



**US Army Corps
of Engineers®**
Engineer Research and
Development Center

Instrumenting an All-Terrain Vehicle for Off-Road Mobility Analysis

Kyle D. Wesson, Michael W. Parker, Barry C. Coutermarsh,
Sally A. Shoop, and Jesse M. Stanley

January 2007



Instrumenting an All-Terrain Vehicle for Off-Road Mobility Analysis

Kyle D. Wesson, Michael W. Parker, Barry C. Coutermarsh,
Sally A. Shoop, and Jesse M. Stanley

*Cold Regions Research and Engineering Laboratory
U.S. Army Engineer Research and Development Center
72 Lyme Road
Hanover, NH 03755*

Final report

Approved for public release; distribution is unlimited.

Prepared for U.S. Army Corps of Engineers

Abstract: With small mobile vehicles, even robots, becoming increasingly important for military operations, Cold Regions Research and Engineering Laboratory (CRREL) researchers set out to instrument an all-terrain vehicle (ATV) with mobility sensors to obtain and understand small-vehicle mobility data in all seasons. Extensive mobility research has already been performed at CRREL on the CRREL Instrumented Vehicle (CIV), which collects mobility data with large and expensive vehicle performance sensors. However, a small vehicle such as an ATV is not suited to carry large data collection instruments. In an effort to overcome cost and size limitations while maintaining functionality, an ATV was instrumented with low-cost sensors to collect mobility data comparable to the CIV. At the U.S. Army's Ethan Allen Firing Range, ATV mobility performance tests, such as coast down and drawbar tests, were performed alongside the CIV for comparison, while cross range test runs were performed to demonstrate the system's capabilities. This paper presents one option for researchers looking to instrument a small-vehicle with mobility performance sensors, describes the testing methodology and results, and offers a comparison to the CIV. Low-cost, portable vehicle mobility instrumentation systems would allow for accurate vehicle simulations and mobility awareness that can be used *in situ* by the warfighter and lead to further applications of all-terrain vehicles in force protection and border patrol scenarios.

DISCLAIMER: The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products. All product names and trademarks cited are the property of their respective owners. The findings of this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

DESTROY THIS REPORT WHEN NO LONGER NEEDED. DO NOT RETURN IT TO THE ORIGINATOR.

Contents

Figures and Tables	iv
Unit Conversion Factors	vi
Acronyms	vii
Preface	viii
1 Introduction	1
2 Suzuki King Quad All-Terrain Vehicle Dynamics	2
ATV Center of Gravity Measurements.....	2
Engine Dynamometer Measurements	5
3 All-Terrain Vehicle Instrumentation	6
Sensor Storage and Mounting.....	6
Campbell 23x Data Acquisition System	7
Inertial Navigation System	7
Vehicle Speed	9
Geographic Location	9
Drawbar Load	9
Video Documentation	10
4 Testing All-Terrain Vehicle on Ethan Allen Firing Range	11
Drawbar Pull	12
Coast Down Test.....	12
Rolling Resistance Pull Test.....	12
Circle Breakout Test	13
Trail Traverse.....	13
5 All-Terrain Vehicle Snow Testing	14
6 Data Analysis	15
Traction Tests: Drawbar.....	15
Rolling Resistance: Coast Down Test and Rolling Resistance Pull Test	17
Circle Breakout Test	19
Trail Traverses.....	20
7 Comparison to CRREL Instrumented Vehicle	23
8 Recommendations/Applications	25
References	26
Appendix A: ATV Engine Torque Dynamometer Data	27

Appendix B: LoggerNet	28
Appendix C: Campbell 23x Programs.....	33
Appendix D: Ethan Allen Firing Range Soil Conditions	41
Appendix E: Snow Measurements at Claremont Airport	43
Appendix F: ATV Snow Data.....	44
Appendix G: DIAdem Data Synchronization.....	45
Report Documentation Page.....	46

Figures and Tables

Figures

Figure 1. The instrumented ATV waits for a mission.	1
Figure 2. Side view of the ATV sitting level with scales under the front tires.....	3
Figure 3. A front view of the ATV with scales under the front tires.....	3
Figure 4. ATV's Y center of gravity location.	4
Figure 5. ATV's X and Z center of gravity locations.	4
Figure 6. Horsepower and torque versus rear wheel speed in fourth gear.	5
Figure 7. The data acquisition system box mounted to the rear rack of the ATV.....	6
Figure 8. The Vicon Pan-and-Tilt Drive setup to verify the angular rate output.	9
Figure 9. Camera mounted on the ATV.....	10
Figure 10. Ethan Allen Firing Range with testing areas marked.....	11
Figure 11. The ATV pulls the CIV during a traction test at EAFR.	12
Figure 12. Conducting a rolling resistance test on the ATV.	13
Figure 13. ATV rolling resistance test on snow.....	14
Figure 14. Typical drawbar results.....	15
Figure 15. Traction coefficients plotted versus vehicle speed.....	16
Figure 16. ATV traction coefficient summary for moist gravel and snow	16
Figure 17. Rolling Resistance data for ATV.....	18
Figure 18. ATV's recorded yaw rate and the calculated yaw rate.....	19
Figure 19. Calculated lateral force using Newton's second law and eq 5.	20
Figure 20. Figure 1. Castle Trail run..	21
Figure 21. Screenshot of National Instruments DIAdem software with video taken from the front of the ATV and its corresponding data synchronized.....	22
Figure 22. Comparison between ATV and CIV rolling resistance and traction coefficients	23

Tables

Table 1. Weight under each wheel (lb)..... 3
Table 2. Center of gravity locations. 4
Table 3. Sample Campbell output..... 7

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	28316.85	cubic centimeters
cubic inches	16.38706	cubic centimeters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	$(F-32)/1.8$	degrees Celsius
feet	0.3048	meters
foot-pounds force	1.355818	joules
horsepower (550 foot-pounds force per second)	745.6999	watts
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
pounds (force)	4.448222	newtons
pounds (force)	453.5924	grams (force)
pounds (force) per foot	0.01601846	grams per centimeter
pounds (force) per inch	27.6799	grams per centimeter
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
tons (force) per square foot	95.76052	kilopascals
tons (2,000 pounds, mass)	907.1847	kilograms
tons (2,000 pounds, mass) per square foot	9,764.856	kilograms per square meter
yards	0.9144	meters

Acronyms

ASCII	American Standard Code for Information Interchange
ATV	All-Terrain vehicle
CG	Center of Gravity
CIV	CRREL Instrumented Vehicle
CRREL	Cold Regions Research and Engineering Laboratory
DAS	Data Acquisition System
EAFR	Ethan Allen Firing Range
GPS	Global Positioning System
LED	Light-Emitting Diode
SAE	Society of Automotive Engineers
WD	Wheel Drive

Preface

This report was prepared by Kyle D. Wesson, Michael W. Parker, Barry C. Coutermarsh, Dr. Sally A. Shoop, and Jesse M. Stanley, all of the Cold Regions Research and Engineering Laboratory, U.S. Army Engineer Research and Development Center.

The authors thank Ileaner Maldonado and Rosa Affleck for their work characterizing Ethan Allen Firing Range soils; Christopher Donnelly and William Burch for their work in the machine shop; Byron Young and Dr. Gary Phetteplace for their work with the all-terrain vehicle in snow; the Vermont National Guard at Ethan Allen Firing Range for allowing testing on their range; and Peter Seman and Rosa Affleck for reviewing this report.

This report was prepared under the general supervision of Justin Berman, Chief, Force Projection and Sustainment Branch; Lance Hansen, Deputy Director; and Dr. Robert Davis, Director, CRREL. The Commander and Executive Director of the Engineer Research and Development Center is COL Richard B. Jenkins. The Director is Dr. James R. Houston.

1 Introduction

With the increasing need for smaller vehicles and robots in military and homeland security applications, accurate mobility data are needed to assess and assure vehicle performance. While researchers at the Engineer Research and Development Center's Cold Regions Research and Engineering Laboratory have conducted extensive mobility research with the CRREL Instrumented Vehicle (CIV) and military vehicles, little analysis or simulation has been done on a small, light-weight manned vehicle such as a 4×4 or 6×6 all-terrain vehicle (ATV). ATVs are well suited to meet the demands encountered while conducting strategic ground or border patrol missions. These vehicles are also suited for conversion to autonomous operations (Dolan *et al.* 1999). The potential of ATVs inspired a project to outfit a Suzuki King Quad 300 4×4 ATV with mobility sensors and then to evaluate the sensors' and the ATV's performance. Figure 2 shows the instrumented ATV.



Figure 2. The instrumented ATV waits for a mission.

2 Suzuki King Quad All-Terrain Vehicle Dynamics

The 2001 Suzuki King Quad 300 ATV is powered by a 280 cm³, four-stroke, single-cylinder engine, with a five-speed transmission having two-wheel and four-wheel-drive settings. It weighs approximately 633 lb with instrumentation (base weight of 606 lb), has a wheelbase of 45.9 in., and 8.3 in. of ground clearance. The ATV has two Dunlop AT 24x8-11 PP tires on the front inflated to 4 psi and two Dunlop AT 25x10-12 PP tires on the rear at 6 psi. It has a towing capacity of 400 lb gross trailer weight on uneven ground.

Extensive vehicle dynamic measurements and engine specifications were taken for accurate mobility measurements and to simulate ATV operation in a virtual world. Aside from the ATV's basic geometry and weight, two important vehicle characteristics needed to model the ATV are the center of gravity and the engine dynamics.

ATV Center of Gravity Measurements

When instrumenting a vehicle or when modeling a vehicle in a simulator, it is essential to know the location of the CG because this is the point about which the vehicle rolls, pitches, and yaws. Therefore, when a motion pack measuring angular velocities and angular accelerations is mounted on a vehicle, its location with respect to the CG must be known so that a correction factor can compensate for the offset.

The CG on the Suzuki King Quad 300 was determined from a series of weight measurements under the front and rear wheels of the ATV while it was level and on a decline. Two scales were used to calculate the CG. When weighing the ATV on a level surface, all tires were blocked to an equal height to make sure that a true normal force was measured (Figure 3 and Figure 4).



Figure 3. Side view of the ATV sitting level with scales under the front tires.



Figure 4. A front view of the ATV with scales under the front tires.

The measured weight on each wheel is given in Table 1. The weight under the rear tires, while the ATV was declined, was not measured because the back of the ATV was suspended by a cable attached to the center of the rear rack. These measurements were taken with and without a rider, so the center of gravity could be calculated in both configurations.

Table 1. Weight under each wheel (lb).

		Right Front	Left Front	Right Rear	Left Rear
Without Rider	Level	152.8 lbs	157.0	167.7	146.0
	7.5° decline	204.0	192.0	--	--
With Rider	Level	183.0	193.5	211.5	195.0
	7.5° decline	255.0	239.5	--	--

The locations of the lateral, longitudinal, and vertical center of gravity of the ATV with a 160-lb rider are given in Table 2.

Table 2. Center of gravity locations.

	Location (in.)
Lateral CG	0.13
Longitudinal CG	23.83
Vertical CG	19.2

The lateral CG is measured from the geometric centerline of the vehicle to the lateral CG. A positive value indicates that the center of gravity is closer to the right side of the ATV from the rider's perspective (Figure 5). The longitudinal CG is measured from the center of the front hub and the vertical CG is measured from the ground as shown in Figure 6.



Figure 5. ATV's Y center of gravity location.

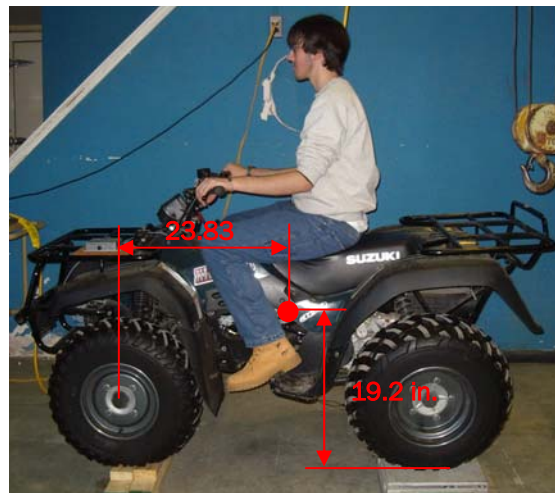


Figure 6. ATV's X and Z center of gravity locations.

Engine Dynamometer Measurements

Dynamometer testing on the ATV was conducted to measure torque at the rear wheels. Knowing the wheel torque and gearing of the vehicle, the engine torque can be calculated. These values were used in a simulated engine model to match the accelerations measured for the ATV. A Dynojet model 168/188 chassis dynamometer was used to measure the torque at the rear wheel-ground interface. Dynamometer testing was conducted at A.C.S. Racing in Hanover, MA.

Dynamometer tests were conducted over a range of engine speeds, from 1500 rpm to the maximum engine rpm, for gears one through four in both high and low gear. For each gear, four throttle settings were used: one-quarter, half, three-quarters, and full throttle, with the throttle limited by a mechanical stop at each of the four settings. The different throttle settings were required to map the ATV's full range engine torque. Each test started at an engine speed of 1500 rpm, the throttle level was pegged until the maximum rpm of the ATV was reached, and then the throttle was released. Only one run was conducted at each throttle setting. For each run, the engine speed, rear wheel torque, rear wheel horsepower, and rear wheel speed were recorded. The torque versus engine speed for one gear at the four throttle settings was used in the engine component of the simulator. A sample plot of rear wheel horsepower and torque versus wheel speed is shown in Figure 7. The engine torque map used in the simulator is in Appendix A.

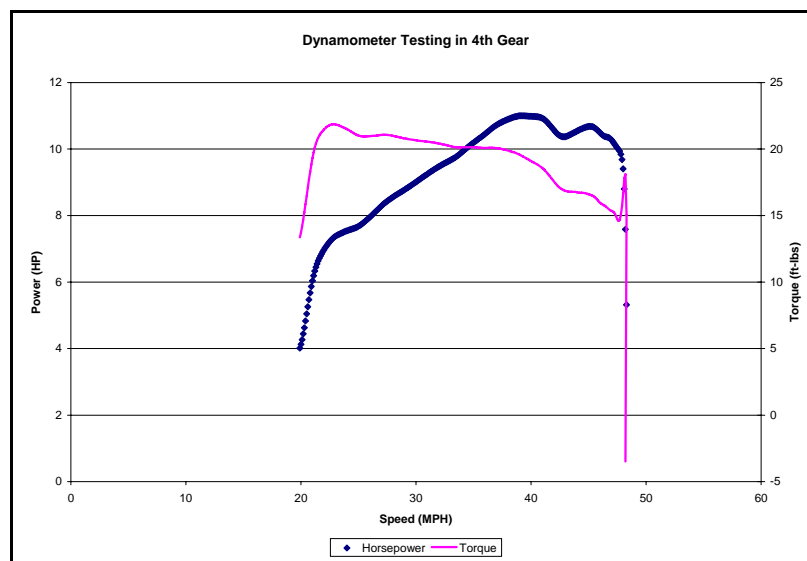


Figure 7. Horsepower and torque versus rear wheel speed in fourth gear.

3 All-Terrain Vehicle Instrumentation

The ATV instrumentation was chosen to accurately measure mobility while also being portable and easily accessible. One of the main goals of the ATV instrumentation was to replicate portions of the instrumentation capabilities of the CRREL Instrumented Vehicle (CIV) (Blaisdell 1983). To understand tire-terrain force generation, the CIV acquires mobility data from traction, rolling resistance, and maneuverability tests on mud, snow, gravel, and pavement. The CIV is equipped with a Systron Donner MotionPak motion sensor to measure roll, pitch, and yaw rates and accelerations in three axes, as well as triaxial load cells on each wheel, a linear motion potentiometer for steering angle, a 10-Hz GPS, a fifth-wheel speed and distance recorder, and a user-configurable braking system.

The ATV was equipped with an accelerometer that measured accelerations in three axes and roll, pitch, and yaw rates, a fifth-wheel speed sensor, GPS, and video camera. An optional load cell and case can be attached for rolling resistance and traction tests.

Sensor Storage and Mounting

The data acquisition system (DAS) and accelerometer are housed in a hermetically sealed box mounted on the rear rack of the ATV. The DAS box is mounted with L-clamps and bolts to a ¼-in. plate of aluminum with padding between the L-clamps and the plate. The plate is then mounted to the rack with conduit clamps, hard rubber, and bolts. This method of mounting helped minimize the high frequency vibrations produced by the ATV's engine. The mounting configuration can be seen in Figure 8.



Figure 8. The data acquisition system box mounted to the rear rack of the ATV.

Campbell 23x Data Acquisition System

The Campbell 23x data acquisition system collection rates are 10 Hz from the accelerometer and fifth-wheel and 1 Hz from the GPS. The accelerometer and fifth-wheel signals are in volts, while the GPS is serial. The data are stored in a memory module and transferred via Bluetooth to a computer for analysis as an ASCII comma separated file. An external switch toggles recording to the storage module so that data are collected only when necessary. When the Campbell is turned on, it automatically loads, compiles, and runs the program stored in the memory module and is ready to record data within 1 minute.

Data are exported from the DAS using the LoggerNet 2.1c software package. See Appendix B for more information on extracting data and Appendix C for copies of the programs used. Sample output can be seen in Table 3.

Table 3. Sample Campbell output (HHMM = hour, hour, minute, minute; SS = second, second; Marker greater than 4000 indicates marked button pushed. Array 103 indicates all data except for GPS data which is stored in array 102.)

Array	Day	HHMM	SS	Time	Battery	Roll Rate	Pitch Rate	Yaw Rate	Long_Acc	Lat_Acc	Vert	Marker	Speed
103	164	1752	35.1	1.679	13.01	1.058	-7.09	2.285	-0.005	0.089	-0.787	4943	0.013
103	164	1752	35.2	1.790933333	13.5	0.049	-4.171	1.171	0.048	-0.109	-1.327	4943	-0.007
103	164	1752	35.4	1.902866667	13.36	0.527	-8.42	0.905	-0.028	-0.031	-1.079	8.41	0
103	164	1752	35.5	2.0148	13.06	-0.163	-8.95	1.913	0.023	0.082	-0.969	15.05	0.106
103	164	1752	35.6	2.126733333	13.44	-0.64	4.053	0.162	0.03	-0.095	-1.586	8.08	0.113
103	164	1752	35.7	2.238666667	13.43	-0.322	7.45	1.118	-0.03	0.05	-0.835	8.41	0.1
103	164	1752	35.8	2.3506	13.34	0.633	-11.33	2.762	0.065	0.082	-0.818	8.08	0.093
103	164	1752	35.9	2.462533333	13.1	3.127	-5.02	2.709	0.023	0.044	-1.367	7.42	0.04
103	164	1752	36	2.574466667	12.87	0.58	-3.588	3.134	0.39	0.067	-1.132	7.42	-0.007
103	164	1752	36.1	2.6864	13.37	-0.64	6.653	1.542	-0.163	-0.122	-0.704	8.75	-0.026
103	164	1752	36.2	2.798333333	13.29	-0.375	8.3	0.534	0.035	0.069	-1.135	8.08	-0.013
103	164	1752	36.4	2.910266667	12.81	-1.808	3.363	-0.103	0.113	-0.016	-0.639	9.08	0.007
103	164	1752	36.5	3.0222	13.33	0.368	-2.049	0.375	-0.007	0.062	-0.785	9.74	0
103	164	1752	36.6	3.134133333	13.05	0.156	-5.179	-0.421	-0.008	0.002	-0.944	8.41	0.02
103	164	1752	36.7	3.246066667	12.94	0.049	-4.224	1.754	0.051	-0.039	-1.072	8.41	0.013
103	164	1752	36.8	3.358	13.45	0.58	-4.914	0.428	0.088	-0.18	-1.286	8.41	-0.007
103	164	1752	36.9	3.469933333	13.06	-1.861	1.082	-0.209	0.121	0.024	-1.351	7.75	-0.033
103	164	1752	37	3.581866667	13.32	1.323	3.841	2.603	-0.245	0.067	-1.259	7.75	-0.007
103	164	1752	37.1	3.6938	13.35	1.907	-9	0.162	0.103	0.094	-1.507	8.75	0
103	164	1752	37.2	3.805733333	13.18	0.739	-5.604	1.011	-0.058	-0.019	-1.289	7.09	-0.013
103	164	1752	37.4	3.917666667	13.18	0.368	5.698	1.383	-0.131	0.022	-1.172	8.75	0.013
103	164	1752	37.5	4.0296	13.17	-1.861	-5.285	0.216	-0.111	-0.006	-0.976	14.05	-0.033
103	164	1752	37.6	4.141533333	13.28	1.27	-5.498	-0.421	-0.086	0.014	-0.926	8.41	0.007
103	164	1752	37.7	4.253466667	13.08	0.792	-6.241	-0.209	-0.118	0.04	-0.958	8.75	0.671
103	164	1752	37.8	4.3654	13.43	0.527	-5.551	-0.74	-0.126	0.042	-0.825	8.08	0.651
103	164	1752	37.9	4.477333333	12.89	0.898	-8.68	-1.27	-0.187	0.001	-0.745	9.08	1.906
103	164	1752	38	4.589266667	13.08	1.535	-5.604	-0.315	-0.206	0.026	-0.807	8.41	1.806
103	164	1752	38.1	4.7012	12.92	-0.428	-6.347	0.003	-0.257	0.016	-0.964	8.08	2.556
103	164	1752	38.2	4.813133333	12.71	0.739	-5.816	-0.686	-0.302	-0.102	-1.024	8.41	2.556
103	164	1752	38.4	4.925066667	12.91	1.376	-3.375	0.375	-0.373	0.017	-0.848	9.74	4.01
103	164	1752	38.5	5.037	13.2	0.898	2.09	0.64	-0.161	0.147	-1.125	10.4	3.997

Inertial Navigation System

The accelerometer was mounted inside a 2- × 4- × 2-in. aluminum box, which was secured to the bottom of the DAS box via a steel plate and

thumb screws for portability. The center of the accelerometer was mounted along the vehicle's longitudinal center axis.

The accelerometer is an O-Navi Analog Inertial Sensor Gyrocube 3F. The Gyrocube 3F is a six degree-of-freedom inertial measurement unit module that measures acceleration in three axes and roll, pitch, and yaw rates. Angular rate ranges are $\pm 400^\circ/\text{s}$ and accelerations can be measured up to $\pm 10\text{ g}$. Its total volume is just over 1 in^3 .

The sensor output was adjusted to the Society of Automotive Engineers (SAE) tire axis system (Gillespie 1992) using the following procedure. Because the output range of the accelerometer is 0–5 V with 2.5 V nominal, a linear scaling factor ($y = mx + b$) must be used to correctly convert the volts into the correct range of accelerations and rates. To determine the multiplier (the m value), the absolute range ($800^\circ/\text{s}$) was divided by a bias of 5000 mV (from the calibration sheet) leading to a multiplier of $0.16^\circ/(\text{s}\cdot\text{mV})$. Likewise, the range of the accelerations ($20\text{ g}'\text{s}$) was divided by a bias 4000 mV, leading to a multiplier of $0.005\text{ g}/\text{mV}$. To conform to SAE tire axis standards (Gillespie 1992), some multipliers were multiplied by -1 to give the correct polarity.

After determining the multiplier, the offset (the b values) was then determined, taking average noise over 10 minutes, and programmed into the DAS. This resulted in longitudinal and lateral accelerations reading approximately 0.0 g and vertical acceleration reading approximately 1.0 g when the sensor rested flat on the ground.

To calibrate the angular rates, the sensor was mounted onto a Vicon Pan-and-Tilt Drive that moved at either $2^\circ/\text{s}$ tilting or $12^\circ/\text{s}$ panning (Figure 9). Using an assortment of mounts, we verified all roll, pitch, and yaw rates to manufacturers' specifications.

With the sensor still and level mounted on the ATV with the ATV off, the "zero" value ranges are:

- Roll Rate: -0.26 to $+0.62^\circ/\text{s}$.
- Pitch Rate: 0.20 to $1.20^\circ/\text{s}$.
- Yaw Rate: -0.32 to $+0.00^\circ/\text{s}$.
- Longitudinal Acceleration: $+0.03\text{ g}$.
- Lateral Acceleration: -0.05 g .
- Vertical Acceleration: -1.00 g .

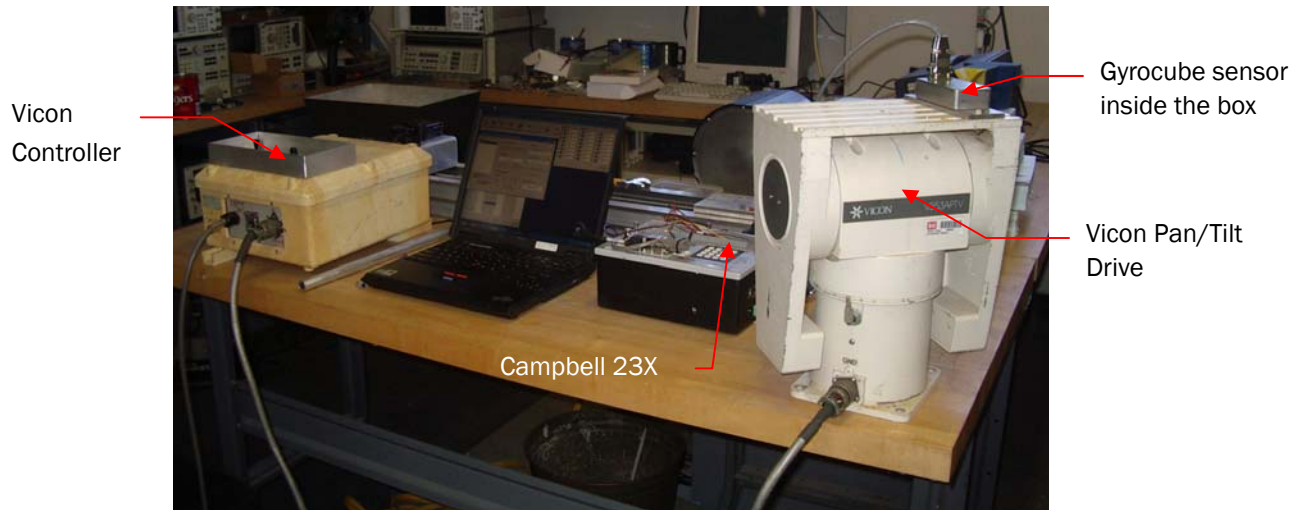


Figure 9. The Vicon Pan-and-Tilt Drive setup to verify the angular rate output.

Vehicle Speed

The TrackTest fifth-wheel is an accurate way to determine true vehicle speed. The unit has a performance meter that reads optical pulses and displays the speed. The display was mounted on the front rack to be visible to the rider. The fifth-wheel was attached to the ATV's rear rack. The Campbell DAS receives an analog signal from the performance meter display, converts it into speed values, and stores the data. The fifth-wheel tire requires 34-psi inflation pressure for accurate measurements of speed. Information regarding fifth-wheel procedures is referenced in SAE (1967) J939.

Geographic Location

A Garmin GPS was used to locate vehicle position for post-processing procedures and to synchronize the vehicle position with video. The GPS was mounted to the roof of the DAS box with a steel plate. The GPS system fed location data into the DAS at 1 Hz. It will not output data unless there are at least three satellites available to define its position. The GPS data are recorded through the Campbell's serial port.

Drawbar Load

A Lebow Model 3161-5K 5000-lb load cell was attached to the ATV to measure rolling resistance and traction. A second Campbell 23x program was used to record data with the load cell active because adding the program instruction for exciting and measuring the load cell limited the recording frequency to 3 Hz (see the 10 command in program 2 in Appendix

C). The load cell was either mounted on the front or rear hook on the ATV, depending on the test configuration (see Figure 12 and Figure 13). The load cell was removed when it was not in use.

Video Documentation

A Sony Handycam camcorder was attached to a camera mount on the front of the ATV to record terrain conditions (Figure 10). During testing, a LED was placed within the camera's field of view and connected to a marker button to mark events and synchronize video and data during post-processing. The marker trigger is located on the left handle of the ATV within reach of the driver. A marker value of 4000 indicated the button has been pushed. The camera recorded at 30 frames per second and had built in image stabilization.



Figure 10. Camera mounted on the ATV.

4 Testing All-Terrain Vehicle on Ethan Allen Firing Range

ATV performance and traverse testing was conducted at the U.S. Army's Ethan Allen Firing Range (EAFR) in Jericho, VT, from 11–13 June 2006. EAFR was chosen for its varied terrain, which had recently been modeled in a simulated world (Shoop et al. 2004). Tests were conducted on the range's trails, specifically Porcupine Pass, Feigel Hill, Range 6-6, and Castle Trail. Tests were also conducted in a gravel parking lot. The parking lot was gravelly sand, and its surface had some standing water that evaporated as testing continued. The moisture content of the soil ranged from 14.41 to 28.63% by volume. The average slope for the tests was between 1 and 2°. Test site soil conditions are given in Appendix D. A map showing the test location is given in Figure 11.

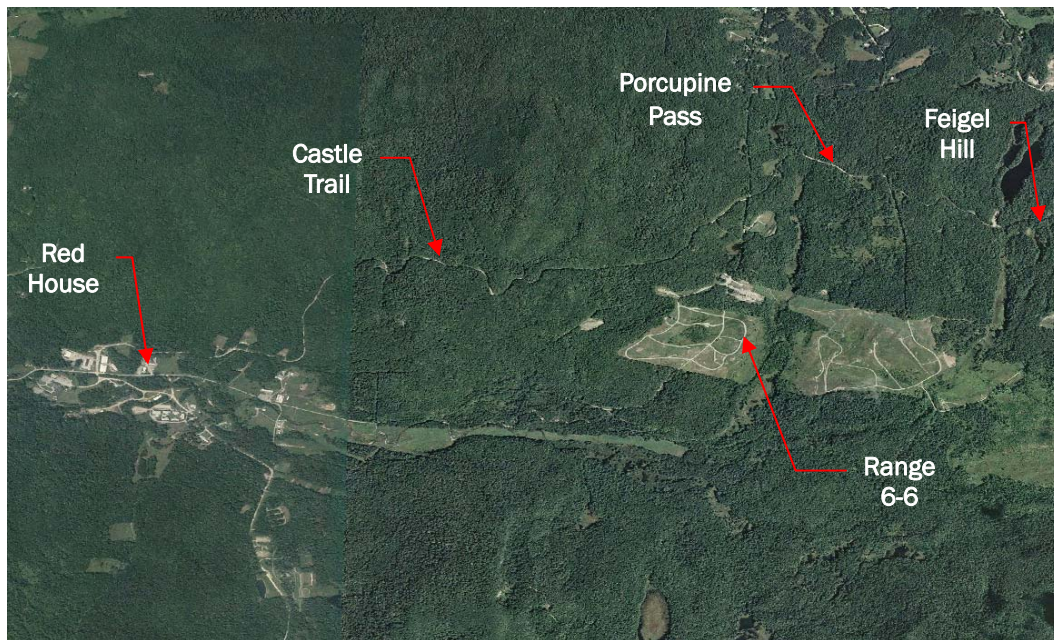


Figure 11. Ethan Allen Firing Range with testing areas marked (US Geological Service).

For each test done, a brief summary and reference to the appropriate standard follows. All tests were conducted with the ATV in first gear set to 2WD low or neutral (depending on the test requirements).

Drawbar Pull

Drawbar pull tests are used to calculate the coefficient of traction (SAE [1986] J872 and SAE [1967] J939). The setup may vary slightly, but for the ATV, a cable and a load cell are attached to the ATV's trailer hitch. The other end of the cable was attached to a much larger "hold back" vehicle (the CIV, for example). After aligning the vehicles and making sure the cable was taut, the ATV began to pull the trailing vehicle at a constant 5 mph. After approximately 30 ft, the trailing vehicle gently braked until the ATV increasingly spun its tires while trying to maintain speed. Eventually, the ATV was brought to a complete stop by the towed vehicle. Combining data from the load cell and fifth-wheel speed sensor, traction coefficients as a function of wheel slip or vehicle speed can be calculated. The setup can be seen in Figure 12.



Figure 12. The ATV pulls the CIV during a traction test at EAFR.

Coast Down Test

Coast down tests is one way to determine rolling (motion) resistance coefficients (SAE [1999] J2452 and Bosch 2004). Starting approximately 10 ft behind a cone, the driver rode the ATV towards the cone at constant speeds of 5 or 10 mph, downshifting into neutral at the cone, and rolling to a stop some distance away. The distance was then measured. Together with speed, the rolling resistance can be calculated from one of three formulas, which are presented as eq 1–3 in the data analysis section.

Rolling Resistance Pull Test

Rolling resistance tests are very similar to draw bar tests, but the ATV is now the trailing vehicle. The vehicle pull method of measuring rolling resistance is given in SAE (1967) J939, SAE (1987a) J1269, and SAE (1987b)

J1270. The ATV and a towing vehicle were attached by the load cell and cable and positioned so that the cable was taut. With the ATV in neutral, the towing vehicle pulled the ATV at a constant 5 mph for approximately 30 ft. The average pulling force divided by the ATV weight produces the coefficient of rolling resistance. The setup can be seen in Figure 13.



Figure 13. Conducting a rolling resistance test on the ATV.

Circle Breakout Test

Circle breakout tests (SAE [1993] J2181) were performed around a set of cones in the gravel parking lot. The steering angle was held constant, and the ATV was driven as fast as possible around the circle just on the verge of slipping. The diameter of the circles was 60 ft. The circle tests allowed yaw rate to be verified, and the rider to gain some feel for the vehicle dynamics.

Trail Traverse

The ATV test vehicle was driven on several trails throughout EAFR to collect data to validate the vehicle simulation and for side-by-side comparison between the real and virtual data. The data collected during these longer trail runs were also used to demonstrate the ATV's capabilities and the instrumentation's abilities.

5 All-Terrain Vehicle Snow Testing

The ATV was tested on snow in March of 2003 at the Claremont, NH, airport. The test setup was similar to EAFR gravel lot testing with the ATV in 2WD high or neutral. Drawbar and rolling resistance tests were done.

A rolling resistance test is shown in Figure 14. The snow rolling resistance coefficient was approximately 0.058 and is plotted with EAFR values later in Figure 18. On snow, the traction coefficient was approximately 0.35. A summary of all data collected can be seen in Appendix F.

All tests were conducted on snow with an average depth of 9.87 cm and an average density of 0.1542 g/cm³. Air temperature was approximately 2.8°C. Detailed snow measurements are listed in Appendix E.



Figure 14. ATV rolling resistance test on snow.

6 Data Analysis

Traction Tests: Drawbar

Traction coefficients are calculated by dividing the longitudinal force by the vertical force acting on the vehicle during a drawbar test. They are unitless values that indicate how well the vehicle can grip the terrain. It is essential to make sure that the wheel gradually slips on the surface during the test, so that maximum traction is reached because traction varies with wheel slip. Because there were no wheel speed sensors on the ATV to indicate wheel slip, wheel spin was visually observed during testing.

An example plot of load cell values and vehicle speed versus time is given in Figure 15. Additionally, a plot of traction coefficients versus speed is given in Figure 16.

Traction coefficients for the ATV at EAFR on gravel ranged between 0.55 and 0.68 at a constant speed of 5 mph. On snow, the traction coefficient was approximately 0.35. A summary can be seen in Figure 17.

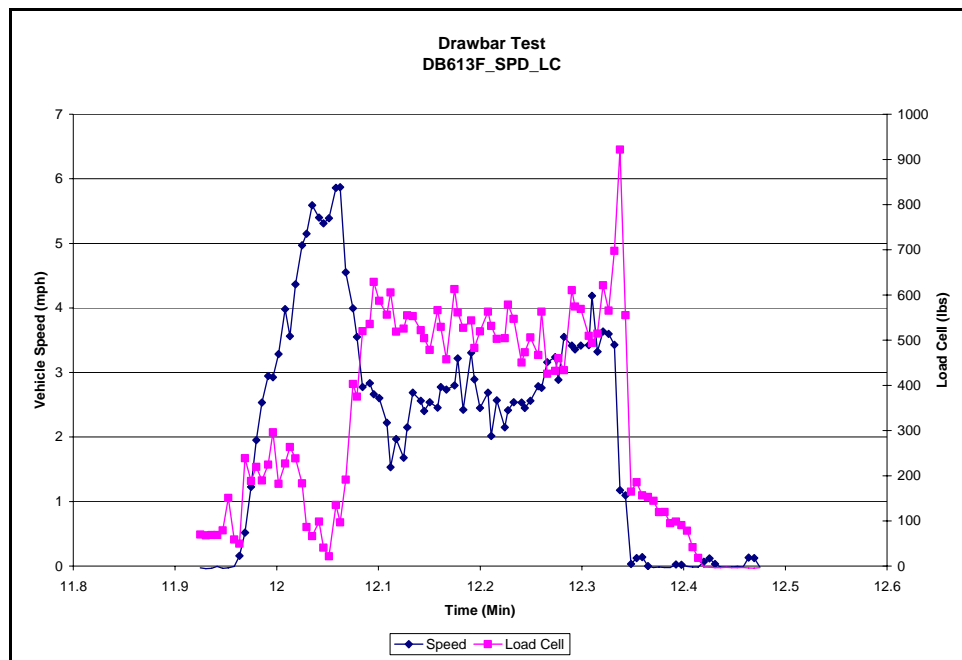


Figure 15. Typical drawbar results show that the speed of the ATV gradually increased as it continued to pull the trailing vehicle.

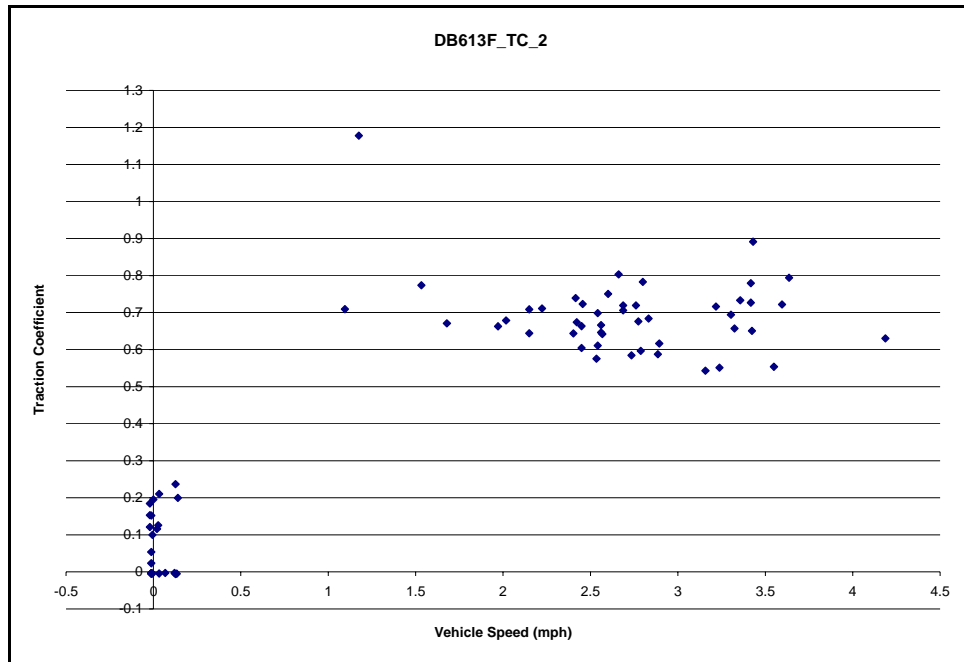


Figure 16. Traction coefficients plotted versus vehicle speed.

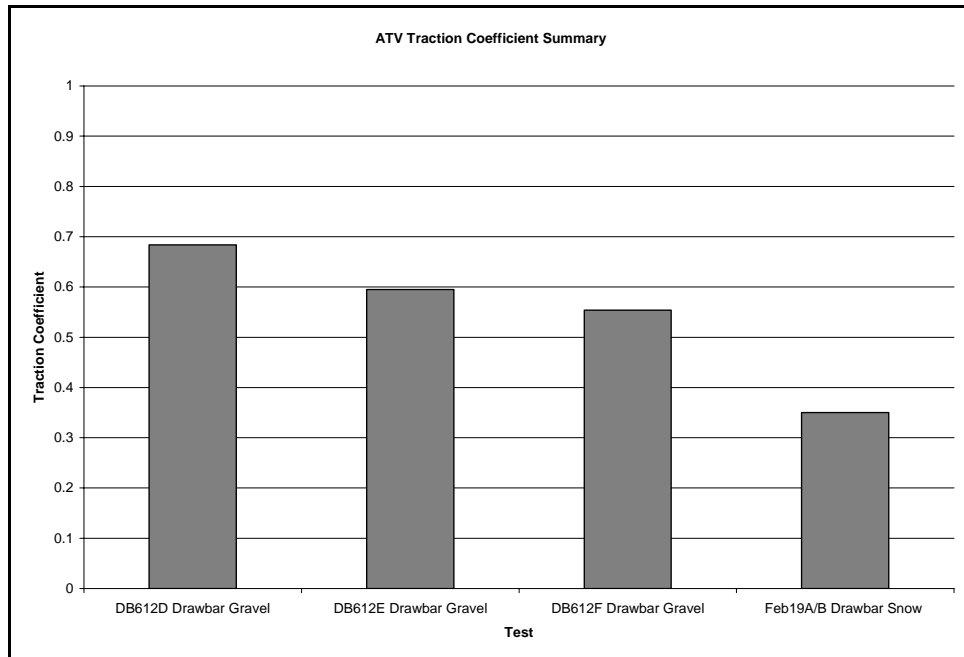


Figure 17. ATV traction coefficient summary for moist gravel and snow. Vehicle speed was 5 mph.

Rolling Resistance: Coast Down Test and Rolling Resistance Pull Test

Three equations were used to calculate estimates of the separate coefficient of rolling resistance from the coast down test. The first, which is empirically defined, is:

$$f_r = \frac{28.2(a \cdot V^2)}{10^3(V^2)} \quad (1)$$

where

- f_r = coefficient of rolling resistance
- a = mean deceleration after reaching the cone ([km/hr]/s)
- V = mean velocity after reaching the cone (km/hr) (Bosch 2004).

The second equation is:

$$RR_x = \frac{CV_i^2}{\left(e^{\left(\frac{2 \cdot C \cdot x_s}{m_v} \right)} - 1 \right)} \quad (2)$$

where

- RR_x = resistive force of the vehicle (N)
- C = aerodynamic drag factor ($0 < C < 1$)
- V_i = velocity at the start of the test (m/s)
- m_v = mass of the vehicle (kg)
- x_s = stopping distance (m) (Shoop et al. 2001).

To get the coefficient of rolling resistance, simply divide RR_x by the normal force of the vehicle in newtons. The C value ranges from 0 to 1. Trial values from 0 to 1 did not affect the data, so a C value of 1 was used in the equation.

The final equation:

$$F = \frac{W}{g} a_x = -RR_x \quad (3)$$

where

- F = force (lbf)
 RR_x = resistive force of the vehicle (lbf)
 W = weight (lbs)
 g = gravity (ft/s²)
 a_x = deceleration (ft/s²) (Shoop et al. 2001).

To get the coefficient of rolling resistance, simply divide RR_x by the vehicle weight in pounds.

Rolling resistance coefficients are calculated by dividing the longitudinal force by the weight of the vehicle. Care must be taken to use only the data recorded during the constant speed part of the test. Also note that these rolling resistance values do include internal (hard surface) rolling resistance.

A summary of rolling resistance coefficients for gravel, snow, and a hard surface is shown in Figure 18.

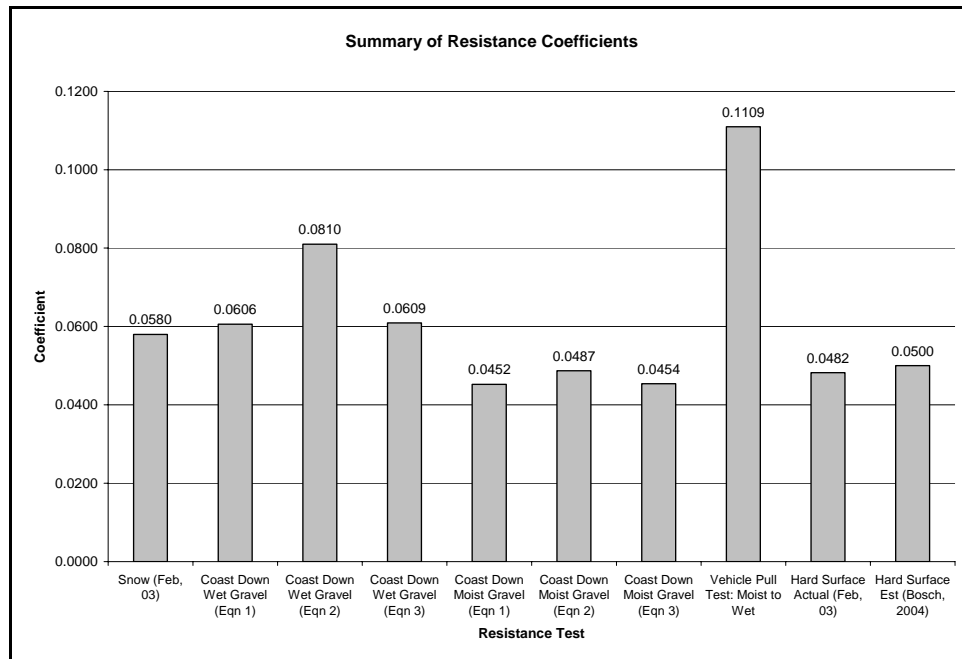


Figure 18. Rolling Resistance data for ATV. This figure includes values on snow, gravel, and a hard surface. It uses two types of methods and eq 1-3 to determine the coefficients. Wet Gravel refers to the wet side of the parking lot on June 12, while moist refers to the “dry” side of the lot. See Appendix D.

Circle Breakout Test

To validate the yaw rate sensor and calculate the maximum lateral traction, calculations were made from the speed measurements and plotted against time. To calculate yaw rate from speed, the following equation is used:

$$y = \frac{V}{c} * 360^\circ \quad (4)$$

where

- y = yaw rate (deg/s)
- v = velocity (ft/s)
- c = circumference of the circle (ft).

A plot of recorded yaw rate and the calculated yaw rate are shown in Figure 19.

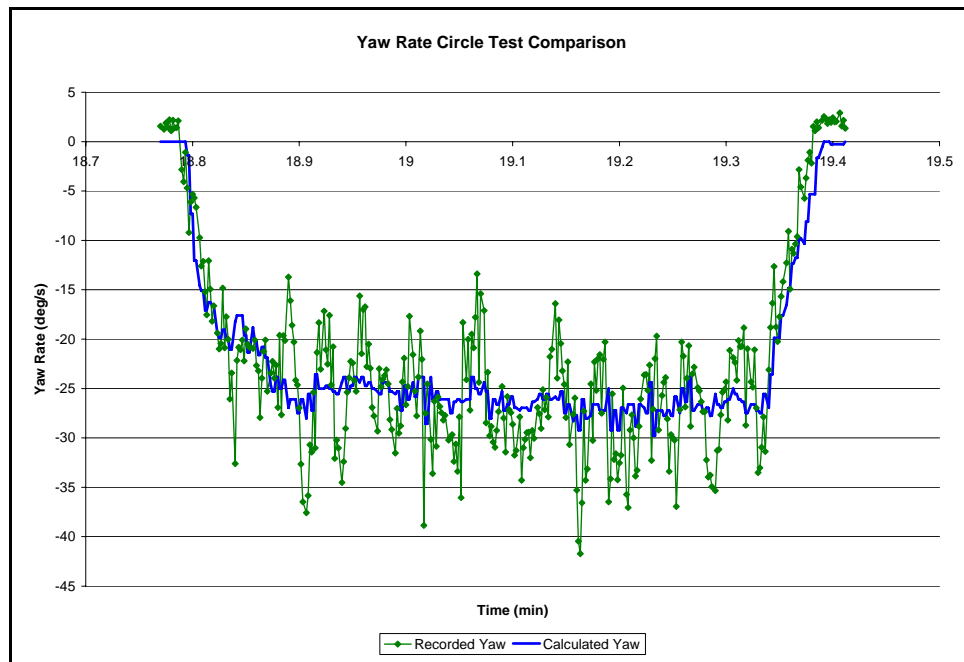


Figure 19. ATV's recorded yaw rate and the calculated yaw rate.

To calculate lateral traction, two force calculations were used. The first is simply Newton's second law, while the second is the ideal circular motion and centripetal force calculation:

$$F = \frac{mv^2}{r} \quad (5)$$

where

- F = force (newtons)
- m = mass of vehicle (kg)
- v = velocity (m/s)
- r = radius of circle (m).

As Newton's second law accepts the lateral acceleration as recorded by the accelerometer, the data are noisy. Therefore, in Figure 20, the lateral force calculated with Newton's second law is a 12-point running average, while eq 5 is calculated at each point. The noise in the data also makes it difficult to determine the maximum lateral force, because a small change in value can drastically impact the traction coefficient. Additionally, as there was no way to verify exact steering wheel angle or to keep speed perfectly constant, at best, the lateral force is approximate.

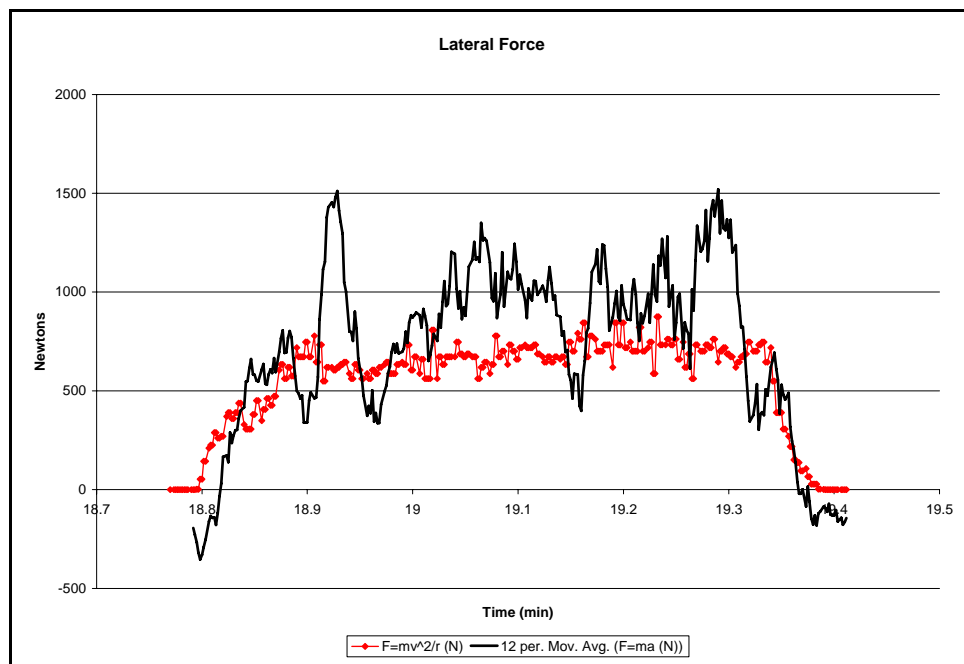
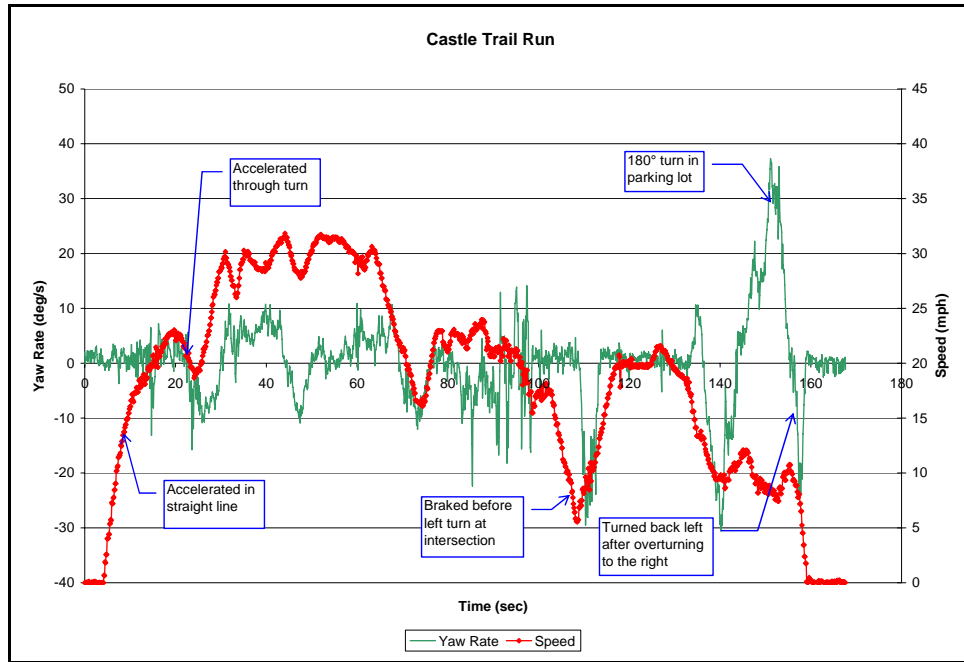


Figure 20. Calculated lateral force using Newton's second law and eq 5.

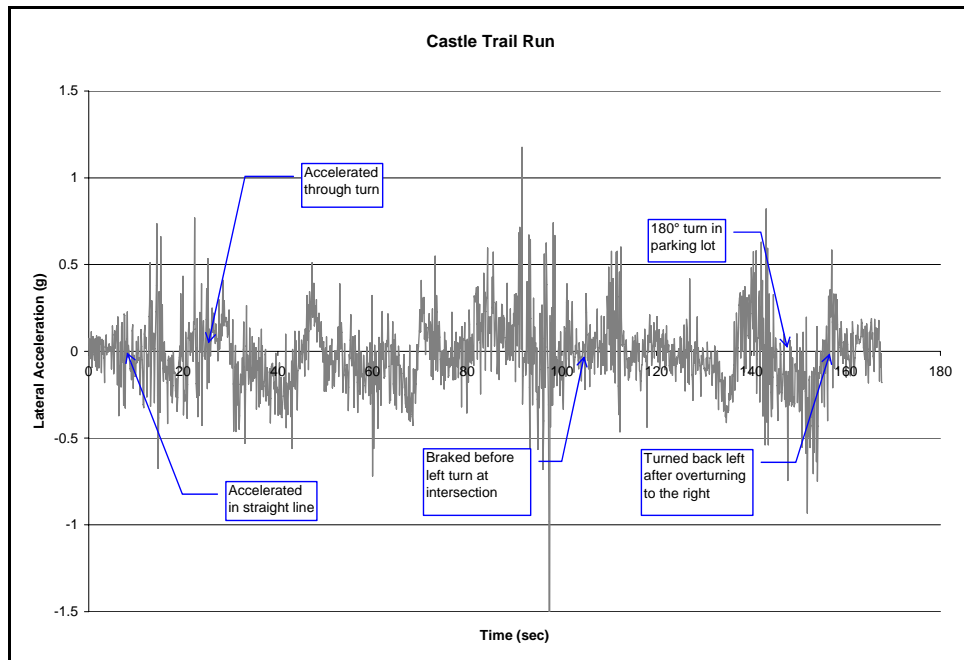
Trail Traverses

ATV data from EAFR trail runs were used for video-data post-processing synchronization. All data from the DAS were taken and large-scale plots of

output were graphed against time. A typical test lasted between 1 and 2 minutes. Yaw rate and speed are shown versus time for one trail run in Figure 21a, and lateral acceleration is graphed in Figure 21b.



a. Yaw and speed plotted against time with highlights noted.



b. Lateral acceleration plotted against time with highlights noted.

Figure 21. Castle Trail run.

Video data plots for several traverses were also synchronized with video using National Instruments DIAdem 10.0 software. This software allows the video to be displayed in concert with the data from the sensors and the GPS. During playback of the synchronized video and data, trends can be assessed and verified. The ATV video synchronized traverse was saved using a screen capture program for comparison with similar runs by the CIV. These videos and the corresponding data sets are available on CD. Figure 22 shows the display of the synchronized data and video. A description is given in the in the upper left, the video in the middle left, yaw rate in the lower left, speed in the upper right, and a GPS trace in the lower right. Playback can be controlled using the buttons at the top middle, and all other recorded parameters can be graphed and synchronized as desired. See Appendix G for more information on synchronizing data using DIAdem.

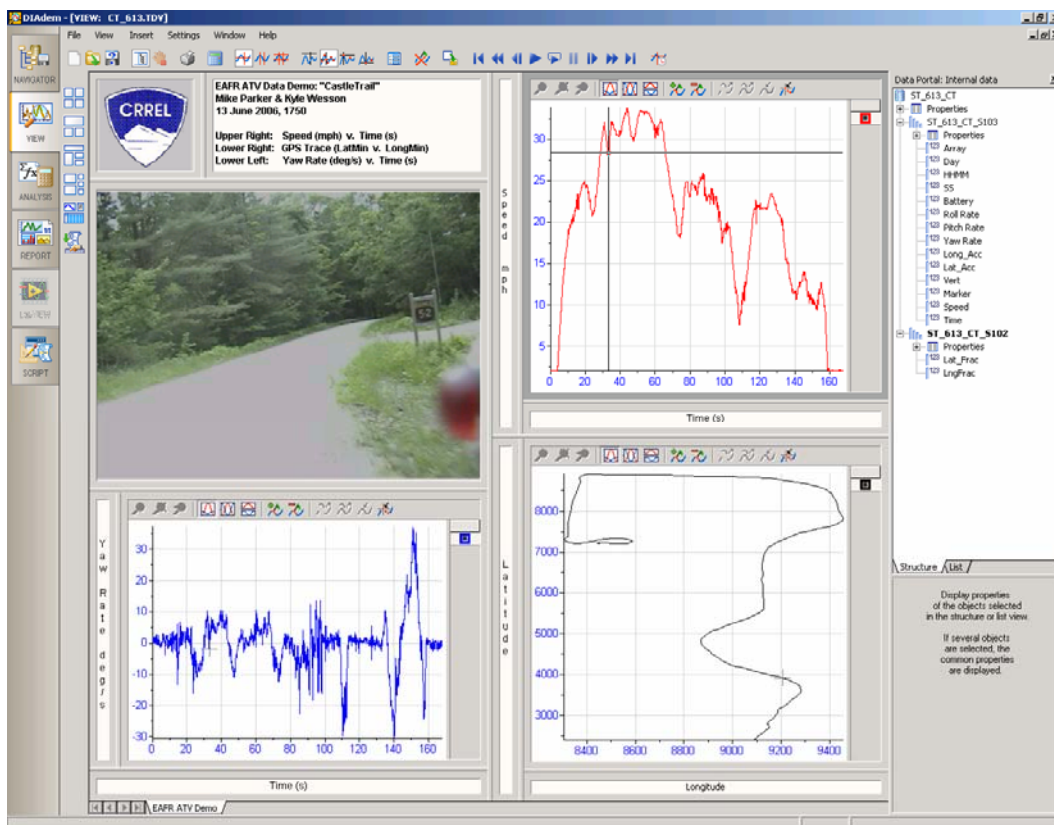


Figure 22. Screenshot of National Instruments DIAdem software with video taken from the front of the ATV and its corresponding data synchronized.

7 Comparison to CRREL Instrumented Vehicle

The CIV performed similar traction, rolling resistance, and traverse tests at EAFR. Traction and rolling resistance coefficients for both vehicles were determined and compared in Figure 23. Rolling resistance and traction tests were done each day. In Figure 23, dry gravel refers to the “dry side of parking lot,” while wet gravel refers to the “wet side of the parking lot” in Appendix D.

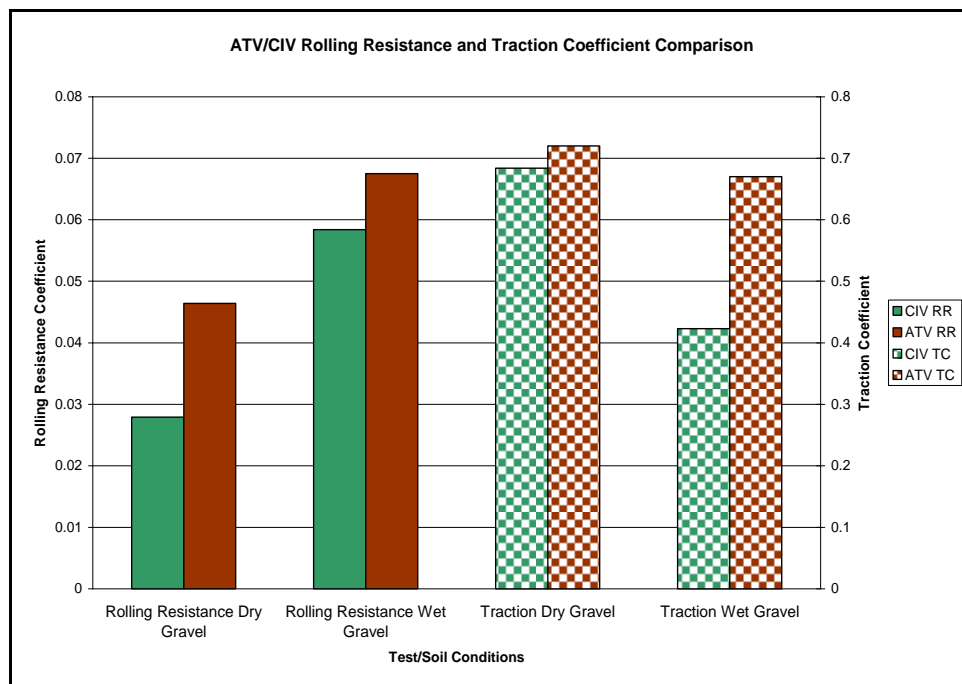


Figure 23. Comparison between ATV and CIV rolling resistance (RR) and traction coefficients (TC).

Rolling resistance values were greater on both dry and wet gravel for the ATV than for the CIV. It seems most likely that the larger tire tread patterns on the ATV’s tires created more resistance on the ground, and the CIV’s “street-ready” tires would cause a lower value. This added tread also gave the ATV a significantly larger traction coefficient on wet gravel. However, the ATV wet gravel traction test was done a day later than the CIV

test when the soil had 1% less moisture by volume, so the ATV may have been able to grip the dry surface better.

The CIV also performed trail-running tests with video. These have also been synchronized in DIAdem and the data are available on CD.

8 Recommendations/Applications

Low-cost, portable systems for mobility analyses of small, lightweight vehicles are instrumental in determining proper use requirements during field operations. Gathering necessary mobility data for a simulation would allow for accurate predictions of an ATV's capabilities in varied terrain conditions. Synchronized output of all sensor data with video could allow an evaluation of terrain-vehicle-driver interaction. Real-time data analysis with a visual output could enhance a driver's situational awareness of the vehicle's capabilities. Since the Department of Homeland security uses ATVs to protect the border and since soldiers use ATVs in combat, proper instrumentation of ATVs and understanding of their mobility would increase their applicability, functionality, and dependability. Collection and analysis of such data may make the realization of robotic ATVs more affordable and assure ATV reliability in security operations around the world.

References

- Bosch, R. 2004. *Automotive Handbook*. Warrendale, Pennsylvania: Society of Automotive Engineers.
- Blaisdell, G.L. 1983. The CRREL Instrumented Vehicle Hardware and Software. U.S. Army Cold Regions Research and Engineering Laboratory, Special Report 83-3.
- DIAdem 10.0. 2005. National Instruments Ireland Resources Limited.
- Dolan, J.M., A. Trebi-Ollennu, A. Soto, and P. Khosla. 1999. Distributed tactical surveillance with ATVs. In *SPIE Proceedings on Unmanned Ground Vehicle Technology*. Vol. 3693.
- LoggerNet 2.1c. 2003. Campbell Scientific Inc.
- Gillespie, T.D. 1992. *Fundamentals of Vehicle Dynamics*. Warrendale, Pennsylvania: Society of Automotive Engineers.
- SAE. 1986. *Drawbar Test Procedure for Construction, Forestry, and Industrial Machines*. SAE Handbook. Vol. 3. SAE J872. Warrendale, Pennsylvania: Society of Automotive Engineers.
- SAE. 1967. *Off-road Vehicle Mobility Evaluation*. SAE Recommended Practice Handbook Supplement. SAE J939. Warrendale, Pennsylvania: Society of Automotive Engineers.
- SAE. 1987a. *Rolling Resistance Measurement Procedure for Passenger Car, Light Truck, and Highway Truck and Bus Tires*. SAE Handbook. Vol. 3. SAE J1269. Warrendale, Pennsylvania: Society of Automotive Engineers.
- SAE. 1987b. *Measurement of Passenger Car, Light Truck and Highway Truck and Bus Tire Rolling Resistance*. SAE Handbook. Vol. 3. SAE J1270. Warrendale, Pennsylvania: Society of Automotive Engineers.
- SAE. 1993. *Steady-State Circular Test Procedure for Trucks and Busses*. SAE Handbook. Vol. 3. SAE J2181. Warrendale, Pennsylvania: Society of Automotive Engineers.
- SAE. 1999. *Stepwise Coastdown Methodology for Measuring Tire Rolling Resistance*. SAE Handbook. Vol. 3. SAE J2452. Warrendale, Pennsylvania: Society of Automotive Engineers.
- Shoop, S. A., P. Richmond, and R. Eaton. 2001. Estimating Rolling Friction of Loose Soil for Aircraft Takeoff on Unpaved Runways. U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory. Technical Report TR-01-11.
- Shoop, S. A., B. Coutermarsh, and A. Reid. 2004. All-season Virtual Test Site for a Real-Time Vehicle Simulator. In *Society of Automotive Engineers Commercial Vehicle Symposium, Chicago, Illinois, October 2004*. SAE Paper No. 2004-01-2644.

Appendix A: ATV Engine Torque Dynamometer Data

RPM	Engine Torque N*m									
	0	0.125	0.25	0.375	0.4375	0.5	0.625	0.75	0.875	1
1000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1500	0.000	0.000	0.000	0.161	0.241	0.322	0.248	0.174	0.144	0.113
2000	0.000	0.020	0.340	0.660	0.820	0.980	0.987	0.993	0.965	0.936
2250	0.000	0.000	0.234	0.741	0.994	1.247	1.247	1.248	1.235	1.223
2500	0.000	0.000	0.137	0.645	0.900	1.154	1.279	1.405	1.408	1.411
2750	0.000	0.000	0.063	0.566	0.817	1.069	1.235	1.402	1.420	1.438
3000	0.000	0.000	0.000	0.780	0.884	0.988	1.195	1.402	1.422	1.441
3500	0.000	0.000	0.000	0.500	0.631	0.762	1.024	1.287	1.309	1.332
3750	0.000	0.000	0.000	0.353	0.492	0.631	0.910	1.188	1.202	1.216
4000	0.000	0.000	0.000	0.167	0.309	0.450	0.734	1.017	1.037	1.056

Appendix B: LoggerNet

To communicate with the station (data acquisition system) and storage module, one must use LoggerNet, Campbell Scientific's data logger software. The main screen for the program is shown in Figure B1, and the five main buttons are highlighted.

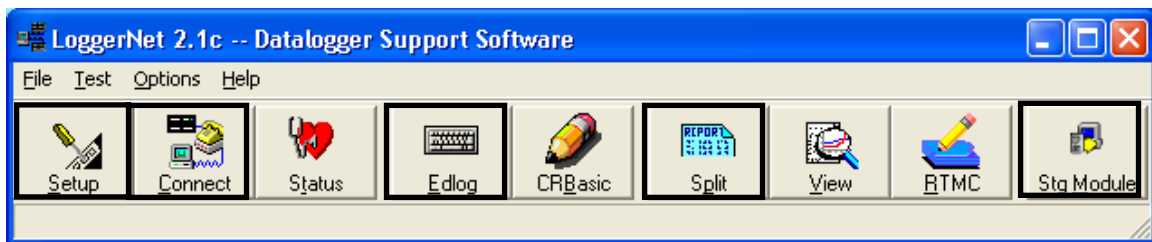


Figure B1. Main LoggerNet screen.

Connecting the Computer to Station and Viewing Data

To connect the computer to the station, press the “Connect” button in Figure B1 after opening the software, correctly connecting the wireless Bluetooth device to the machine, and turning on the Campbell DAS. The following screen will appear:

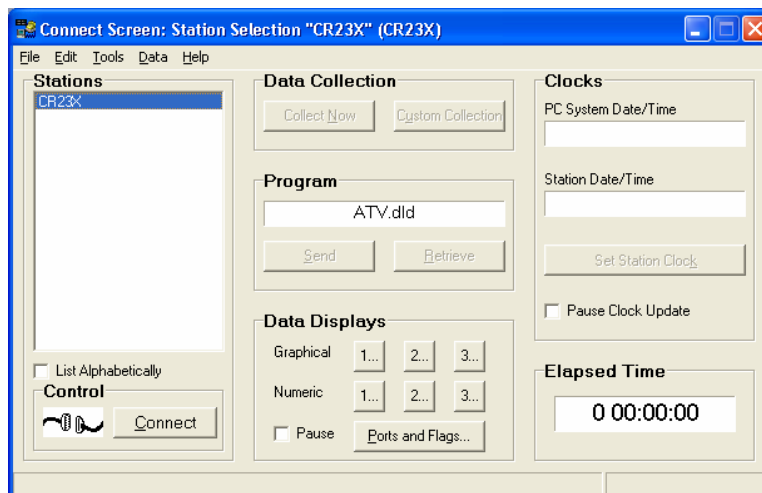


Figure B2. Station to computer connect screen.

Select “CR23x” from the menu, and then click on the “Connect” button. After the station connects, the button will then say “Disconnect.” From this menu, you can view the real-time data and send a new program directly to the data logger. To view real-time data, click on the “1” button

next to “Numeric” in Figure B2. This will open a screen that displays the requested data as in Figure B3.

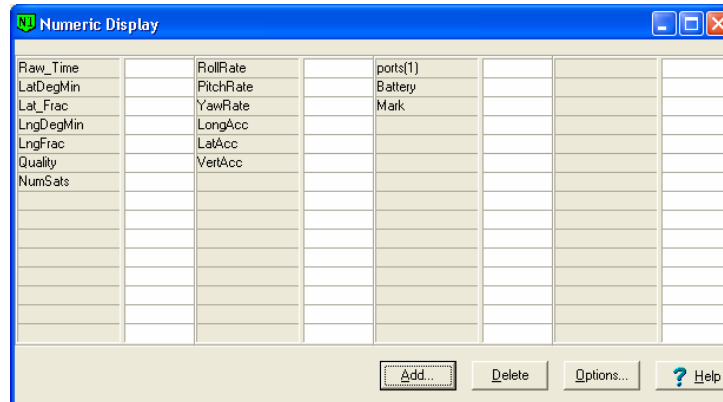


Figure B3. LoggerNet real-time data viewing screen.

Next to each of the data elements will be a number that changes about once a second after the connection is made—these are the real-time data.

Sending Program to the Station Directly

To send a program directly to the Campbell instead of its storage module, click on “Send” in Figure B2, and select the program to send using the browser that opens. This will delete all program data on the DAS and will automatically restart the station running the new program. Only perform this operation if cycling power to the station is impractical, because after a restart, the program in the storage module will automatically overwrite the station.

Connecting to Storage Module and Collecting Data

To connect to the storage module, click on “Stg Module” on the main screen of LoggerNet. Make sure you are disconnected from the station first. The following screen in Figure B4 should appear. Make sure to click on the “SM4M/SM16M” tab.

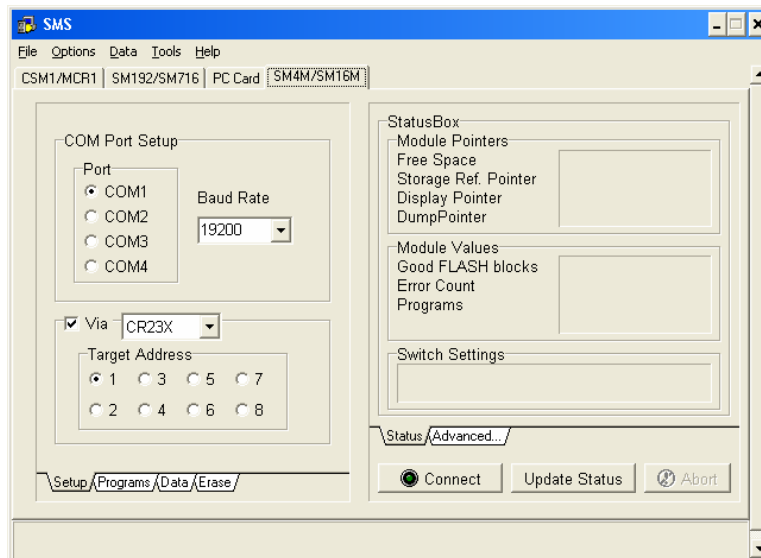


Figure B4. Screen to connect to the storage module.

Verify the following settings in Figure B4 under the lower “Setup” tab, and proceed to the data collection screen by clicking on the “Data” tab.

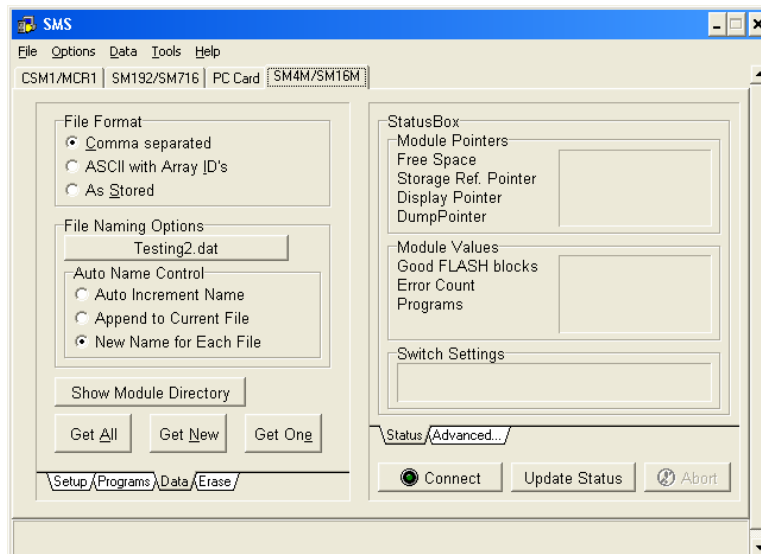


Figure B5. Storage module’s data collection screen.

To collect from the “Data” tab display, click on either “Get All” or “Get New,” depending how many data you would like to receive. Be sure the connection Campbell DAS is not active, and then click “Connect” in Figure B5. Select the options for data collection format and name control, and save the data to the correct directory.

Send a Program to the Storage Module

To send a program to the storage module, click “Program 8” in Figure B6, and click “Store.” Select the correct *.dld* file to store on the module. Program 8 is the only program that automatically loads, compiles, and runs when the system is powered up, so make sure to save the program there.

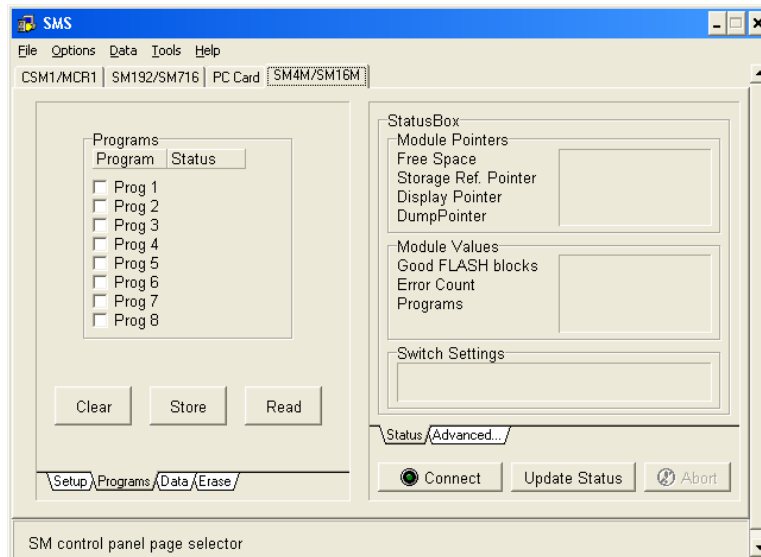


Figure B6. Program storage screen.

Erase Data from the Storage Module

To erase data, go to the “Erase” tab in the bottom left of Figure B6, and select the type of erase you would like to perform. You can either erase all data or erase all of the data and test the storage module—the former is most applicable. This may take some time depending on the amount of data in the storage module.

Splitting Data after Collection

Once data have been collected, they must be split to separate the arrays. In this case, array 102 stores GPS data, and 103 stores all other data. Open LoggerNet’s Split program from the main list in Figure B1.

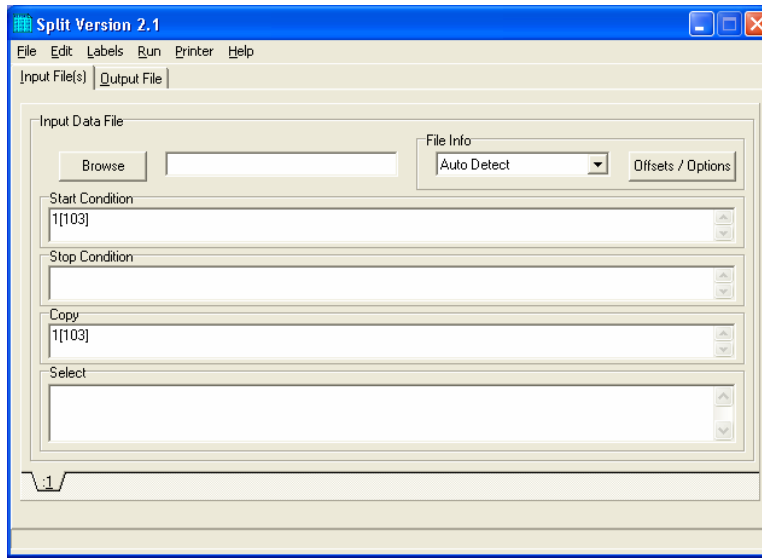


Figure B7. LoggerNet's Split program.

Select the Input Data File by clicking “Browse” from the list and selecting the correct data file. Enter the start condition to split. To split out the accelerometer data, enter 1[103] as the “Start Condition” and the same in the “Copy Condition.” This will split only lines with the value 103 in the column named “array,” and save them to the specified output file. To select the output file, select the “Output File” tab.

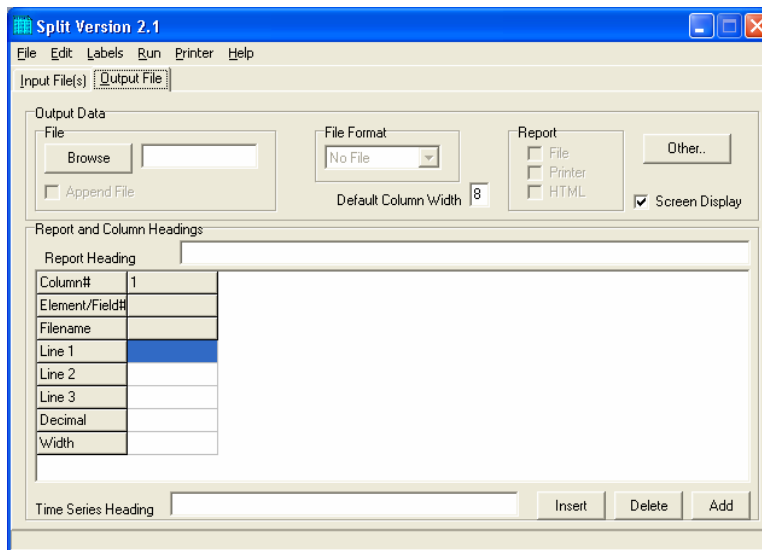


Figure B8. Output options for Split.

Browse again to create the file or directory to save the split data. Then click on “Run” and “Go” in Figure B8. This will begin the splitting process. Data can then be opened and imported into Excel as a .CSV file.

Appendix C: Campbell 23x Programs

Program to Record Accelerometer, GPS, Marker, and Vehicle Speed

```
:{CR23X}
*Table 1 Program
01: 0.1000 Execution Interval (seconds)

1: Batt Voltage (P10)
1: 8 Loc [ Battery ]

2: Volt (SE) (P1)
1: 1 Reps
2: 15 5000 mV, Fast Range
3: 1 SE Channel
4: 9 Loc [ RollRate ]
5: -.16 Mult
6: 398 Offset

3: Volt (SE) (P1)
1: 1 Reps
2: 15 5000 mV, Fast Range
3: 2 SE Channel
4: 10 Loc [ PitchRate ]
5: -.16 Mult
6: 382 Offset

4: Volt (SE) (P1)
1: 1 Reps
2: 15 5000 mV, Fast Range
3: 3 SE Channel
4: 11 Loc [ YawRate ]
5: .16 Mult
6: -411 Offset

5: Volt (SE) (P1)
1: 1 Reps
2: 15 5000 mV, Fast Range
3: 4 SE Channel
4: 12 Loc [ LongAcc ]
5: .005 Mult
6: -12.64 Offset

6: Volt (SE) (P1)
1: 1 Reps
2: 15 5000 mV, Fast Range
```

3: 5 SE Channel
4: 13 Loc [LatAcc]
5: -.005 Mult
6: 12.11 Offset

7: Volt (SE) (P1)
1: 1 Reps
2: 15 5000 mV, Fast Range
3: 6 SE Channel
4: 14 Loc [VertAcc]
5: .005 Mult
6: -11.83 Offset

8: Volt (SE) (P1)
1: 1 Reps
2: 15 5000 mV, Fast Range
3: 8 SE Channel
4: 15 Loc [Mark]
5: -1 Mult
6: 4943 Offset

9: Volt (SE) (P1)
1: 1 Reps
2: 15 5000 mV, Fast Range
3: 14 SE Channel
4: 16 Loc [Speed]
5: 0.02002 Mult
6: -0.03 Offset

10: If Flag/Port (P91)
1: 41 Do if Port 1 is High
2: 10 Set Output Flag High (Flag 0)

11: Set Active Storage Area (P80)
1: 1 Final Storage Area 1
2: 103 Array ID

12: Serial Out (P96)
1: 71 Destination Output

13: Real Time (P77)
1: 111 Day,Hour/Minute,Seconds (midnight = 0000)

14: Average (P71)
1: 10 Reps
2: 8 Loc [Battery]

*Table 2 Program
01: 0.0000 Execution Interval (seconds)

*Table 3 Subroutines

1: Beginning of Subroutine (P85)

1: 98 Subroutine 98

2: Port Serial I/O (P15)

1: 1 Repts
2: 65 RS-232 ASCII (decimal delimiter), 19200 Baud
3: 0 TX after CTS
4: 9 RS-232 Port
5: 1 Start Loc for TX [b]
6: 0 Number of Locs to TX
7: 42 Termination Character for RX
8: 100 RX Buffer Size or Max Chars to RX if Par 2 indexed (-)
9: 80 Time Out for CTS (TX) and/or RX (0.01 sec units)
10: 1 Start Loc for RX [b]
11: 1.0 Mult for RX
12: 0.0 Offset for RX

3: Extended Parameters (P63)

1: 36 Option
2: 71 Option
3: 80 Option
4: 71 Option
5: 71 Option
6: 65 Option
7: 0 Option
8: 0 Option

4: If (X<=>F) (P89)

1: 7 X Loc [NumSats]
2: 3 >=
3: 3 F
4: 30 Then Do

5: If Flag/Port (P91)

1: 41 Do if Port 1 is High
2: 10 Set Output Flag High (Flag 0)

6: Set Active Storage Area (P80)

1: 1 Final Storage Area 1
2: 102 Array ID

7: Serial Out (P96)

1: 71 Destination Output

8: Real Time (P77)

1: 111 Day,Hour/Minute,Seconds (midnight = 0000)

9: Resolution (P78)

1: 1 High Resolution

10: Sample (P70)
1: 6 Reps
2: 2 Loc [LatDegMin]

11: Sample (P70)
1: 1 Reps
2: 10 Loc [PitchRate]

12: Resolution (P78)
1: 0 Low Resolution

13: $Z=F \times 10^n$ (P30)
1: -1 F
2: 0 n, Exponent of 10
3: 6 Z Loc [Quality]

14: Delay w/Opt Excitation (P22)
1: 1 Ex Channel
2: 4 Delay W/Ex (0.01 sec units)
3: 1 Delay After Ex (0.01 sec units)
4: 5000 mV Excitation

15: End (P95)

16: End (P95)

End Program

Program to Record Accelerometer, GPS, Marker, Vehicle Speed, and Load Cell

;(CR23X)
*Table 1 Program
01: 0.33 Execution Interval (seconds)

1: Batt Voltage (P10)
1: 8 Loc [Battery]

2: Volt (SE) (P1)
1: 1 Reps
2: 15 5000 mV, Fast Range
3: 1 SE Channel
4: 9 Loc [RollRate]
5: -.16 Mult
6: 398 Offset

3: Volt (SE) (P1)
1: 1 Reps

2: 15 5000 mV, Fast Range
3: 2 SE Channel
4: 10 Loc [PitchRate]
5: -.16 Mult
6: 382 Offset

4: Volt (SE) (P1)

1: 1 Reps
2: 15 5000 mV, Fast Range
3: 3 SE Channel
4: 11 Loc [YawRate]
5: .16 Mult
6: -411 Offset

5: Volt (SE) (P1)

1: 1 Reps
2: 15 5000 mV, Fast Range
3: 4 SE Channel
4: 12 Loc [LongAcc]
5: .005 Mult
6: -12.64 Offset

6: Volt (SE) (P1)

1: 1 Reps
2: 15 5000 mV, Fast Range
3: 5 SE Channel
4: 13 Loc [LatAcc]
5: -.005 Mult
6: 12.11 Offset

7: Volt (SE) (P1)

1: 1 Reps
2: 15 5000 mV, Fast Range
3: 6 SE Channel
4: 14 Loc [VertAcc]
5: .005 Mult
6: -11.83 Offset

8: Volt (SE) (P1)

1: 1 Reps
2: 15 5000 mV, Fast Range
3: 8 SE Channel
4: 15 Loc [Mark]
5: -1 Mult
6: 4943 Offset

9: Volt (SE) (P1)

1: 1 Reps
2: 15 5000 mV, Fast Range
3: 14 SE Channel

4: 16 Loc [Speed]
 5: 0.02002 Mult
 6: -0.03 Offset

10: Full Bridge (P6)

1: 1 Reps
 2: 21 10 mV, 60 Hz Reject, Slow Range
 3: 6 DIFF Channel
 4: 1 Excite all reps w/Exchan 1
 5: 5000 mV Excitation
 6: 17 Loc [LoadCell]
 7: 1876.17 Mult
 8: 80 Offset

11: If Flag/Port (P91)

1: 41 Do if Port 1 is High
 2: 10 Set Output Flag High (Flag 0)

12: Set Active Storage Area (P80)

1: 1 Final Storage Area 1
 2: 103 Array ID

13: Serial Out (P96)

1: 71 Destination Output

14: Real Time (P77)

1: 111 Day,Hour/Minute,Seconds (midnight = 0000)

15: Average (P71)

1: 10 Reps
 2: 8 Loc [Battery]

*Table 2 Program

01: 0.0000 Execution Interval (seconds)

*Table 3 Subroutines

1: Beginning of Subroutine (P85)

1: 98 Subroutine 98

2: Port Serial I/O (P15)

1: 1 Reps
 2: 65 RS-232 ASCII (decimal delimiter), 19200 Baud
 3: 0 TX after CTS
 4: 9 RS-232 Port
 5: 1 Start Loc for TX [b]
 6: 0 Number of Locs to TX
 7: 42 Termination Character for RX
 8: 100 RX Buffer Size or Max Chars to RX if Par 2 indexed (-)
 9: 80 Time Out for CTS (TX) and/or RX (0.01 sec units)

10: 1 Start Loc for RX [b]
11: 1.0 Mult for RX
12: 0.0 Offset for RX

3: Extended Parameters (P63)
1: 36 Option
2: 71 Option
3: 80 Option
4: 71 Option
5: 71 Option
6: 65 Option
7: 0 Option
8: 0 Option

4: If (X<=>F) (P89)
1: 7 X Loc [NumSats]
2: 3 >=
3: 3 F
4: 30 Then Do

5: If Flag/Port (P91)
1: 41 Do if Port 1 is High
2: 10 Set Output Flag High (Flag 0)

6: Set Active Storage Area (P80)
1: 1 Final Storage Area 1
2: 102 Array ID

7: Serial Out (P96)
1: 71 Destination Output

8: Real Time (P77)
1: 111 Day,Hour/Minute,Seconds (midnight = 0000)

9: Resolution (P78)
1: 1 High Resolution

10: Sample (P70)
1: 6 Repts
2: 2 Loc [LatDegMin]

11: Sample (P70)
1: 1 Repts
2: 10 Loc [PitchRate]

12: Resolution (P78)
1: 0 Low Resolution

13: Z=F x 10^n (P30)
1: -1 F

2: 0 n, Exponent of 10

3: 6 Z Loc [Quality]

14: Delay w/Opt Excitation (P22)

1: 1 Ex Channel

2: 4 Delay W/Ex (0.01 sec units)

3: 1 Delay After Ex (0.01 sec units)

4: 5000 mV Excitation

15: End (P95)

16: End (P95)

Appendix D: Ethan Allen Firing Range Soil Conditions

Gravel Parking Lot

Location	date/time	Soil Description	Average Moisture		Trafficability Cone Index** (max)		Average slope	
			% Vol	mV*	Depth (in.)	CI	ATV test area	CIV test area
dry side of parking lot	June 12th morning tests	gravelly sand	19.55	497.00	3	300	0.92°	1.74°
wet side of parking lot		gravelly sand, surface has small water puddles	23.57	584.00	-	300	2.10°	1.02°
dry side of parking lot	June 12th afternoon tests	gravelly sand	15.60	404.75	-	-	-	-
wet side of parking lot		gravelly sand, water puddles are smaller	28.63	688.14	-	-	-	-
dry side of parking lot	June 13th morning tests	gravelly sand	14.41	373.71	-	-	-	-
wet side of parking lot		gravelly sand, water puddles are gone	14.41	373.71	-	-	-	-

*mV reading by DynaMax HH2 moisture probe

** Trafficability Cone express in Cone Index (CI) in psi. (ASAE Standard S313.3 (1999) Soil cone penetrometer)

Feigel Hill

Location	Soil Description	Coordinates		Average Moisture		Trafficability Cone Index** (max)	
		E	N	% Vol	mV*	Depth (in.)	CI
Beginning of ATV trail	Sandy gravel; Found grey and orange clay at about 8 inch depth	669480	4927854	36.65	538.76	2	220
ATV Waypoint 1	GM highly-variable soils with grey ML (w/ clay); Reddish-blueish grains of weathered organics where the water table is high	669583	4927792	30.00	699.00	7	180
ATV Waypoint 2	Thick organic layer; Some GM	669717	7927813	51.40	970.80	-	-
ATV Waypoint 3	Organic layer on top then pockets of gray sand and pockets of reddish-brown sand.	669593	4927925	38.97	863.83	4	230

Porcupine Pass

Location	Coordinates		Moisture		Trafficability Cone Index** (max)	
	Easting	North	% Vol	mV*	Depth (in.)	CI
Porcupine road	666707	4928898	18.7	481		280
	666728	4928892	-	-	1.5	200
	666746	4928879	10.6	291		280
	666819	4928844	10.6	291	-	-
	666823	4928846	-	-	1.5	280

Appendix E: Snow Measurements at Claremont Airport

Undisturbed snow density (average of all tests)	0.005571 lb/cubic inch
Undisturbed snow depth (average of two RR tests)	3.88 in.
Sinkage	3.34 in.
Terrain resistance	50.1 lbf
Gross Traction	396.9 lbf

Appendix F: ATV Snow Data

File	Test	Result	Roll Coefficient	Rut Depth	Undisturbed Snow Depth	Undisturbed Snow Density
Name	Description		Unitless	(cm)	(cm)	(g/cc)
FEB19F	Average Hard Surface Rolling Resistance (R-internal), Forward (lbf) =	33.8	0.0391	NA	NA	
FEB19G	Average Hard Surface Rolling Resistance (R-internal), Return (lbf) =	49.5	0.0573	NA	NA	
	Average two-way Hard Surface RR (R-internal) (lbf)	41.7	0.0482	NA	NA	
FEB19A	Gross Rolling Resistance (R-internal+ R-terrain), Test 1 (lbf) =	92.1	0.1066	8.57	9.75	0.1542
FEB19B	Gross Rolling Resistance (R-internal+ R-terrain), Test 2 (lbf) =	91.4	0.1058	8.38	10.00	0.1542
	Net Rolling Resistance (R-terrain), Test 1 (lbf) =	50.4	0.0584	8.57	9.75	
	Net Rolling Resistance (R-terrain), Test 2 (lbf) =	49.8	0.0576	8.38	10.00	
	Two Test Average Gross Rolling Resistance (R-internal+ R-terrain) (lbf) =	91.8	0.1062	8.47	9.87	
	Two Test Average Net Rolling Resistance (R-terrain) (lbf) =	50.1	0.0580	8.47	9.87	
FEB19C	Appx. Max. Net Traction (T-net), Test 1 (lbf) =	287.2	0.3324		9.54	0.1542
FEB19D	Appx. Max. Net Traction (T-net), Test 2 (lbf) =	291.5	0.3374		10.20	0.1542
FEB19E	Appx. Max. Net Traction (T-net), Test 3 (lbf) =	336.6	0.3896		10.13	0.1542
	Three Test Average Appx. Max. Net Traction (T-net) (lbf) =	305.1	0.3531		9.96	0.1542
	Appx. Max. Gross Traction (T-gross), Test 1 (lbf) =	379.0	0.4386		9.54	0.1542
	Appx. Max. Gross Traction (T-gross), Test 2 (lbf) =	383.3	0.4436		10.20	0.1542
	Appx. Max. Gross Traction (T-gross), Test 3 (lbf) =	428.4	0.4958		10.13	0.1542
	Three Test Average Appx. Max. Gross Traction (T-gross) (lbf) =	396.9	0.4593		9.96	0.1542

Appendix G: DIAdem Data Synchronization

Synchronizing data with DIAdem requires both data and video from the same test. To begin, open DIAdem and select Help > Introduction. Click “Synchronizing Video and Data Playback.” This brief video will demonstrate how to import data and roughly synchronize the data with the video.

Synchronization can be tricky with the video, however, because the software must have a common time base between the data and the movie. Essentially, the data time must be as long as the length of the video. To find the length of the video, right click on the video area in DIAdem and select synchronize (Menu in Figure G1 is displayed). The last row will list the video’s duration. In the data editor of your choice, insert a new data column into the data. Divide the time by the number of data cells to get your step size, and create a new time base in the newly created column. Label, save, and re-import the data into DIAdem. Once imported, the data should synchronize more easily.

To perfect the synchronization, right click on the video area in DIAdem and select synchronize. Modifying the Start time option allows you to begin the movie earlier or later with regard to the time base. A selection of 5 will postpone the video for playing until the time base on the data reads five. Choosing a negative number will begin the video before the data.

Once synchronized, using the play buttons at the top or sliding the cursor across the data will move the video at the same time.

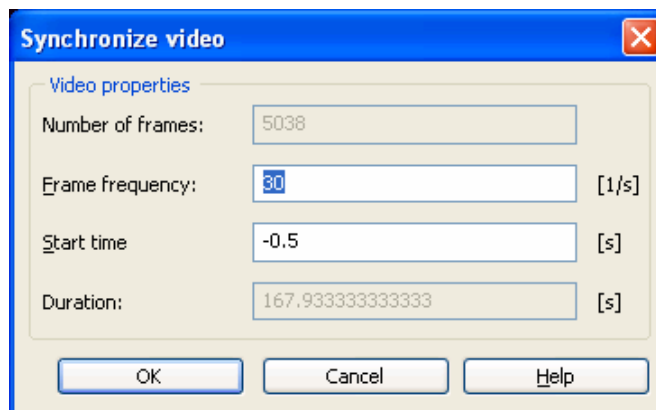


Figure G1. DIAdem's synchronization options for video.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY) January 2007			2. REPORT TYPE		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Instrumenting an All-Terrain Vehicle for Off-Road Mobility Analysis					5a. CONTRACT NUMBER	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Kyle D. Wesson, Michael W. Parker, Barry C. Coutermarsh, Sally A. Shoop, and Jesse M. Stanley					5d. PROJECT NUMBER	
					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Cold Regions Research and Engineering Laboratory U.S. Army Engineer Research and Development Center 72 Lyme Road Hanover, NH 03755					8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CRREL TR-07-1	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S)	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT With small mobile vehicles, even robots, becoming increasingly important for military operations, Cold Regions Research and Engineering Laboratory (CRREL) researchers set out to instrument an all-terrain vehicle (ATV) with mobility sensors to obtain and understand small-vehicle mobility data in all seasons. Extensive mobility research has already been performed at CRREL on the CRREL Instrumented Vehicle (CIV), which collects mobility data with large and expensive vehicle performance sensors. However, a small vehicle such as an ATV is not suited to carry large data collection instruments. In an effort to overcome cost and size limitations while maintaining functionality, an ATV was instrumented with low-cost sensors to collect mobility data comparable to the CIV. At the U.S. Army's Ethan Allen Firing Range, ATV mobility performance tests, such as coast down and drawbar tests, were performed alongside the CIV for comparison, while cross range test runs were performed to demonstrate the system's capabilities. This report presents one option for researchers looking to instrument a small-vehicle with mobility performance sensors, describes the testing methodology and results, and offers a comparison to the CIV. Low-cost, portable vehicle mobility instrumentation systems would allow for accurate vehicle simulations and mobility awareness that can be used <i>in situ</i> by the warfighter and lead to further applications of all-terrain vehicles in force protection and border patrol scenarios.						
15. SUBJECT TERMS ATV ATV instrumented for research			CRREL Instrumented Vehicle (CIV) Mobility tests			
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)	
U	U	U	U	57		