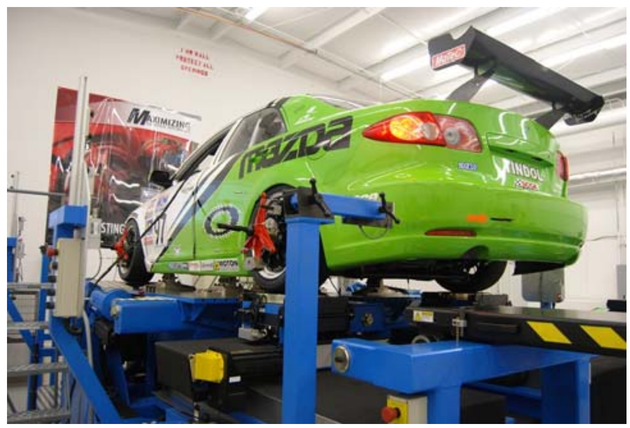
SUMMARY OF STANDARD K&C TESTS AND REPORTED RESULTS

The Morse Measurements K&C test facility is the first of its kind to be independently operated and made publicly available in North America. The facility utilizes an Anthony Best Dynamics SPMM machine. The vehicle is clamped securely to the SPMM center table which can move the chassis in vertical bounce pitch and roll. The tires stay in contact with a level road plane at four individual wheel pads. These wheel pads can be free-floating -or- they can introduce ground level forces to simulate braking, tractive, and lateral loads at the tire contact patches. Precision digital encoders and load cells measure tire loads and wheel orientations at all times.



Morse Measurements' standard K&C tests are described below. Bear in mind that this testing is flexible, and tests are customized to suite the needs of the customer. Special cases often arise and tests are designed to suite. For example, application of offset lateral loads to simulate pneumatic trail effects, or combined loading tests to better understand the full impact of compliance, etc. The following overview of standard tests provides an idea of the types of measurements that can be made on the K&C test machine. If specific vehicle measurements are required, give us a call, challenge us, and we'll do our best to create tests that will capture the measurements that *you* want to see.

K&C testing at Morse Measurements is goal-driven. Each test session is tailored to meet the specific needs of the customer. The following questions should be answered in advance of each test session:

"What are the objectives of this test session?"

"What primary K&C measurements are of interest?"

Primary K&C Measurements :

Rates & Friction
- Wheel, Ride Rates
- Tire Rates

Bounce & Roll Geometry
- Bump Toe, Camber, Caster
- Roll Steer, Camber, Caster
- Track, Wheelbase change
- Lateral, Long. W/C displacement
- Roll center height & offset
- Virtual swing arms
- Anti-dive / Anti-squat angles

Stiffnesses
- Lat & Long W/C, Toe, Camber
- Mz Stiffness

Weight Transfer
- F / R Roll Stiffness (total)
- F / R Roll Stiffness (suspension)
- Wheel vertical load distribution
- Jacking Ratios, Force Roll Centers

Steering Characteristics
- Steering Ratios
- Ackerman
- Scrub, Mechanical Trail
- Steering friction

Special Investigations
- Local deflections
- Motion ratios
- Combined loadings; Track Sims

Answers to these questions direct the planning of test sessions. For reference, the ***K&C Test Session Examples*** document describes some specific testing goals and scenarios, representative of what clients might typically request.

Once the objectives are known, tests are designed to make the needed measurements. There are some standard K&C tests (and variations thereof) that make up the basic building blocks of most test sessions. These tests are:

- Bounce
- Bounce-Pitch
- Roll (fixed axis and/or natural axis)
- Longitudinal Compliance, Braking
- Longitudinal Compliance, Traction
- Longitudinal Compliance, Single Side
- Lateral Compliance, Parallel
- Lateral Compliance, Opposed
- Lateral Compliance, with Trail
- Lateral Compliance, Single Side
- Aligning Torque, Parallel
- Aligning Torque, Opposed
- Aligning Torque, Single Side
- Steering (with and without load)

In addition, event simulation tests are available that provide additional insight. These are categorized as:

- Cornering Simulation
- Braking Simulation
- Traction Simulation
- Combined Loading Simulation
- Track Simulation

During each test, key suspension parameters are measured, recorded, and graphed real-time. Upon the completion of each test, real-time summary reports are generated that provide all of the key metrics from that test. These include relevant curve fits, a compiled bookmarked PDF, and a spreadsheet summarizing all of the curve fit coefficients in one place.

In addition to reports, data for all tests is provided in ASCII text and Matlab® formats. Text files which can be readily imported into Pi Toolbox® are also available. Further, a free *MS Excel™ K&C Grapher Tool* is provided. This program reads in data files and allows easy curve fitting and overlays of multiple data sets.

Measurement results are presented in a clear, concise and digestible way. Rather than being “overwhelmed with data,” customers leave Morse Measurements with *useful* results that will help improve the vehicle!

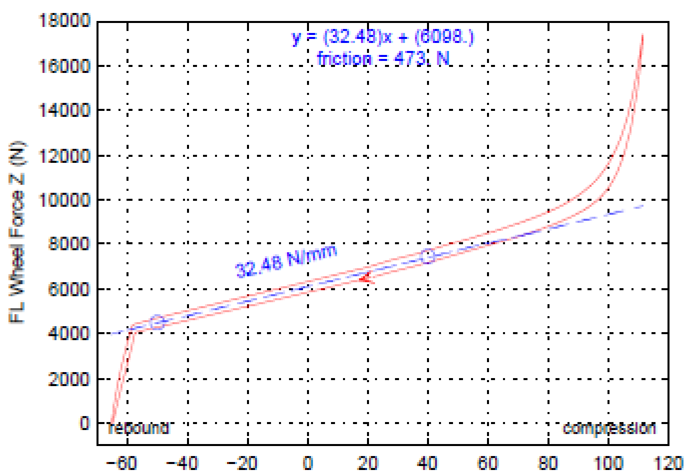
Standard measured suspension parameters are listed below, per test.

BOUNCE

The vehicle chassis is exercised in a pure bounce motion. This is accomplished by moving the K&C rig’s center table straight up and down within defined displacement bounds (For example, ± 2.0 inches from baseline ride height). The vehicle chassis is clamped directly to the center table, thus it is exercised straight up and down as well.

During this test lateral and longitudinal forces, and aligning moments are maintained at zero at each tire contact patch, thus canceling any unwanted tire “scrub” forces, and allowing the suspension to move freely without binding. The slow speed of this test (cycle times are typically ~ 1 minute) removes unwanted damper and inertial forces from the tire vertical load measurements. Corresponding loads, displacements, and orientations are measured at each of the four wheels.

Here are some characteristics that are measured in a ***Bounce Test****:*



Bump Steer
Bump Camber
Bump Caster
Wheel Recession
Tire Radial Rates
Wheelbase Change
Track Width Change
W/C Lateral & Longitudinal Displacement
Kinematic Anti-Dive & Anti-Squat Angles
Virtual Swing Arm (VSA) Length & Angle
Ride Rates (ground to chassis, includes tire)
Kinematic Roll Center (KRC) Height & Locus
Wheel Rates (wheel to chassis only, without tire)
Friction / Hysteresis
Lateral & Longitudinal Tire Center of Geometry (COG) Displacement
Lateral & Longitudinal Tire Center of Pressure (COP) Displacement

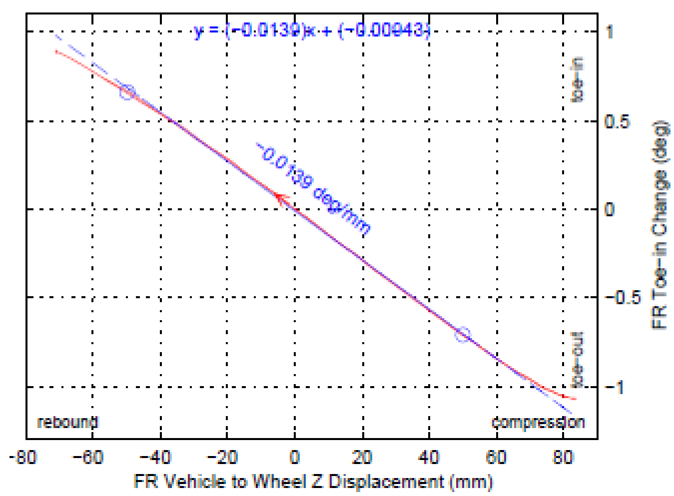
BOUNCE-PITCH

The vehicle is exercised in a bounce motion with some pitch angle introduced to achieve a differing amount of wheel travel front and rear. For example, if the chassis is pitched forward as it is bounced, the front will travel further than the rear.

During this test lateral and longitudinal forces, and aligning moments are maintained at zero at each tire contact patch, thus canceling any unwanted tire “scrub” forces, and allowing the suspension to move freely without binding. The slow speed of this test (cycle times are typically ~ 1 minute) removes unwanted damper and inertial forces from the tire vertical load measurements. Corresponding loads, displacements, and orientations are measured at each of the four wheels.

*Here are some characteristics that are measured in a **Bounce-Pitch Test**:*

Bump Steer
Bump Camber
Tire Radial Rates
Track Width Change
W/C Lateral Displacement
Ride Rates (ground to chassis, includes tire)
Wheel Rates (wheel to chassis only, without tire)
Friction / Hysteresis
Lateral Tire Center of Geometry (COG) Displacement
Lateral Tire Center of Pressure (COP) Displacement



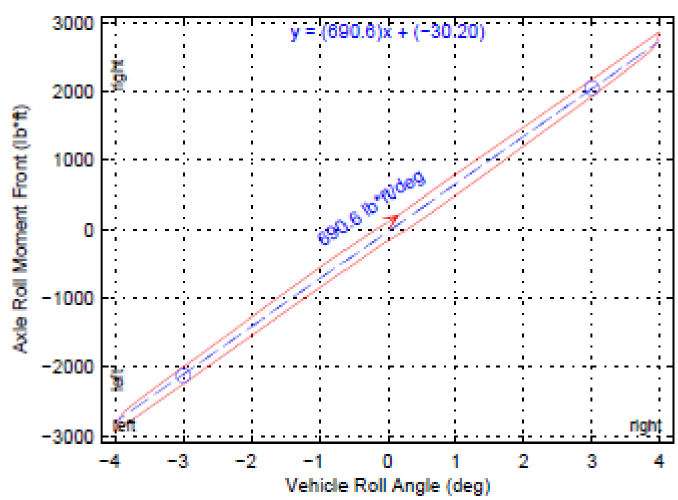
ROLL

The vehicle chassis is exercised in roll. This may be done about a fixed axis in the ground plane, or it may be done about a “natural” roll axis. In the natural axis test, compensation is provided to allow pitch and heave in order to maintain constant front and rear axle loads. This results in vehicle roll about its “natural” roll axis. Roll tests are accomplished by moving the K&C rig’s center table in roll within defined displacement bounds (For example, ± 1.5 degrees from baseline ride height, zero roll angle). The vehicle chassis is clamped directly to the center table, thus it is exercised in roll as well.

During a roll test lateral and longitudinal forces, and aligning moments are maintained at zero at each tire contact patch, thus canceling any unwanted tire “scrub” forces, and allowing the suspension to move freely without binding. The slow speed of this test (cycle times are typically ~ 1 minute) removes unwanted damper and inertial forces from the tire vertical load measurements. Corresponding loads, displacements, and orientations are measured at each of the four wheels.

*Here are some characteristics that are measured in a **Roll Test**:*

- Axle Steer
- Total Roll Steer
- Tire Vertical Force
- Total Roll Camber
- Total Roll Stiffness
- Track Width Change
- Suspension Roll Steer
- Suspension Roll Camber
- Suspension Roll Stiffness
- Static Roll Weight Transfer Coefficient
- Wheel Rates in Roll
- Friction / Hysteresis
- Tire Contact Patch (TCP) Lateral Displacement



LONGITUDINAL COMPLIANCE, BRAKING

The vehicle chassis is held fixed by the K&C rig center table while longitudinal forces are applied through each of the four tire contact patches. Vehicle brakes are applied. Forces are applied in the direction consistent with braking. Corresponding loads, displacements, and orientations are measured at each of the four wheels.

LONGITUDINAL COMPLIANCE, TRACTION

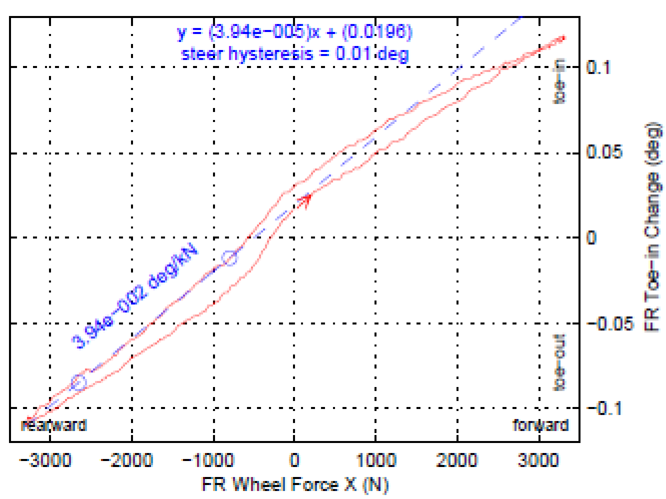
The vehicle chassis is held fixed by the K&C rig center table while longitudinal forces are applied at each tire contact. Vehicle brakes are not applied. A transmission or drivetrain lock is used on the driven axle(s) to transmit ground plane forces to the wheel centers while ground plane forces are applied through the tire contact patches. Force is applied in the direction consistent with vehicle forward acceleration. Corresponding loads, displacements, and orientations are measured at each of the four wheels.

LONGITUDINAL COMPLIANCE, SINGLE WHEEL

The vehicle chassis is again held fixed and longitudinal force is applied to wheels on one side of the vehicle only. This shows how force applied to one side affects the other side. It also simulates a worst case split mu surface condition.

Here are some characteristics that are measured in a ***Longitudinal Test****:*

W/C Stiffness
Toe Stiffness
Jacking Forces
Caster Stiffness
Camber Stiffness
Hysteresis
Force Anti-Dive Angle (Braking Test)
Force Anti-Squat Angle (Traction Test)



LATERAL COMPLIANCE, PARALLEL

The vehicle chassis is held fixed by the K&C rig center table while lateral forces are applied through each of the four tire contact patches, in line with the center of tire contact pressure. 'Parallel' indicates that force is applied through each wheel in the same direction (i.e. all forces to the left, and/or all forces to the right). Corresponding loads, displacements, and orientations are measured at each of the four wheels.

LATERAL COMPLIANCE, OPPOSED

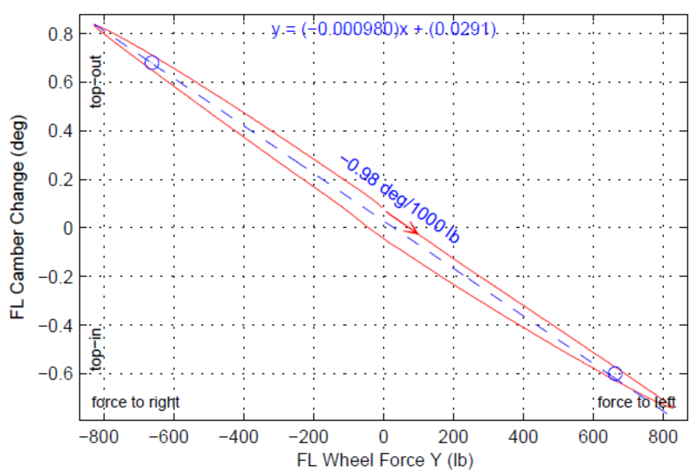
The vehicle chassis is held fixed by the K&C rig center table while lateral forces are applied through each of the four tire contact patches, in line with the center of tire contact pressure. 'Opposed' indicates that force is applied through each wheel in opposing directions at each axle. While a lateral parallel test will capture the effects of left/right suspension connectivity components (such as the steering system, subframes, anti-roll bars, etc.), the opposed test, by nature of applying equal and opposite forces to left and right side suspensions – and thus "shorting out" any right/left connective components, will capture the effects of an individual suspension corner. Corresponding loads, displacements, and orientations are measured at each of the four wheels.

LATERAL COMPLIANCE, SINGLE WHEEL

The vehicle chassis is again held fixed and lateral force is applied to wheels on one side of the vehicle. This allows you to measure the reaction of wheels on the opposite side of the car to forces.

Here are some characteristics that are measured in a
Lateral Compliance Test:

Axle steer
Tire Stiffness
W/C Stiffness
Toe Stiffness
Jacking Forces
Camber Stiffness
Force-Based Roll Center (FBRC)
Height & Locus (Parallel Test *only*)



ALIGNING TORQUE, PARALLEL

The vehicle chassis is held fixed by the K&C rig center table while ground plane torques are applied through each of the four tire contact patches. 'Parallel' indicates that torque is applied through each wheel in the same direction (i.e. all torques clockwise, and/or all torques counter-clockwise). Corresponding loads, displacements, and orientations are measured at each of the four wheels.

ALIGNING TORQUE, OPPOSED

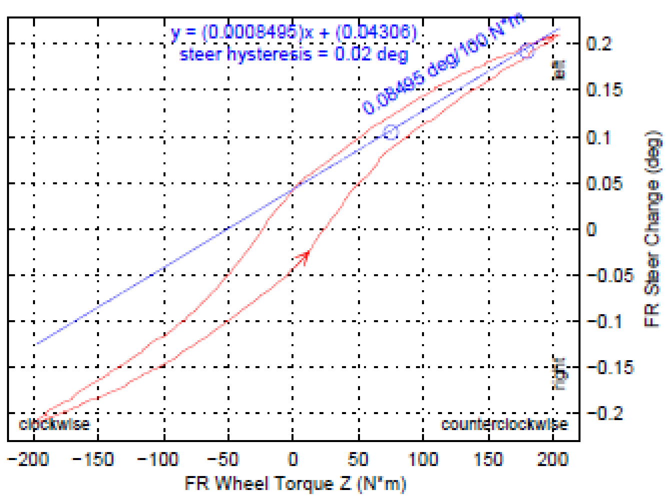
The vehicle chassis is held fixed while ground plane torques are applied through each of the four tire contact patches. 'Opposed' indicates that torque is applied through each wheel in opposing directions at each axle. While an aligning torque parallel test will capture the effects of left/right suspension connectivity components (such as the steering system, subframes, anti-roll bars, etc.), the opposed test, by nature of applying equal and opposite torques to left and right side suspensions – and thus "shorting out" any right/left connective components, will capture the effects of an individual suspension corner. Corresponding loads, displacements, and orientations are measured at each of the four wheels.

ALIGNING TORQUE, SINGLE WHEEL

The vehicle chassis is again held fixed while aligning torque is applied to wheels on one side of the vehicle only.

Here are some characteristics that are measured in an ***Aligning Torque Test****:*

Toe Stiffness
Tire Aligning Stiffness
Hysteresis
Steering Torque Feedback

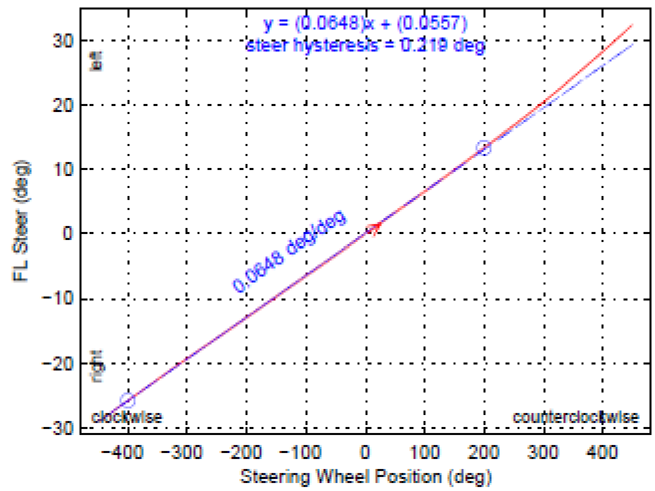


STEERING

The vehicle chassis is held fixed by the K&C rig center table. The handwheel is steered smoothly through its full range of motion with a computer-controlled steering robot. Loads, displacements, and orientations are measured at the handwheel and at each of the steered wheels. This test may be run with no load on the road wheels, or with resistive aligning torque and/or lateral and longitudinal loads.

Here are some characteristics that are measured in a ***Steering Test****:*

Kingpin Offset
Caster Angle
Mechanical Trail
Camber Change
Roadwheel Steer
Handwheel Torque
Ackermann Percent
Kingpin Inclination Angle
Instantaneous Steering Ratio
Tire Contact Patch (TCP) Locus
Scrub Radius vs. Handwheel Steer
Friction / Hysteresis



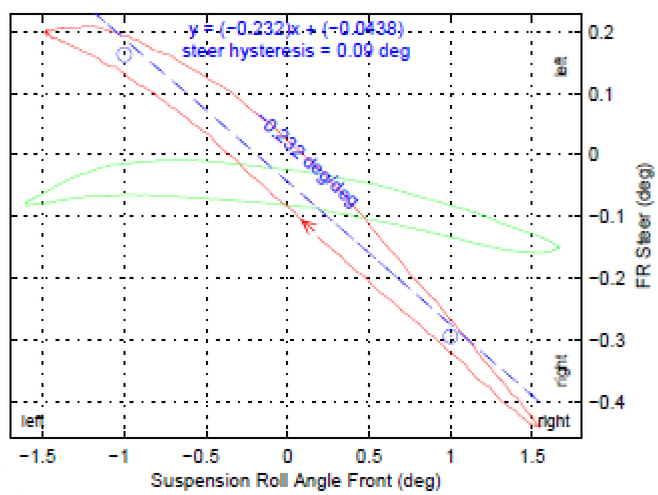
CORNERING SIMULATION

The test simulates a pure cornering event. Inputs are the c.g. height, the desired cornering g load, and optionally aerodynamic download and tire pneumatic trail. Based on the c.g. height, the g load, and the vehicle weight, a roll moment is applied to the chassis while corresponding ground plane lateral force is applied at each tire contact. Lateral force distribution amongst the four tires may be specified or can be proportional to the vertical load. The chassis is controlled in force control such that it finds a natural steady-state cornering attitude. Chassis loads and displacements, as well as corresponding loads, displacements, and orientations at each of the four wheels are measured.

Further, after running the cornering simulation, the chassis motion is replayed through the rig without the ground plane forces present. This allows you to separate kinematics effects from compliance effects.

Here are some characteristics that are measured in a ***Cornering Simulation Test****:*

Axle Steer
Steer Rate
Camber Rate
Jacking Forces
Roll Rate (per G)
Roll Stiffness Total
Lateral Weight Transfer
Tire COP Migration
Tire Deflection Lateral
Roll Rate (per Torque)
Tire Lateral & Vertical Forces
Dynamic Cross Weight
Friction / Hysteresis



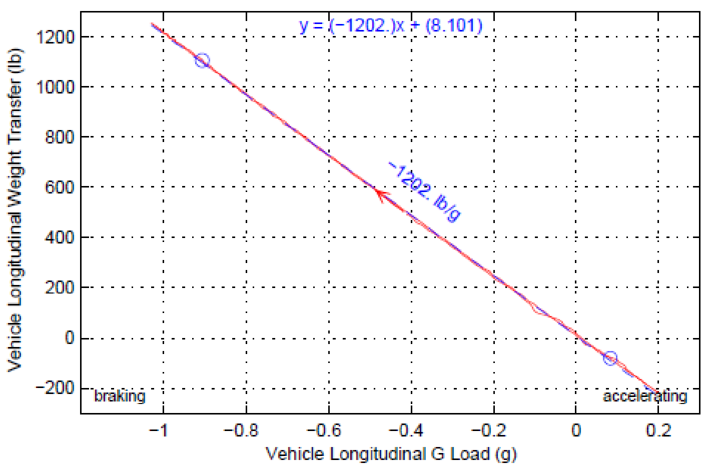
BRAKING SIMULATION

The test simulates a pure braking event. Inputs are the c.g. height, the desired braking g load, and optionally aerodynamic download. Based on the c.g. height, the g load, and the vehicle weight, a pitch moment is applied to the chassis while corresponding ground plane longitudinal force is applied at each tire contact. Longitudinal force distribution amongst the four tires may be specified or can be proportional to the vertical load. The chassis is controlled in force control such that it finds a natural steady-state braking attitude. Chassis loads and displacements, as well as corresponding loads, displacements, and orientations at each of the four wheels are measured.

After running the braking simulation, the chassis motion is replayed through the rig without the ground plane forces present. This allows you to separate kinematics effects from compliance effects.

Here are some characteristics that are measured in a ***Braking Simulation Test****:*

Axle Steer
Steer Rate
Jacking Forces
Pitch Rate (per G)
Pitch Stiffness Total
Longitudinal Weight Transfer
Tire COP Migration
Tire Deflection Lateral
Pitch Rate (per Torque)
Tire Longitudinal & Vertical Forces
Dynamic Cross Weight
Friction / Hysteresis



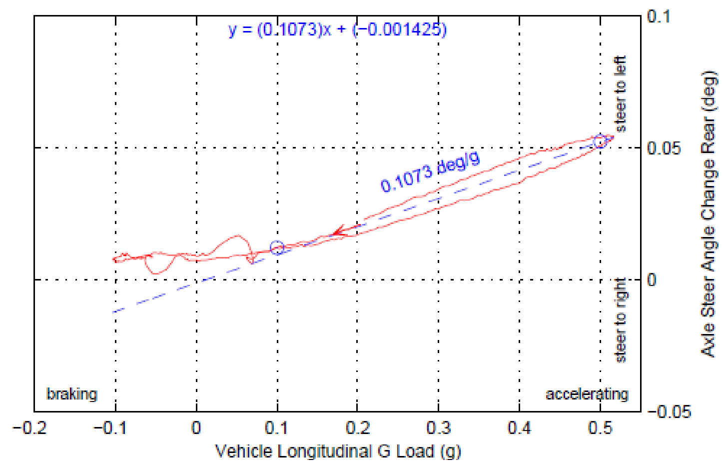
TRACTION SIMULATION

The test simulates a pure acceleration event. Inputs are the c.g. height, the desired acceleration g load, and optionally aerodynamic download. Based on the c.g. height, the g load, and the vehicle weight, a pitch moment is applied to the chassis while corresponding ground plane longitudinal force is applied at each driven tire contact. Longitudinal force distribution amongst the driven tires may be specified or can be proportional to the vertical load. The chassis is controlled in force control such that it finds a natural steady-state acceleration attitude. Chassis loads and displacements, as well as corresponding loads, displacements, and orientations at each of the four wheels are measured.

After running the traction simulation, the chassis motion is replayed through the rig without the ground plane forces present. This allows you to separate kinematics effects from compliance effects.

Here are some characteristics that are measured in a ***Traction Simulation Test****:*

Axle Steer
Steer Rate
Jacking Forces
Pitch Rate (per G)
Pitch Stiffness Total
Longitudinal Weight Transfer
Tire COP Migration
Tire Deflection Lateral
Pitch Rate (per Torque)
Tire Longitudinal & Vertical Forces
Dynamic Cross Weight
Friction / Hysteresis



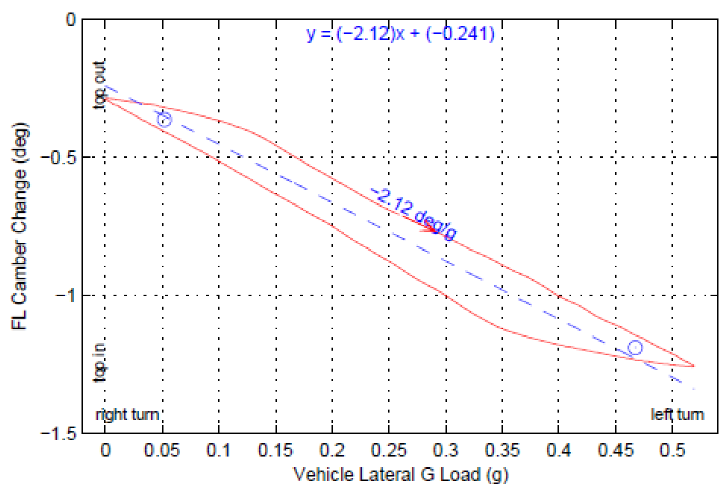
COMBINED LOADING SIMULATION

This test is a combination of a cornering simulation and a braking or traction simulation. Simultaneously, a lateral and longitudinal g loading is specified, corresponding roll and pitch moments are applied to the chassis, and corresponding ground plane forces (lateral and longitudinal) are applied at the four tire contacts.

The vehicle chassis is exercised to match known on-road/track conditions of interest. Typically this is done for several conditions through a known corner (for example, corner entry, mid, and exit). Using acquired vehicle data (such as damper pots, steering sensors, etc.) it is possible to load a vehicle with roll and pitch moments and corresponding lateral and longitudinal tire loads. Some vehicle information is required in order to properly set up this test, namely: Overall CG height, desired braking and cornering acceleration levels, steering position (handwheel, rack travel, etc.), aerodynamic downforce loads, front/rear brake %, and banking angle (if applicable).

After running the combined loading simulation, the chassis motion is replayed through the rig without the ground plane forces present. This allows you to separate kinematics effects from compliance effects.

*Here are some characteristics that are measured in a **Combined Loading Simulation Test**:*



Axle Steer
Steer Rate
Camber Rate
Jacking Forces
Roll Rate (per G)
Pitch Rate (per G)
Roll Stiffness Total
Tire COP Migration
Tire Deflection Lateral
Roll Rate (per Torque)
Pitch Rate (per Torque)
Tire Lateral, Longitudinal, & Vertical Forces
Dynamic Cross Weight
Friction / Hysteresis

TRACK SIMULATION

Unlike the above described simulation tests which are cyclical in nature, the Track Simulation test provides an arbitrary non-cyclical input to the vehicle. Data gathered on-track or from simulation software is used to define chassis motion and corresponding ground plane forces. Driver handwheel inputs can also be included, if the data is available, using the steering robot.

Typically, a short segment of on-track data will be used (2-10 seconds). The event might be corner entry, mid-corner, corner exit, or any relevant event. The event will be played back on the rig over a longer period of time, typically about 60-90 seconds. The event will be simulated on the rig, both with and without the corresponding ground plane forces. This allows separation of kinematics from compliance effects. Further, an on-track time vector is included in the data set, so plots may be made against actual time, as opposed to rig time.

After running the track simulation, the chassis motion is replayed through the rig without the ground plane forces present. This allows you to separate kinematics effects from compliance effects.

Here are some characteristics that are measured in a ***Track Simulation Test****:*

Chassis Position vs. Time
Wheel Steer vs. Time
K&C Contributions to Steer
Wheel Camber vs. Time
K&C Contributions to Camber
Wheel Forces vs. Time
Dynamic Cross Weight vs. Time
Vehicle g Loading vs. Time
Axle Steer vs. Time