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SUSPENSION PARAMETER MEASUREMENTS OF WHEELED MILITARY VEHICLES

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ABSTRACT

At the request of the US Army's Tank Automotive Command (TACOM) a device was built to measure the suspension parameters of any military wheeled vehicle. This is part of an ongoing effort to model and predict vehicle dynamic behavior. The new machine is called the Suspension Parameter Identification and Evaluation Rig (SPIdER) and has a capacity intended to cover all of the military's wheeled vehicles. The machine operates by holding the vehicle body nominally fixed while hydraulic cylinders move an "axle frame" in bounce or roll under each axle being tested. Up to two axles may be tested at once. Forces at the tires and motions of the wheel centers in three dimensions and two angles are measured. Other motions of the suspension and the minimal motions of the vehicle body are measured. For steer axles the steering ratio, Ackerman steer characteristics, and kingpin orientation are measured.

INTRODUCTION

As part of an effort by the US Army Tank Automotive Command to study the dynamics of military wheeled vehicles, S-E-A was contracted to build a suspension testing machine. The machine, which was named the Suspension Parameter Identification and Evaluation Rig (SPIdER) by the army has been completed and installed in TACOM's facility in Warren, Michigan. TACOM plans to use this rig to assist them in their ongoing efforts to model and predict vehicle dynamic behavior, so as to build vehicles that are less prone to roll over, have better handling stability, and perform better in rough terrain. The SPIdER is a companion to the Vehicle Inertia Parameter Evaluation Rig (VIPER) previously built by S-E-A [1]. Together, these machines allow measurement of the important parameters affecting vehicle handling and dynamics, so as to lead to better understanding of handling and dynamic performance of the vehicles.

This paper covers the suspension machine, hereafter referred to as the SPIdER. The SPIdER measures quasi-static suspension properties and tire vertical static stiffness. The SPIdER is not intended to be used for durability or strength testing.

In the past there have been few attempts to build suspension testing machines for large vehicles. Much of the foremost and earliest work on heavy truck suspension parameter measurement has been done at the University of Michigan Transportation Research Institute [2, 3], and more recently Michelin has designed and built a suspension measurement facility for heavy trucks [4].

MECHANICAL DESIGN

The SPIdER can accommodate all current military vehicles with track widths up to 110 inches. The maximum allowed vertical motion from the drive-on position is +/- 11.5 inches and maximum roll angle that can be attained is +/- 5 degrees.

Figure 1: Overall view of the SPIdER being used to test a 3-axle vehicle. The axle frames are under the first and second axles. The third axle is on a wheel stand. For this setup, only the first axle is being test

The SPIdER operates by holding the body of the vehicle stationary while the wheels are moved under the vehicle. The machine is installed on a heavy steel T-bed, and a variety of restraint components are used to nominally fix the body of the vehicle to the T-bed base. The minimal vehicle body motions, on the order of tenths of an inch, are directly measured and accounted for in the calculations. The vehicle body is not assumed to be rigid, rather, vertical motion measurements are taken at two locations for each wheel being tested. These measurements are just ahead of and just behind the wheel location being tested, and a linear interpolation is made to estimate the motion of the vehicle body directly above the wheel being tested. A total of eight string potentiometers are used for these measurements.

Up to two axles at a time can be tested, however a single axle can also be tested. If tandem linked axles are present on a vehicle they must be tested together. For each axle there is an axle frame that supports the main test hardware. This can be seen in Figure 1. At the ends of each axle frame is a vertical hydraulic cylinder. The bottom of the cylinder, the rod end, is attached to the axle frame, and a pylon attached to the T-bed supports the stationary top of the cylinder. In Figure 1, the pylons are blue and the axle frame units are yellow.

Each axle frame holds a wheel pad for the left and right wheels. The wheel pads are shown in Figure 2. Each wheel pad is capable of supporting very wide sets of dual tires. Each wheel pad is free to float in the longitudinal (x) and lateral (y) directions on linear rails with circulating balls. The effective coefficient of friction of these rails is in the range of 0.002. Steer motion of the wheel pad is allowed by a large crossed roller bearing under the wheel pad. The bearing can support load significantly offset from the centerline of the bearing, so the tire need not be perfectly centered.

Directly under the tire is a heavy steel top plate. Under the top plate is the crossed roller bearing that allows steer. Under the bearing is a heavy steel plate supported by four load cells. Using four cells allows one to calculate not only the total load on the wheel but also the center of pressure of that load. For single tires the center of pressure is essentially in the center of the contact patch, but for dual tires this may not be true. Dual tires can have different inflation pressures, and also during the roll tests the dual tires will typically not have the same load.

The lateral location of the wheel pad is also measured using a linear potentiometer, so as to directly measure changes in track width. Longitudinal motion of the vehicle body is measured with a string potentiometer in one location, on the vehicle centerline.

The hydraulic cylinders (four for the total machine) can be operated individually, but the normal modes of operation are to have them move equally during a bounce test, or equal and opposite during a roll test. During the bounce test the frames and wheel pads move strictly vertically, while during the roll test the frames and wheel pads are forced to rotate about a point in the plane of the tops of the wheel pads, which is the ground (road) plane, halfway between the left and right wheels.

Each axle frame has heavy steel ears sticking out the left and right sides, and each of these ears rides in a vertical groove. These ears and grooves prevent the axle frame from rotating about the vertical yaw axis and lateral pitch axis while allowing it to rotate only about the longitudinal roll axis. The ears also prevent longitudinal and lateral motion, while allowing vertical motion. Together, the ears, grooves, and cylinders specify the motion of the axle frame without over constraining it. It is therefore impossible to bind the axle frame, even if the cylinders are not synchronized.

The motions of the wheel center relative to the ground, along with the wheel loads, constitute the most important measurements on the entire machine. The five wheel measurements, x-motion, y-motion, z-motion, and the steer and camber angles are taken together using a coordinate measuring machine attached to each wheel (Figure 3). The stylus of this device is mounted co-linearly with the spin axis of the wheel, and the distance from the tip of the stylus to the centerplane of the tire is measured. Thus, the five degrees of motion of the wheel center can be calculated.

Figure 2: A typical wheel pad. The top plate and the heavy plate supporting the load cells are visible. The linear rails allowing longitudinal and lateral motions are visible. The crossed roller bearing allowing steer motion is not visible in the photograph, but it is between the top plate and the load cell plate.

Figure 3: The coordinate measuring machine used to measure wheel motion in the x-, y-, and z-directions, as well as the steer and camber angles. A commercially made alignment fixture is used to adapt the stylus of the measuring machine to the tire rim, and the alignment fixture automatically finds the centerline of the tire.

The base of the coordinate measuring machine is mounted to a stand that does not move during the test. The exact location and orientation of the base is not set exactly, however. During the test setup, once the base of the coordinate measuring machine is fixed, a calibration fixture is used to “teach” the machine the orientation of the x-, y-, and z-axes, and also the location of the z=0 plane (the ground plane). The true steer and camber angles can therefore be measured.

During the bounce and roll tests the handwheel in the cab is locked by attaching suction cups to the windshield and then attaching rods between the suction cups and the handwheel.

During the steering ratio test the handwheel in the cab is unlocked. The same coordinate measuring machine is used to measure the steer angles of the wheels. Inside the cab of the vehicle a rotary encoder is used to measure the angle of the handwheel, as an operator manually turns the handwheel through a specified range of motion. Typically, the handwheel is rotated through its full range of motion (lock to lock) however a smaller range can be used. This test is typically done with the engine and power steering turned on. Steering resistance is minimal, as the steer wheels are free to steer on the crossed roller bearings.

CONTROLS

The only controlled motion during the test is that of the four hydraulic cylinders. Each cylinder is controlled by a servo valve, and each cylinder has a linear potentiometer attached directly to it. The maximum flow in either the extending or retracting direction is controlled by a pressure compensated flow control valve (two valves per cylinder) that essentially sets the nominal speed of the cylinder. While the servo valves could be used to input complex motion and speed profiles, they are used essentially as up-down valves with the speed of motion being controlled by the flow control valves. Measurements are taken at stopping points about every quarter inch of wheel pad vertical motion, and the stopping points are the only points that are strictly controlled. By matching the flow rates of all the flow control valves, all cylinders arrive at each stopping point at about the same time. Final stopping position is controlled to about 0.02 inches.

Once the test is set up, the operator needs to only hit a button on the computer screen to start the test. The computer controls the motion to each measurement point, stops the motions, collects the position and force data, and then moves to the next measurement point. The computer decides when the motion should reverse, based on several criteria. For a bounce test the wheel pads (entire axle frame unit) move down a short distance, then move back up to the starting point before the first measurements are taken. Then the wheel pads move up to the point of maximum suspension compression, taking measurements about every quarter inch. Typically, the reversing point is when a user-specified maximum axle load or maximum suspension deflection is reached. The wheel pads move down until the suspension extension reaches a point when the loads on the wheel pads reach some user specified minimum value. Finally, the wheel pad motion is reversed to the up direction until they reach their original zero position. Each axle has its own stopping point for suspension compression and extension limits, based on the user-specified test limits. There are numerous checks in place to protect both the SPIdER and the vehicle.

For a roll test, one end of the axle frame unit moves up while the other end moves down an equal amount. The frame units are rolled to user specified angle, and then they are reversed to roll up to the same user-specified angle in the opposite direction. Finally, the frame units are rolled back to their original zero position.

CURRENT TESTS: BOUNCE TEST, ROLL TEST, AND STEERING RATIO TEST

The SPIdER is currently capable of doing three types of tests, all of them quasi-static. The tests are the bounce, roll, and steering ratio tests. During each of these tests over 70 transducers are used to monitor displacements, angles, forces, and pressures. Some of these signals are used to control the SPIdER frame motions and check for test and safety limits. However, the majority of the transducer signals are used to compute engineering quantities of interest for these suspension and steering tests. Table 1 contains a list of representative engineering quantities determined during SPIdER tests.

During a bounce test the axle or axles are moved vertically while the vehicle body is held stationary. Vertical forces at the tires are measured, the wheel location in three dimensions is measured, the wheel steer and wheel camber angles are measured, and the slight vertical motion of the body is measured. The vertical motion of the wheel pad is not measured directly but is calculated from the known hydraulic cylinder motions and the estimated machine deflection. The frames under the wheel pads are very stiff, but may deflect a few tenths of an inch under maximum load.

Typically, the suspension is exercised over a range of motion such that the minimum force is about 10% of the initial drive-on force, and the maximum force is a user-specified value. The SPIdER is designed for a maximum possible force of about 40,000 lbs per wheel position, or 80,000 lbs per axle. The maximum force is intended to bring the suspension well into the bump stops.

The engineering outputs listed in Table 1 are in various ways depending on the application. For example, some vehicle dynamics computer simulations require look-up tables to model such things as suspension vertical force versus suspension vertical deflection. In this case, the output data is simply formatted in tabular form. As another example, if the end user is using a computer simulation that requires parametric input data based on curve fits to portions of various suspension measurement characteristics curves, then the curve fit parameters are determined. The current post-processing of the SPIdER data provides TACOM engineers much of the data they need for their various applications.

Table 1: Representative List of SPIdER Suspension Measurements

Engineering Output	Quantity
Wheel Center Longitudinal Displacement	4
Wheel Center Lateral Displacement	4
Wheel Center Vertical Displacement	4
Wheel Pad Lateral Displacement	4
Wheel Camber Angle	4
Wheel Steer Angle	4
Chassis Vertical Displacement	4
Tire Vertical Deflection	4
Tire Vertical Force	4
Suspension Roll Angle	2
Chassis Longitudinal Displacement	1
Steering Wheel Angle	1

The SPIdER has run-time and post-processing routines to generate plots of typical suspension measurement characteristics curves. Table 2 lists a subset of the numerous characteristic curves that can be generated from SPIdER data, and representative graphs containing some of these curves are contained in the Appendix. The graphs are taken from tests of more than one vehicle, and they contain data from both solid axle as well as independent suspensions.

In the roll test the maximum possible angles are 5 degrees. When a single wheel load goes to 10% of its initial value the motion automatically reverses, as loss of wheel ontact is very undesirable, especially when the axle frames and wheel pads are tilted at a large angle. Generally, the roll test produces lower forces than the bounce test. With the ability to measure the center of pressure on the wheel pad, roll torque is accurately measured even for wide sets of dual tires.

During a roll test data plots such as those listed in Table 2 for a roll tests are generated. In order to simulate rolling with differing loads on the axle, it is possible to give some initial compression or extension to the suspension and then perform the roll test. The rolling always occurs about an axis in the ground plane, which is the plane of the tops of the wheel pads.

Suspension bounce and roll stiffness characteristic curves often have a hysteresis loop, especially if the suspension contains leaf springs. At the slow speeds used for these tests, the sizes of these loops provide a measure of the static damping in the leaf springs, suspension bushings and other parts of the suspension system.

During a steering ratio test the suspension is normally held at the initial drive-on position, but this need not always be the case. The SPIdER has been designed to accommodate and measure large roadwheel steer angles (angles up to at least 45° are usually possible). For most vehicles, the steering wheel inputs can go to their full lock angles in both right and left steer directions.

Table 2: Representative List of SPIdER Characteristic Curves

Characteristic Curve	Test
Suspension Vertical Stiffness Characteristic Curve	Bounce
Tire Static Vertical Stiffness Characteristic Curve	Bounce
Bounce Steer (or Toe) Characteristic Curve	Bounce
Bounce Camber Characteristic Curve	Bounce
Wheel Center Longitudinal Deflection vs. Suspension Deflection	Bounce
Wheel Center Lateral Deflection vs. Suspension Deflection	Bounce
Roll Center Height as a Function of Suspension Deflection (for Independent Suspensions)	Bounce
Roll Stiffness (Overall, Suspension, and Auxiliary) Characteristic Curves	Roll
Roll Steer (or Toe) Characteristic Curve	Roll
Roll Camber Characteristic Curve	Roll
Steering Ratio Characteristic Curve	Steering

If a large range of steering input is used, the steering ratio test produces a non-linear plot of roadwheel steer angle versus handwheel angle. This plot will have a linear range giving the steer ratio (a single number) and then the curvature of the lines at the larger steer angles show the

Ackerman steering effect. The steer ratio test can also be used to calculate the Kingpin Inclination Angle, Kingpin Offset, and Caster Offset.

FUTURE ADDITIONS AND TESTS

The bounce, roll, and steering ratio tests are tests where motion is put into the suspension. Other common suspension tests are tests where forces and torques are applied to the suspension through the wheel pads. The SPIdER was designed so that in the future, with a modest amount of modification, it can be upgraded to include the following tests.

Lateral Stiffness (Lateral Compliance) Tests

In these tests lateral forces are applied to the right side and left side wheel pads, in any combination of lateral directions: both left, both right, both in, or both out. The lateral forces may be as high as the frictional limits of the tire on the wheel pad. Lateral force and lateral motion would be measured during these tests, as would all of the other SPIdER transducer signals and relevant engineering outputs.

Longitudinal Stiffness (Longitudinal Compliance) Tests

In these tests longitudinal forces are applied to the right side and left side wheel pads, also in any combination. Similar quantities would be measured as with the lateral tests described above. For this and the lateral test, the force is applied precisely through the center of the tire contact patch, so as not to produce any steering torque.

Steering (Aligning Moment) Compliance Tests

In this test a pure steer torque with no linear forces is applied to the wheel through the wheel pad. This test provides for measurements of the aligning moment compliance in the suspension and steering column, as well as the characteristics of power steering assist systems.

Frame Twist Tests

With minimal additional hardware the SPIdER could be modified to measure frame twist stiffness. The chassis restraint system would need to be modified so the vehicle is held to the frames, and then the frames would be rolled in opposite directions. On some vehicles, the vehicle would be held to the ground on a lateral line above one axle and the other axle would be rolled.

Low Speed Dynamic Tests

For the quasi-static SPIdER bounce and roll tests, the frame ends are moved at a slow rate, less than 0.10 in/sec. The SPIdER hydraulics allow for much faster motions. With minimal additional hardware it would be possible to do non quasi-static tests, though probably not enough to do a full test of the hydraulic dampers. Non quasi-static tests can be different from quasi-static tests for at least two reasons. First, hydraulic suspension dampers will produce more friction at higher speeds. Second, if the suspension is an air suspension, faster motion will produce greater change in force, since there is less time for the air in the suspension to transfer heat to the solid parts. In compression, for example, the air will be compressed and heat up, and the faster the test the less time is available for the air to lose heat and go down in pressure. Thus, the force versus deflection curve will be steeper. Although the non quasi-static tests will likely not be capable of providing complete damper and air suspension characteristic data, they could be useful in providing information for simulation evaluation/validation studies.

SUMMARY

A suspension testing machine for large military vehicles has been built and is working well. Three tests are currently being done, bounce, roll, and steering ratio. All tests are done quasi-statically. Other tests may be added to the machine's capabilities later. The suspension tester and its software include a number of safety and data checks to ensure that the data is reliable. The software also includes the ability to automatically generate reports and calculate key suspension parameters from the raw data.

REFERENCES

[1] "Inertia Measurements of Large Military Vehicles", Andreatta, D.A., Heydinger, G.J., Bixel, R.A., and Coovert, D.A., SAE Paper 2001-01-0792, 2001.

[2] "Measurement of Inertial Properties and Suspension Parameters of Heavy Highway Vehicles," Winkler, C. B., SAE Paper 730182, 1973.

[3] "A Test Facility for the Measurement of Heavy Vehicle Suspension Parameters," Winkler, C.B. and Hagen, M.R., SAE Paper 800906, 1980.

[4] "Facility for the Measurement of Heavy Truck Chassis and Suspension Kinematics and Compliances," Warfford, J. and Frey, N., SAE Paper 2004-01-2609, 2004.

APPENDIX (SAMPLE GRAPHICAL RESULTS FROM TWO DIFFERENT VEHICLES)

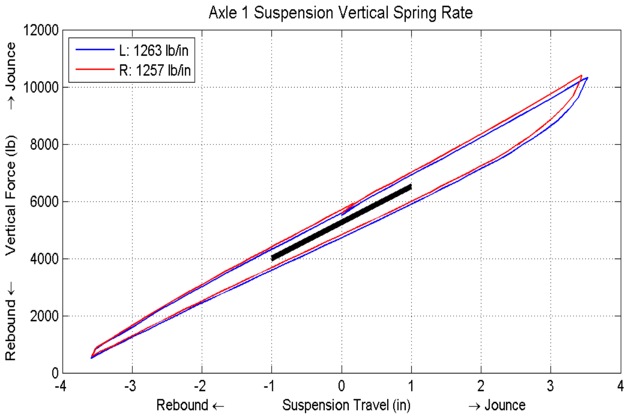

Figure 4: Suspension Vertical Stiffness Characteristic Curve

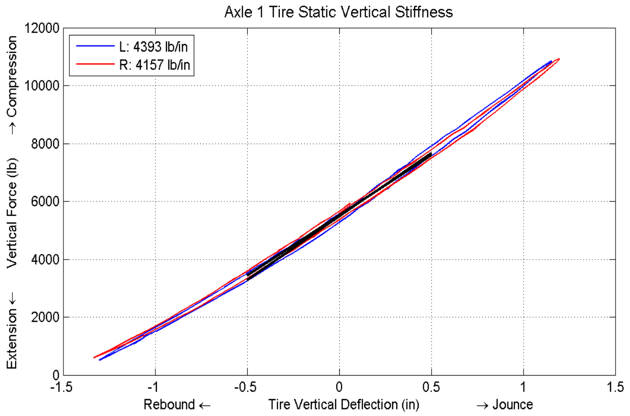

Figure 5: Tire Static Vertical Stiffness Characteristic Curve

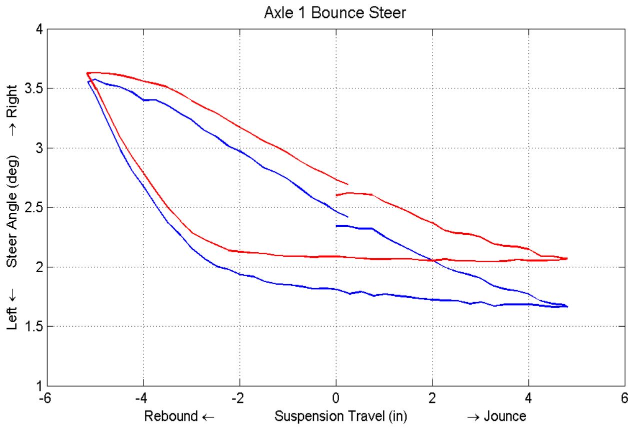

Figure 6: Bounce Steer Characteristic Curve

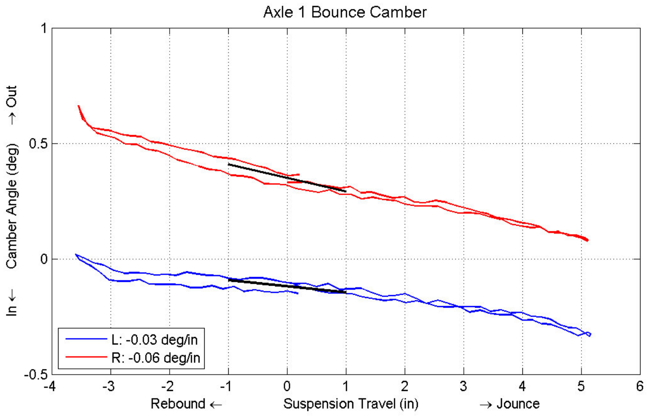

Figure 7: Bounce Camber Characteristic Curve

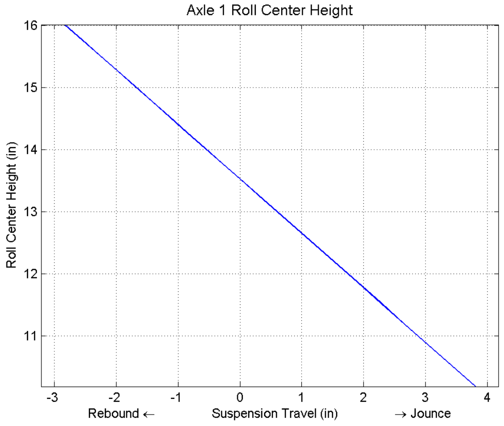

Figure 8: Roll Center Height as a Function of Suspension Deflection

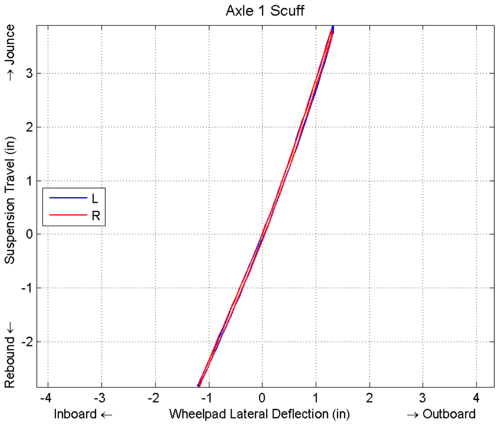

Figure 9: Wheel Center Lateral Deflection vs. Suspension Deflection

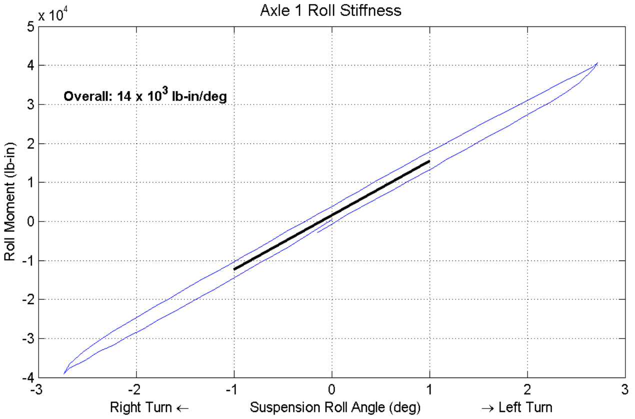

Figure 10: Suspension Roll Stiffness Characteristic Curve

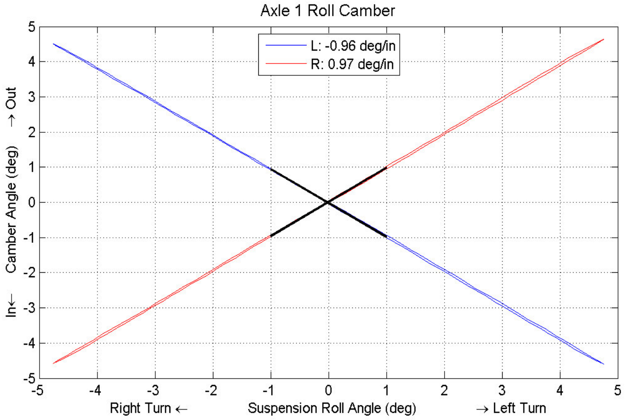

Figure 12: Roll Camber Characteristic Curve

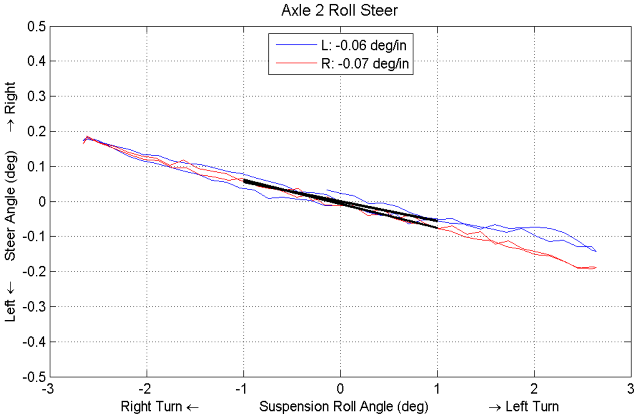

Figure 11: Roll Steer (or Toe) Characteristic Curve

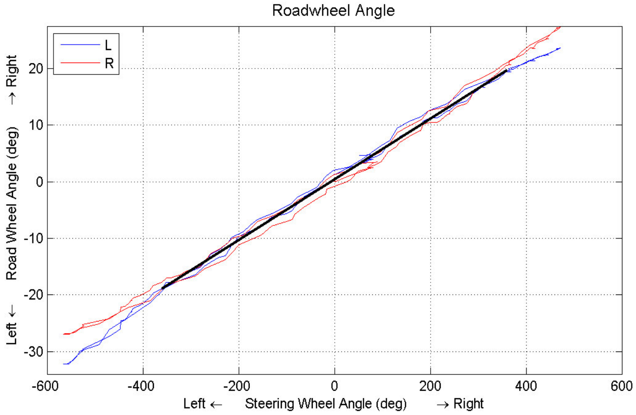

Figure 13: Steering Ratio Characteristic Curve