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Evaluation of Retrofit ARFF Vehicle Suspension Enhancement to Reduce Vehicle Rollovers

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16. Abstract

The Aircraft Rescue and Firefighting (ARRF) industry has experienced several vehicle rollovers in recent years. Emergency One Corporation and Davis Technologies, of Dallas, TX, collectively developed a prototype hydraulic suspension strut that replaces the standard shock absorber. This strut is intended to attenuate undesirable vehicle dynamics, thereby significantly reducing the potential for rollover. This evaluation compares the performance of the standard to the prototype suspension system.

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EXECUTIVE SUMMARY

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This report is comprised of two individual test sequences. The first phase was conducted to establish a baseline set of performance data for a typical E-One High Performance Rescue vehicle equipped with standard Gabriel shock absorbers (one per wheel end). The second phase was an exact duplicate of the first, with a modified suspension, conducted on the same vehicle, and under the same conditions. A total of eight suspension struts (two per wheel end) were substituted and installed inside the coil springs in place of the four shock absorbers.

By replacing the shock absorbers with struts, the amount of body roll that is experienced as a result of both steering and ground inputs was reduced. As a direct result, steering response and handling feedback to the operator are greatly improved, resulting in greater vehicle stability.

INTRODUCTION

BACKGROUND.

The Federal Aviation Administration (FAA) William J. Hughes Technical Center's Aircraft Rescue and Firefighting (ARFF) Research and Development (R&D) Program has conducted a heavy rescue vehicle rollover study at the request of the Office of Airport Safety and Compliance, AAS-310. This was an investigation and study of the recent occurrences of airport heavy rescue vehicle rollovers/turnovers. The vehicles involved in these rollover incidents were manufactured in the United States (U.S.) and certified to be in compliance with FAA Advisory Circular 150/5210-10A or B, *Guide Specification for Water/Foam Aircraft Rescue and Fire Fighting Vehicles*.

Aircraft rescue and firefighting vehicles are high-performance vehicles designed to get to the aircraft crash site within minutes over airfield and off-field, cross-country courses to extinguish fires and save the lives of passengers and crews. The number of rollover incidents of ARFF vehicles in the last few years clearly indicates the need to increase the stability of these vehicle platforms. This must be done to protect the occupants and enable these vehicles to safely perform the critical missions of aircraft fire rescue for which they were intended. Lateral accelerometer warning systems and increased operator training will no doubt contribute to overall operator safety and awareness of present vehicle limitations. These programs are needed; however, they will not solve the problem or create a long-term solution that can be used to meet increasing mission requirements for future fire rescue vehicles.

Forty-eight ARFF vehicle rollovers have been documented since 1977. Twenty-seven of those have occurred since 1995. This is an alarming number of occurrences considering the few miles and operational hours that the rescue and fire services use these vehicles each year. What is even more puzzling is the fact that most of these occurrences have occurred in actual nonemergency response situations. Most of the documented cases occurred in training, practice, or in vehicles that were in transit for maintenance or other nonemergency reasons.

Because of the serious nature of the ARFF response and the potential for loss of life of the operators of these vehicles as well as the safety of the flying public, this issue needed to be investigated. Should rollover situations occur under actual emergency response situations, it would put the flying public at great risk. Though few of these accidents have occurred in actual response situations, the high-response speeds necessary to maintain recommended response requirements dictates that rescue vehicle drivers have the utmost confidence in the vehicles they are driving.

The typical airport response includes acceleration, high-speed driving, heavy braking, and the need to perform several 90-degree or greater turns. ARFF services respond under emergency situations at airports, thus, requiring that the rescue vehicles have rapid acceleration. They must be able to brake under high-weight loads with transferring inertia conditions. Rescue vehicles must be responsive to large center of gravity shifts under the high-speed turning radius at intersections of taxiways and runways at modern airports. Performance testing of all rescues vehicles should include those tests, which emulate these types of mission requirements.

In general, as the jet age developed, aircraft grew in size, length, and capacity, leading to the need for longer runways and taxiways. The need to respond to emergencies in several minutes on these longer runways has required the development of faster responding rescue vehicles. Larger capacity aircraft also have very large fuel tanks. Certain wide-body aircraft, such as the Boeing 747-400, carry greater than 300,000 pounds (50,000 gal) of fuel for long-range applications. Therefore, there is a great potential for massive postcrash fuel fires. To meet this potential emergency, heavy rescue vehicles have steadily increased in size and complexity as well. Airports with runways of over 10,000 feet in length are not uncommon. The need to carry large amounts of water and extinguishing agents to deal with these postcrash fuel fires has resulted in vehicles with critically high centers of gravity routinely reaching speeds in excess of 65 mph.

Manufacturers responded to the need for quicker responding vehicles with dramatic changes in diesel engine and transmission designs. Vehicles are now produced with dual turbocharger exhaust systems, which can increase engine outputs to over 1,000 horsepower. This has resulted in high center of gravity heavy-laden rescue vehicles weighing in excess of 50,000 pounds with uncompromising speed and acceleration. Stopping and turning these large vehicles has become a serious problem.

Many of the drivers involved in rollover accidents reported that the vehicles were traveling at relatively low speeds when the incidents occurred. Eyewitnesses and accident reconstruction have validated this in some cases. Yet in some accidents, drivers have not been found faultless.

OBJECTIVE.

The objective of this research was to engineer, design, build, and demonstrate a dynamic suspension system that modifies the spring and damping forces to provide high-performance vehicle control and optimum roll resistance. This system would have to be a retrofitable configuration, which could be installed in place of the existing shock absorbers inside the steel coil springs.

ANALYSIS OF THE ISSUE.

There is no FAA requirement that mandates reporting major accidents that occur to any emergency vehicle at an airport. It is believed that there are additional vehicles that were involved in rollovers but have not been reported. Military operations may use the same types of equipment or vehicles, but only recently has the Department of Defense started reporting these accidents.

A recently published document (August 1999), “Aircraft Rescue and Fire Fighting (ARFF) Vehicle Stability Study,” by Captain William Wekenborg of the Dallas Fort Worth International Airport, draws some very important conclusions. This study and analysis of recent accidents states, “The typical ARFF vehicle rollover accident occurred in a nonemergency situation, on dry pavement, while being operated by a 33 year old experienced firefighter with nearly four years of experience as a driver-operator who had completed a basic driver operator training program.” There are several questions that need to be answered after reviewing this study. The data collected in his study indicate that all but three rollover accidents were in nonemergency situations. Does the data collected show that drivers are more careful under actual emergency situations? If the majority of these accidents have occurred under nonemergency situations, does this mean that drivers are not paying as close attention to driving under nonemergency situations?

Table 1 is a list of reported ARFF vehicle rollovers by date, location, and the type of vehicles.

Not all accidents happened in nonemergency situations. A recent Oshkosh T-3000 rollover accident at the Phoenix Sky Harbor International Airport points to an alarming situation. As the vehicle operator left the station on an actual declared emergency response run, the driver exited the station, accelerated and traveled approximately 85 feet straight out of the firehouse. The vehicle then made close to a 90-degree right-hand turn onto a roadway. The vehicle then drove straight for approximately 75 to 85 feet. The vehicle then made close to a 90-degree left-hand turn onto a roadway and rolled over. This turn had a measured radius of 86 feet. It is estimated that the vehicle was traveling more than 17 mph when it made this final left-hand turn. The combination of these left and right turns and running over the taxiway light caused the instability situation, which resulted in the rollover, and substantial damage to the vehicle. Therefore, the vehicle did not arrive at the scene, which in itself, created another emergency.

Another reported low-speed rollover occurred in Ottawa, Canada, with a similar Oshkosh T-3000. In this particular accident, the driver was performing a routine airport visitation tour of the airfield. The driver reported that he made a slow left-hand turn, under 20 mph, while turning the wheel and applying the brakes at the same time. He reported the vehicle pitched over into the rollover situation before he realized that he had a vehicle problem.

In these accidents, as well as many of the more recent rollover accidents, the vehicles were not reported to be traveling at a high rate of speed. In several interviews, conducted by Captain Wekenborg, the drivers reported that the vehicles were going below 25 mph. The vehicles were in the radius of a moderate turn when the brakes were applied. Shortly after the brakes were applied the vehicle proceeded to roll around the rear axles. In each case, the drivers said there was no warning preceding the event. In fact, the back end appeared to snap or pitch into the rollover and occurred before they realized that they had a problem.

An experiment with 28 individuals, with various driving experience, was conducted in which the view of the speedometer was blocked. The drivers were asked to drive the vehicle at 20 miles per hour. When the drivers indicated they had accelerated to 20 miles per hour, the cover was removed from the speedometer. The speeds at which the vehicles were traveling ranged from 28 to 42 mph, with the average speed being 29.3 mph. This test indicates that drivers have trouble determining their vehicle speed. Drivers are generally looking out around the airport surface and are not particularly observing the speedometer. They are very aware of the latent dangers of driving on an airport.

TABLE 1. AIRCRAFT RESCUE AND FIREFIGHTING VEHICLE ROLLOVERS

Date	Location	Manufacturer
1977	Chicago, IL	Walter
1978	Kansas City, MO	Walter
1985	Seattle-Tacoma, WA	Oshkosh
1987	Dallas-Fort Worth, TX	
1988	Goose Bay	E-One
1989	Washington-Dulles Airport	Oshkosh
1989	Ottawa, Canada	Foam Boss
1989	Trenton, Canada	Walters
1989	USAF	Oshkosh
1989	US Navy	Oshkosh
1990	Anchorage, AK	E-One
1990	Anchorage, AK	E-One
1991	Edmonton, Canada	Walters
1991	Monterey, Mexico	E-One
1992	Jamaica	Walter
1992	Puerto Rico	Walter
1992	Dallas-Fort Worth, TX	Oshkosh
1993	Fallon NAS, NV	Oshkosh
1993	Evansville, IN	Oshkosh
1994	Keflivik, Iceland	Oshkosh
1994	Winnipeg, Canada	Oshkosh
1995	Winnipeg, Canada	ATV-CNF
1995	Dayton, OH	Oshkosh
1995	Dallas-Fort Worth, TX	Oshkosh
1995	Dallas-Fort Worth, TX	Oshkosh
1995	Denver, CO	Oshkosh
1995	Buenos Aires	E-One
1995	Pretoria, South Africa	E-One
1996	Wainwright	Walters
1996	Orlando, FL	Oshkosh
1996	White Plains, NY	Oshkosh
1996	Ottawa, Canada	Oshkosh
1997	St. Louis, MO	Oshkosh
1997	Patrick AFB, FL	E-One
1997	Phoenix, AZ	Oshkosh
1998	Bermuda	Oshkosh
1999	Alberta, Canada (CAF)	E-One
2000	St. John’s Newfoundland	Oshkosh
2000	Cambodia	E-One
2000	Malaysia	E-One
2000	Cairo, Egypt	E-One
2000	Trenton, Canada	Oshkosh
2000	Portugal	E-One
2000	Canada	Walteck
2001	Wisconsin	Oshkosh
2001	Nashville, TN	Oshkosh
2001	Midland	Oshkosh
2001	Cincinnati, OH	Oshkosh

Different drivers were asked to drive with the speedometer covered and to accelerate to what they perceived to be 35 mph. After establishing their target speed, the speedometer was uncovered. Speeds ranged from 38 to 47 mph. In both of these studies drivers exceeded the targeted speed by an average of greater than 9 mph. On most rescue vehicles manufactured today, the steering wheel and seat position is near the center of the vehicle. When an individual is driving down the highway, there are references such as automobiles, trees, signs, and buildings, which help the driver approximate how quickly they are traveling. In a large rescue vehicle being driven on a runway or taxiway, a driver has none of these references near the ARFF vehicle.

VEHICLE DYNAMIC STABILITY.

The current generation of heavy rescue vehicles places the large capacity water tank on top of the vehicle chassis frame. This situation results in rescue vehicles with centers of gravity (c.g.'s) of 5 to 6 feet off the ground. Vehicles with high c.g.'s do not exhibit good dynamic stability. As the vehicle commences into the turn, a large shift of the water content can occur. This weight shift moves toward the outside of the turning radius. Vehicle operators who were questioned in recent rollover accidents stated that they felt a rapid shift of water movement just prior to realizing that they were losing control of the vehicle.

Both solid axles with springs and independent suspension system vehicles can be modified to reduce vehicle weight shift and side loading (see figure 1).

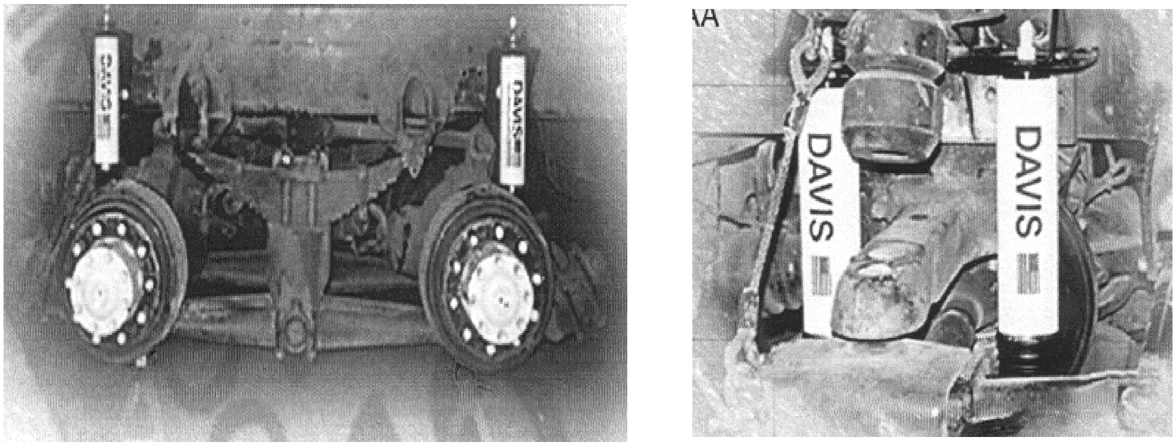


FIGURE 1. STRAIGHT AXLE AND INDEPENDENT SUSPENSION SYSTEMS

There are several manufacturers, including Emergency One Corporation (E-One), Oshkosh Truck Company, and Colet Special Vehicles, that each offer some type of suspension roll modifier. New suspension designs have been developed and tested which resist this outward shift of the c.g. In one vehicle case, the Colet Special Vehicle Jaguar, which is being used at Atlanta Hartsfield International Airport, a computer-controlled interactive strut system is used to modulate or shift the weight of the truck to the inside of the turning radius. The FAA's High Performance Research Vehicle (HPRV) has a modified suspension system of struts that resist movement of the chassis loads. A viscous liquid, under high pressure, is used within the strut system to reduce roll tendencies.

A comprehensive study of vehicle cornering stability improvements was undertaken in a joint effort consisting of personnel from the United States Air Force, Air Force Research Laboratory, Tyndall A.F.B., Emergency One Corporation (E-One) of Ocala, Florida, and the Federal Aviation Administration, Williams J. Hughes Technical Center, Airport Technology Research and Development Branch, AAR-410, Atlantic City International Airport, New Jersey, and the Davis Technologies International Inc. (DTI) of Dallas, Texas. This specific study included the installation of a new stability strut device that modified vehicle antiroll characteristics on several different heavy rescue response vehicles.

FAA AND U.S. AIR FORCE SYSTEM REQUIREMENTS.

- It must be able to be installed on a new vehicle as well as a retrofit to existing ARFF fleets.
- It must achieve significant roll stability.
- Within the vehicle static and dynamic characteristics it must increase roll stiffness.
- The tests must directly compare the existing vehicle vs the new configuration and validate the test results using ARFF and industry Society of Automotive Engineering (SAE) standards and their comparisons.
- The devices must be cost-effective and easy to install as a retrofit solution.

Several technical approaches were proposed, discussed, and evaluated in a meeting at Tyndall Air Force Base. Personnel from the United States Air Force, FAA, DTI, and E-One participated in this first meeting.

A consensus was reached to implement a configuration which would add the required roll stiffness and superior shock damping force that was capable of achieving the level of lateral force stability required to prevent rollover. A system designed by DTI was selected for evaluation in this test program. The DTI strut performance capability is added to the present system by removing the existing shock and replacing it with the Integrated Suspension System (ISS).

A contract was awarded to E-One and DTI to jointly engineer, make prototypes, and test both the existing vehicle and the proposed solution in the same test runs and test courses. This test report validates the results of the E-One HPR 4 x 4 FAA research truck.

INTEGRATED SUSPENSION SYSTEM OVERVIEW.

DTI developed the ISS that fully integrates spring and damping functions in one compact strut unit. It features the flexibility of application as a direct replacement for traditional spring/shock units as well as leaf springs and rigid axle systems.

The DTI technology offers significant advantages over other technologies in spring and damping performance, compact configuration, and overall system design/function flexibility. The ISS system is configured to allow for adjustments in the spring and damping forces to maintain effective use of the full strut travel while accommodating variations in weight. Therefore, one compact system design can cover an entire range of vehicle variants, providing near identical ride and performance characteristics for all versions regardless of load weight variations.

The ISS system can be configured to almost any level of functionality: from a passive to adaptive, to an active system by the addition of only the relevant support control systems with interactive leveling modes and ride-height control in real time.

FAA HPRV SPECIFICATIONS.

The 4 x 4 FAA HPRV weighs approximately 45,000 pounds with a Snozzle™ elevated boom and was fitted with eight Davis Technology Inc. (DTI) ISS struts (see figures 2 and 3). The E-One AB50 4 x 4 used for baseline testing weighs approximately 45,000 pounds with the E-One aerial device and was fitted with normal Gabriel shock absorbers. The wheelbases of these vehicles are slightly different and the trucks are not exactly identical; however, it was a very good comparison.

This test report is comprised of two individual test sequences. The first phase was conducted to establish a baseline set of performance data for a typical HPRV equipped with standard Gabriel shock absorbers (one per wheel end). The second phase was an exact duplication of the first, conducted on the very same vehicle, and under the same conditions, with the only change being substituting a total of eight suspension struts (two per wheel end) installed inside the coil springs in place of the four shock absorbers.

- 1992 FAA HPRV 4 x 4 (with Snozzle™)

  VIN #: 46JDBAA82N1O03350
  Original E-One Shop Order: 008152(D)&O-B-3350(A)
  1998 Research Shop Order: 018796
  Testing Supervised by: James Merten, Sr. Engineer
  Test Dates: February 19-20 (Phase I) and March 10-12 (Phase II),1998.

- Vehicle Configuration

Water Tank Rating:	750 gal. (Full)	Tire Pressure:	67 psi x 4 – Phase I
Foam A:	Approx. 60 gal. (25% Full)		70 psi x 4 – Phase II
Foam B:	Approx. 60 gal. (Full)	Dry Chemical:	500 pounds
Fuel:	50 gal. (50% Full)	Ballasting:	None Additional
Shock Absorbers:	E-One PN 518274	Struts (Phase II):	E-One PN 566290

Minimal equipment in compartments.

Weights	Left Side	Right Side	Totals
Front	11,020	10,680	21,700
Rear	12.020	11,760	23,780
Totals	23,040	22,440	45,480*

*Phase II, weight was approximately 300 lbs. heavier due to the installation of the struts.

FIGURE 2. STRUTS WITHOUT SPRINGS

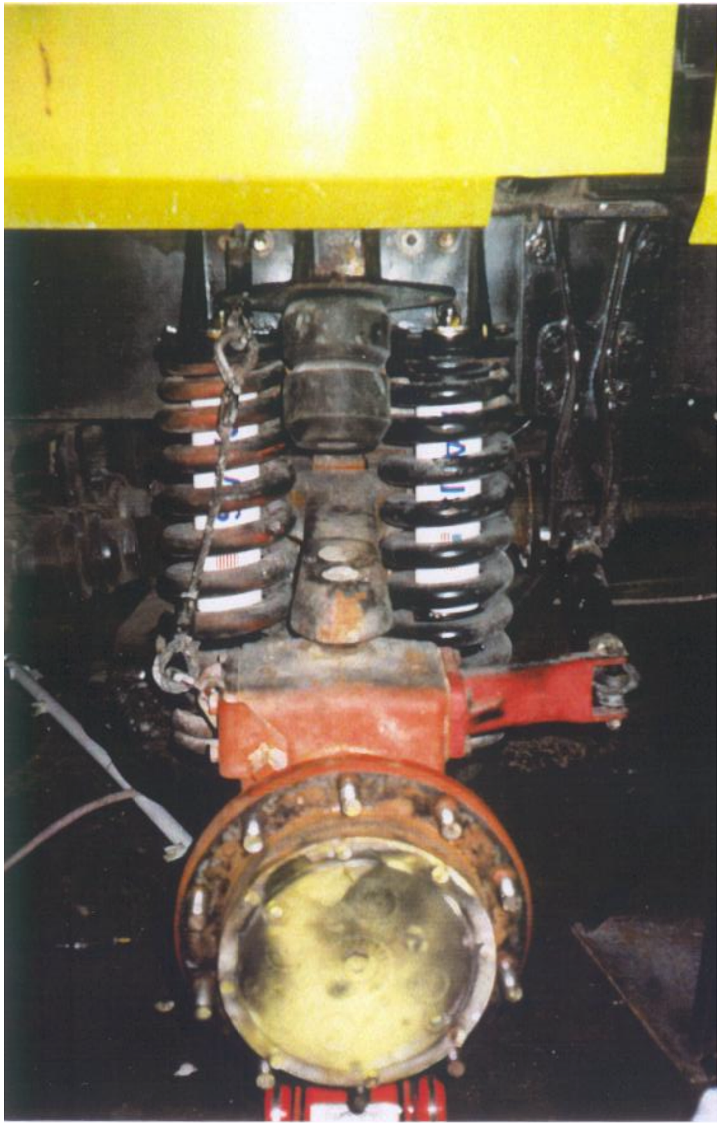


FIGURE 3. STRUTS WITH SPRINGS

INSTRUMENTATION.

Steering Position:	String Potentiometer (pitman arm lateral position)
Horizontal Acceleration:	Accelerometer (reference vehicle coordinate system, near c.g.)
Vertical Acceleration:	Accelerometer (reference vehicle coordinate system, near c.g.)
Yaw Rate:	Gyroscope (reference vehicle coordinate system, near c.g.) speed vehicle speedometer
Data Logger:	Astro-Med Dash IV

Calibration	Function	Zero Value	Baseline	Sensitivity	Conversion
Channel 1	Steering	1.28 V	12.1 mm	750 mV/cm	See Appendix A
Channel 2	Horizontal Acceleration	-9.60 mV	11 mm	3 mV/cm	8.36 mV/g
Channel 3	Vertical Acceleration	-2.60 mV	9.4 mm	400 µV/cm	3.05 mV/g
Channel 4	Yaw Rate	3.34 V	12.2 mm	2 V/cm	See Appendix A

TESTING METHODS

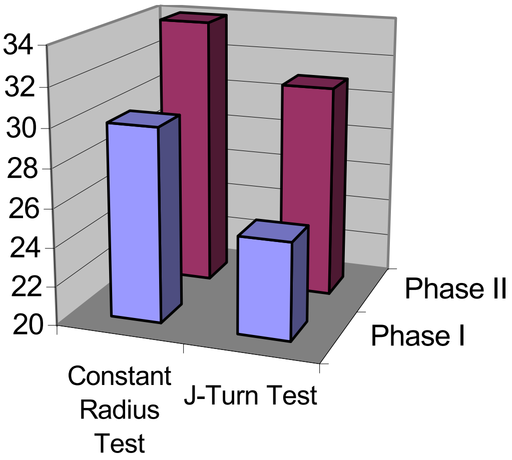
The FAA HPRV was tested in a Phase I and Phase II (with and without DTI strut system) configuration, along with the baseline E-One AB-50, in a series of static and dynamic tests. The evaluation consisted of the following tests procedures.

- Constant radius turn
- J-Turn
- Slalom course
- NATO lane change
- Tilt table
- Off-road course
- Single bump

CONSTANT RADIUS TURN.

SAE J2181 tests procedures were used as guidance for this test evolution. The vehicle was driven around a level 100 ft. radius circle, slowly increasing speed until vehicle began to appear or feel unstable. Current FAA, AC 150/5220-10-B specifications require that this class of vehicle should be stable at a minimum of 22 mph. Phase I testing showed this vehicle to be stable at 30 mph. During the steady-state test, the nominal horizontal acceleration was 0.56 g and the nominal yaw rate was 21.9°/sec. Phase II testing demonstrated a 13% improvement in cornering speed up to 34 mph, with a corresponding nominal horizontal acceleration of 0.64 g and a nominal yaw rate of 22.2°/sec. See figure 4 and appendix A for data tabulation (chart A-2).

An interesting observation made during this test was the change in the handling characteristics near the performance limit. In Phase I, the handling limit seemed to be governed by the roll stability of the vehicle. In Phase II, however, the handling limit was clearly governed by the tire adhesion, causing the front tires to slide out of the turn before approaching the roll sensation experienced in Phase I. This understeer characteristic is highly desirable, as it provides the operator a gradual and predictable response to extreme steering inputs from which it is easy to recover.



	Constant Radius Test	J-Turn Test
🟦 Phase I	30	25
🟥 Phase II	34	31

FIGURE 4. CONSTANT RADIUS AND J-TURN TEST SPEEDS

J-TURN.

On level ground, the vehicle was driven in a straight line at constant speed then subjected to a 90° sudden turn. Hard braking was introduced approximately 45º into the turn and maintained until the truck stopped. There is no current National Fire Protection Association (NFPA) or FAA requirement for this maneuver. The testing showed this vehicle to be stable at approximately 25 mph. During these tests, the average maximum horizontal acceleration was 0.62 g and the average maximum yaw rate was 24.4°/sec. Phase II data proved this vehicle to be stable in excess of 31 mph. This was a 24% improvement over the Phase I configuration. During Phase II tests, the average maximum horizontal acceleration was 0.71g and the average maximum yaw rate was 28.6°/sec.

As with the Constant Radius test, the Phase I testing indicated that the roll stability performance limit was determining the maximum cornering performance, whereas Phase II testing showed tire adhesion to be the performance limit. Additionally, a combination of front-wheel slip and rear-wheel slip could be achieved by varying the timing and intensity of the braking force. Once again, it is important to note the predictable nature in which this vehicle handles at its performance limit.

There has been considerable discussion about including a test of this type in the required FAA, AC 150/5220-10-C truck advisory. While this test does simulate the conditions known to precede some actual vehicle rollovers, it is the opinion of the testers that it offers an excessive number of variables that are driver dependent, and thereby impractical to control. By their nature, the tests mandated by the FAA are used as a comparison between various vehicles. Unless the variables in those tests are kept to a minimum and the unavoidable variables are tightly controlled, there will remain the potential that the tests will not be administered equally, making them useless for their intended purpose of equal comparison. In an effort to minimize the differences in our testing, the same operator was used for both Phase I and Phase II testing.

SLALOM COURSE.

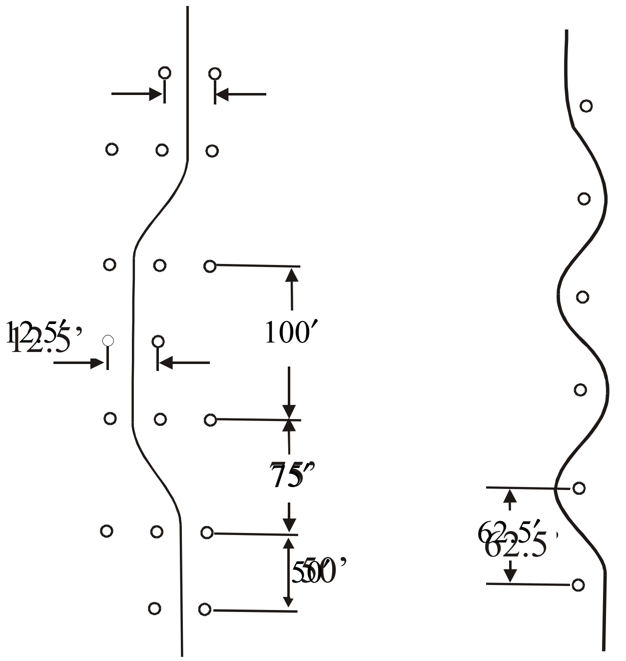
On level ground, the vehicle was driven through a course of six traffic cones which were placed in a straight line, 62.5 feet between each cone. Starting in a straight line on the right side of the cones at constant speed, the vehicle was turned left after the first cone, turned right around the second cone, etc. This sequence required three left-hand turns alternated with two right-hand turns. (See figure 5 for a diagram of this course.) The time duration from passing the first cone to the last cone was recorded for each run. There is no current NFPA or FAA requirement for this maneuver. During Phase I testing, the average negotiation time was 10.1 seconds, the maximum horizontal acceleration was 0.5l g, and the maximum yaw rate was 19.6°/sec. Phase II testing showed a 15% reduction in average course time to 8.6 seconds, with a maximum horizontal acceleration of 0.73 g and a maximum yaw rate of 25.0°/sec. Figure 6 shows a graph of the test data, and appendix A contains this data in tabulated form (chart A-2).

The change to the struts for Phase II testing offered the operator a much more controllable feel of the truck. Since the vehicle's response to severe steering inputs was so predictable (understeer), the slalom course time became limited by the speed with which the driver could turn the steering wheel.

NORTH AMERICAN TREATY ORGANIZATION (NATO) LANE CHANGE.

The NATO Lane Change test was conducted in accordance with NATO AVTP 03-160W. On level ground, the vehicle was driven through a course of traffic cones that outlined a 50-foot-straight approach, followed by a 75-foot transition area in which the vehicle's path shifted 12 feet to the side. The vehicle then travels on a 100-foot-straight path parallel to the approach path, followed by another 75-foot transition back to the original line of travel, and a 50-foot-straight departure lane. All straight sections of the course were 12 feet wide. (See figure 5 for a diagram of this course.) In Phase I testing, the operator was able to confidently negotiate the course in an average of 7.8 seconds. Phase II testing demonstrated a 3% reduction in course time to 7.6 seconds. Corresponding peak horizontal accelerations and yaw rates were 0.47 g and 20.6°/sec for Phase I, and Phase II was 0.43 g. The yaw rate data was unobtainable due to instrumentation failure. Figure 6 shows are graph of the test data, and appendix A contains this data in tabulated form (chart A-2).

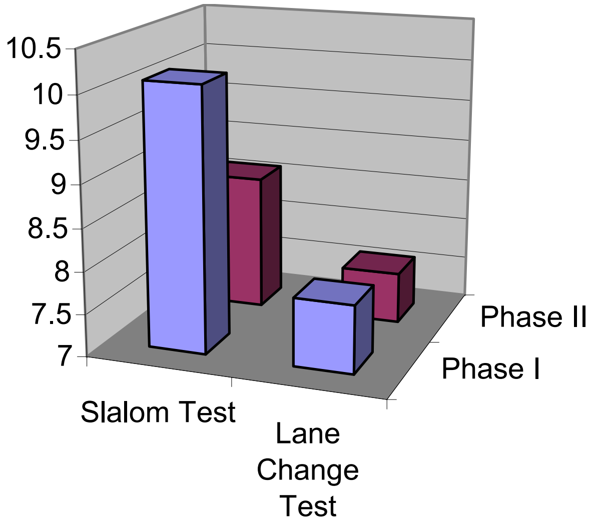
As this test was repeated, a gradual increase in the times was observed. This could have been due to the fact that the operator was challenged to accelerate and decelerate in a short, restricted area, thus preventing him from obtaining speeds that would have otherwise been possible.



NATO LANE CHANGE

SLALOM

FIGURE 5. NATO LANE CHANGE AND SLALOM COURSE TEST TRACKS



	Slalom Test	Lane Change Test
🟦 Phase I	10.1	7.8
🟪 Phase II	8.6	7.6

FIGURE 6. SLALOM AND LANE CHANGE TEST TIMES (sec.)

TILT TABLE.

SAE J2180 tests procedures were used as guidance for this test evolution. The tilt table is a device that rolls the surface of the table supporting a vehicle about a longitudinal axis. The device can be one table or multiple tables. The tables must maintain angles of tilt within 0.1° under the wheels of the axle. This static test is designed to simulate a nonvibratory steady turn.

The vehicle was driven onto the tilt table. The high side of the vehicle was then tethered to the tilt table to catch the vehicle once rollover had started. The tilt table was then gradually elevated at a rate not exceeding 0.25°/sec. The dynamic response of the test vehicle as it transitions the various events of the tilt table procedure is typically very slow. For example, when the vehicle begins to fall as the roll limit is reached, it accelerates very slowly. If the table speed is too fast, the table can chase the vehicle, making precise identification of the moment of instability difficult. The angle was increased to a point at which a rollover was imminent. Figure 7 shows the FAA HPRV being tilt table tested as part of this evaluation.

The current FAA requirement for this class of vehicle is 28°. All fluids were allowed to drain freely through their overflow systems. The air pressure of the tires was recorded to be 70 psi. The rollover threshold, expressed as a simulated lateral g-force, was then calculated by the following formula:

$$Rollover = Tangent\ (TABLE\ ANGLE)$$

FIGURE 7. FAA HPRV BEING TILT TABLE TESTED

Phase I testing established a rollover threshold of 0.49 g, while Phase II testing showed an 8% improvement to 0.53 g. Additionally, there was a 19% reduction in the roll angle at the rollover threshold. See figures 8 and 9 for tilt table data.

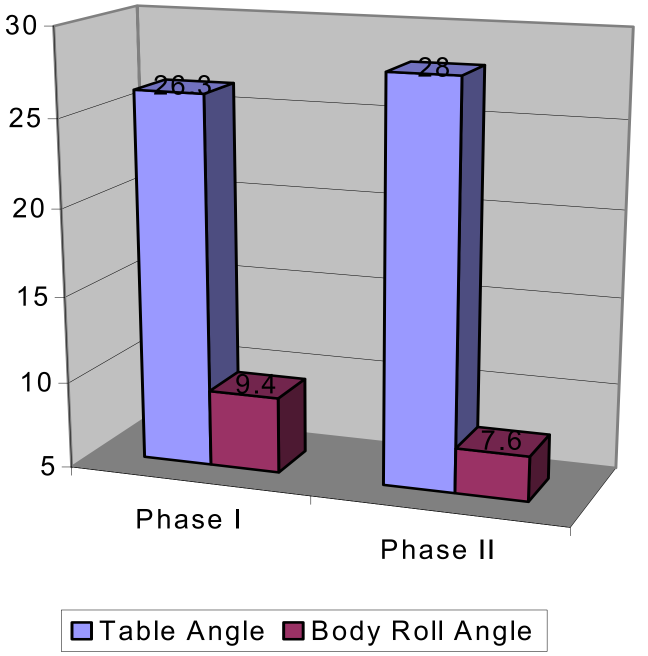


FIGURE 8. TILT TABLE ANGLE AND BODY ROLL ANGLE

Phase I		Phase II	
Table Angle	Body Roll	Table Angle	Body Roll
0°	0°	0°	0°
10°	3.3°	10°	3.2°
15°	5.2°	15°	4.9°
20°	7.2°	20°	6.7°
25°	8.7°	25°	7.2°
26.3°	9.4°	28°	7.6°

Note: When the HPRRV was delivered, the tilt table tested at 28.5° after the installation of the elevated boom waterway system. It was felt that this 26.3° angle was a result of spring softening due to the several thousand miles of off-road research testing the vehicle had undergone.

FIGURE 9. TILT TABLE TEST DATA

OFF-ROAD COURSE.

In an effort to simulate typical off-road ride conditions, a course was selected that involved establishing a constant speed on a paved course, transitioning to a grass-covered soil, traversing a moderately aggressive ditch at approximately a 30° angle, and then coasting to a stop across some additional bumps that introduce a suspension oscillation frequency of approximately 0.9 Hz (at 35 mph) and amplitude of roughly 8 inches. Both Phase I and Phase II testing showed good-vehicle stability through the ditch crossing. On the suspension oscillations however, a 54% reduction in peak vertical acceleration was measured, from 0.39 g with the shock absorbers (Phase I) to 0.18 g with the struts (Phase II). The number of noticeable oscillations after the bumps was also reduced from 4 to approximately 1.5.

A substantial amount of additional off-road driving was conducted to subjectively evaluate the overall vehicle performance. This type of evaluation is not effectively communicated by numerical data. Several operators with significant experience operating both rigid-axle and independent-suspension ARFF vehicles were asked to comment on their observations of this suspension system. All operators responded that the Phase II configuration offered a feel of confidence and predictability that they had not experienced in an ARFF truck of this size before.

Florida Emergency Training Facility (FETF students (approximately 100 students), over an 18-month period, drove the strut-modified vehicle as well as a standard straight-axle vehicle and a new E-One Model HPR independent-suspension vehicle. The students were asked to rank the vehicle ride quality from one to three with one being the best. The rankings of their observations are shown in table 2.

TABLE 2. VEHICLE RANKINGS BY RIDE QUALITY

	FAA HPRRV w/ Strut System	E-One HPR w/Ind. Suspension	Straight Axle ARFF Vehicle
Off-road ride quality	1	2	3
Confidence in Handling	1	2	3
Feel of control of the Vehicle	1	2	3
Stability in turns	1	2	3
Bump over street curb	1	2	3

SINGLE BUMP.

On a paved course at the E-One aerial plant, the FAA HPRV and AB-50 were driven at a constant speed and at a 90° angle across a typical two-lane road crown. Additional tests were conducted at increasing speeds from both directions. Strain gages were installed on the suspensions of the two vehicles in identical locations (see figure 10). The vehicles were also driven over a parking lot concrete bump stop at increasing rates of speed. Strain gage data from strip charts can be found in appendix A.

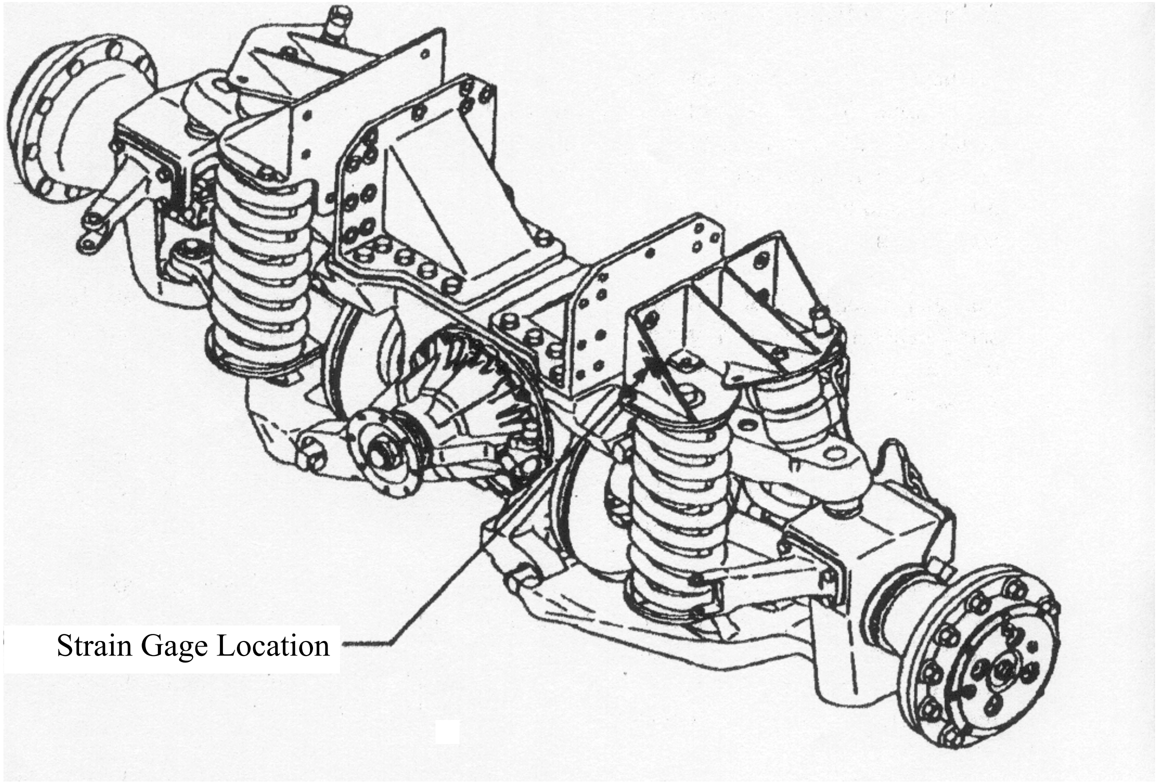


FIGURE 10. LOCATION OF STRAIN GAGES ON VEHICLE SUSPENSION

Phase I testing was conducted at speeds up to 35 mph, at which time the vehicle's pitch motion became severe. The vertical acceleration recorded during this event peaked at 0.38 g. It was determined that the natural frequency of the vehicle's suspension (ω_n) was 0.88 Hz. Phase II testing was conducted at speeds of 35 to 45 mph. Speeds higher than 45 mph were not possible due to limited acceleration distance. The vertical acceleration recorded during this event (at 35 mph, corresponding to Phase I) peaked at 0.08 g. This was a 79% frequency reduction. It should be noted that the natural frequency of the suspension system increases as the suspension is stiffened. This was not observable in this testing however, due to the use of a low-pass filter set at 1 Hz.

This type of ground input offers the most severe vehicle response as the forcing frequency (a function of the ground geometry and vehicle speed) nears one of the natural frequencies of the vehicle's suspension system. Typically, speeds well under or well over that threshold offer a smoother ride. The response near the natural frequency in Phase II was greatly reduced from Phase I. This should significantly reduce the concern of operators who have ground features on their airfield that cause severe vehicle reactions with their current ARFF trucks. Figures 11 and 12 contain graphs of bump steer input comparison between baseline E-One model AB-50 and the FAA HPRRV with strut installed.

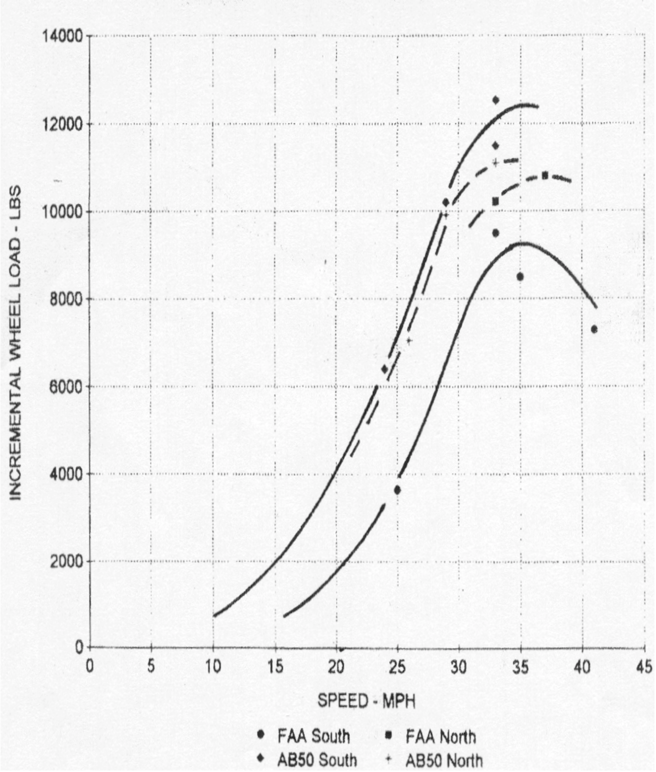


FIGURE 11. ROAD BUMP RESPONSE

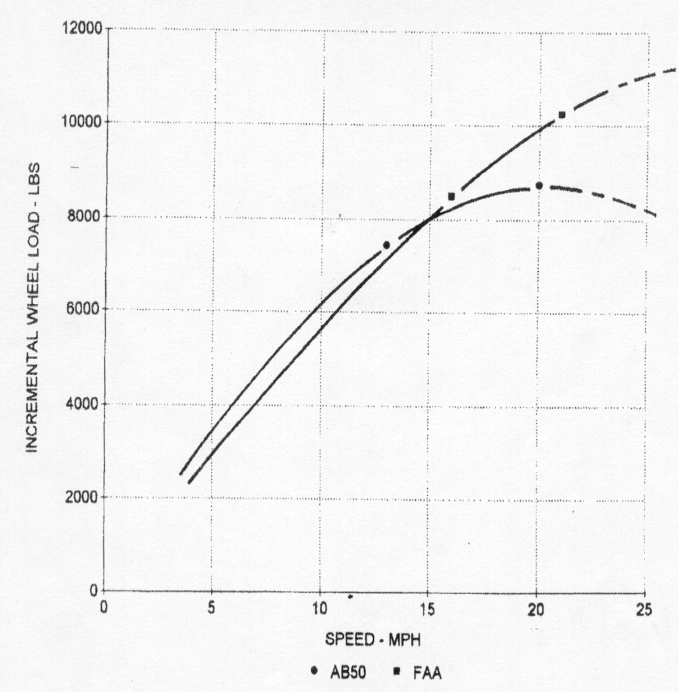


FIGURE 12. CONCRETE PARKING BARRIER RESPONSE

The testing indicated the struts increase pitch dampening by a factor of 3.3 and increased the suspension stiffness by 30%. The increased dampening greatly improves ride quality by reducing the transient response in both magnitude and frequency of the system.

The strain gage printouts in appendix A and figure 12 show that the axle stress and, thus, the axle loads as well, are reduced by the struts by as much as 25% in some of the runs. In all cases, except the bump stop, the stress on the DTI-equipped unit was less than the normal suspension. Due to the 30% increase in suspension stiffness, the bump stop data was higher above 15 mph but not as high as the normal suspension in the road bump mode, 11,300 pounds vs 12,500 pounds. Figure 13 contains a graph of road bump response comparison between baseline E-One model AB-50 vs FAA HPRRV with struts installed. Appendix A contains a graph of wheel loading data when the vehicle traversed over a parking lot concrete barrier 10.5 inches high. Appendix A also shows strain gage readings taken during various test sequences (see figures A-1 through A-7 for actual strip chart recordings) and a comparison between baseline E-One model AB-50 vs FAA HPRRV with struts installed.

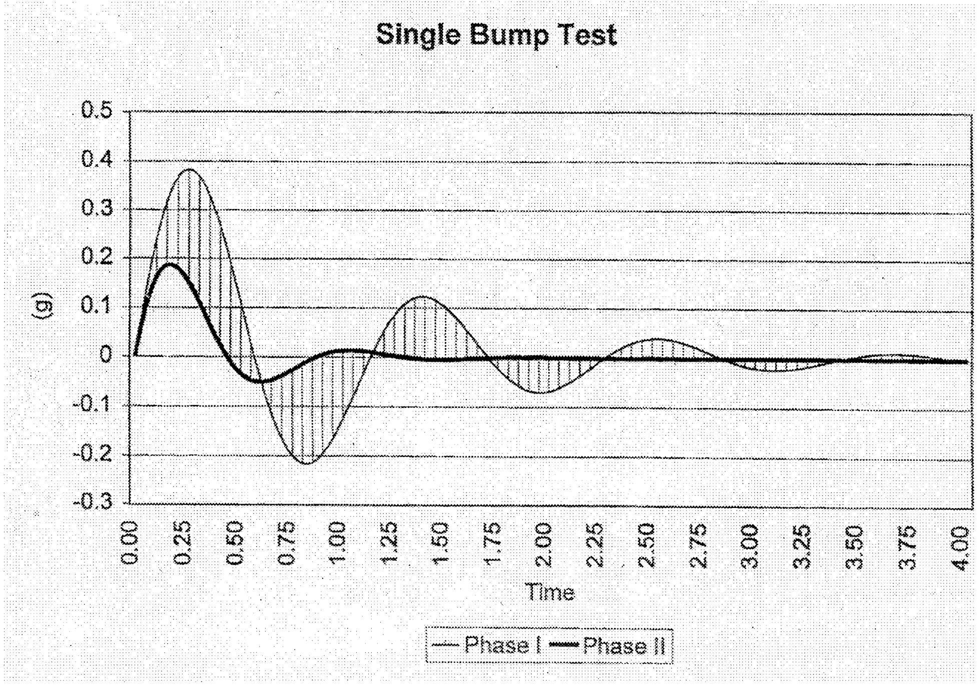


FIGURE 13. VEHICLE RESPONSE FREQUENCY

The testing also indicates that the magnitude of the G-forces on the chassis were reduced by almost 50%, and the frequency of the loading is reduced by 50%-60%. This reduction in magnitude and frequency can have a huge favorable impact on the expected fatigue life of some suspension and chassis components.

RESULTS

The most noteworthy vehicle handling characteristic was the apparent change in the way that the vehicle reacted to extreme maneuvers. Previous to the installation of the strut, the vehicle's handling limit appeared to be governed by its roll stability. After strut installation, the handling limit was clearly governed by tire adhesion. There appeared to be a threshold of cornering ability, beyond which the vehicle's front wheels would slide out of the turn. This was found to be very significant, as an operator's natural reaction to an unanticipated motion is to slow down, which in this situation would allow the vehicle to predictably resume its intended path of travel. When the handling limit is governed by roll stability, the situation can be exaggerated by a sudden change in the vehicle's operating characteristics, with little advance warning for the driver to react.

Once the struts had been installed in the vehicle, the driver could feel a significant difference in how the vehicle operated. Previous to the strut installation, the operator would experience a slight delay after initiating a steering input. At this point, the vehicle would begin to compress the suspension, and then start turning. As the cornering force was increased, the operator would need to anticipate the additional steering effect caused by the body/chassis roll. After strut installation, this effect was substantially reduced, providing a much faster response to steering input and provided the operator with a high level of confidence that the vehicle will react predictably to continued steering input.

Wherever possible, consistency was maintained between Phase I and Phase II testing. Each test was repeated several times, any anomalies were discarded, and the remaining results were averaged. Additionally, the same operator for each test in Phase I was also used for Phase II.

Even with these measures, some other limitations were incurred that may have prevented the measurement of the full potential of the struts. One such limitation experienced was the physical size of the available testing facility. All testing was done at the FETF driver-training pad at the southwest corner of the Ocala Regional Airport. Due to the increased stability of the strut-equipped vehicle, some tests required more acceleration room to reach the performance limits than was available on this training pad.

This particular suspension configuration was influenced by the Air Force's request that any proposed modification to the standard suspension be a "bolt-on" upgrade in addition to the standard coil springs. The potential exists to totally replace the coil springs with a dual-strut arrangement, saving both the material cost and the weight of the springs. DTI has indicated that the struts are capable of supporting the entire vehicle without the assistance of the springs (with a moderate increase in size). In fact this proposed arrangement offers a higher degree of control over the vehicle dynamics beyond what was achieved in this testing.

As this higher degree of control is achieved, it may be appropriate to re-evaluate the current recommended tire pressures for vehicles with this type of suspension system. The potential may exist to realize the extended tire life and even further improved ride characteristics by increasing the tire pressures, however, this must be done in balance with vehicle cone index (VCI) which is a measure of a vehicle's ability to negotiate various soil types, weight, and the vehicles speed ratings, and rim design.

CONCLUSIONS

The objective of this research was to engineer, design, build, and demonstrate a dynamic suspension system that modifies the spring and damping forces to provide high-performance vehicle control. Optimum roll resistance was met with the development and demonstration of the DTI Integrated Suspension System (ISS).

The approach to a retrofitable configuration, which could be installed in place of the existing shock absorbers inside the steel coil springs, proved to be a very practical and affordable way of implementing the dynamic suspension system. This configuration allows the system to be retrofitted to the existing fleet of ARFF vehicles as well as new vehicles. By using a retrofit, the increase in safety operations can be implemented immediately rather than waiting for the phaseout of the existing fleets.

Dynamic stability systems that reduce vehicle roll rates, body, and chassis deflection, enhance the vehicle ride quality, stability, and safety of operation.

The dynamic suspension enhancement tested in the evaluation reduced vertical acceleration of the vehicle by 54% on the off-road course and 79% during the single bump test. It also increased the performance during the constant radius and J-turn tests by 13% and 24%, respectively.

All of the testing conducted in this evaluation indicated that in addition to the significant improvement in ride quality, the evaluation showed lower stresses in the suspension and vehicle chassis components and improve fatigue life of these components.

RECOMMEDATION

Dynamic stability suspension systems that reduce vehicle roll rates and reduces body and chassis deflection should become eligible for purchase under the FAA Airport Improvement Program (AIP) for new ARFF vehicles, as well as retrofitted to existing vehicles.

APPENDIX A—DATA CHARTS AND PLOTS

Steering Calibration:

Steering Position	Output (volts)
Full Left	0.77
Center	1.28
Full Right	1.66

Gyroscope Calibration:

Applied Load (deg./sec.)	Output (volts)
20	4.891
15	4.494
10	4.103
5	3.714
0	3.352
-5	2.971
-10	2.593
-15	2.237
-20	1.878

* Some readings above 20°/sec. were interpolated using the closest 2 calibration points. Any readings above 20°/sec. are outside the calibration range and are thus subject to inaccuracies.

CHART A-1. STEERING AND GYROSCOPE CALIBRATIONS

	Phase I	Phase II	Difference
Constant Radius Test			
Speed (mph)	30	34	13%
Lat. Accel (g)	0.56	0.64	14%
Yaw Rate (deg./sec.)	21.9	22.2	1%
J-Turn Test			
Speed (mph)	25	31	24%
Lat. Accel (g)	0.62	0.71	15%
Yaw Rate (deg./sec.)	24.4	28.6	17%
Slalom Test			
Time (sec.)	10.1	8.6	-15%
Lat. Accel (g)	0.51	0.73	43%
Yaw Rate (deg./sec.)	19.6	25	28%
NATO Lane Change Test			
Time (sec.)	7.8	7.6	-3%
Lat. Accel (g)	0.47	0.43	-9%
Tilt Table Test			
Table Angle (deg.)	26.3	28	6%
Roll Angle (deg.)	9.4	7.6	-19%
Off Road Test			
Vert. Accel (g)	0.39	0.18	-54%
Number of Oscillations	3.5	1.5	-57%
Constant Radius Test			
Vert. Accel (g)	0.38	0.08	-79%

CHART A-2. TABULATED RESULTS

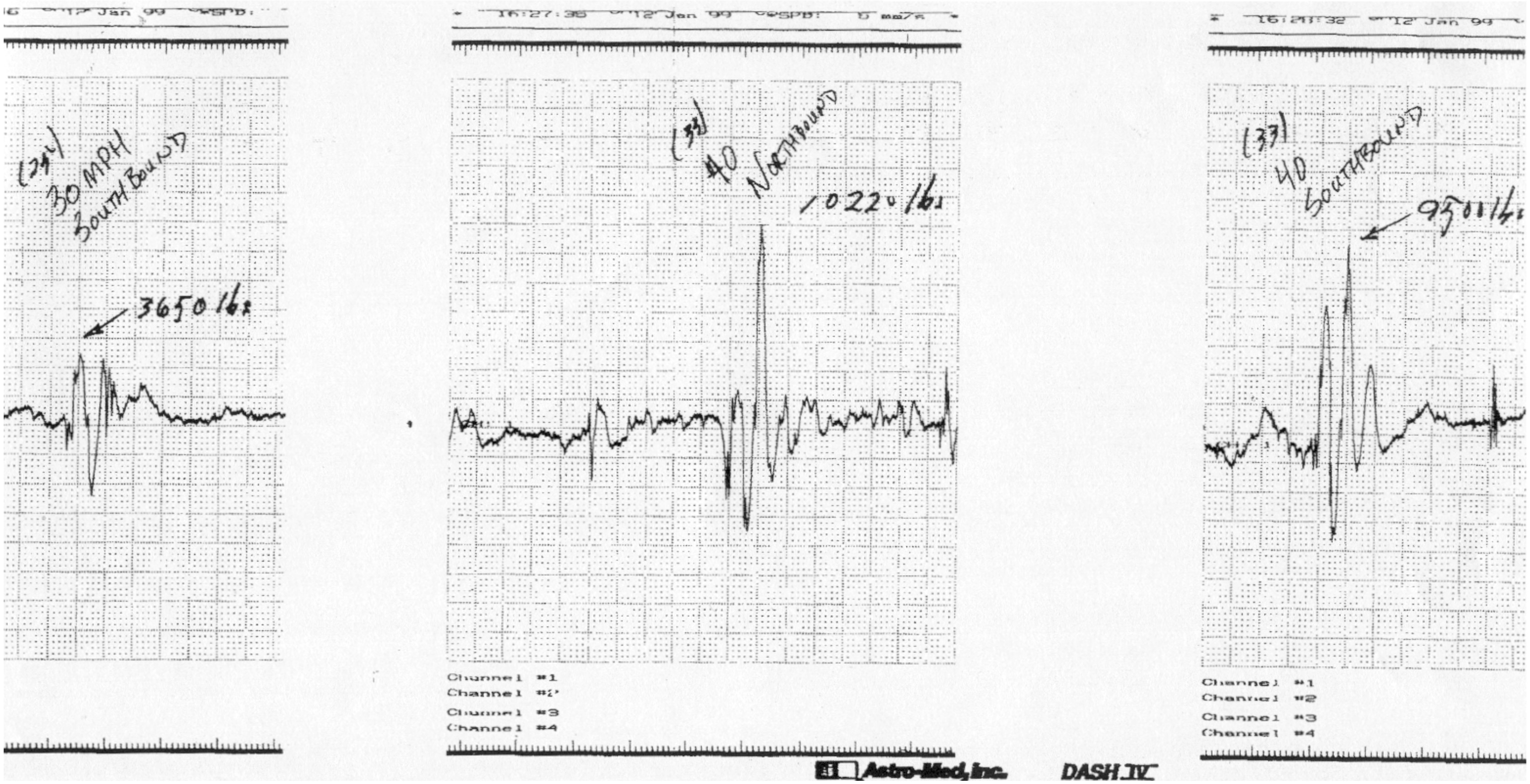


FIGURE A-1. FAA VEHICLE SUSPENSION TIME-HISTORY RESPONSE OVER ROAD BUMP

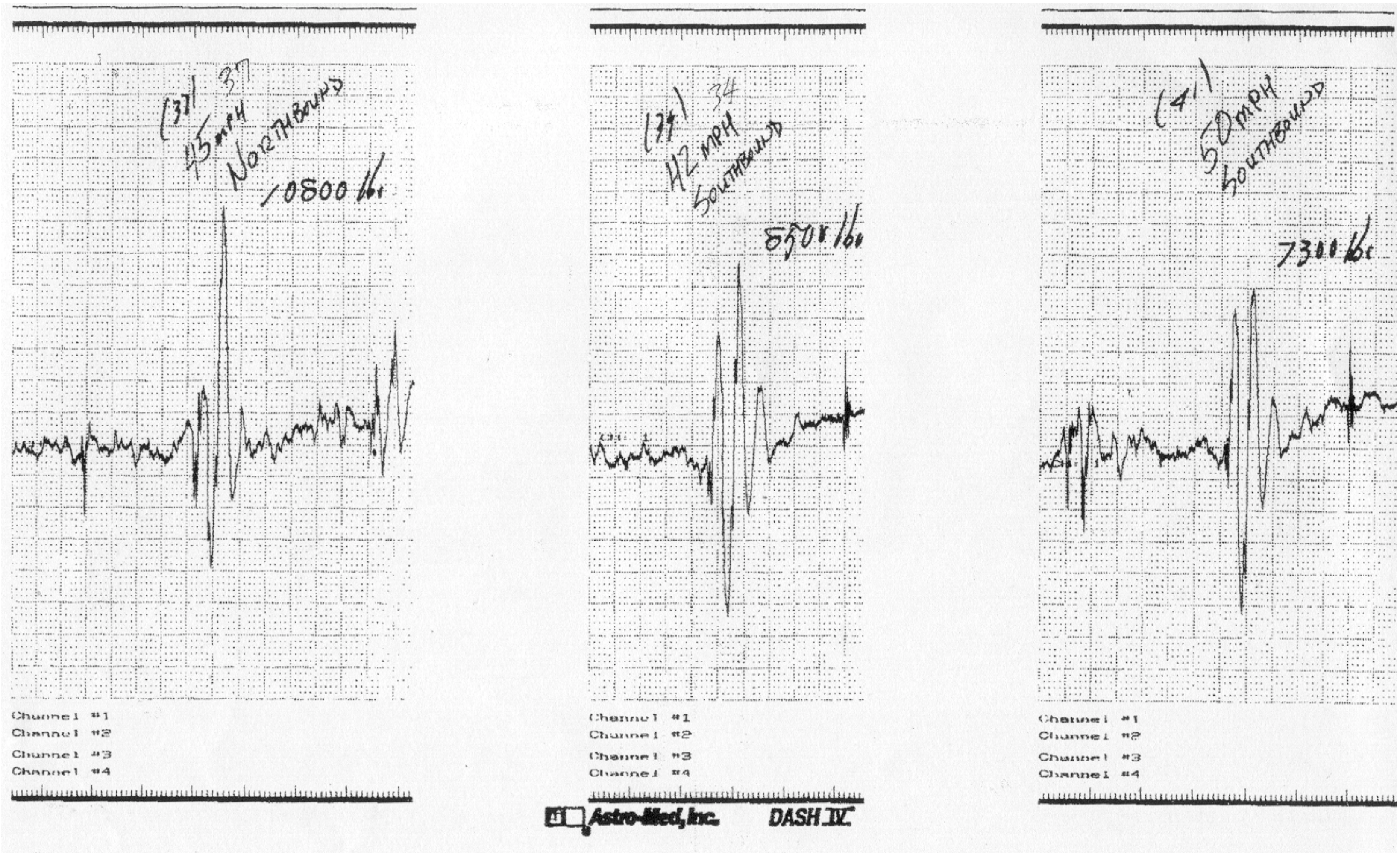


FIGURE A-2. FAA VEHICLE SUSPENSION TIME-HISTORY RESPONSE OVER ROAD BUMP

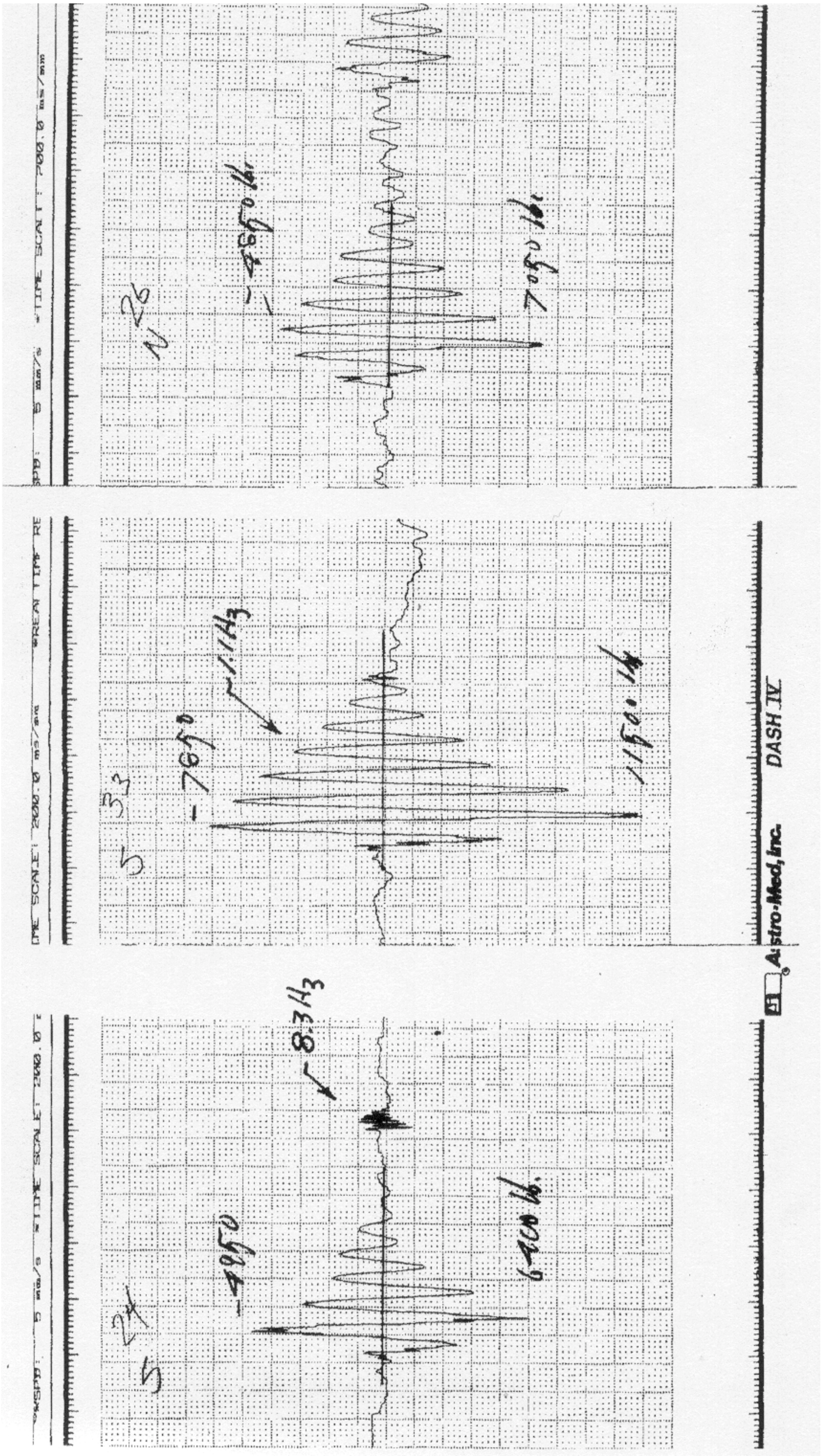


FIGURE A-3. AB50 SUSPENSION TIME-HISTORY RESPONSE OVER ROAD BUMP

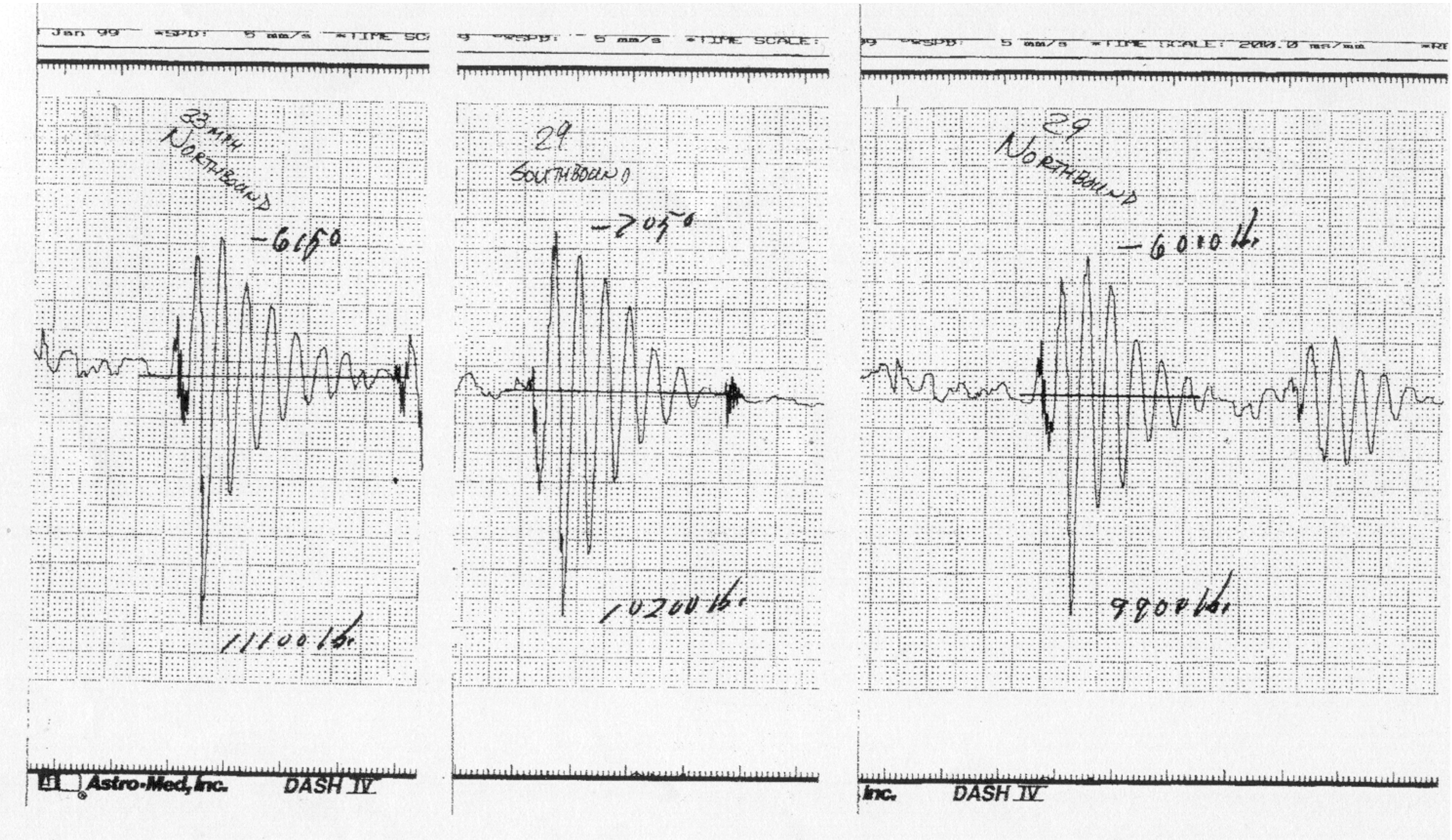


FIGURE A-4. AB50 SUSPENSION TIME-HISTORY RESPONSE OVER ROAD BUMP

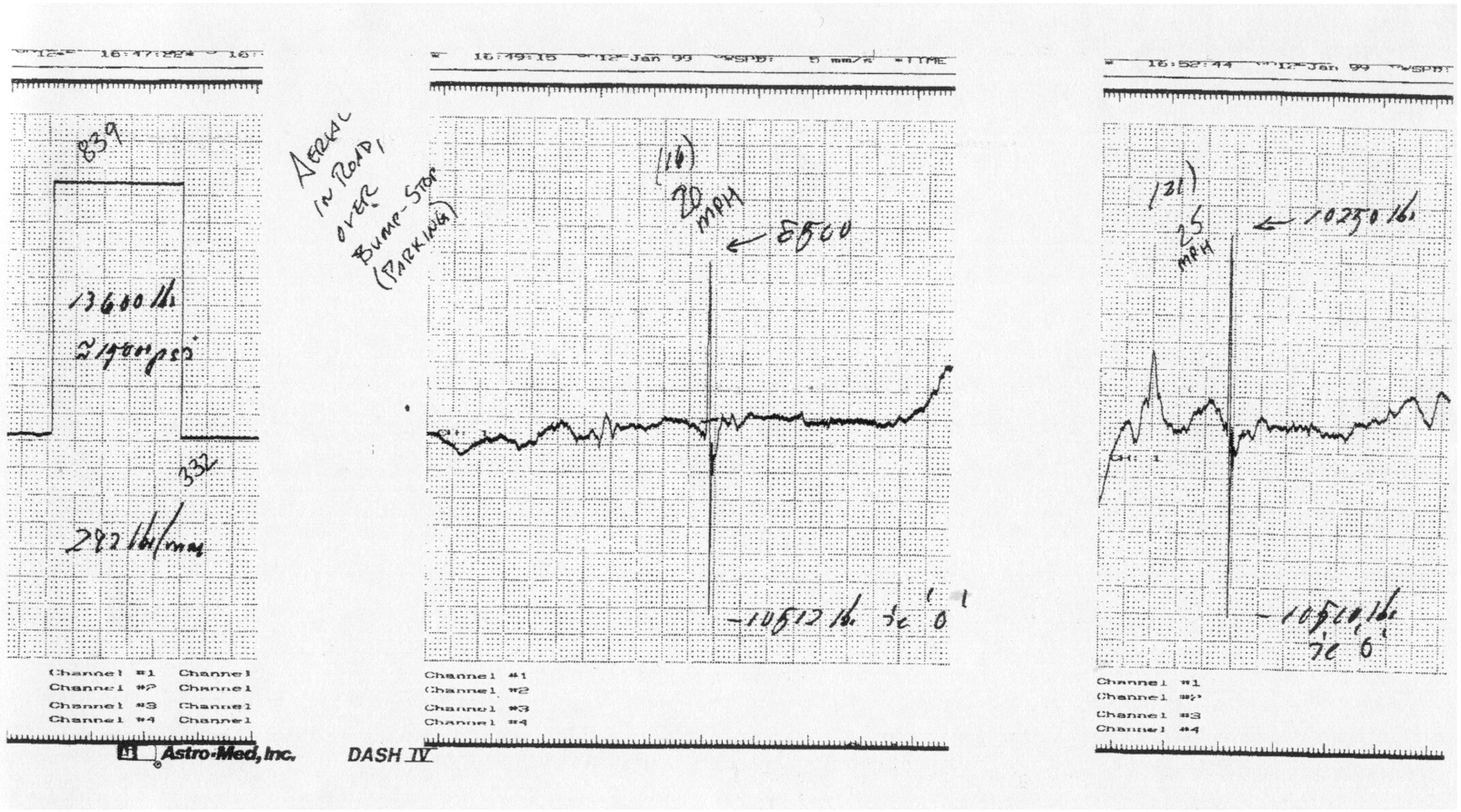


FIGURE A-5. FAA VEHICLE SUSPENSION TIME-HISTORY RESPONSE OVER PARKING BARRIER

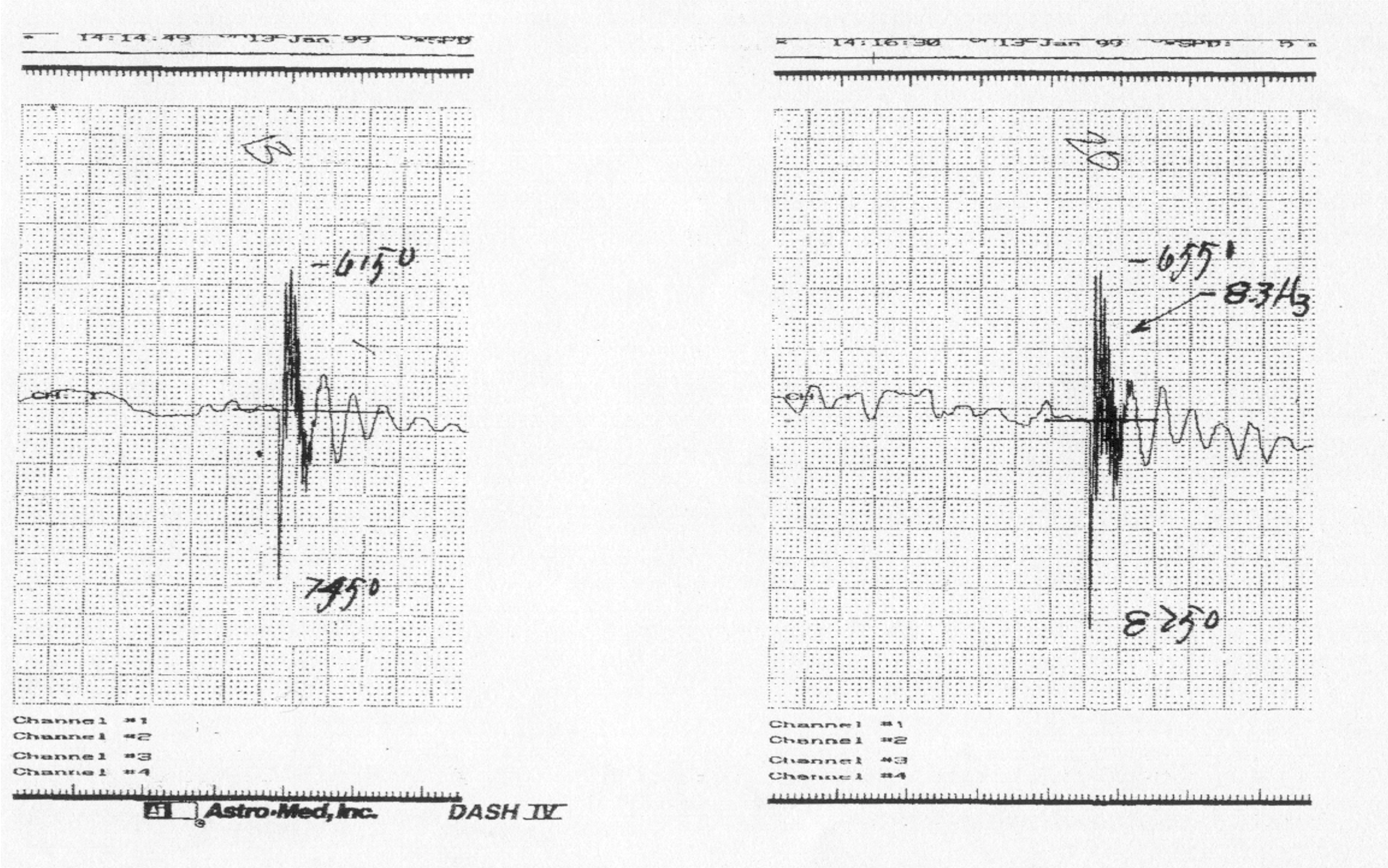


FIGURE A-6. AB50 SUSPENSION TIME-HISTORY RESPONSE OVER PARKING BARRIER

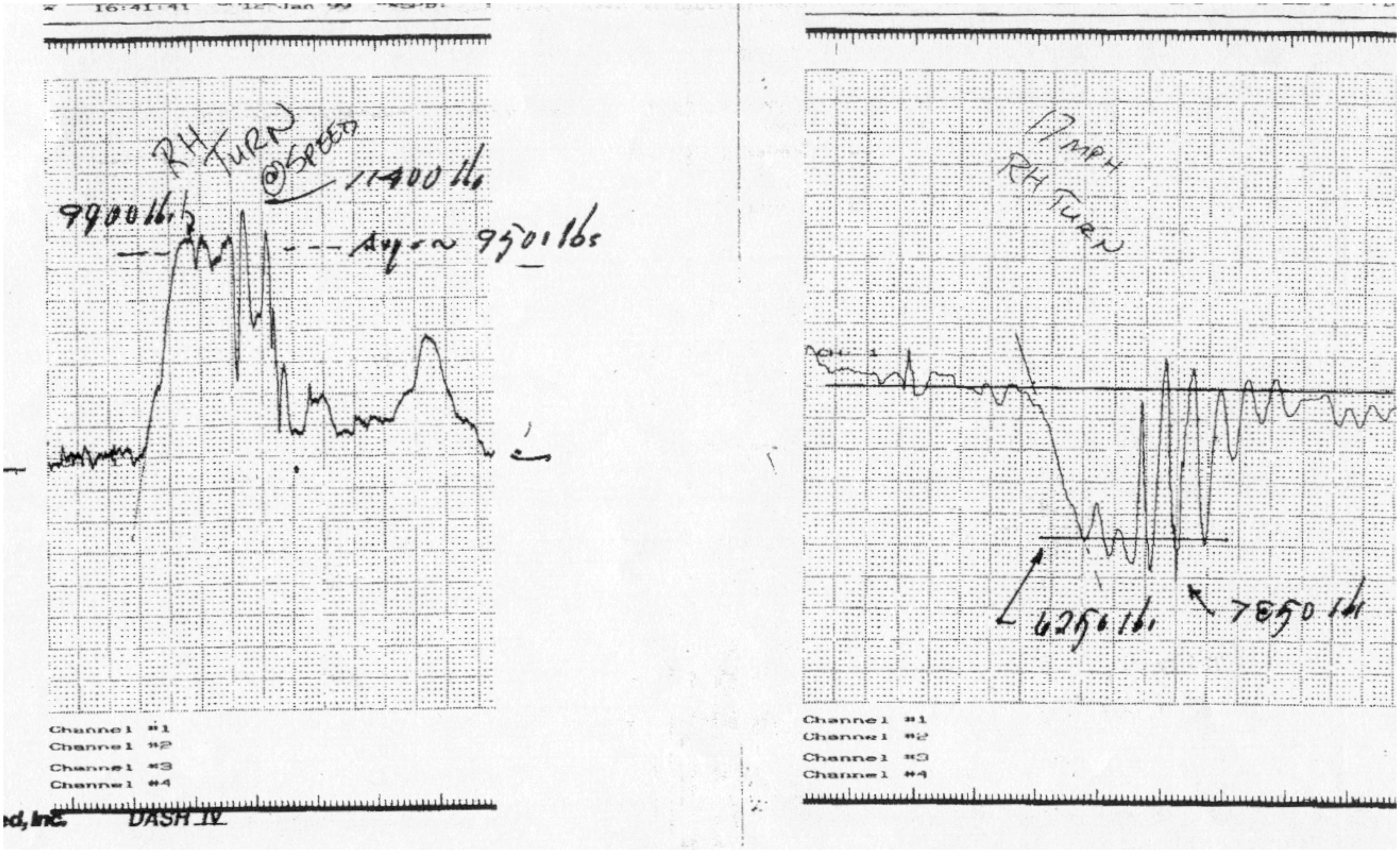


FIGURE A-7. TIME-HISTORY RESPONSE IN TURNS—FAA ON LEFT AND AB50 ON RIGHT