull and tractive efficiency performance in soft-to-medium hard soils that results from using flexible tires at relatively large deflections.

Accomplish this by:

1. Challenging the tire industry to produce such tires.

2. Developing and implementing reliable central inflation-deflation systems for our military trucks that operate a significant portion of time off-road.

Figure 112. The major recommendation arising from the laboratory study of radial and bias ply tires.

1. Communication: The ABCT is an existent, reasonable strawman for starting serious discussions between the U. S. Government/military and the U. S. tire/vehicle manufacturing communities.

2. Timeliness: Production of the Army's Tactical Truck Fleet has already begun. Approximately 156,000 vehicles will be procured through FY 90 at a projected cost of about $7 billion. The time for starting close cooperation between the U. S. Government/military with the U. S. tire/vehicle manufacturing communities in producing the best possible tires for the military is now.

Figure 113. Two significant associated considerations in satisfying U.S. military needs for improved tires.

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FIELD DEMONSTRATION OF TRACTION TESTING PROCEDURES

George L. Blaisdell U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, U.S.A. 03755-1290

A field demonstration of snow traction testing was performed in a section of the Upper Albion parking lot in Alta, Utah. Although snow conditions were slightly warmer than would be prescribed by the SAE recommended practice, a suitable test course for demonstration and comparison purposes existed.

Two instrumented vehicles were utilized to demonstrate two variations of the "self-contained" type test procedures and a traditional drawbar-pull test. The drawbar tests and a rear-wheel, single-wheel traction test were performed by W. Janowski using equipment generously supplied for the demonstration by DataMotive, Inc. A front-wheel, two-wheel test was performed by G. Blaisdell using equipment belonging to the U.S. Army Cold Regions Research and Engineering Laboratory (USACRREL).

All of the tests were run in accordance with the SAE recommended practice, with the exception that the CRREL instrumented vehicle does not conform to the recommended configuration for a test vehicle. Originally, it was intended that two tire types be tested using both "drawbar" and "self-contained" techniques with the DataMotive equipment and using only "self-contained" procedures for the USACRREL vehicle. The tires used were a Uniroyal Steeler (P205/75R15) and a Goodyear Wrangler (8.75R16.5).

The intent of the field demonstration was primarily to demonstrate and observe the test equipment and tire performance measurement techniques. Secondly, it was hoped that the results from the two test types and the two test vehicles could be used to demonstrate tire performance evaluation. Unfortunately, the CRREL vehicle experienced a mechanical failure during testing and was unable to complete tests on the Goodyear Wrangler.

Results for the Uniroyal Steeler using the "mu-area" (or SAE coefficient) method of data analysis (the easiest method for both vehicles to supply for comparison) showed statistical equivalence for both vehicles and with both test methods (drawbar-pull and self-contained). Using the DataMotive vehicle, the performance comparison between the two tire types also showed no significant difference on the snow tested. These results, although based on slightly fewer test repetitions than some testers would have preferred (due to test course size limitation), were in accordance with previous results obtained by most of the tire testers in attendance.

CONCLUDING REMARKS

Raymond N. Yong and George L. Blaisdell

It would be nice to report that the Workshop solved all the problems of winter tire assessment and performance evaluation. Unfortunately, this was not so. However, it became evident that the Workshop did indeed provide a very useful and meaningful forum to not only debate the various issues, but also to place, in perspective, the many heretofore unresolved problems into categories that permit proper focus of priorities and relevance; not the least of which is the problem of the need for systematic and controlled winter testing.

Bringing together the user, tester and manufacturer permitted each party to seek out agreement on both standards and acceptance criteria for winter tires. More important, the discussions generated between user and manufacturer in regard to proposed acceptance criteria for tires were most instructive.

We believe that having now established a more interactive forum between the three groups, perhaps some of the complex issues existent heretofore have been better identified and hopefully clarified. This is only one collective step towards a final satisfactory working arrangement between user, tester and manufacturer. We hope that more working sessions can be planned for future meetings.

We wish to record our appreciation to all the participants at the Workshop (attendance listing at the beginning of these proceedings) and especially to those who responded to the challenges set forth in the panel discussions of this Workshop. A special thanks is extended to W.R. Janowski of DataMotive, Inc., to CRREL test crew M. Hutt and B. Greeley, and N. Garcia who assisted in the field demonstrations. Finally, we are obliged to H. Hodges and W.L. Harrison for their roles in the planning and implementation of this Workshop.

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