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Experimental Evaluation of a Non-Intrusive Automotive Suspension Testing Apparatus

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ABSTRACT

Proper performance of a vehicle's suspension system is required to ensure safe, comfortable operation of a vehicle. A suspension-testing device that can determine the condition of the suspension system, specifically the dampers, has been designed. The tests described by this paper seek to evaluate the performance of the device by testing vehicles and comparing to other methods of measuring suspension system performance that are currently in use. The suspension-testing device has the ability to discover degraded performance of the suspension system through a 2-minute test with the vehicle in operating condition.

INTRODUCTION

An automotive suspension system provides both safety and comfort for the occupants. Road irregularities cause the tire and suspension components to displace, thereby storing energy in the suspension spring. The spring then releases this energy as a damped oscillation.

A shock absorber, or strut, is a hydraulic mechanism positioned between the tire and body to dissipate energy generated by road surface irregularities. The struts and shock absorbers control, or damp, excessive spring and suspension movement [1]. For simplicity, the word "damper" is used to represent either a shock absorber or a strut.

Proper interaction between the components of the suspension system will produce a vehicle that exhibits safe handling and a smooth ride in the presence of road surface irregularities. As with any automotive system, the suspension system components wear out gradually. Dampers in particular are subject to wear. A suspension system with weak dampers will allow the vehicle to bounce excessively when road surface irregularities are encountered, adversely affecting both the comfort and safety of the vehicle's operation.

In 1971, the European Shock Absorber Manufacturers' Association (EuSAMA) was formed. This group established a set of guidelines for vehicle suspension evaluation called "Recommendations for a Vehicle Suspension Performance Evaluation" [2]. This document standardized the "road adhesion" measurement, which is an excellent vehicle safety comparison. Many countries in Europe use EuSAMA type testers as part of an annual vehicle safety certification.

Test devices that conform to the EuSAMA specification have been developed for the in-service testing of vehicle suspension systems. These devices displace a wheel and measure the response of the wheel to the displacement. From the individual responses, the device determines the condition of the suspension components.

S.A.E. Technical Paper 960735, "An Improved Non-Intrusive Automotive Suspension Testing Apparatus with Means to Determine the Condition of the Dampers" [3], describes an in-service testing device that measures EuSAMA adhesion and determines the condition of the dampers. The paper presents a theoretical justification for the device and compares the device's output to a mechanical apparatus that simulates a single wheel and its suspension components.

The equipment described by S.A.E. Technical Paper 960735, model SA400, was developed and manufactured by Hunter Engineering located in Bridgeton, Missouri. This study will build on the theoretical justification, providing experimental validation of the SA400's measurements. Results from the SA400 will be compared to test methods used by General Motors in the development and validation of suspension systems.

TEST METHODOLOGY

Adhesion is defined as "the minimum percentage of the instantaneous remnant vertical tire contact force between the tire and the road surface." This percentage is calculated by taking the ratio of the minimum remnant vertical load to the static weight (vertical tire contact force) on the SA400. The data acquired can be seen graphically in Figure 1.

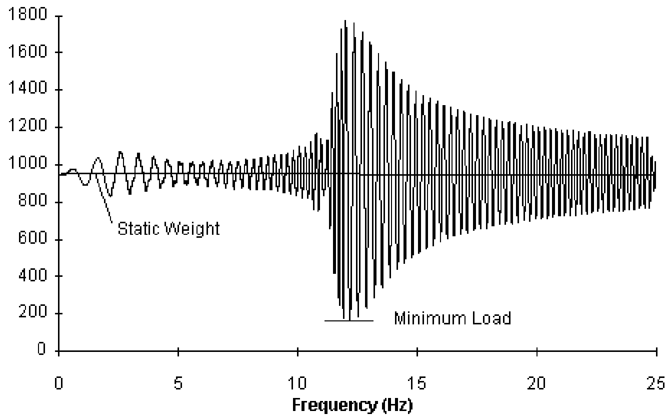

Figure 1. Graphical Explanation of Adhesion

The phase angle is the angular difference between the absolute sinusoidal position of the SA400 platform (X_3 relative to the ground) and the sinusoidal vertical contact force between the tire and the SA400 platform (sinusoidal position of the unsprung mass (X_{23}) relative to the SA400 platform) [3].

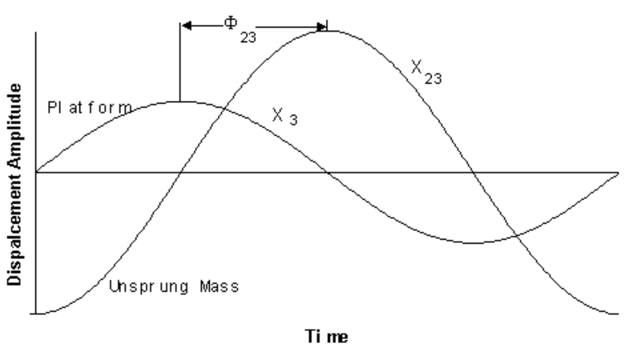

Figure 2. Explanation of Phase Angle

This phase angle is computed throughout all frequencies of the test. The minimum phase angle, called damping for simplicity, is the lowest phase angle measured between the sprung and unsprung mass resonant frequencies. The damping measurement is indicative of the strength of the damper.

The SA400 computes a side-to-side balance value for both adhesion and damping. By definition, an independent suspension system has separate, decoupled suspension components at each corner of the vehicle. It is therefore expected that the performance measured at each wheel should be relatively the same. Large values of side-to-side balance for adhesion or damping typically indicate a problem with components on one side of the vehicle.

The computed balance values are also useful with a solid axle suspension system. However, since the left and right suspension systems are coupled by the solid axle, it is more difficult to isolate a balance failure to a particular side of the vehicle

The SA400 generates conclusions from the adhesion, damping, and balance measurements by comparing the measurements to a preset specification. This specification sets predetermined limits on the desired performance of the suspension. Initially, the specifications used by the device were "universal", in other words not tied to a specific vehicle configuration. During the course of this study, it was determined that the performance of the SA400 could be improved by customizing the specifications, based on the vehicle being tested.

A sample printout of the results from a SA400 test can be found in the Appendix.

Several test types were conducted on actual vehicles in an attempt to compare the SA400's results on actual vehicles to other testing methods. The vehicles used for the tests were drawn from several sources:

- production and test vehicles
- low and high mileage production vehicles
- vehicles before and after suspension repair work

The variety of vehicle applications better simulated the empirical conditions often experienced by vehicles in the field. The ability to utilize vehicles which, by their current condition, were representative of actual (serviceable) states, further contributed to the confidence in the results.

CORRELATION TO RIDE ENGINEER EVALUATION – An SA400 suspension tester was installed at the General Motors Milford Proving Ground located in Milford, Michigan. Vehicles were tested on the SA400 and subsequently evaluated by General Motors Ride Engineers. The evaluations were conducted on a test track commonly used for its variety of road conditions. The Ride Engineer's rated the overall integrity of the suspension system using a subjective scale with Pass / Marginal / Fail ratings.

The Ride Engineer's rating was used as a reference for comparing the conclusions generated by the SA400.

Durability vehicle test – The durability vehicles were selected from the durability fleet at the General Motors Proving Ground. Vehicles selected consisted of various models and durability schedule designations. Consequently, vehicles tested represented a wide range of suspension system conditions. Generally, vehicles were tested prior to the start of the durability test cycle and subsequently at various points throughout their test cycle. Ride Engineer evaluations and tests on the SA400 were conducted as soon as possible to ensure the validity of the comparison.

Vehicle retrofit test – The vehicle retrofit test was conducted by utilizing General Motors employee vehicles. Vehicles selected were typically of the high mileage variety and consisted of various ages and models. Each vehicle was evaluated by a Ride Engineer and subsequently tested on the SA400. Next, the vehicles were inspected by a technician who was instructed to replace any suspension-related component that gave evidence of wear capable of influencing ride and handling characteristics. Front and rear damper replacement was mandatory. Following the diagnosis/repair process, each vehicle was re-tested on the SA400. Due to the extensive nature of the repairs on the majority of the vehicles, it was determined that no additional Ride Engineer evaluation was required.

COLD AMBIENT TEMPERATURE TEST – It is commonly accepted that damper replacement in the aftermarket tends to be a seasonal practice. Dampers and associated mounting hardware tend to become stiffer in colder temperatures, potentially masking weak or poorly performing dampers.

To determine the affects of cold ambient temperature on the test device, five high mileage (~120,000 to 145,000 kilometers) vehicles were run through a series of tests. Each of the vehicles selected was determined to have marginal or failing suspension characteristics when tested on the SA400 at 20 °C (68°F).

With the objective of the test being to directly compare the results of the SA400 on the same vehicles under various ambient temperatures, it was convenient to conduct this test in February in Detroit, Michigan. The vehicles were first tested cold upon arrival at the test facility following a 40-kilometer (25-mile) drive (Cold Drive). The vehicles were then stored inside the test facility until the suspension systems had stabilized to the ambient temperature (20°C / 68°F) at which time they were re-tested (Warm Soak). Finally, the vehicles were parked outdoors overnight, during which time the temperature dropped below 2°C (35°F). On the following morning, the vehicles were taken for a short 3-kilometer (2-mile) drive and then tested on the SA400 (Cold Soak).

Comparison of the results from these tests will allow determination of the effect of ambient temperature on the SA400's conclusions. It will also be possible to determine if a pretest drive routine can be used to compensate for the effects of a colder ambient temperature.

MODIFIED DAMPER TEST – As dampers wear, they gradually lose the ability to provide damping force. In order to determine the ability of the SA400 to differentiate between dampers with varying levels of damping capabilities, several sets of dampers were modified to simulate worn dampers. The range of modification represented *fully degraded* to *acceptable* damper performance. The modifications involved draining various amounts of oil from sets of dampers. Dampers were tested with the original oil volume (control units) as well as 66, 33, and 10% of original oil volume. Based on observed suspension system behavior and Force vs. Displacement Tests, dampers with 50% or less original oil volume display compromised performance. Consequently, the dampers with 33% and 10% of original oil volume were determined to represent dampers exhibiting unacceptable performance.

Prior to on-vehicle testing, the "control" and modified dampers were subjected to a Force vs. Displacement Performance Test at an independent testing facility. This test yields a compression and rebound force characterization curve at various (excitation) frequencies. Dampers with less than 50% remaining oil will be expected to show a reduction of rebound force and an increase in reaction time (phase lag). The vehicle test was performed using two production vehicles, both with low mileage. A 1997 Chevrolet Malibu, which has four wheel independent suspension, had all four dampers replaced in various configurations. A 1997 GMC C1500 pickup, which has a solid rear axle, received several combinations of rear dampers.

One of the results from the SA400 is a comparison of results from one side of the vehicle to the other. A test matrix for each vehicle was developed to reveal the ability of the SA400 to differentiate between dampers with varying performance, identify defective dampers and accurately measure side to side performance variations. The test matrix for the 1997 Chevrolet Malibu is shown in Table 1.

Table 1. Test matrix for 1997 Chevrolet Malibu

% of Original Oil Volume			
Left Front	**Right Front**	**Left Rear**	**Right Rear**
100	100	100	100
10	100	100	10
66	66	66	66
33	66	66	33

Due to unforeseen events, it was not possible to replace the front dampers on the GMC 1500. As might be expected, the solid rear axle makes separation of the performance of the left and right dampers more difficult. The test matrix for the GMC C1500 is shown in Table 2.

Table 2. Test matrix for 1997 GMC C1500

% of Original Oil Volume	
Left Rear	**Right Rear**
100	100
100	10
66	66
66	33

DATA ANALYSIS

CORRELATION TO RIDE ENGINEER EVALUATION

Durability vehicle test – Table 3 shows the General Motors Ride Engineer evaluations compared to the SA400 adhesion and damping conclusions for each of the durability vehicles. The durability vehicles are tested on schedules of varying length. Vehicles with a Ride Engineer Evaluation of "No Eval" indicate that no Ride Engineer was available at the point in the durability schedule where the vehicle was tested on the SA400. Due to the nature of extreme durability schedules, it is not uncommon to exceed the capabilities of various suspension components- resulting in an "unacceptable" rating.

Vehicle retrofit test – Eleven vehicles were used in the vehicle retrofit test. Each time the Ride Engineer had an evaluation other than "Pass", the SA400 made at least one conclusion that was "Marginal" or "Fail". In cases where the Ride Engineer evaluation and the SA400 conclusions disagreed, typically the SA400 tended to fail vehicles that the Ride Engineers passed. The SA400 also generated marginal conclusions for several of the tests run after suspension retrofit was complete.

While no discrepancy is desirable, errors of commission (failing a vehicle that should pass) were considered more severe than errors of omission (passing a vehicle that should fail). In order to eliminate errors of commission, a new method of determining specifications for the SA400 was developed that relied on vehicle specific information rather than a (theoretical) model based approach.

Development of vehicle specific specifications – Initially, the SA400 used a specification that was "universal" or not specific to the vehicle being tested. This specification was generated using tests run on some 2000 post-repair vehicles in aftermarket repair shops. Based on the results of the comparison to the Ride Engineer evaluation data, a vehicle specific specification method was developed. A formula was developed to generate a specification from actual SA400 measurements. The calculated specifications, along with year, make, model, and submodel information were stored in a database. After each test on the SA400, the operator can enter year, make, model and submodel information to recall the appropriate vehicle specific specifications.

Table 3. Ride Engineer Evaluation vs. SA400 Conclusions for Durability Vehicles – Universal Method

Percent of Durability Schedule Completed	**Ride Engineer Evaluation**	**SA400 Adhesion Conclusion**	**SA400 Damping Conclusion**
63	Pass	Pass	Pass
49	Pass	Pass	**Marginal**
76	No Eval	Pass	Marginal
20	No Eval	Pass	Pass
19	No Eval	Fail	Fail (LR)
12	No Eval	Pass	Marginal
100	Pass	Pass	**Marginal**
52	Pass	Pass	**Marginal**
78	No Eval	Pass	Pass
85	Marg Unacceptable	**Pass**	Marginal
82	Unacceptable	Marginal	Marginal
Unknown	Marg Pass	Pass	Marginal
18	Marg Pass	Marginal	Marginal
36	Marg Pass	Pass	Pass
100	Pass	Pass	**Fail** (Front)
20	Marg Pass	Pass	Marginal
100	Pass	Pass	**Marginal**
6	Pass	Pass	Pass
100	Marg Unacceptable	Pass	Marginal
100	Marg Pass	**Fail**	Marginal
96	Pass	Pass	Pass
2	Pass	Pass	Pass
20	Pass	Pass	**Marginal**
100	Unacceptable	Fail	Fail
60	Pass	Pass	Pass
100	Pass	Pass	Pass
61	Pass	Pass	**Marginal**
78	Pass	Pass	Pass
100	Pass	Pass	Pass
63	Unacceptable	Pass	Pass
19	Pass	Pass	Pass
4	Pass	**Marginal**	Pass
43	Unacceptable	Marginal	Marginal
0	Pass	**Marginal**	**Marginal**
2	Pass	**Fail**	**Fail**
0	Pass	**Marginal**	**Marginal**

Table 4 shows the Ride Engineer Evaluations compared to the SA400 conclusions based on vehicle specific specifications. The vehicle specific method eliminated errors of commission. Errors of omission increased from 3% to 19%.

Table 4. Ride Engineer Evaluation vs. SA400 Conclusions for Durability Vehicles – Vehicle Specific Method

Percent of Durability Schedule Completed	Ride Engineer Evaluation	SA400 Adhesion Conclusion	SA400 Damping Conclusion
63	Pass	Pass	Pass
49	Pass	Pass	Pass
76	No Eval	Pass	Pass
20	No Eval	Pass	Pass
19	No Eval	Pass	Pass
12	No Eval	Pass	Pass
100	Pass	Pass	Pass
52	Pass	Pass	Pass
78	No Eval	Pass	Pass
85	Marg Unacceptable	**Pass**	Pass
82	Unacceptable	Pass	Pass
Unknown	Marg Pass	Pass	Pass
18	Marg Pass	Pass	Pass
36	Marg Pass	Pass	Pass
100	Pass	Pass	Pass
20	Marg Pass	Pass	Pass
100	Pass	Pass	Pass
6	Pass	Pass	Pass
100	Marg Unacceptable	Pass	Pass
100	Marg Pass	Pass	Pass
96	Pass	Pass	Pass
2	Pass	Pass	Pass
20	Pass	Pass	Pass
100	Unacceptable	**Pass**	**Pass**
60	Pass	Pass	Pass
100	Pass	Pass	Pass
61	Pass	Pass	Pass
78	Pass	Pass	Pass
100	Pass	Pass	Pass
63	Unacceptable	**Pass**	**Pass**
19	Pass	Pass	Pass
4	Pass	Pass	Pass
43	Unacceptable	**Pass**	**Pass**
0	Pass	Pass	Pass
2	Pass	Pass	Pass
0	Pass	Pass	Pass

Based on the results of this test, a program to baseline the entire GM fleet of vehicles each year was begun. This effort is described in the “New Vehicle Baseline Testing” section.

COLD AMBIENT TEMPERATURE TEST – The results of the cold ambient temperature test consist of three sets of measured values from the SA400 for each vehicle tested.

Table 5 shows the measured damping values for each segment of the test. The “Test Order” fields indicate the actual order that the tests were run. The cold data tests have been grouped together to allow easier comparison between the types of tests.

The table shows that the damping values measured during cold ambient tests were always higher than values measured during warm tests. The increase in damping can be attributed to an increase in the damping coefficient of the suspension system.

When the suspension system components are cold, it is expected that the system damping will increase. The viscosity of the oil in the dampers increases as the oil becomes colder. In addition, oil in the dampers tends to drain to the bottom of the damper during the soak period. Rubber mounting parts also become stiffer as they become colder.

Table 5. Cold Ambient Test: Damping Results

Test Order	2	1	3
	Warm Soak	**Cold Drive**	**Cold Soak**
90 Lumina			
FR	64°	75°	82°
FL	52°	60°	74°
RR	53°	64°	64°
RL	49°	60°	60°
90 Grand Am			
FR	50°	66°	73°
FL	49°	59°	69°
RR	71°	75°	80°
RL	66°	69°	73°
90 Caprice Wagon			
FR	51°	64°	64°
FL	19°	31°	32°
RR	69°	72°	76°
RL	70°	69°	78°
90 Riveria			
FR	56°	68°	74°
FL	56°	70°	77°
RR	64°	66°	65°
RL	45°	59°	55°
90 Skylark			
FR	49°	61°	68°
FL	40°	57°	60°
RR	37°	43°	51°
RL	56°	68°	73°

The effect of the pretest drive routine can be seen by comparing the results from the two cold ambient segments. Within the test to test repeatability, the value measured after the 3-kilometer (2-mile) pretest drive were greater than or equal to the values measured by the 40-kilometer (25-mile) pretest drive. The increase is primarily due to the redistribution of the oil as the dampers are exercised during the drive.

Table 6 shows the measured adhesion values for each segment of the test. The adhesion values measured during the cold ambient tests were always higher than values measured during warm tests. Higher adhesion values translate into increased road traction and vehicle control. The increase in adhesion can be attributed to the greater control force exerted by the dampers, as shown previously by the damping measurements.

Table 6. Cold Ambient Test: Adhesion Results

Test Order	**2**	**1**	**3**
	Warm Soak	**Cold Drive**	**Cold Soak**
90 Lumina			
FR	67%	71%	72%
FL	67%	70%	73%
RR	38%	42%	42%
RL	35%	44%	43%
90 Grand Am			
FR	52%	59%	61%
FL	56%	63%	65%
RR	25%	30%	32%
RL	26%	33%	34%
90 Caprice Wagon			
FR	52%	57%	59%
FL	50%	53%	57%
RR	56%	60%	60%
RL	55%	60%	60%
90 Riveria			
FR	64%	68%	69%
FL	69%	73%	74%
RR	49%	50%	49%
RL	45%	51%	50%
90 Skylark			
FR	53%	60%	61%
FL	53%	61%	61%
RR	7%	17%	16%
RL	22%	30%	33%

A comparison of the cold ambient tests shows no significant change in the measured adhesion as a result of the 40-kilometer (25-mile) pretest drive routine.

The SA400 correctly indicates a substantial change in damping at each wheel in the colder tests, along with a smaller change in the suspension’s ability to keep the tire in contact with the road.

The results of this test indicate the test conclusions generated by the SA400 will be more conservative when tests are run in cold temperatures. The test conclusion will also be more conservative when tests are run after the vehicle has been parked for some time, as opposed to tests conducted after the vehicle has been driven.

MODIFIED DAMPER TEST – The modified dampers were tested on a shock dynamometer by an independent testing facility. The shock dynamometer exercises a damper at various frequencies while monitoring the control force generated by the damper. Comparison of the control forces generated by the dampers with different oil volumes will determine which dampers would be expected to show performance deficiencies when mounted on a vehicle.

Table 7. Rebound Control Forces for Malibu Dampers with Varying Oil Volume

% Original Oil		**Cycles Per Minute**			
		25	**50**	**100**	**170**
100	N	902	1193	1765	2720
	Lbs.	203	268	397	612
33	N	146	321	520	932
	Lbs.	33	72	117	210

The shock dynamometer exercises the unit under test at several frequencies with a fixed displacement of 5 cm (2 inches). The control forces produced by the drained damper were substantially less than for the control damper.

Full SA400 results for the 1997 Chevrolet Malibu are shown in the Appendix in Table 11. Shock Dynamometer output plots from a control damper and 33% of original oil remaining damper are shown in the Appendix in Figure 5. Table 8 shows the measured values obtained for each damper configuration. The values shown for each damper configuration were computed by averaging the results of all tests including a particular combination.

Table 8. SA400 Results for Malibu Dampers with Varying Oil Volume

% Original Oil	Avg. Front Adhesion	Avg. Front Damping	Avg. Rear Adhesion	Avg. Rear Damping
100	80%	100°	59%	99°
66	81%	100°	55%	84°
33	17%	0°	1%	0°
10	8%	0°	1%	0°

The results show that the 33% and 10% of original oil remaining dampers performed significantly worse than dampers containing 100% and 66% of their original oil. Comparing Table 7 and Table 8 shows that the SA400 was able to differentiate between dampers with acceptable and inferior performance, regardless of their configuration (i.e. left front) on the vehicle.

Full test results for the 1997 GMC C1500 are shown in Table 9 and Table 10. The averaging analysis employed with the Malibu data cannot be used with the C1500 data due to the “coupling” effect of the solid rear axle.

Table 9. SA400 Adhesion Results for C1500 Dampers with Varying Oil Volume

Rear			
Left		Right	
% Original Oil	Adhesion	% Remain	Adhesion
100	44%	100	40%
66	45%	66	40%
66	40%	33	31%
100	39%	10	31%

Table 10. SA400 Damping Results for C1500 Dampers with Varying Oil Volume

Rear			
Left		Right	
% Original Oil	Damping	% Remain	Damping
100	58°	100°	58°
66	64°	66°	58°
66	14°	33°	19°
100	24°	10°	18°

The adhesion and damping values are measured at a frequency substantially higher than the sprung mass resonant frequency. At such frequencies, there will be very little movement of the sprung mass during the measurement. In the case of an independent suspension, the measurement made at one wheel of an axle will not be experiencing any contribution from the opposite wheel. The same cannot be said of the solid axle case. The solid axle acts as a link between the two sides of the suspension, introducing an additional mode of vibration into the suspension. This effect can be seen very clearly in the adhesion vs. frequency data. A comparison between a 100% and a 10% (original oil volume) damper can be seen in Figure 3.

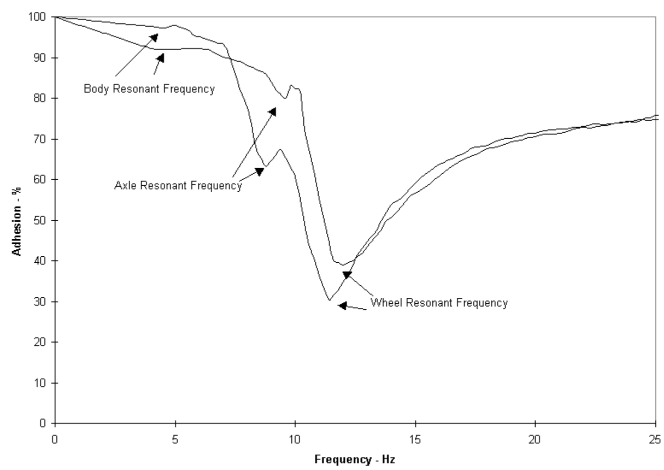

Figure 3. Adhesion vs. Frequency C1500 100% Damper vs. 10% Damper

There are three clearly visible resonant frequencies shown in each of the tests- wheel, axle and body. The figure shows that when a single weak 10% damper was installed, the adhesion at the axle resonant frequency experiences the greatest change. The damping vs. frequency data (not shown) confirms that the minimum damping occurred at the axle resonant frequency rather than at the wheel resonant frequency, as was the case for the 100% damper case.

The first two damper configurations in Table 9 contain only dampers expected to perform well. Each of the final two damper configurations included one damper that was expected to perform poorly. The introduction of a single weak damper did cause a drop in the measured damping for the right side in the final two configurations as expected. However, the left side, which still had a strong damper, also exhibited a significant decrease in performance. The result clearly indicates the “coupling” that a solid axle can cause.

While the more complex interactions of the solid axle make the results from the SA400 more difficult to interpret, the SA400 did detect a failure when a single weak damper was installed.

NEW VEHICLE BASELINE TESTING

Suspension system design takes many factors into account, some of which are subjective. A “vehicle specific” specification method was developed to remedy the differences between the Ride Engineer evaluations and the SA400 conclusions. In order to generate vehicle specific specifications, a program to test new production General Motors vehicles was begun.

Over one hundred production General Motors vehicles for the 1997 model year were tested on the SA400. The vehicles tested were new production vehicles, drawn from the stock of several dealerships. Approximately 200 tests on vehicles that had just seen suspension repair were also included in the data set. These test results establish a “signature”, or baseline, for each vehicle

The vehicle signatures were used to create a vehicle specific specification database. Once the database was integrated into the SA400 software, the operator was given the option of selecting the year, make, model, and submodel of the vehicle under test. SA400 conclusions are then based on the vehicle specific specification. The use of the vehicle specific database has eliminated errors of commission, which involve failing a vehicle that is performing as designed.

The testing of new production vehicles has continued from the 1997 model year through the 2000 model year and will continue indefinitely. A new database is integrated into the SA400 each year.

STATE CERTIFICATION PROGRAM

The State of New Jersey is in the process of implementing an Enhanced Inspection Program that will incorporate the SA400 described in this paper. The device will be used to test the front suspensions of in-service vehicles as part of a bi-annual safety and emission inspection. A special universal specification, designed to focus on safety, will be used to ensure that vehicles licensed by the State are operating properly.

VEHICLE SERVICE PROGRAMS

The SA400 is currently approved by General Motors Dealer Equipment Services for use in their dealerships and in use in the independent automotive repair businesses. Users include new car dealer service departments, tire dealers, and general automotive repair facilities. These three user types generally use the equipment in a similar fashion. Every customer vehicle that is in for service has a suspension test performed on it, free of charge. This is advertised and presented to the vehicle owner as a free safety check. The results are printed and given to the customer regardless of pass or fail status. If a failure is observed on the suspension analyzer, the vehicle owner is advised of the failure, and it is suggested that the vehicle receive further inspection. The vehicle is inspected by jacking it up, removing wheels, and generally seeking out cause of failure according to Motorist Assurance Program Guidelines.

Another type of facility that uses the SA400 is the automotive aftermarket facility that caters to the high-performance automobile owner who is very particular about their vehicle. This type of vehicle owner frequently modifies their vehicle and seeks to quantify the changes that have been made. These specialty shops often charge for testing using the SA400 because vehicle owners utilize this service on a semi-regular basis.

CONCLUSION

- Though previously proven on a theoretical (model) basis, this study provided empirical support that the SA400 can detect worn dampers based on the performance of the entire suspension system. In each case tested, the SA400 was able to identify dampers that were shown to have reduced control forces when tested on a shock dynamometer. The SA400 can detect single worn dampers, even on a solid axle suspension system that couples both sides of the suspension system together.
- It was determined that a universal (non-vehicle specific) test reference algorithm was not capable of producing the low level commission error desired. Use of vehicle specific specifications refines the replacement conclusions, eliminating errors of commission. The vehicle specific specification database is generated using signatures obtained from tests on no mileage production vehicles.
- The SA400 damping and adhesion measurements will be higher for vehicles tested at lower (colder) ambient temperatures. With the effect of the low ambient temperature, the SA400 will generate a more conservative result. Since conclusions requiring damper replacement occur less often in the colder weather, the SA400 will mirror current trends in damper replacement.
- The SA400 has the ability to discover degraded performance of the suspension system via a two-minute test with the vehicle in operating condition. This conclusion was confirmed by direct comparison between GM Ride Engineers and SA400 results. In each case, “real world” test conditions were used to verify the condition of the suspension system. The SA400 has begun to be applied to in-service testing, both as a diagnostic / repair device as well as an integral part of a state mandated vehicle safety inspection program.

ACKNOWLEDGMENTS

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APPENDIX

Table 11— SA400 Test Data for 1997 Chevrolet Malibu Modified Damper Test

Front Axle					
Left	**Right**	**Left**		**Right**	
% Oil Remaining	**% Oil Remaining**	**Adhesion**	**Damping**	**Adhesion**	**Damping**
100	100	80%	100°	81%	100°
10	100	8%	0°	81%	100°
66	66	80%	100°	81%	100°
33	66	56%	67°	81%	100°

Rear Axle					
Left	**Right**	**Left**		**Right**	
% Oil Remaining	**% Oil Remaining**	**Adhesion**	**Damping**	**Adhesion**	**Damping**
100	100	59%	100°	57%	98°
100	10	60%	100°	1%	0°
66	66	52%	78°	54%	85°
66	33	57%	93°	37%	61°

Name

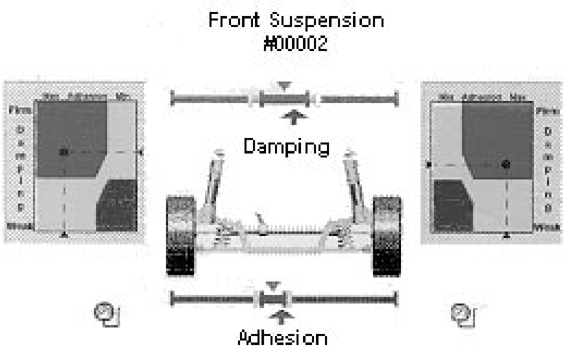
Address

Telephone

Vehicle (VIN)

License

Technician



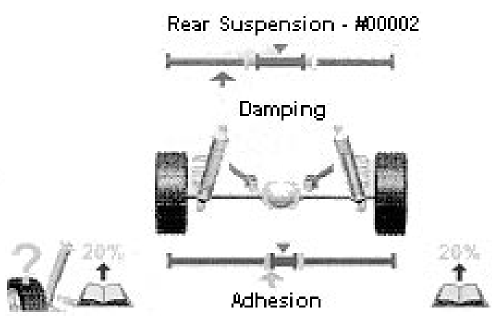
Conclusions - #00002

> SUSPENSION

Recall 'Vehicle Specific Specifications' for possible better correlation with vehicle results.

> SUSPENSION - FRONT AXLE

Check Tire Pressure
Passed.



Conclusions - #00002

> SUSPENSION

Recall 'Vehicle Specific Specifications' for possible better correlation with vehicle results.

> SUSPENSION - REAR AXLE

> LEFT / RIGHT

Check suspension system components, recommend damper replacement.

> LEFT WHEEL

Check for loose, leaking or damaged damper. Consider Damper Replacement.

> RIGHT WHEEL

Passed.

Figure 4. Sample SA400 Result Printout

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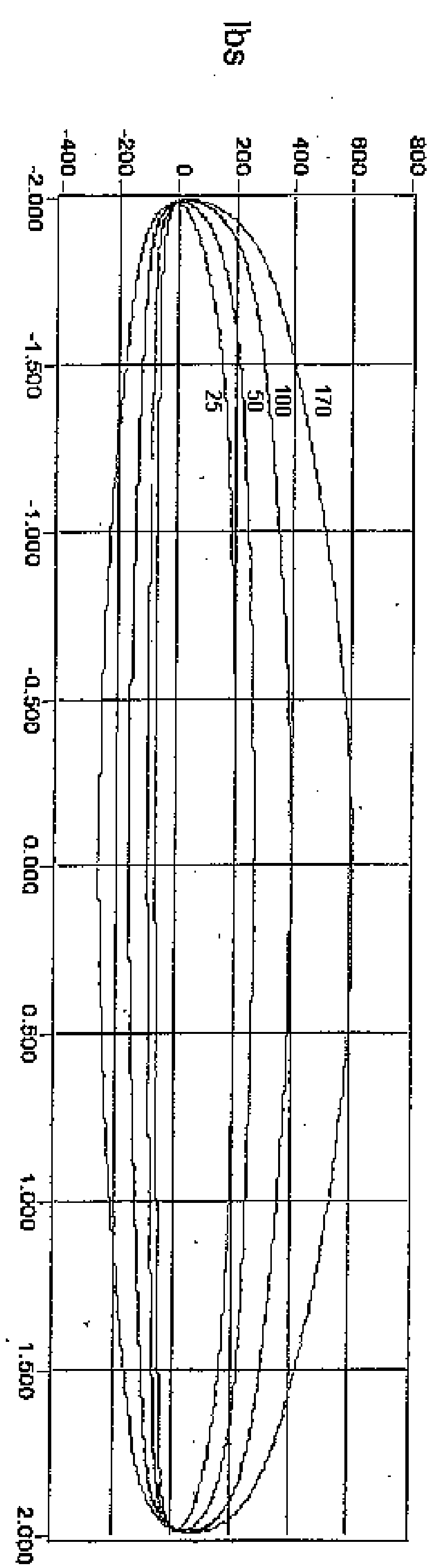
DATA SMOOTHING ENABLED



Project: 97134
Test Name: Shock / Strut Force vs Displacement Performance Test
Sample #: 31
Part #: M1RF
Cust Project: n/a
Lab temp(C): 22

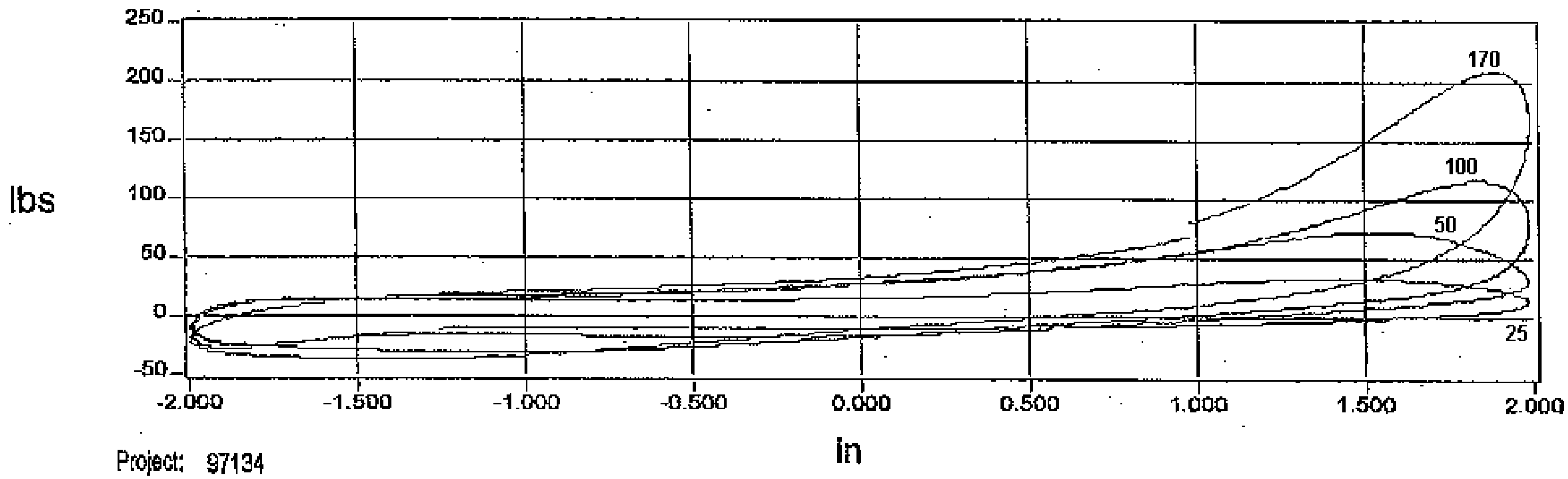
Date: 8/29/97
File Name: M1rf-31.shk
Total Displacement: 4.000
Unit preload: -22.92

	CPM	REBOUND in/sec	REBOUND m/sec	REBOUND lbs.	REBOUND newtons	COMPRESSION in/sec	COMPRESSION m/sec	COMPRESSION lbs.	COMPRESSION newtons
1	25.00	5.15	0.13	202.68	901.61	5.15	0.13	68.53	304.83
2	50.00	10.31	0.26	268.22	1193.16	10.33	0.26	93.40	415.46
3	100.00	21.01	0.53	396.86	1765.39	20.92	0.53	155.96	693.79
4	170.00	35.34	0.90	611.56	2720.45	35.33	0.90	257.95	1147.49
5									
6									
7									
8									

Figure 5. Shock Dynamometer Output Plot – Control Damper

DATA SMOOTHING ENABLED

AUTOMOTIVE TESTING TECHNOLOGIES INC.



Project: 97134
Test Name: Shock/Strut Force vs. Displacement Performance Test
Sample #: 31
Part # : M3RF
Cust Project: 86% Oil Loss
Lab temp(C): 22

Date: 9/3/97
File Name: M3rf-31.shk
Total Displacement: 4.000
Unit preload: 2.78

	CPM	REBOUND				COMPRESSION			
		in/sec	m/sec	lbs.	newtons	in/sec	m/sec	lbs.	newtons
1	25.00	5.14	0.13	32.91	146.39	5.15	0.13	26.44	117.62
2	50.00	10.31	0.26	72.20	321.18	10.33	0.26	28.34	126.06
3	100.00	21.03	0.53	116.81	519.61	20.95	0.53	30.90	137.47
4	170.00	35.42	0.90	209.60	932.37	35.40	0.90	37.24	165.67
5									
6									
7									
8									

Figure 6. Shock Dynamometer Output Plot – Damper With 33% Original Oil Remaining