# Vehicle Roll Centers and Roll Axis Examined Again!

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**Chrysler Core Vehicle Dynamics**

- **Background**
  - Suspension Roll Centers and the Roll Axis are established very early in the mechanical design process of a vehicle's suspension architecture. A significant amount of discussion occurs regarding these parameters. This project attempts to clarify the impacts of Roll Centers and Roll Axis on vehicle performance.

- **Project Process**
  - Historical and Analytical Review
  - Experimental Vehicle Build, Subjective Evaluation and Instrumented Test
  - Data Analysis and Summary of vehicle "performance patterns"

- **Conclusions**
  - Vehicle performance patterns do emerge regarding roll centers and roll axis orientations that will be shared in this presentation



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# Contents







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# A Publication Review of Roll Center and Roll Axis Definitions

# Olley - Chassis Design (Milliken) Definitions

- ROLL AXIS
  - “The best definition seems to be that the roll axis defines, in the median plane of the car, a transverse plane in which horizontal forces applied to the rolling mass of the car will move the car sideways without causing it to roll.”
- ROLL CENTERS
  - “These are obviously the points where the roll axis intersects the transverse plane of the front or rear wheel pair.” (pages 451-452)





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# Milliken Race Car Vehicle Dynamics Definitions

- ROLL CENTER
  - "It is not necessarily at the centerline of the car …The Roll Center establishes the force coupling point between the un-sprung and sprung masses. …" (page 613-614)
  - "That point in the transverse vertical plane through any pair of wheel centers and equidistant from them, at which lateral forces may be applied to the sprung mass without producing an angular displacement of the sprung mass."
- ROLL AXIS
  - "Neutral Roll Axis - the line joining the front and rear roll centers", (page 680)

References SAE670e "Vehicle Dynamics Terminology"

# Observations

- The SAE 670e definition and these publications are making some assumptions
  - Roll centers and the roll axis are on or near the vehicle centerline
  - Vertical location changes are recognized due to ride and load conditions
  - Lateral location and migration generally ignored (except a comment in Race Car Vehicle Dynamics)

- These assumptions are not necessarily true
  - Asymmetrical vertical motions of roll and ride occur during vehicle operation
  - Suspension geometries and designs produce roll center and roll axis migrations vertically and laterally





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# Vehicle Performance as Discussed in Publications

- Vehicle steady state examined extensively
  - Vertical and lateral load transfer
  - Roll angle character

- Vehicle transient states were examined by Olley and his contemporaries
  - Roll and Yaw Transient characteristics examined by Schilling, Segal; Section 4.3 - Chassis Design Principles and Analysis
  - Roll Axis inclination and roll/yaw damping was quantified by Olley; Section 3.2 - Chassis Design Principles and Analysis

- Investigations of the vehicle’s transient states are limited





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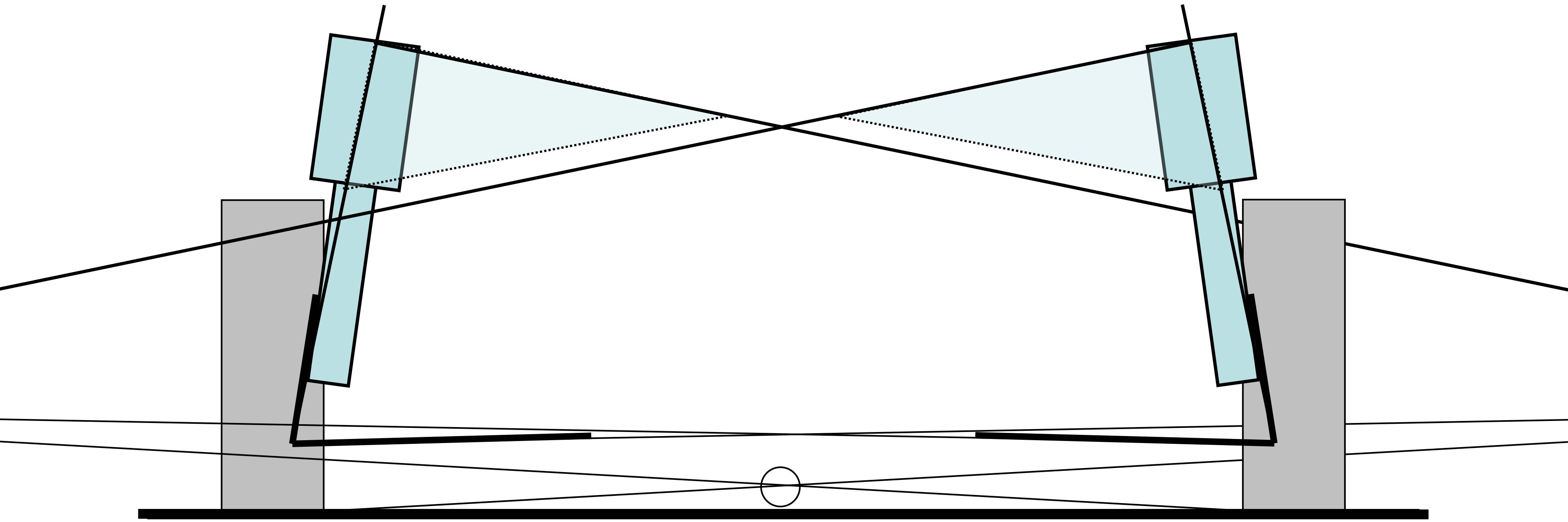
# Where are the Roll Centers and Roll Axis?

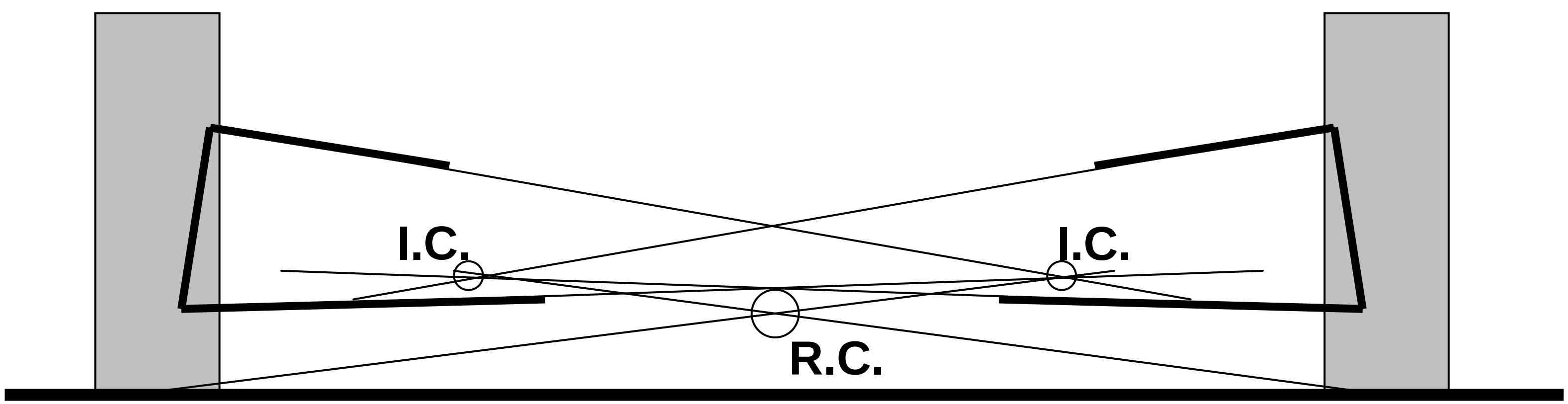
- Classical Graphic Analysis Methods
- Vehicle Kinematic Measurements – Data Clouds
- Kinematic Analysis of a MacPherson Strut Suspension
- Multi-Body Analysis of a MacPherson Strut Vehicle

# Classical Method
# MacPherson Strut Suspension

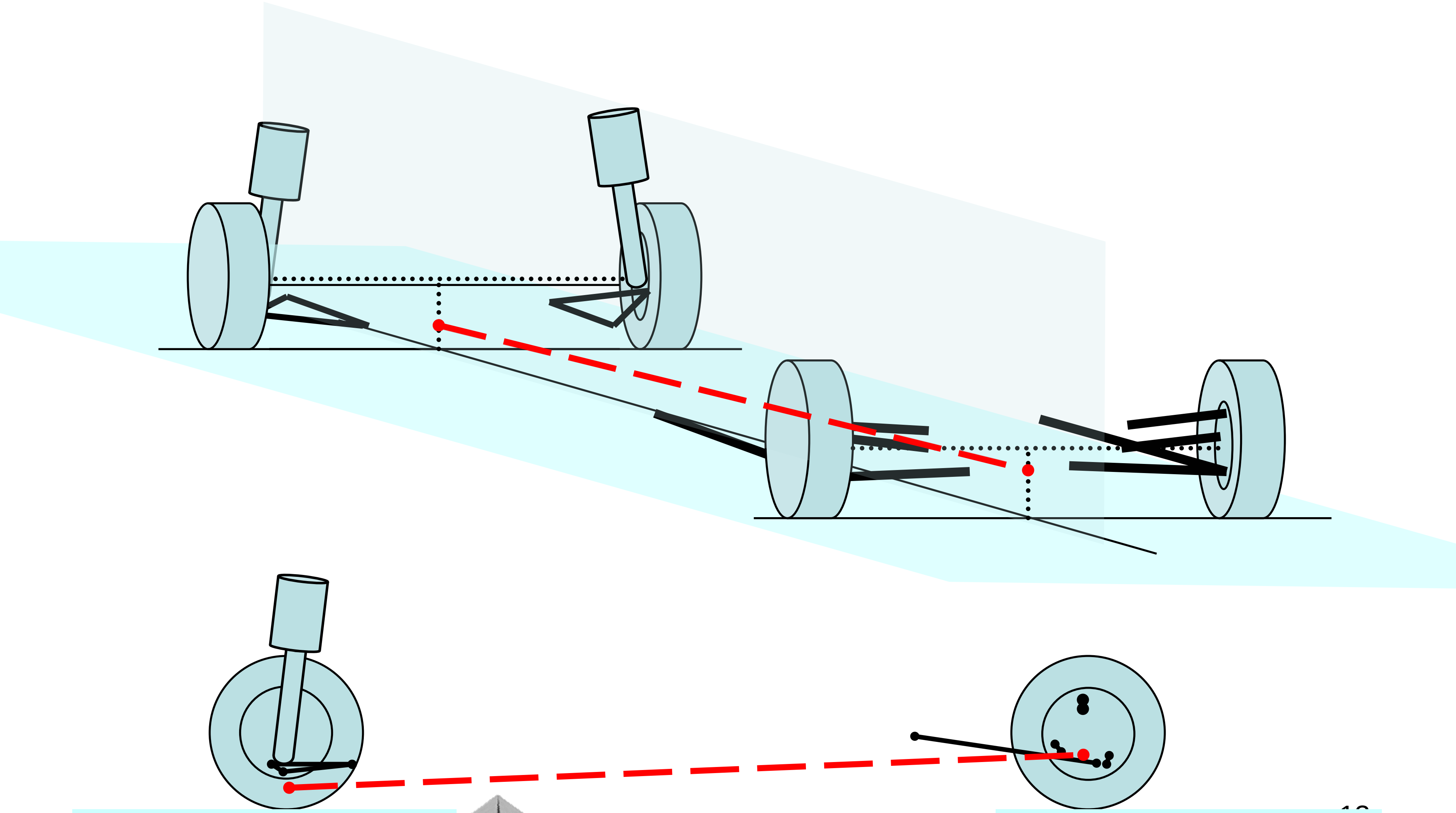


R.C.

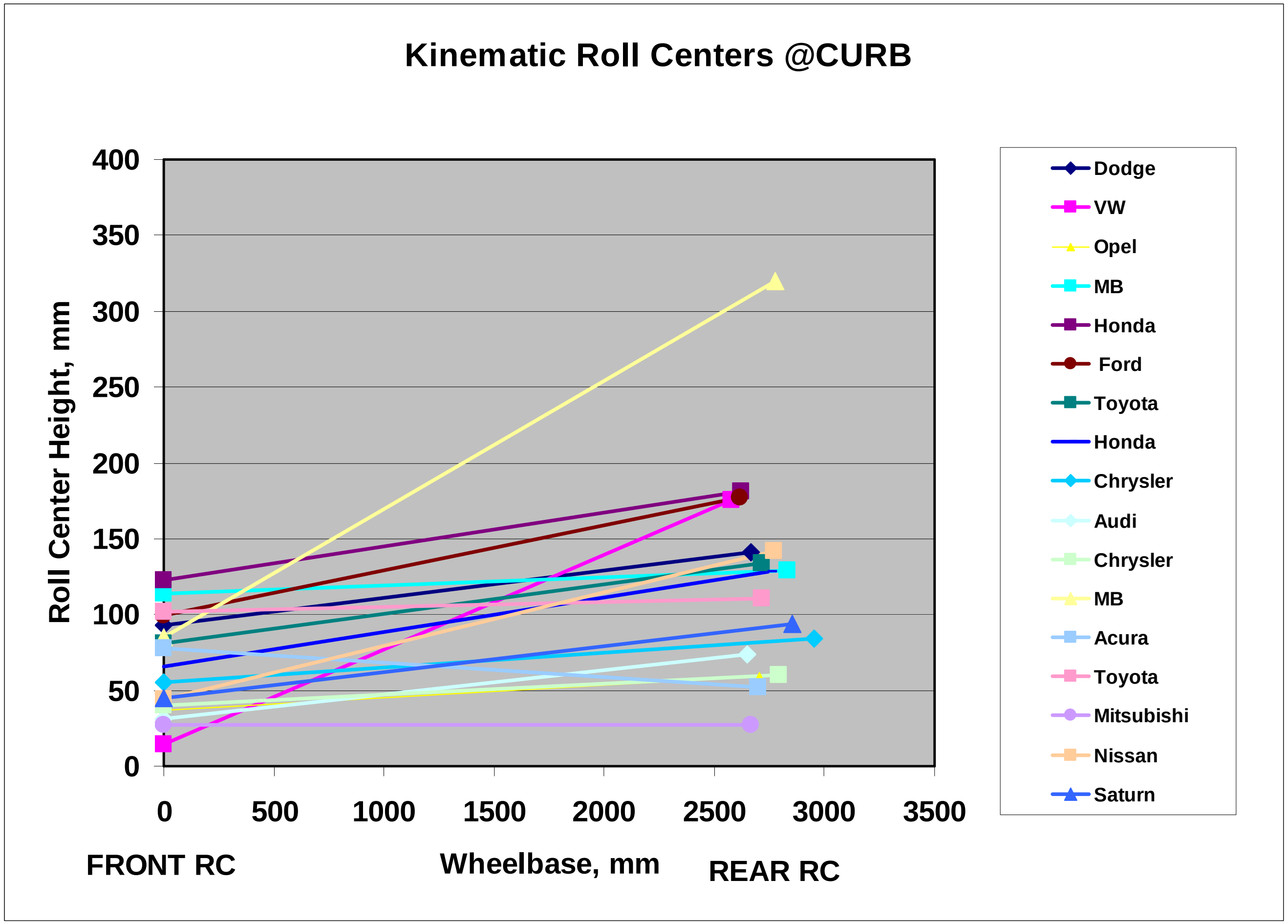
# Classical Method
# Short-Long Arm (SLA) Suspension



# Classical Method
# Roll Axis



# Vehicle Kinematic Measurements
# Roll Center Data Cloud



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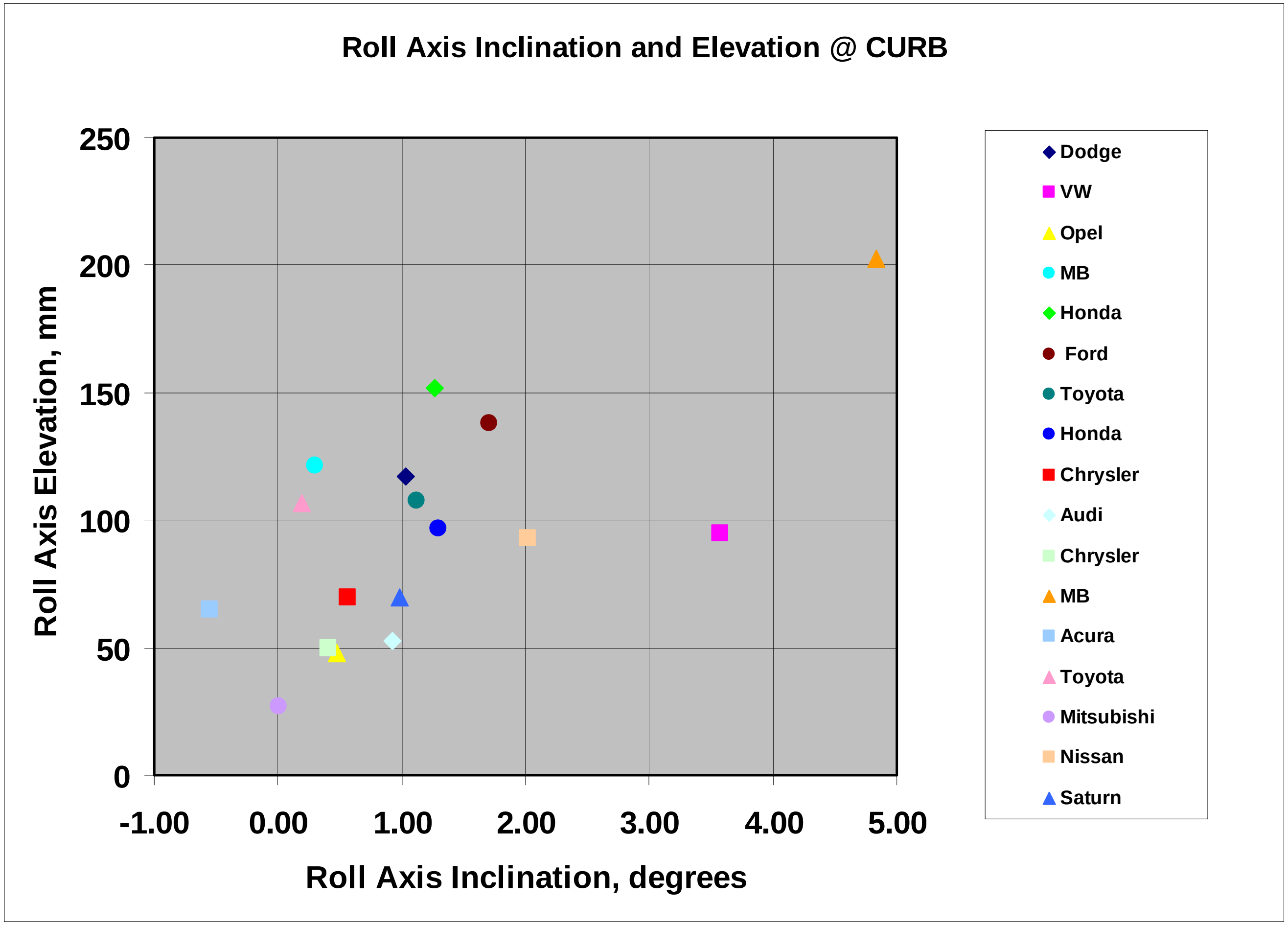
# Vehicle Kinematic Measurements
# Roll Axis Data Cloud




**Roll Axis Inclination:**
**Side View Angle to Horizontal**
**Positive: higher in rear**

**Roll Axis Elevation:**
**Elevation above ground**
**@ wheelbase center**



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# Commentary

- No clear patterns emerge from the data cloud
  - Design specific intent?
  - Design confusion?

- Roll Center Heights - Roll Axis Inclination View
  - 3 variables required
    - Front RC Height, Rear RC Height, Roll Axis Inclination

- Roll Axis Elevation and Inclination View
  - 2 variables required
    - Roll Axis Inclination
    - Roll Axis Elevation (@ wheelbase center)

- Suspension Kinematic Analysis
  - MacPherson Strut Suspension
    - Body grounded
    - Suspension stroked through jounce and rebound attitudes to adjust roll centers vertically
    - Vehicle rolled +5 to -5 degrees at each height
    - roll centers located and plotted



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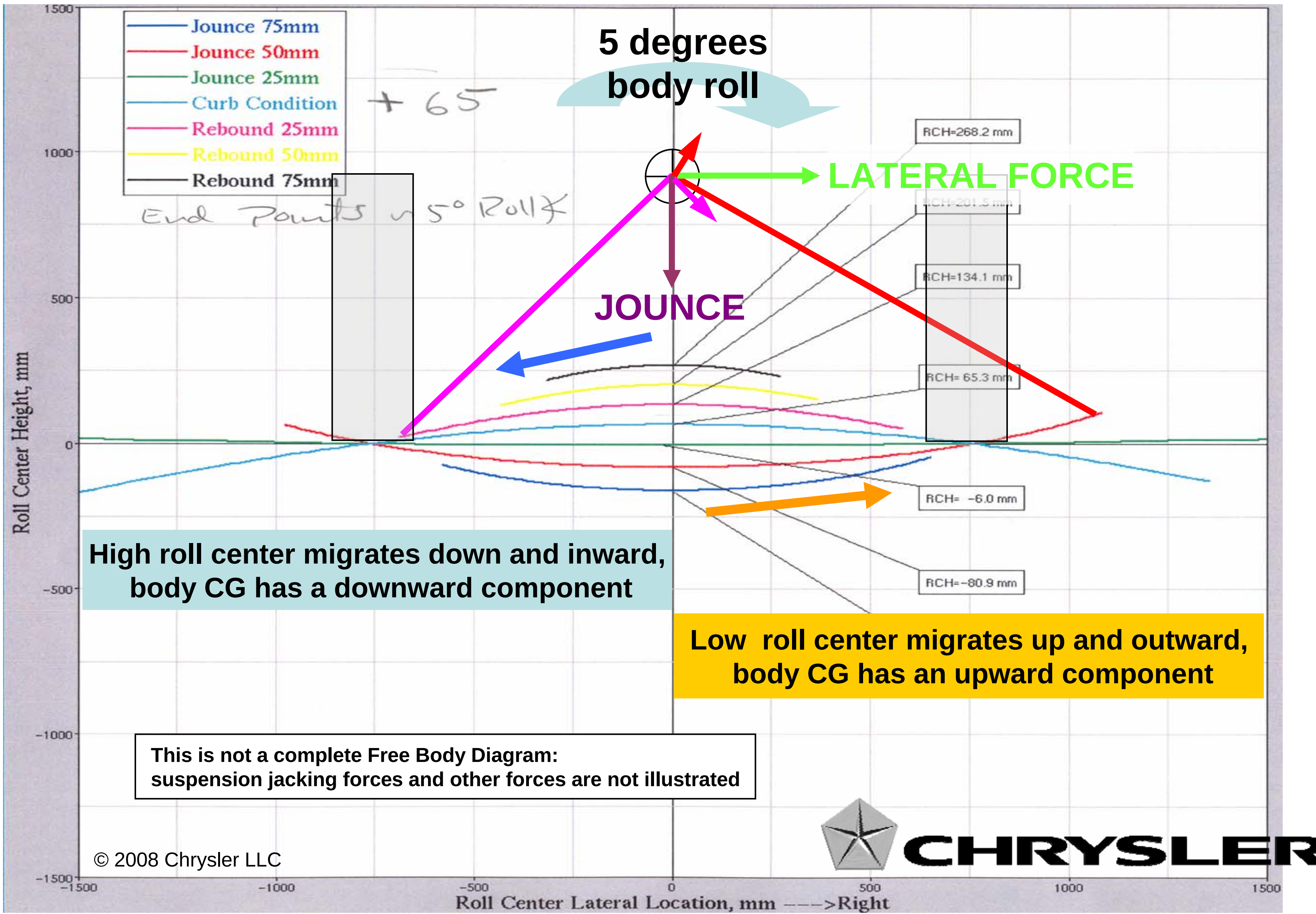
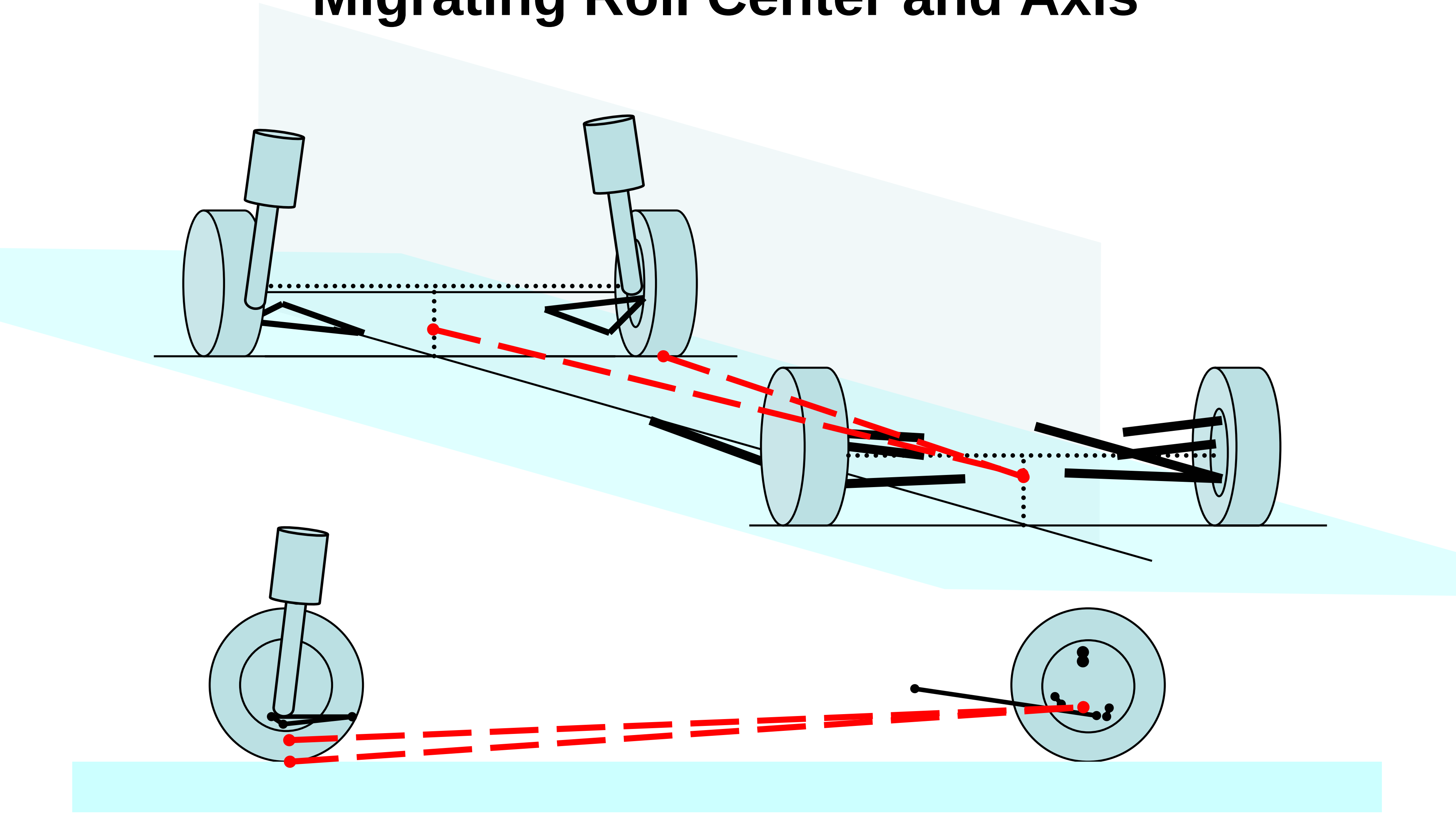
# Kinematic Analysis
## MacPherson Strut Roll Center Migration



# Migrating Roll Center and Axis



**Front Roll Center migrating with roll, Rear Roll Center constant**



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- Multi-Body Roll Center Analysis
  - Model Configuration
    - C-Segment FWD Vehicle
      - 2635 mm wheelbase, 1520 mm front and rear track
      - Weight @ curb 1417 kg, 59% front, 41% rear
      - MacPherson Strut front suspension
      - Multi-link rear suspension
  - Model Variants
    - Three front roll center heights: 130, 59, 14 mm
      - Lower control arm inner pivots raised and lowered, rack relocated to keep toe curves constant
    - Rear suspension kept constant
    - No spring or bar changes to compensate for roll couple changes
  - Model Analysis
    - Full vehicle simulation
    - Vehicle model "frozen" at 0.49 G steady state lateral cornering
      - Roll centers located graphically



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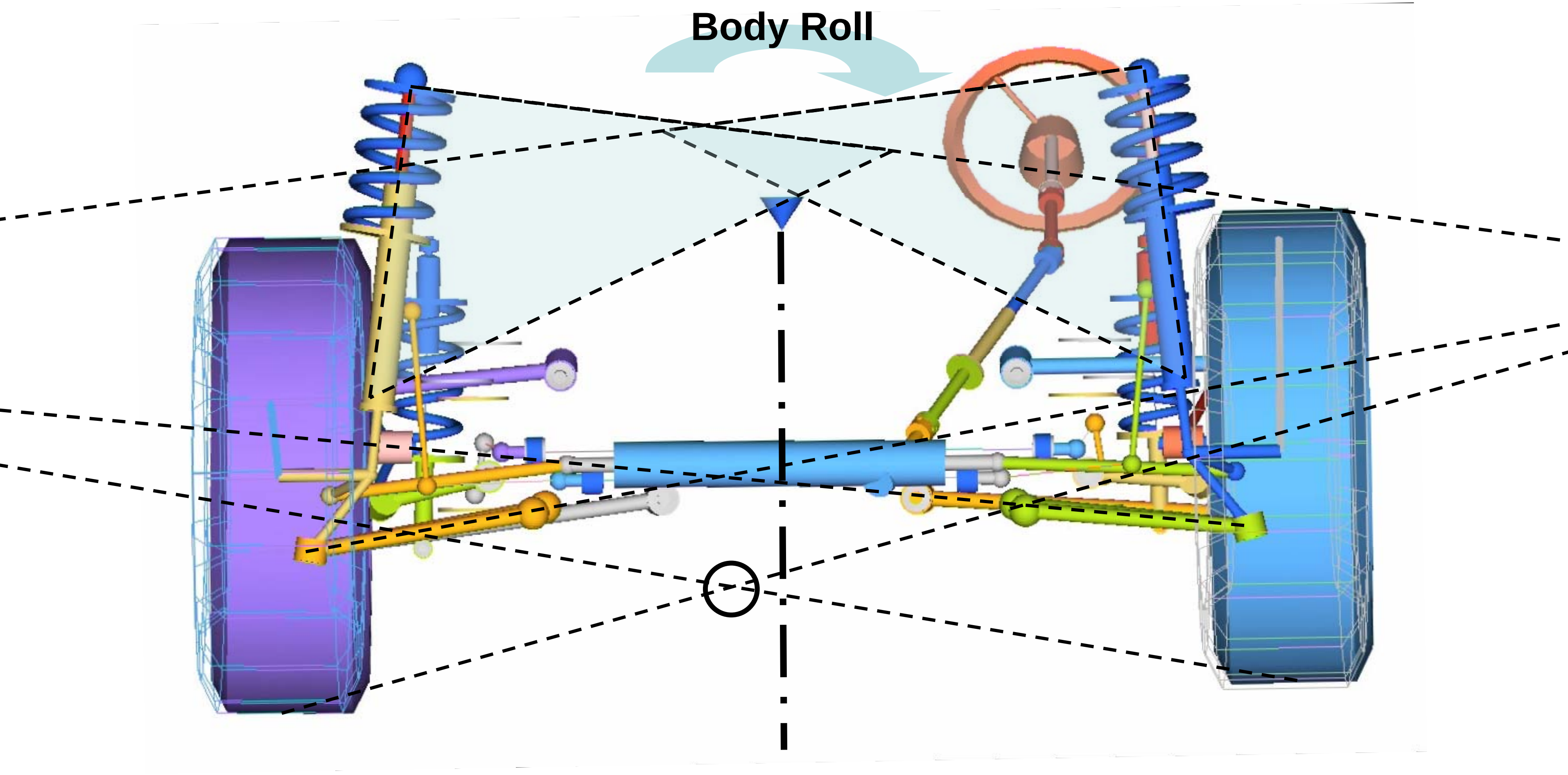
# Vehicle Multi-Body Analysis

## Front RC @ 130 mm



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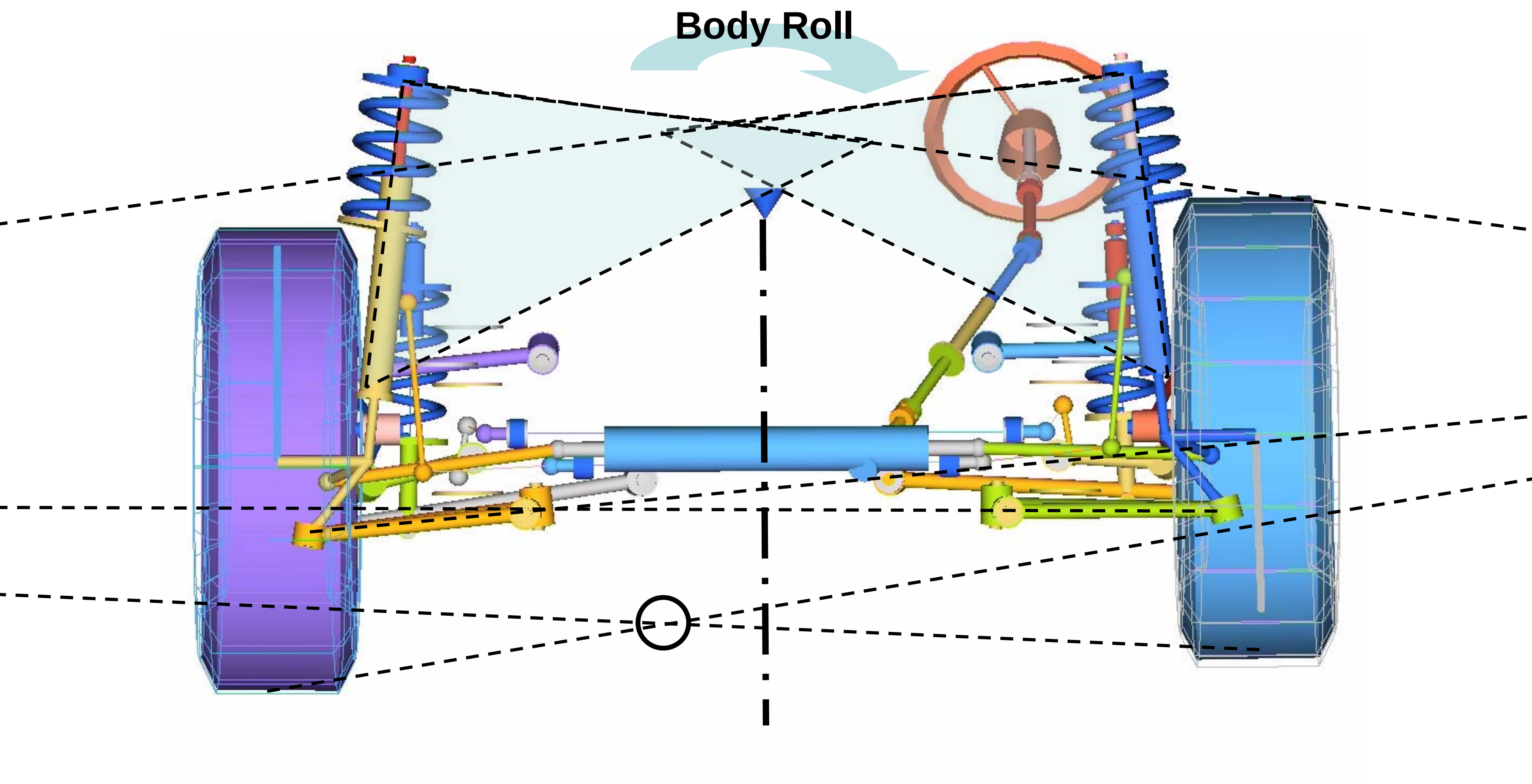
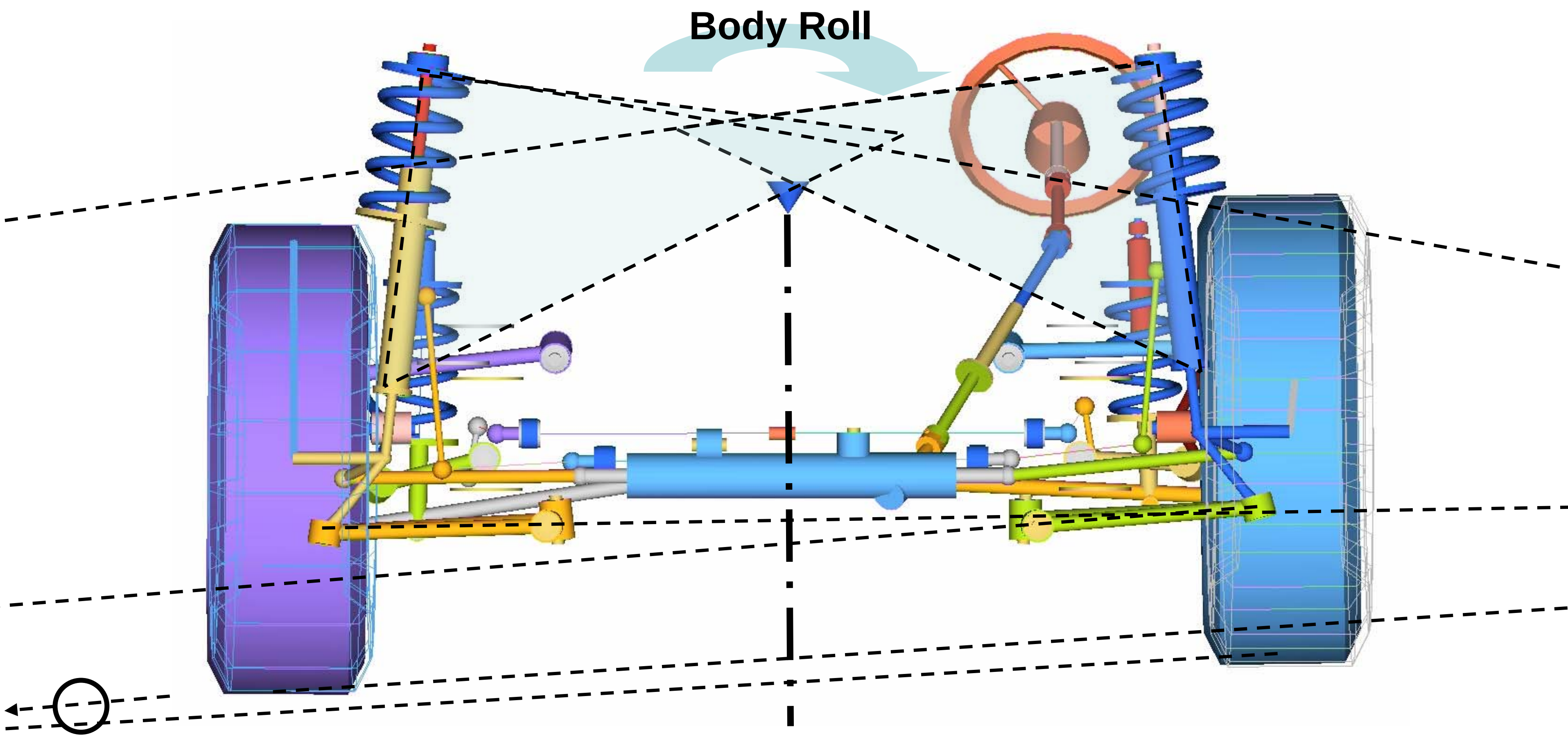
# Vehicle Multi-Body Analysis

## Front RC @ 59 mm



# Vehicle Multi-Body Analysis

## Front RC @ 14 mm



- Further Complications
  - Unsymmetrical Ride and Roll Motions
    - Intentionally biased shock damping in rebound/jounce will temporarily force suspension to asymmetrical rebound/jounce positions and result in roll center/axis migrations
    - Suspension contact with jounce & rebound stops will introduce additional forces and resulting asymmetrical geometry and kinematics of roll centers and roll axis

# So, What's it all Mean?

# "build a car and let the car tell us"





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# Physical Experiment

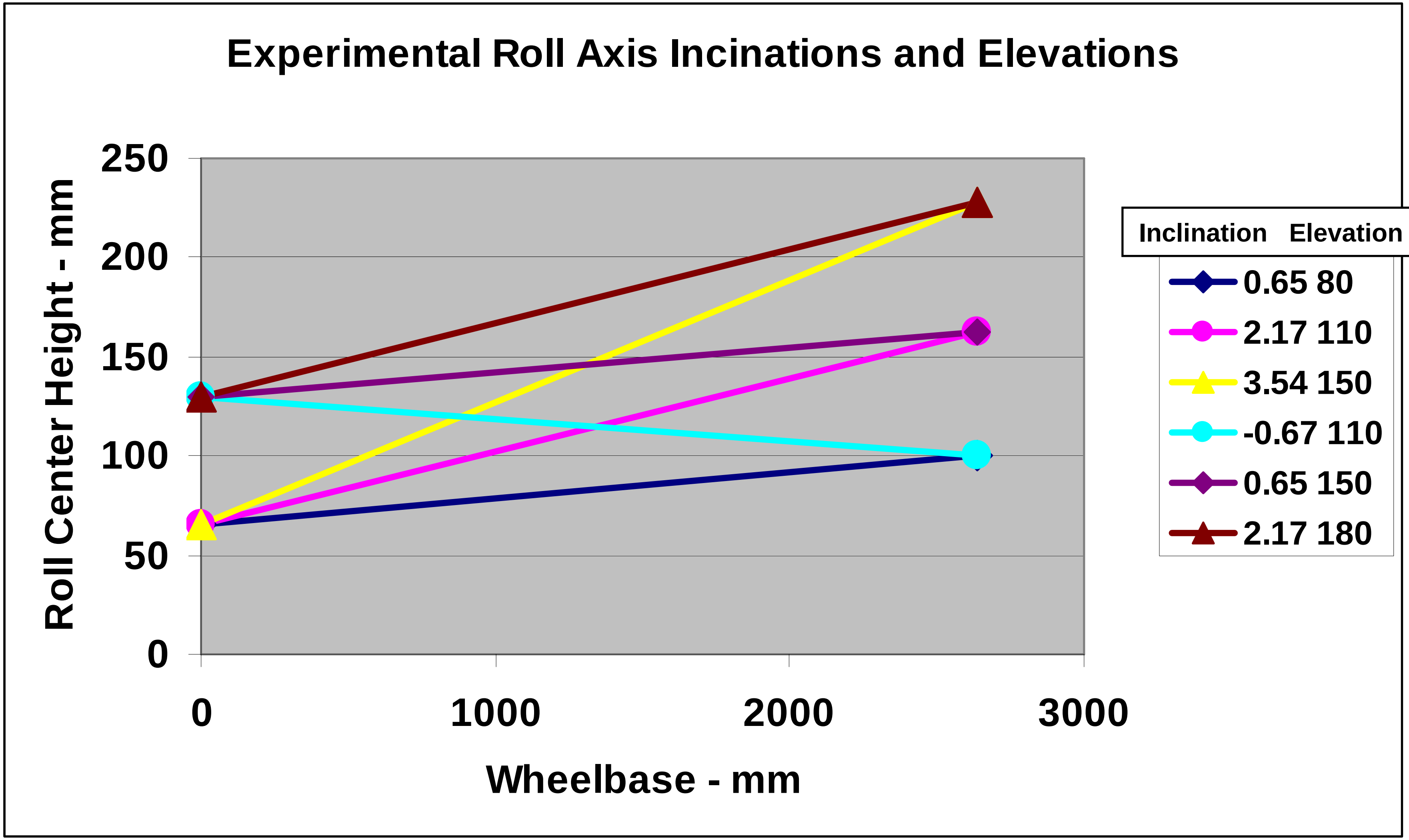
- Vehicle Configuration
- Vehicle Variables Tested
- Evaluation Maneuvers
- Characteristics Evaluated
- Results
- Observations

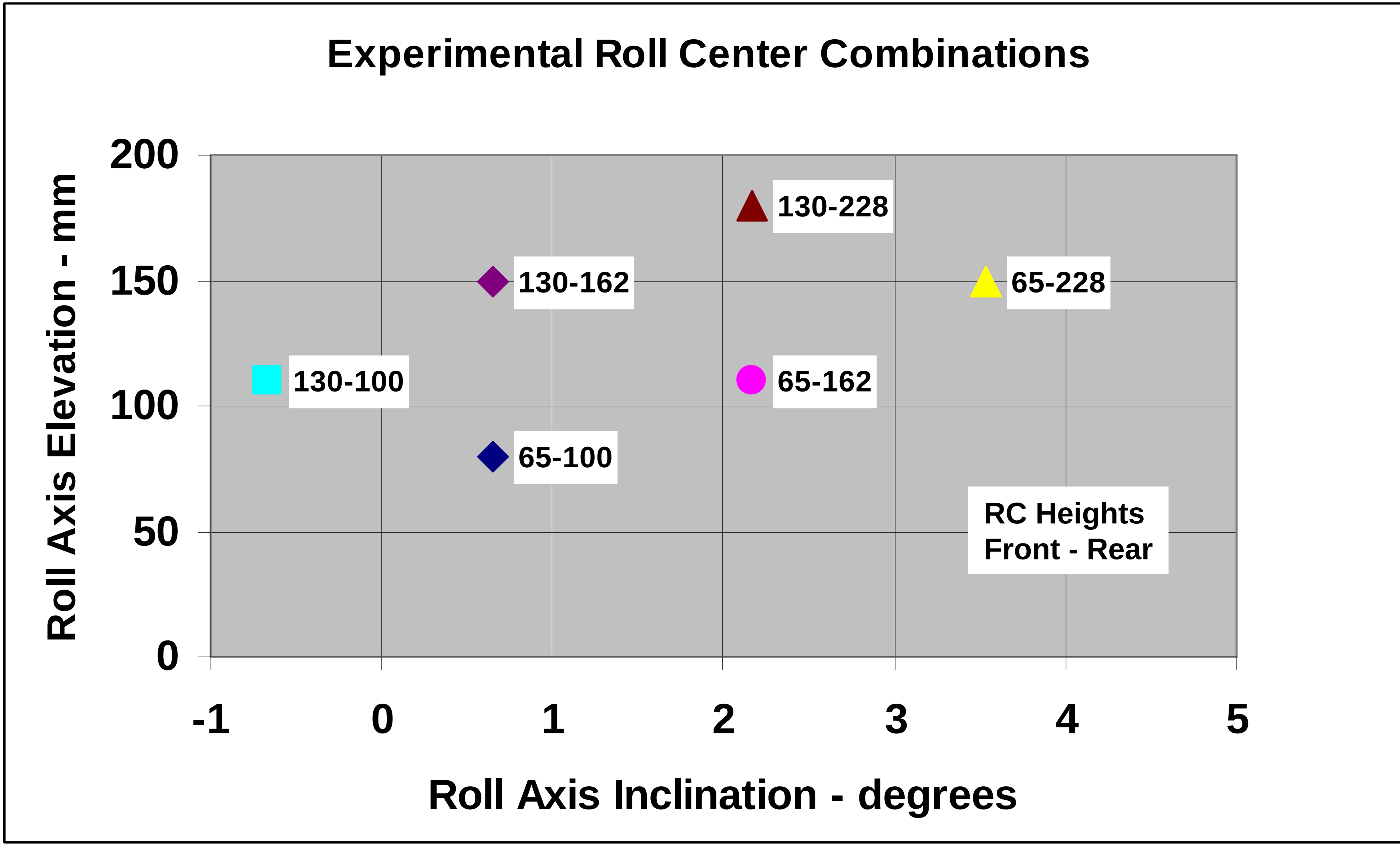
- Vehicle Configuration
  - C-Segment FWD Vehicle
    - 2635 mm wheelbase
    - 1520 mm front and rear track,
    - Weight @ curb 1417 kg, 59% front, 41% rear
    - MacPherson Strut front suspension
    - Multi-link rear suspension
    - 4 Cylinder, automatic
    - Curb + Driver

- Test Configurations
  - Two  front, three rear roll center heights and all possible combinations
  - Roll center changes were accomplished with suspension cradle and steering rack vertical relocations
  - Springs, stabilizer bars and shocks were not revised between combinations
  - Ride heights and toe curves were maintained

# Roll Center Heights
# and
# Roll Axis Inclinations and Elevations

| **Roll Center Height F-R: mm** | **Roll Axis Inclination degrees** | **Roll Axis Elevation mm** |
|---|---|---|
| 65 - 100 | 0.65 | 80 |
| 65 - 162 | 2.17 | 110 |
| 65 - 228 | 3.54 | 150 |
| 130 - 100 | -0.67 | 110 |
| 130 - 162 | 0.65 | 150 |
| 130 - 228 | 2.17 | 180 |


Experimental Roll Axis Incinations and Elevations
Roll Center Height - mm
250
200
150
100
50
0
0
1000
2000
3000
Wheelbase - mm
Inclination Elevation
0.65 80
2.17 110
3.54 150
-0.67 110
0.65 150
2.17 180


Experimental Roll Center Combinations
Roll Axis Elevation - mm
200
150
100
50
0
-1
0
1
2
3
4
5
Roll Axis Inclination - degrees
130-228
130-162
65-228
130-100
65-162
65-100
RC Heights
Front - Rear



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- Subjective Evaluation Process
  - Professional Vehicle Dynamics Driver
  - Sub-limit to limit operation
  - Low speed (30mph) to high speed (100 mph)
  - Steering, steering feel evaluation events
  - Handling evaluation events
  - Customer typical events



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- Characteristics Evaluated
  - Yaw response and damping
  - Roll response and damping
  - Response to steering
  - Steering feel
  - “Blending Character”
    - the synergy of steering angle and effort, roll character, yaw character, and directional change due to a driver input





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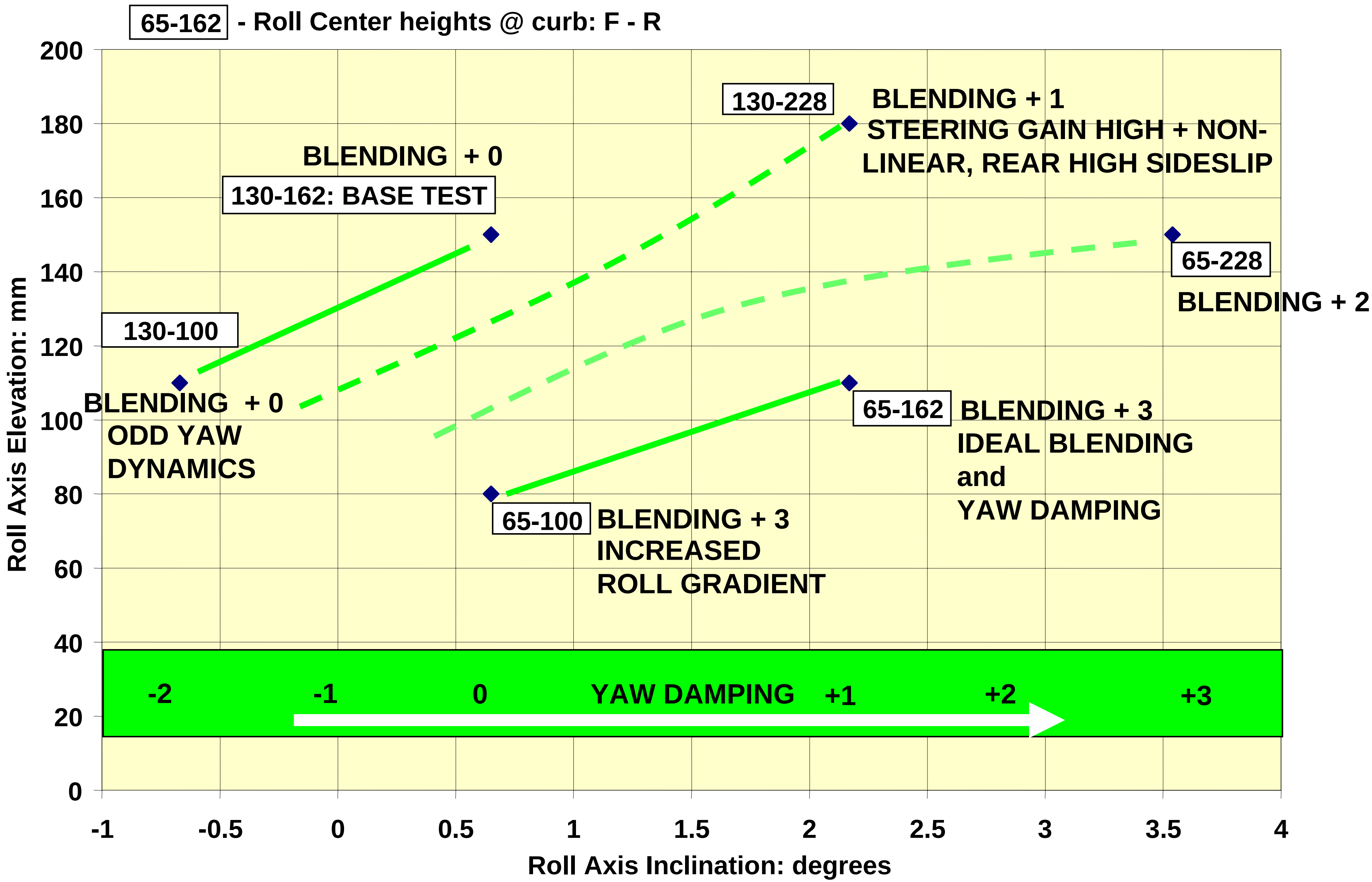
# EXPERIMENTAL RESULTS





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- Experiment Observations
  - As the Roll Axis gets high
    - Steering linearity and blending deteriorates
    - Vehicle response is quicker
  - As the Roll Axis gets low
    - Blending improves but roll increases
    - Vehicle response is slower
  - As the Roll Axis becomes more positive (high in rear)
    - The yaw damping of the vehicle improves
  - As the Roll Axis becomes reversed (high in front)
    - The yaw damping is reduced
  - Curb Load “Blending” was optimal within a range of:
    - ~ 0.75 to ~2.25 degrees roll axis inclination
    - ~ 80 to ~115 mm roll axis elevation

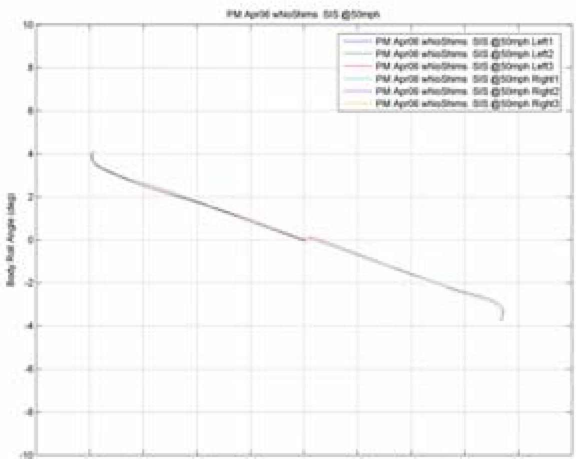
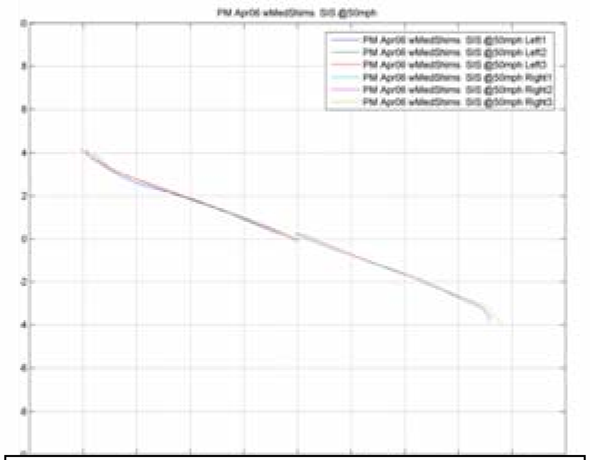
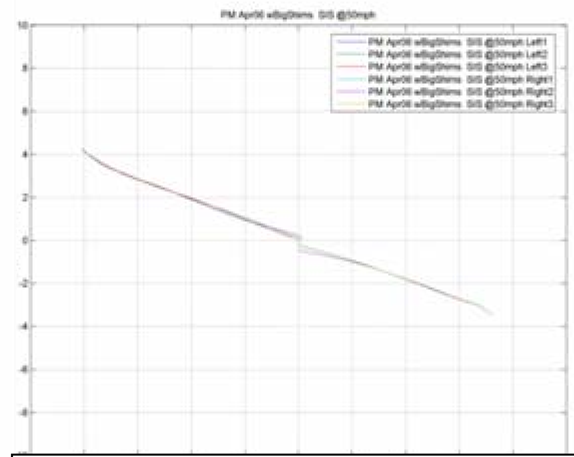
# Instrumented Handling Tests

- Test Vehicle Configuration:  C-segment FWD Vehicle
  - 2635 mm wheelbase
  - 1520 mm front and rear track,
  - Weight @ curb 1417 kg, 59% front, 41% rear
  - MacPherson Strut front suspension
  - Multi-link rear suspension
  - 4 Cylinder, automatic
  - Curb + driver + steering robot

- TEST CONFIGURATIONS
  - Three front roll center heights
    - 0, 65, 132 mm
  - Rear roll center height kept constant @ 162 mm
  - Roll center changes were accomplished with suspension cradle and steering rack vertical relocations
  - Springs, stabilizer bars and shocks were not revised between combinations
  - Ride heights and toe curves were maintained

- Test Maneuvers
  - Slowly Increasing Steer @ 50 mph
  - 0.40 G Step Steer @ 60 mph

# Roll Angle Character

| FRC @ 132 mm | FRC @ 65 mm | FRC @ 0 mm |
|---|---|---|
|  |  |  |
| **Steady-State Roll Rate deg/G @ .2 - .4G**<br>L: 4.40 R: 4.46<br>4.43 avg | **Steady-State Roll Rate deg/G @ .2 - .4G**<br>L: 4.55 R: 4.38<br>4.46 avg | **Steady-State Roll Rate deg/G @ .2 - .4G**<br>L: 4.68 R: 4.24<br>4.46 avg |

**No difference in Steady-State roll gradient**

| Step Steer Roll Rate | Step Steer Roll Rate | Step Steer Roll Rate |
|---|---|---|
| 8.9 deg/sec | 8.2 deg/sec | 9.6 deg/sec |

**Difference in Step Steer roll rate**



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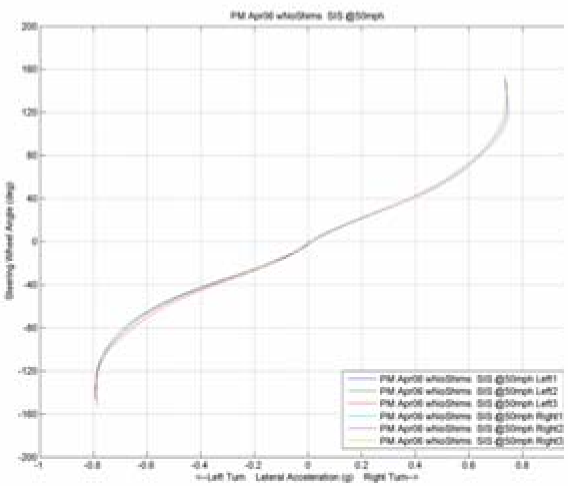
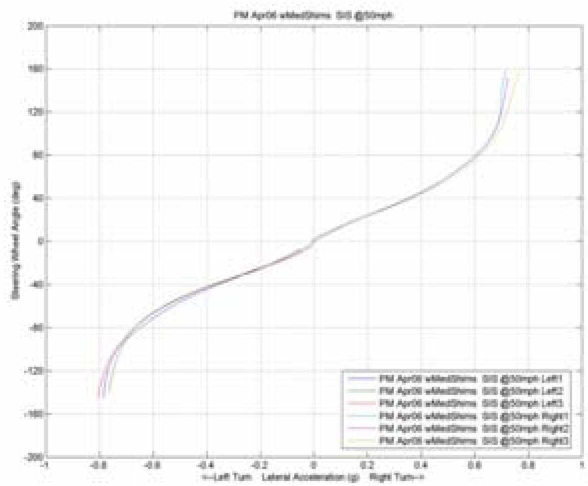
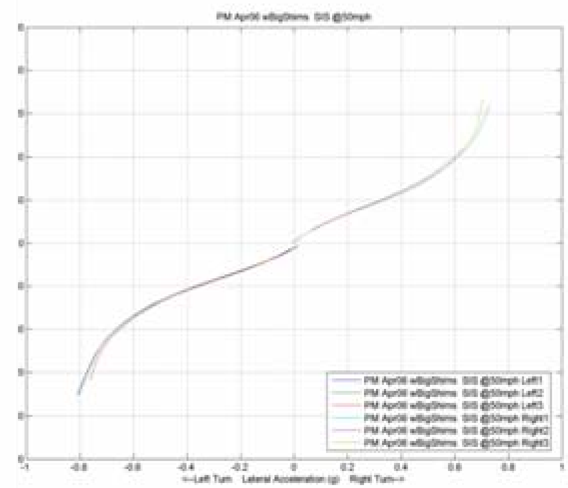
# Under-steer Gradient: deg/G

| FRC @ 132 mm | FRC @ 65 mm | FRC @ 0 mm |
|---|---|---|
|  |  |  |
| **U-steer Grad deg/G @.2 - .4G**<br>**L: 2.4 R: 3.1**<br>**2.8 avg** | **U-steer Grad deg/G @.2 - .4G**<br>**L: 2.5 R: 3.3**<br>**2.9 avg** | **U-steer Grad deg/G @.2 - .4G**<br>**L: 2.3 R: 3.1**<br>**2.7 avg** |
| **U-steer Grad deg/G @.6 - .7G**<br>**L: 8.6 R: 12.6**<br>**10.6 avg** | **U-steer Grad deg/G @.6 - .7G**<br>**L: 10.2 R: 22.3***<br>**10.2 avg** | **U-steer Grad deg/G @.6 - .7G**<br>**L: 10.2 R: 20.0***<br>**10.2 avg** |

**Small differences in understeer gradient**

*** Data not used: out of limits**





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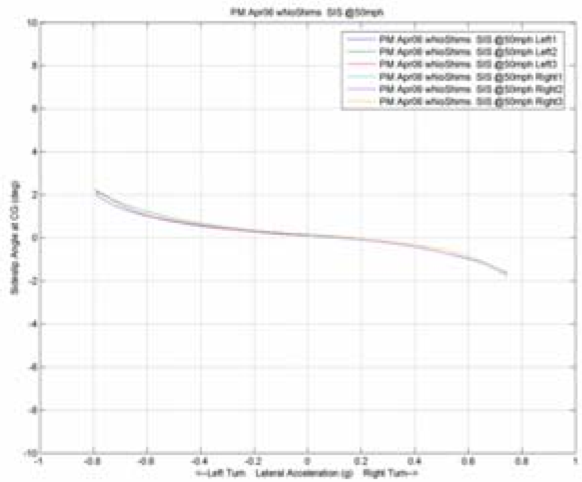
# Side-slip Angle vs. Lateral Acceleration

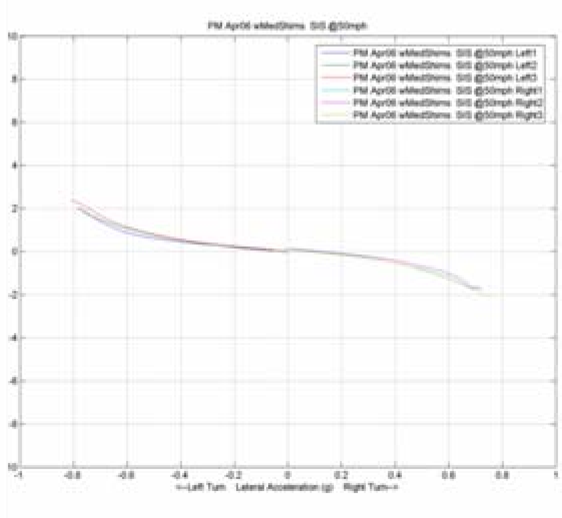
**FRC @ 132 mm**



Side Slip deg/G @ .2 - .4G
L: 3.3 R: 3.3
3.3 avg

Side Slip deg/G @ .6 - .7G
L: 6.4 R: 6.9
6.7 avg

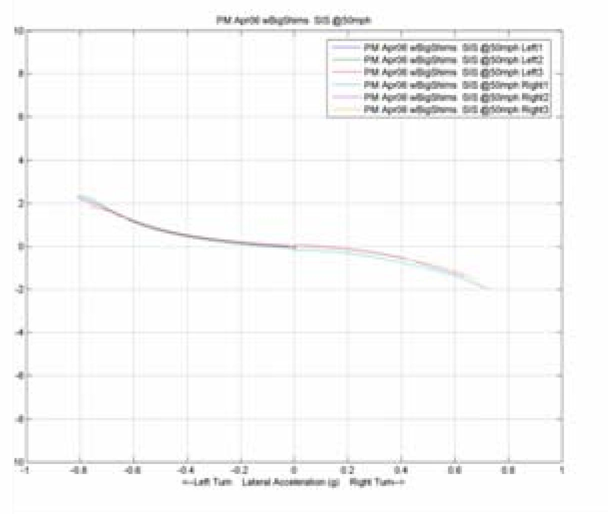
**FRC @ 65 mm**



Side Slip deg/G @ .2 - .4G
L: 3.2 R: 3.5
3.3 avg

Side Slip deg/G @ .6 - .7G
L: 6.7 R: 7.7
7.2 avg

**FRC @ 0 mm**



Side Slip deg/G @ .2 - .4G
L: 3.4 R: 3.7
3.6 avg

Side Slip deg/G @ .6 - .7G
L: 7.4 R: 8.1
7.7 avg

**Small difference in side slip**



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- Observations
  - Measured roll angles, sideslip gradients and understeer gradients were surprisingly similar between the variants tested
  - Step steer roll rates were different: lowest was at the mid-point of roll center height
  - Measured steady-state results did not parallel subjective driver assessments
  - Driver assessment noted significant roll feel changes between roll axis elevations
  - Which is right?  Are both correct?



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# What did We Learn?

- Insights and Conclusions
  - Roll centers, roll axis elevations and inclinations have a significant spread among the vehicle populations
  - Examining the vehicle suspension geometry using two variables: roll axis elevation and roll axis inclination can make the engineering process simpler than using three variables: front and rear roll center heights and roll axis inclination
  - The thought process of visualizing vehicle roll around the roll axis @ vehicle centerline is valuable for general thoughts but not representative enough for detail calculations and development
  - Suspension kinematics can move the roll centers and roll axis significantly vertically and laterally invalidating the original assumption that the roll axis is on the centerline of the vehicle
  - We speculate that shock damping forces, road induced suspension motions and jounce/rebound stops can further force the roll centers and roll axis out of geometrically expected locations

- Insights and Conclusions

  - A more representative perspective of where the roll centers and roll axis go throughout maneuvers would be useful for vehicle dynamics engineering
  - Roll axis inclination has a significant effect on yaw damping
  - Roll axis elevation has a significant effect on vehicle quickness and feel
  - Both roll axis elevation and inclination have an effect on “Blending”: there may be a “sweet spot”
  - Subjective roll feel and measured steady-state roll magnitudes are not necessarily coincident
  - Subjective vehicle development and holistic vehicle understanding provide important insights regarding vehicle performance that calculations and instrumented handling have a challenge to quantify accurately





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# Thank you!

# Questions ?



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