Evaluation of an Adaptive Suspension Vehicle

W. B. Stuart[1]
Virginia Polytechnic Institute
Blacksburg, U.S.A.

W. Michael Aust
Virginia Polytechnic Institute
Blacksburg, U.S.A.

Hubert Lacki
Warsaw Academy of Agricultural Science
Warsaw, Poland

Lisa Andrews
Virginia Polytechnic Institute
Blacksburg, U.S.A.

ABSTRACT

The Adaptive Suspension Vehicle, a proof-of-concept, six-legged robotic walking machine, was subject to a series of field trials to evaluate the maneuverability and trafficability characteristics of walking machines. Maneuverability trials were structured to test performance as a carrier for frame-mounted feller-buncher heads in both thinning and clearcutting applications. The trafficability trials focused on the type and extent of soil disturbance, especially changes in soil bulk density, mechanical resistance, macro- and micro-porosity. the machine was found to impact the soil very differently than wheeled or tracked equipment. Direct comparisons of soil parameters were limited because of time and budget restrictions but seem to indicate that the legged locomotion offered distinct production and soil disturbance advantages, especially on steep slopes and in wetlands.

Key Words: *Walking machine, maneuverability, trafficability, bulk density, mechanical resistance, thinning, clearcut*

INTRODUCTION

Machine impacts on forest soils promise to shape the future of commercial forestry and forest management activities in general, especially on wetland sites and steep slopes, where restrictions imposed by best management practices, soil and water quality legislation, and other regulatory initiatives are most severe. Advances in both tire and track technology have extended the operating ranges of conventional equipment over the last decade, but, the tightening of regulations threatens forestry activities on vast acreages of otherwise commercial forest by proscribing against access either by machine type or machine impact. Three strategies are available to mitigate the impact of these regulatory thrusts: working in the public arena to assure that the regulations are well considered and workable; using the best available technology to carry out current operations; and finally, exploring new technologies which offer promise as alternatives to current equipment and methods. Walking machines are one of the most promising emerging technologies.

No means of movement has been developed which exceeds legged locomotion in the ability to adapt to variations in topography, avoid obstacles, selectively impact footing, and maneuver precisely in tight quarters. Past attempts at developing walking machines met with limited success. Muscles and movements could be duplicated mechanically, but the critical element, a nervous system, was lacking. Advances in computer technology, sensors and hydraulics are lifting this constraint. Rapid advances are being made in walking machine development. Experimental machines have the ability to move quickly (speeds above 7.5 km.h-1), sense the suitability of a foothold before stepping, and have much greater maneuverability than machines of even a few years ago.

The six-legged Adaptive Suspension Vehicle (ASV), the only fully functional terrain-crossing walking machine in the United States, was developed by Adaptive Machine Technologies and the Departments of Electrical and Mechanical Engineering at Ohio State University under a contract from the Defense Advanced Research Projects Agency. The machine has been operational since October 1986, when it was first demonstrated walking over the flat surface of a parking lot, but is still considered to be in the "proof of concept stage." The machine was designed to demonstrate that a fully functional walking machine could be built and to serve as a test vehicle for refining machine capabilities. The software controlling the machine's movements has been refined to the point where the machine can move with equal facility over parking lots and broken

[1]*The authors are, respectively, Associate Professor and Assistant Professor in Industrial Forestry Operations; Visiting Scholar; and Graduate Assistant, Industrial Forestry Operations.*

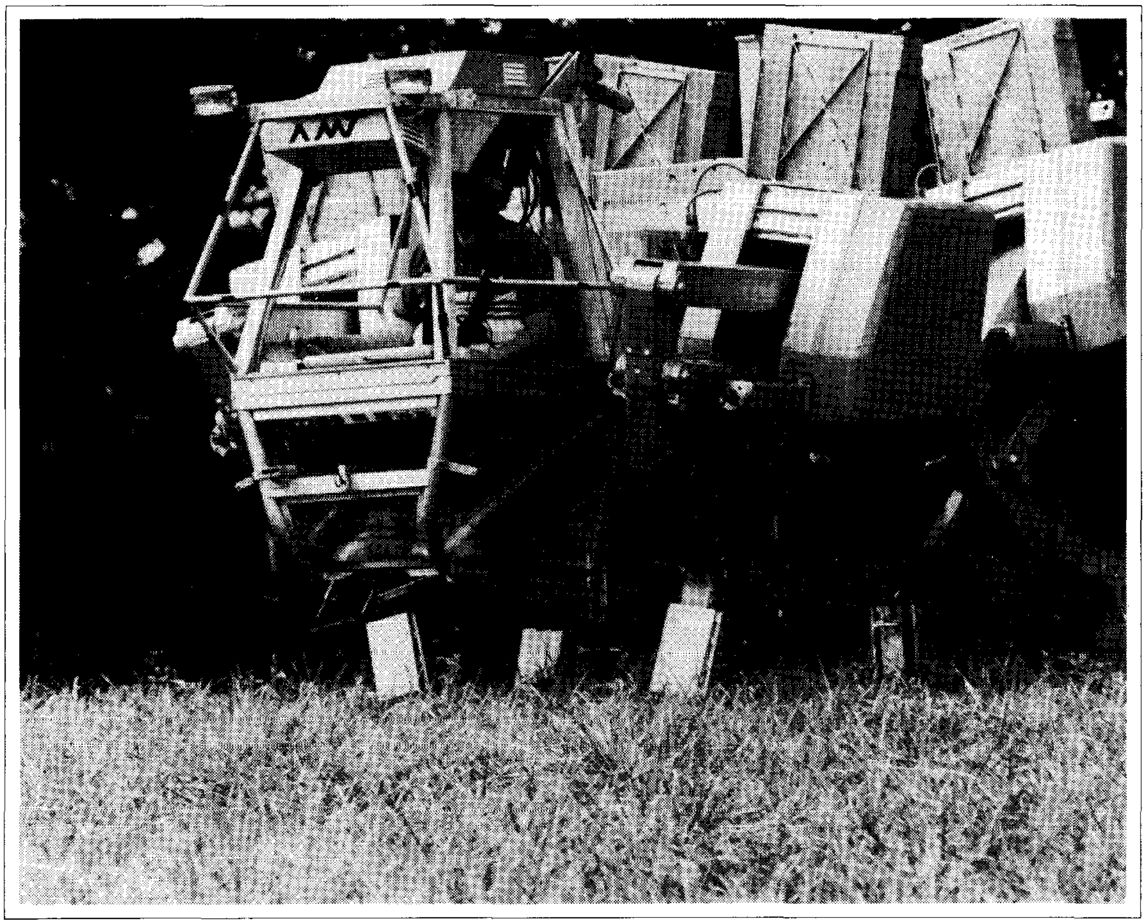

Figure 1a. The six-legged Adaptive Suspension Vehicle (ASV).

terrain, increasingly complex movements are possible, and a variety of gaits are available.

The machine (Figure 1) consists of a central rectangular framework which serves as the major structural component and houses the power plant—a 900-cc four-cycle Kawasaki air-cooled engine; a flywheel; and circuitry. Power is transmitted to the legs through two quill shafts running through the hinge points attaching the legs to the frame and a third along the bottom of the frame. Each leg is connected through a timing belt drive between the quill shaft and hydraulic pumps enclosed in the leg structure. The legs are spaced approximately 1.3 m apart down both sides of the frame. The legs are planar pantograph mechanisms joined to the frame by a horizontal hinge. The legs have 3 degrees of freedom: raise-lower, extend front-rear, and swing in-out. Leg construction is symmetrical; the left front leg is a mirror image of the right, and the left rear leg is a duplicate of the right front. This results in two basic leg constructions which share internal components.

Each "shoulder" contains the pumps and controls to operate the vertical, horizontal, and lateral swing actions of the legs. Each foot has a maximum vertical lift of 1.17 m, a maximum stride of 2.03 m and a lateral swing of 20° either side of vertical. Leg motion is controlled by a general purpose, microprocessor-based multi-processor computer which provides the "nervous system" for the machine. The computer circuitry is off-the-shelf technology. The software controlling machine components is the proprietary feature.

The operator's cab, currently placed at the front of the machine, could be located anywhere a specific application would demand. There are no mechanical linkages between the operator and the machine components. The machine is controlled through a single joystick. Movement directions are forward

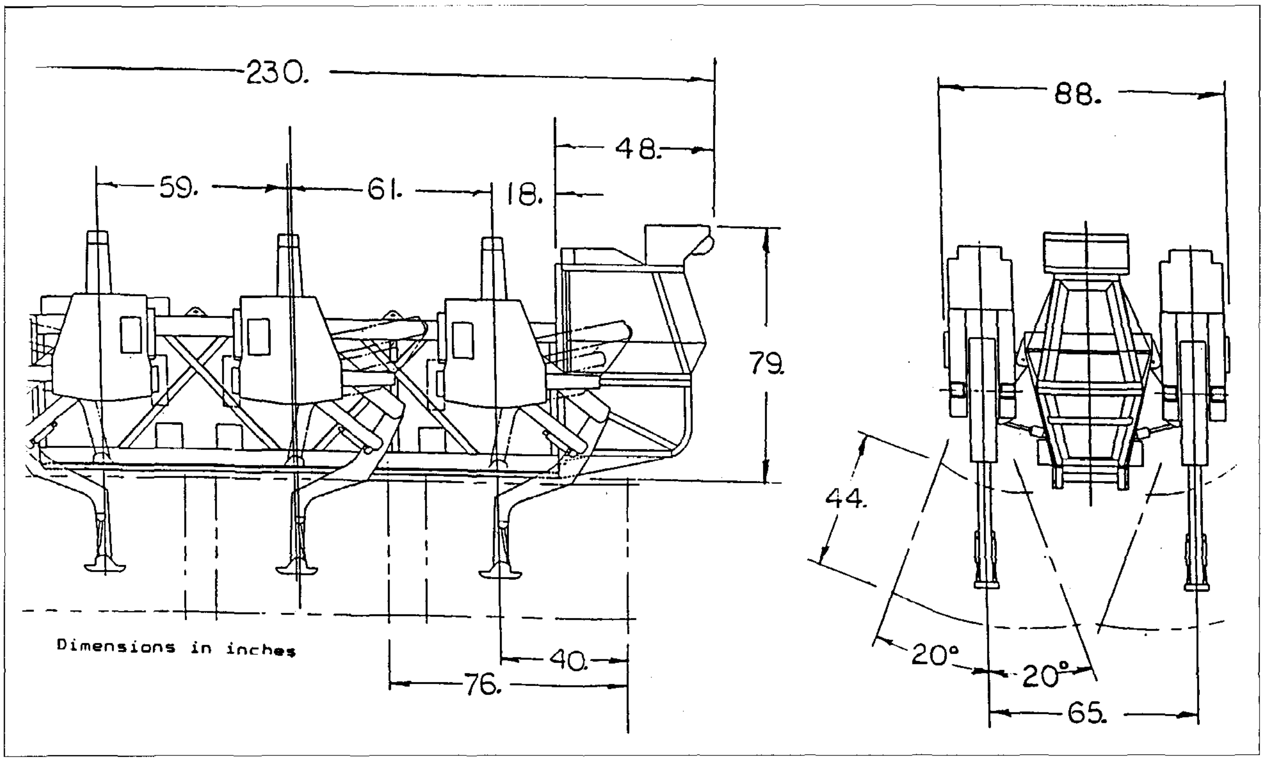

Figure 1b. General machine specifications.

and reverse, sidestepping left and right, "crabbing" along the obliques, and spot turn left and right.

Speed is controlled by the tilt of the joystick. The machine has five different operating modes available—utility, precision footing, close maneuvering, follow the leader, and obstacle crossing. Pitch and roll are compensated for by a self-leveling system. The machine computes stability parameters for each step or movement. If completing the action will put the machine at risk, the movement will not be completed.

The machine, as currently constructed, weighs approximately 3.2 tonnes with a top design speed of 7.5 km.h-1. The achieved speed has been limited to 3.6 km.h-1 by the computational speed of the onboard computers, not by the mechanics of the vehicle. Faster microchips have entered the market since development began, and further increases in computational and walking speed are expected.

EVALUATION AS A FOREST VEHICLE

This series of trials was arranged through a cooperative effort of the USDA Forest Service, the Virginia Center for Innovative Technology, Fettig, Inc., of Springfield, Virginia, Adaptive Machine Technologies of Columbus, Ohio, and the Industrial Forestry Operations Program at Virginia Tech. Although the proof of concept machine used in these tests was not sufficiently robust to be considered a "woods machine," it did effectively serve as a means of evaluating the potential of walking machine technology to determine if this technology is a viable alternative to wheeled and tracked equipment for forest operations on steep slopes, sensitive soils, debris-laden sites, or on areas with advanced reproduction. The test program was designed to test three key capabilities of forest machines: maneuverability, trafficability, and terrainability. The program was restricted by both time and money. Consequently, this effort amounts to a sampler of the walking machine's capabilities rather than a definitive economic or productivity comparison.

Maneuverability Trials

The objective of the first set of maneuverability trials was to test the capabilities of the adaptive suspension vehicle as a carrier for a frame-mounted feller-buncher head in a thinning application. These trials were conducted on a surrogate stand created from data on an 18-year-old loblolly pine plantation from the upper coastal plain of Louisiana which had been mapped as part of an earlier trials of thinning machines and strategies. The actual stand was originally machine-planted on abandoned agricultural land at a nominal spacing of 2.4 x 2.4 m. The planted stock had suffered considerable mortality, and volunteer stems had filled the resulting openings. The result was a stand that averaged 1450 living stems/ha with very little evidence of the original row structure.

The thinning strategy chosen for the test was one of selectively thinning between 5-m corridors spaced 30+ m apart. The feller-buncher operates in a 15-m strip on either side of the corridor, selecting trees for removal on the basis of size, form, and competition with other crop trees. A stem to be removed, a "take" tree, is severed, held upright, and carried forward to the next "take" tree, which is added to the bouquet carried by the machine. When the machine has collected as many stems as it can comfortably carry, the bunch is carried to the corridor and deposited.

Two subunits of the mapped stand, one 15 m x 20 m area containing 40 trees (thinning area 1) and one 15 m x 23 m area containing 47 trees (thinning area 2). The stand subunits were laid out in a mowed field. The microterrain was much smoother than that in a forest environment; the near-lawn condition allowed easy identification of any soil disturbance caused by the machine as it maneuvered through the simulated thinning.

The stand descriptions were reviewed and "take" trees selected using the criteria of size, form, canopy opening, and crop tree competition. The take trees, or those to be harvested, were represented by 1 m tall stakes of 2.5 cm^2 hardwood topped with a 250 cm^2 paper plate carrying an identifying number. Crop trees, those to be left after the thinning, were represented by 3.65 m lengths of 20 cm diameter 16-gauge metal pipe. A 660 m length of 1.90 cm diameter pvc pipe was centered in the base of each pipe and held in place by closed-cell foam. This assembly was held vertical by slipping the pvc pipe over a length of rod driven in the ground at each tree location.

From the operator's position, the brown painted sections of pipe gave the impression of standing tree trunks. The galvanized pipe was given a single coat of cheap brown paint sprayed on without benefit of metal preparation or primer. This assured that even the lightest contact by the machine would scratch the paint. Heavier contact, that sufficiently hard to cause bark damage, would be indicated by denting the pipe and/or tipping the pipe by crushing the supporting foam.

The machine was equipped with a 15 cm diameter sheet metal scoop mounted below and slightly ahead of the operator's position to simulate a feller-buncher head. The resultant length of machine from the rearmost frame member to the center of the scoop was 25 cm longer than a Franklin 105 equipped with a Morbark accumulating shear, a machine combination commonly used for these thinnings. The operator was instructed to maneuver through the stand capturing stakes with the scoop while avoiding contact with the leave trees (pipes). The travel pattern was operator's choice. It was impossible for the operator to see the rear of the machine from the cab, so he was allowed to remain in radio contact with an observer at the block boundary who warned him of stems immediately behind the machine.

Trial 1

This trial simulated the lightest thinning. Twenty-three "take" trees were to be removed, leaving 17 crop trees undisturbed. A map of the stand segment and the machine travel pattern is shown in

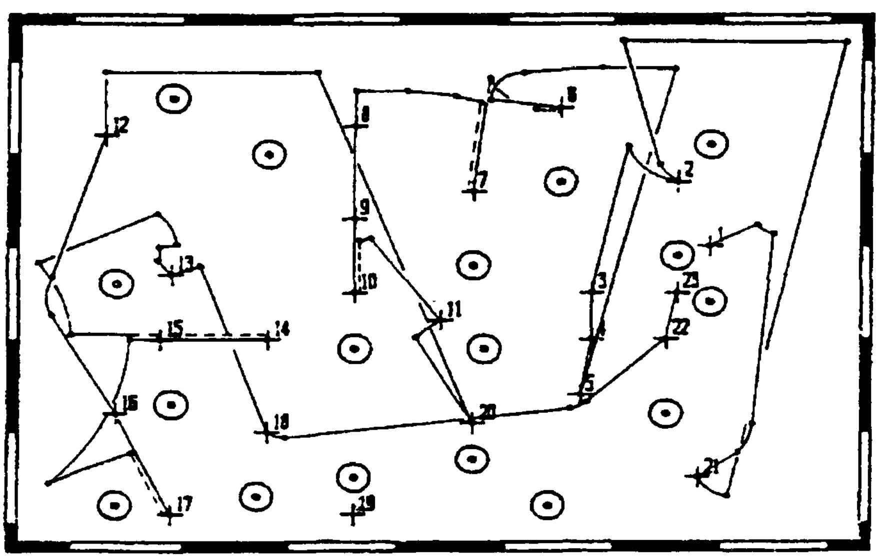

Figure 2. Travel Pattern — Trial 1, Thinning Area 1

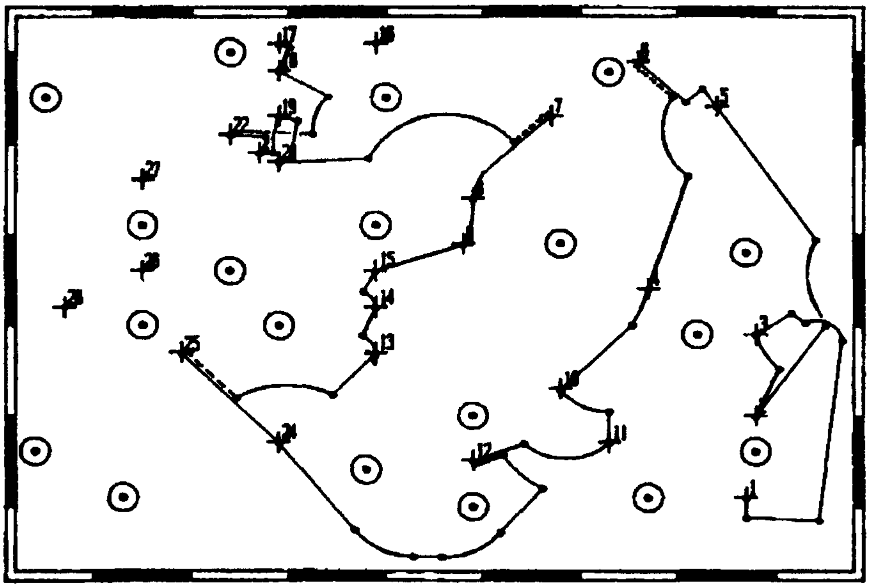

Figure 3. Travel Pattern — Trial 2, Thinning Area 2.

Figure 2. Since the operator had never attempted a test of this type before, he was allowed to travel into an unoccupied 3 m strip at the eastern boundary of the plot, representing the location of an access corridor.

This first trial exercise was completed relying primarily on forward and reverse movement. The machine travelled a total of 201 m while capturing 22 take trees, an average distance of approximately 9.1 m.tree-1. The time between stakes ranged from a low of 0.10 minute to a high of 1.7 minutes, with an average of 0.62 minute.target-1. The density of the leave stand may have compounded the movement problem. The average between-tree distance in the residual stand was 4 m, less than 1.5 times the machine width.

Trial 2

This trial was conducted on a larger segment of the stand to represent a slightly heavier thinning in which 60 percent of the stems were removed. A map of the stand and machine movements is shown in Figure 3. The operator was instructed to enter the stand from the eastern boundary. Route selection was again operator's choice.

The experience gained in the first trial resulted in a much more efficient attack on this block. Greater advantage was taken of the machine's ability to pivot, step sideways, and travel on an oblique. Between-target movements were much smoother and more direct. The machine travelled a total of 111 m to capture the 24 targets, or an average of 4.6 m per target. Total time required to complete the test was 7.70 minutes. The minimum time between targets was again 0.1 minute, but the maximum dropped to 0.95 minute. The average time per target was 0.32 minute. The lower density of the leave stems may have simplified the travel pattern. The average spacing of the leave stems increased to nearly twice the machine width. The trial had to be stopped before the last four targets were accessed because of engine problems.

Trial 3

This trial used the same stand segment as Trial 2, but it was altered to require a maximum amount of movement within the stand. The operator was instructed to enter the stand at the northern boundary and minimize the movements outside of the block boundary as shown in Figure 4. This trial shows a further refinement in machine movement. Twenty-five of the 28 targets were captured in this trial. One blew down before it could be captured, a second was bypassed because of its location between two leave trees, and the third was missed.

The machine travelled a total of 130 m to capture the 25 targets, or roughly 5.2 m.target-1. The between-target time ranged from a low of 0.1 minute to a high of 0.78 minute, with an average of 0.36 minute .target-1.

All three trials were conducted with light contact on only three trees. Virtually no trace of the machine's movements over the field could be identified either immediately after the trials or several days later. The tracks left by a half-ton pickup truck used to move the pipes to and from the site were much more apparent.

Clearcutting Trials

This second component of the maneuverability trials was designed to test machine speed in a simulated clearcut where the machine movements were

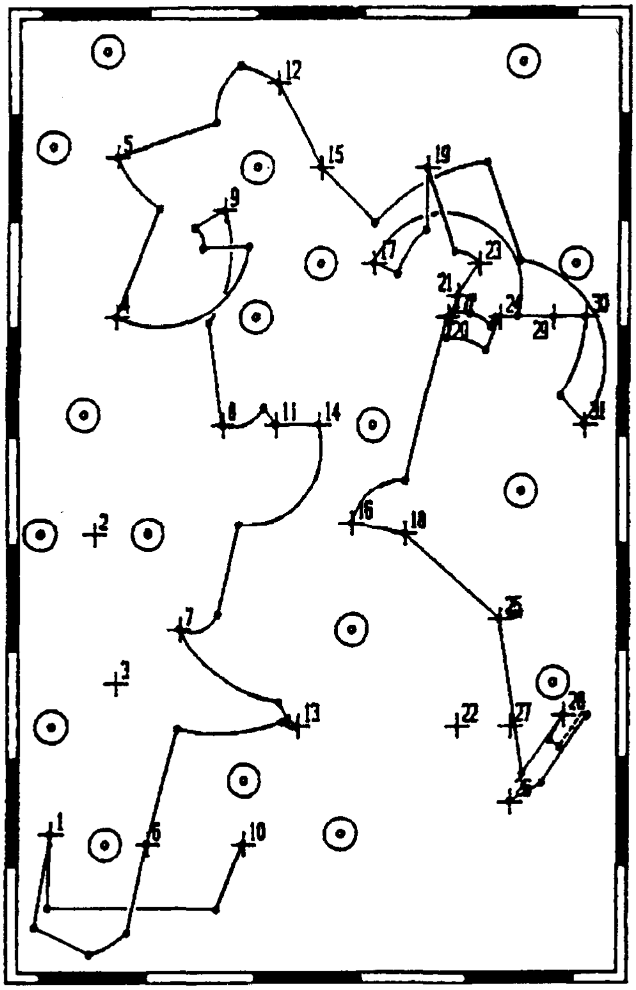

Figure 4. Travel Pattern — Trial 3, Thinning Area 2.

unobstructed by leave trees. Two 15 x 15 m subunits of the same mapped stand, one containing 15 stems and the other 18 stems, were laid out on a hillside in an abandoned old field. Ground cover consisted primarily of broomsedge and blackberry. Each plot contained one large clump of multiflora rose. Both were located on an 18% slope. The area had suffered rill erosion, which left a random pattern of small gullies or trenches ranging to 25 cm deep across the contours.

Tree positions were again marked with hardwood stakes. The operator was instructed to start at the bottom of each block and clear the 15.2-m swath as he proceeded uphill, knocking down the stakes with the scoop mounted on the front of the machine.

The average between-tree (or stake) distance for the first trial was 3.66 m, the range from 1.3 to 7.3. A total of 4.65 minutes was required to complete the first trial, for an average of 0.26 minute.stake-1. The time between target captures shown in Figure 5 demonstrates considerable variability. Midway through this trial, a multiflora rose clump ripped the scoop from the front of the machine and the shielding from the belly. The operator requested permission to touch the stakes with a 2.54-cm eyebolt on the front of the machine as alternative to reattaching the scoop. This change was accepted and used for the last half of this trial and all of Trial 2. The change required much greater precision in positioning the machine and may have increased the time per target slightly. The loss of the belly pan had no effect on machine performance.

The average between-target distance increased to 4 m for the second trial. A total of 3.70 minutes was required to capture the 15 stakes, for an average of 0.25 minute.stake-1. The distribution of times per target for this trial (shown in Figure 6) shows less variability than that for the first trial. The greater

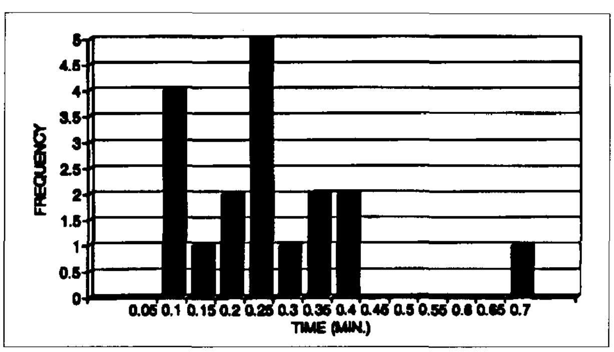

Figure 5. Time between Targets — Clearcut 1.

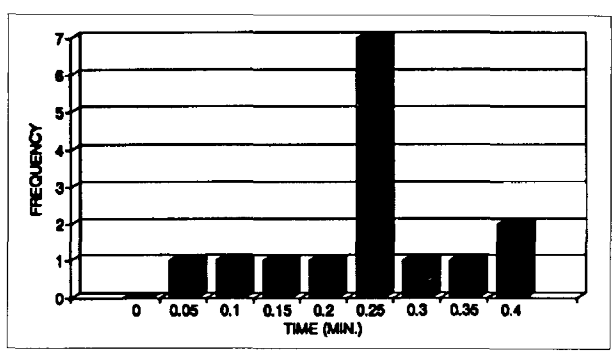

Figure 6. Time between Targets — Clearcut 2.

precision required when using the 2.54-cm eyebolt instead of the 15.24 cm scoop slowed the process somewhat, as evidenced by relatively few observations of less than 0.20 minute.

The machine had no difficulty in dealing with the slope or ground roughness. Machine movements were very smooth. Between 40 and 50 percent of the total time was spent in lateral movement on each of the trials. The machine left the site virtually undisturbed. A faint pattern of movement could be seen from broken broomsedge, but no soil surface disturbance was found.

Trafficability Trials

The Adaptive Suspension Vehicle requires redefinition of some of the common trafficability parameters. The machine has no single ground pressure. Standing with all six feet on the ground and equipped with the 23 x 30 cm rectangular feet used for this trial, the machine has a ground pressure of approximately 773 g.cm-1. In the tripod gait used for most movement, where two feet on one side of the machine and one foot on the other remain on the ground while the other three feet move forward, the feet on the side with two feet down exert a ground pressure of 1139 g.cm-1, while the single foot on the opposite side exerts a pressure of 2278 g.cm-1. The three feet on the same side are not placed in the same spot unless the machine is in the special "follow the leader" gait. A single straight-line pass of the machine therefore results in an untrampled area, a 23 x 30 cm footprint from the front foot subjected to 1139 g.cm-1, an overlapping footprint from the middle leg subjected to 2278 g.cm-1, and a third overlapping footprint from the rear leg subjected to 1139 g.cm-1. The exact placement of the three footprints is a function of the terrain, the type of movement requested, the amount of foot sinkage, and a variety of other operating parameters.

The machine leaves a series of footprints spaced roughly 1.2 m apart, different from the uniformly compacted zone of wheeled or tracked equipment. The net impact of these scattered pockets of disturbance is difficult to assess at this time. Repetitive travel over the same path will, of course, result in relatively uniform compaction such as that found on deer trails or bridle paths. Until that condition is reached, the individual footprints serve as water and sediment traps.

The objective of the trafficability trials was to determine the extent of soil disturbance, compaction, and rutting after one, three, and nine passes of the machine over saturated soils. Parameters of interest were the type of rutting which developed as well as the change in soil mechanical strength, soil bulk density, pore space, and saturated hydraulic conductivity. These tests were conducted at soil moisture levels well above those considered appropriate for conventional harvesting operations. The objective was to achieve the maximum impact.

These trials were conducted on a plot from which a 20- to 30-year-old stand of black locust (*Robinia pseudoacacia L.*) had been harvested about four months prior to the trials. The stumps had been cut at ground line and left in place. The ground cover consisted of locust coppice, weeds, and grasses. The area had been cut with a rotary mower about three weeks prior to the trials. The plot was divided into nine 5 x 15 m strips which were subjected to a gentle, continuous sprinkling for three days prior to the trials.

Volumetric soil moisture content percent in the top two inches at the time of the trials ranged between 45 and 50 percent. Soil mechanical resistance ranged between 432 kPa and 720 kPa, with a median of 504 kPa.

The original study design called for three replications of one-, three-, and nine-pass treatments. All three replications of the single-pass treatment were completed. Only two replications of the three- and nine-pass treatments were completed. The travel zones used for the second of the nine-pass treatments developed a major "wallow" at one end after the third pass. The machine was stepping from a rootmat near the original ground level into a mudhole nearly 0.7 m deep and then climbing back to ground level.

The machine handled the variation in footing depth and terrain with ease, but the torsional forces transferred to the central rectangular frame resulted in stress cracks opening at corner butt welds, allowing the frame to flex. The flexing in turn caused shaft misalignment, which resulted in drive belt problems. The trial was completed by travelling forward to the edge of the "wallow" and then backing to the zone boundary. A decision was reached to forgo the remaining two trafficability tests rather than cause extensive damage to the machine.

Soil Impacts

Physical Dimensions. The physical measurements of disturbance as a function of the number of passes are summarized in Figure 7. The first (black) bar in each cluster represents the number of identifiable footprints or tracks which could be found within the travel zone. Footprints did not increase proportionally with the number of passes. A single pass resulted in 20 footprints; tripling the number of passes increased the number of footprints by approximately 70%. Ten passes resulted in only 2.5 times the number of tracks left by a single pass.

No attempt was made to have the machine step in the same tracks as the number of passes increased. The machine was driven off the test site, turned and re-entered the zone to assure that the footing would vary. The close maneuvering gait used in the trials did not require that the middle and rear feet be placed in the print of the front foot; however, the normal "pace" of the machine resulted in close placement.

Neither the mean length (bar 2) nor mean width (bar 3) of the tracks increased significantly with the number of passes. The 30 cm-long pads left tracks 50 cm long after one pass, indicating that the three feet struck close to the same spot. The relatively small increase to 61 cm after 10 passes indicates minimal increase in slip with deteriorating soil conditions. The width of the footprints remained constant as well. The 23 cm-wide pads left tracks 29 cm wide.

The depth of footprint (bar 4) did increase with the number of passes, but the increase was not directly proportional to the number of traverses. The average depth after a single pass was less than 4.8 cm; the depth nearly doubled (9.3 cm) after three passes and nearly tripled (12.5 cm) after 10 passes.

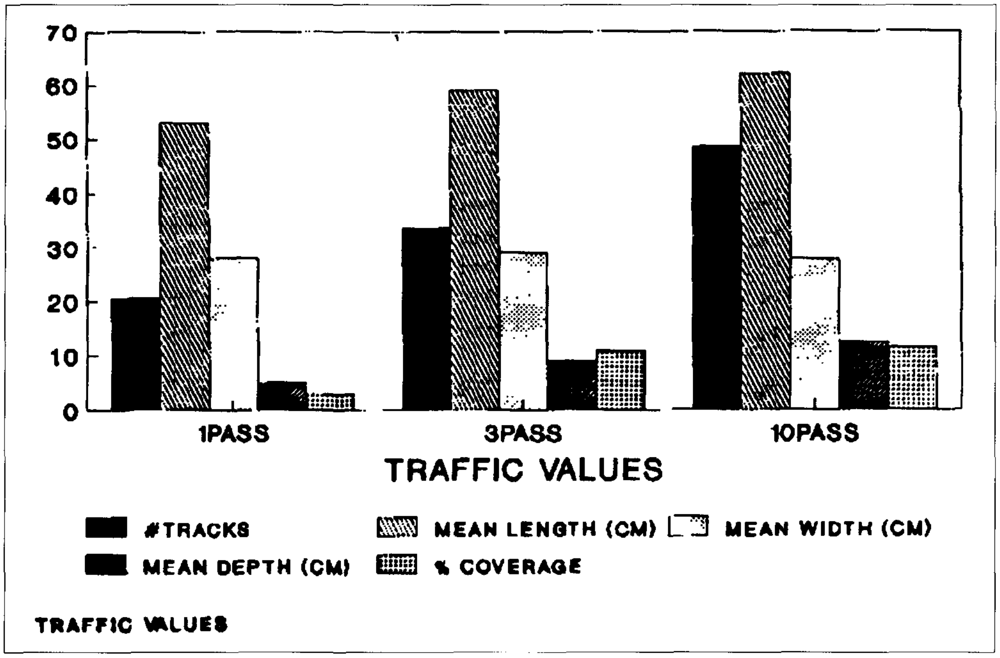

Figure 7.

The percentage of the surface of each zone disturbed by machine traffic rose from 2.85% after one pass through 10.85% after three passes to only 11.5% after 10 passes. A single pass of a wheeled machine, assuming perfect tracking, would disturb 31% of the area if mounted on 710-mm (28-inch) tires and 48% for 1120-mm (44-inch) wide tires.

Bulk Density. Time and money did not permit a comparison of the ASV with forestry equipment on the same site at the same time. This shortcoming was partially alleviated by the completion of one, three and ten passes across the travel zones at the extreme

Table 1. A comparison of the changes in bulk density (g.cm^{-3}) at the 5 cm depth associated with ASV and skidder traffic on the Blacksburg site .

Treatment	Undisturbed	Trafficked	Change
ASV:			
Single Pass	0.86	0.95	+0.09
Three Pass	0.92	0.98	+0.06
Ten Pass	0.94	1.00	0.06
Skidder:			
Single Pass	1.24	1.46	+0.22
Three Pass	1.19	1.15	-0.04
Ten Pass	1.16	1.30	+0.14

northern boundary of the test site by a Franklin 132AXL on 590 x 660 mm (23.1 x 26 inch) tires (ground pressure = 561 g.cm-1) one month after the ASV trial. The area was rewet to a saturated soil condition comparable to that at the time of the ASV trials.

Table 1 compares the change in soil bulk density from the ASV trials with those from the skidder trials. No significant change could be identified for any of the ASV trials. The changes arising from the skidder traffic could not be subjected to statistical testing because of the small sample size (two samples drawn for each trial). The area used for the skidder replications was at the extreme end of the test site where the surface soil had been removed in the past as part of a 1940's construction project. The initial bulk density of the soil was higher than that for the ASV trials and it should have been more resistant to compaction, as the soil in the zone used for the three-pass replication obviously was. This higher initial bulk density influences some of the following comparisons.

Porosity. The changes in total pore space resulting from ASV traffic shown in Table 2 were minimal. The changes arising from the skidder traffic were considerably larger even though the soil had a higher initial bulk density.

Mechanical Resistance. Mechanical resistance is a relative measure of the impact of machine traffic on the soil. Figure 8 shows how mechanical resistance increases with depth from one, three, and ten

Table 2. A comparison of the percentage change in pore space at the 5 cm depth associated with traffic by the ASV and skidder on the Blacksburg site.

	Percent		
Treatment	**Undisturbed**	**Trafficked**	**Change**
ASV:			
Single Pass	49	48	-1
Three Pass	50	50	0
Ten Pass	50	49	-1
Skidder:			
Single Pass	48	43	-5
Three Pass	51	48	-3
Ten Pass	49	41	-8

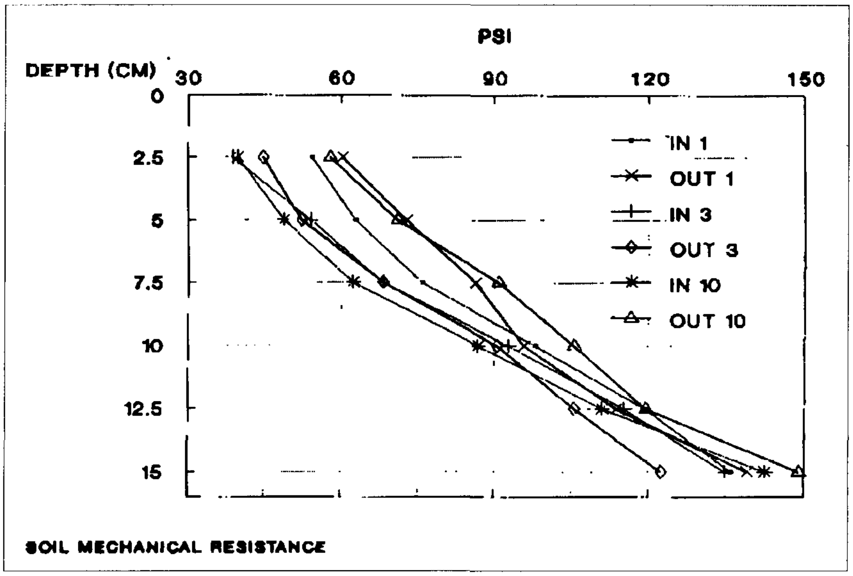

Figure 8. Changes in soil mechanical resistance associated with one, three, and ten passes of the ASV on the Blacksburg site. "In" identifies measuring points in the bottom of a footprint; "out" identifies measuring points from undisturbed areas near the trafficked measurement.

passes of the ASV.

Travel Rate. Travel rates were largely independent of the condition of the soil. Slip, which causes the greatest loss of productivity and causes the most soil damage by wheeled or tracked machines, was absent for the ASV. The feet dug in, stabilized, and the machine was moved over a fixed foundation. The upper bounds on the rates shown in Figure 9 were achieved when the machine was travelling forward, the lower bounds when the machine was travelling backward.

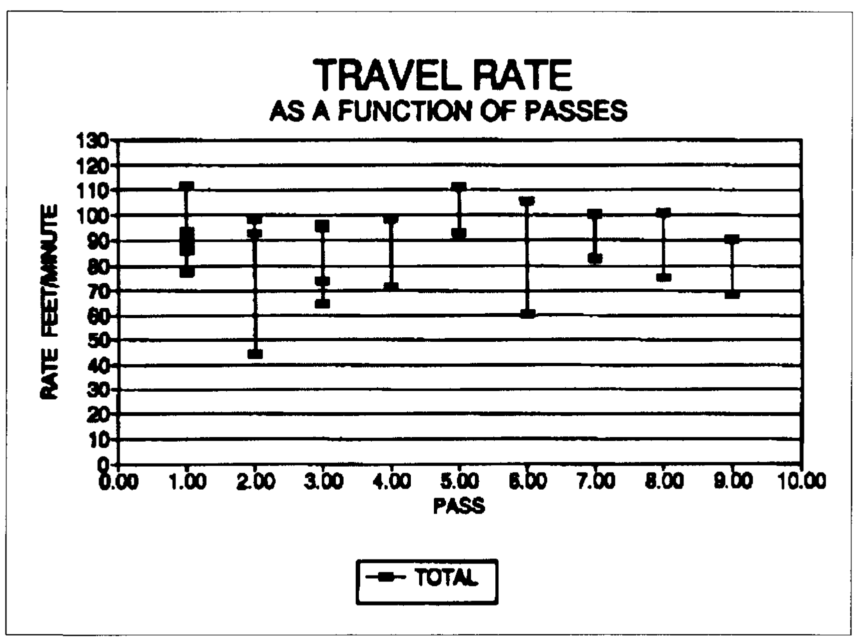

Figure 9.

SUMMARY

The Adaptive Suspension Vehicle used in these trials is the only fully operational terrain-crossing walking machine in the United States. The machine was strictly "proof of concept," built to demonstrate that the requisite technologies could be brought together successfully. The machine was not built to perform any specific task, especially tasks as demanding as those defined for forestry machines. The ASV was sufficiently robust and shielded to serve as a demonstrator of the potential of walking machines and to provide early information on the impacts of machines of this type on forest soils.

Maneuverability was tested by simulating the activities of a feller-buncher in thinning and clearcut harvests. The machine successfully completed five trials, three simulating thinning environments and two modeling clearcut activities on steep slopes. The thinning trials demonstrated that the machine could very efficiently move through a timber stand, accessing trees to be removed with precision while causing minimal disturbance to the forest floor and the residual stand. Neither the machine nor the operator had attempted an extended set of maneuvers as complex and precise as those in the thinning trial; consequently, a learning curve was apparent in the test results. By the third trial the machine was achieving acquisition rates of three trees a minute or better, a rate comparable to those of conventional machines. The ability to move directly from one objective to the next results in less total machine movement and less disturbance to the site.

The simulation of clearcutting on steep slopes demonstrated that the machine had no difficulty moving up, down, or across 18% slopes while making the precision movements required of a feller-buncher at the rate of four trees per minute. The ability to move laterally again reduced the distance travelled and the potential disturbance.

The trafficability trials demonstrated that walking machines do not alter soil characteristics either in the manner or to the extent that wheeled or tracked equipment does. Less soil surface is disturbed by one pass of the machine. The ASV, in moving 12 m (4 feet), leaves two footprints with a combined area of roughly 0.3 m^2 (3.25 square feet). A conventional machine mounted on 590-mm (23.1-inch) tires would impact an area of 4 m^2 (15.4 square feet) in travelling the same distance. The ASV was found to impact soil bulk density, mechanical resistance, macroporosity, and saturated hydraulic conductivity less than conventional equipment, even though its calculated soil loading was three to four times greater. The machine subjects the soil to a vertical rather than rolling load, does not depend as heavily on surface soil shear resistance for mobility, and leaves pits rather than ruts in very soft soils.

This first machine was capable of speeds roughly one-half of those achieved by conventional forestry equipment. (This is expected to improve with further development.) This relative slowness was compensated for by the ability to move directly from one objective to another, to step over obstacles that would otherwise have to be driven around, and by the minimal slip experienced by the machine.

The terrain-crossing abilities were not fully tested during this set of trials. The limited testing which was done demonstrated that the machine had the ability to move easily across rolling and broken terrain, deal easily with uneven footing, and maneuver around and over natural obstacles.

CONCLUSIONS

The trials of the Adaptive Suspension Vehicle demonstrated that legged locomotion has potential for extending mechanized timber harvesting onto steeper slopes and softer soils while minimizing both erosion risk and disturbance of the forest soils. This potential should justify further development activities leading to the construction of a prototype more suitable for extended testing in forestry applications.

Walking machines free the designer from the rectangular or triangular shapes of wheeled and tracked machines. The ant-like machine configuration of the proof of concept machine is only one of several which could be tried. A radial or spider-like design might be more appropriate for a tool carrier design such as a feller-buncher. The central body could be circular or elliptical. Body height or ground clearance can be adjusted to match the operating conditions, since it is not controlled by mechanical linkages of the drive train. Eight legs may be more appropriate than six in transport applications. The operator's location can be anywhere on the machine that provides the best visibility and protection.

Initial applications offering the greatest advantage are those which currently require large amounts of labor, put workers at risk, or where helicopters are the only other way to get the job done. These include a feller-buncher carrier for steep slopes and wet sites, a pre-bunching machine for helicopter or balloon transport, and a primary transporter for forest management operations such as planting, spraying roadside and right of way maintenance. The technology should be able to mature into an economically competitive machine for transporting timber from fragile or steep sites.

This new technology offers the opportunity for better management of difficult-to-access sites, conducting operations on sensitive sites with minimal risk to both personnel and the environment, reducing the down time of mechanized operations caused by adverse weather conditions, and improving the working conditions for forest workers.

Further development of the technology is not without risks. The potential benefits are such that these risks are justified.