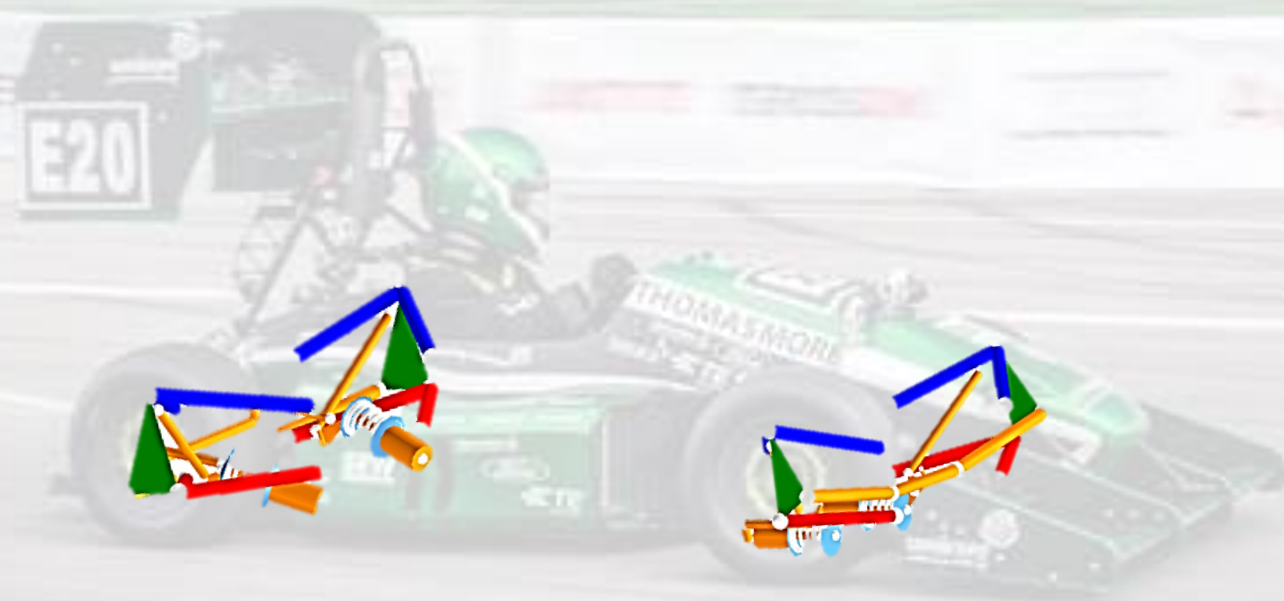


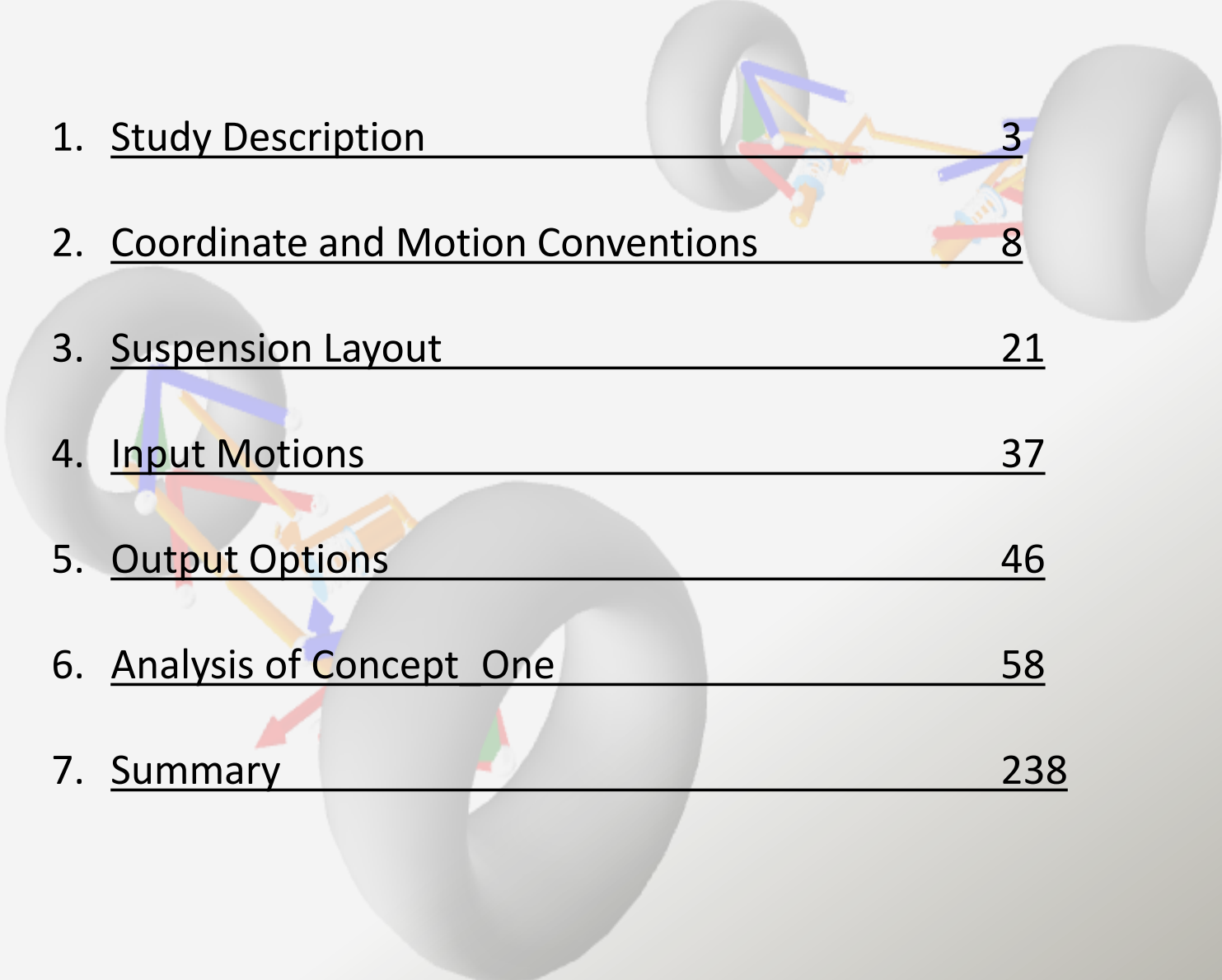
OptimumKinematics

Generic FSAE Case Study



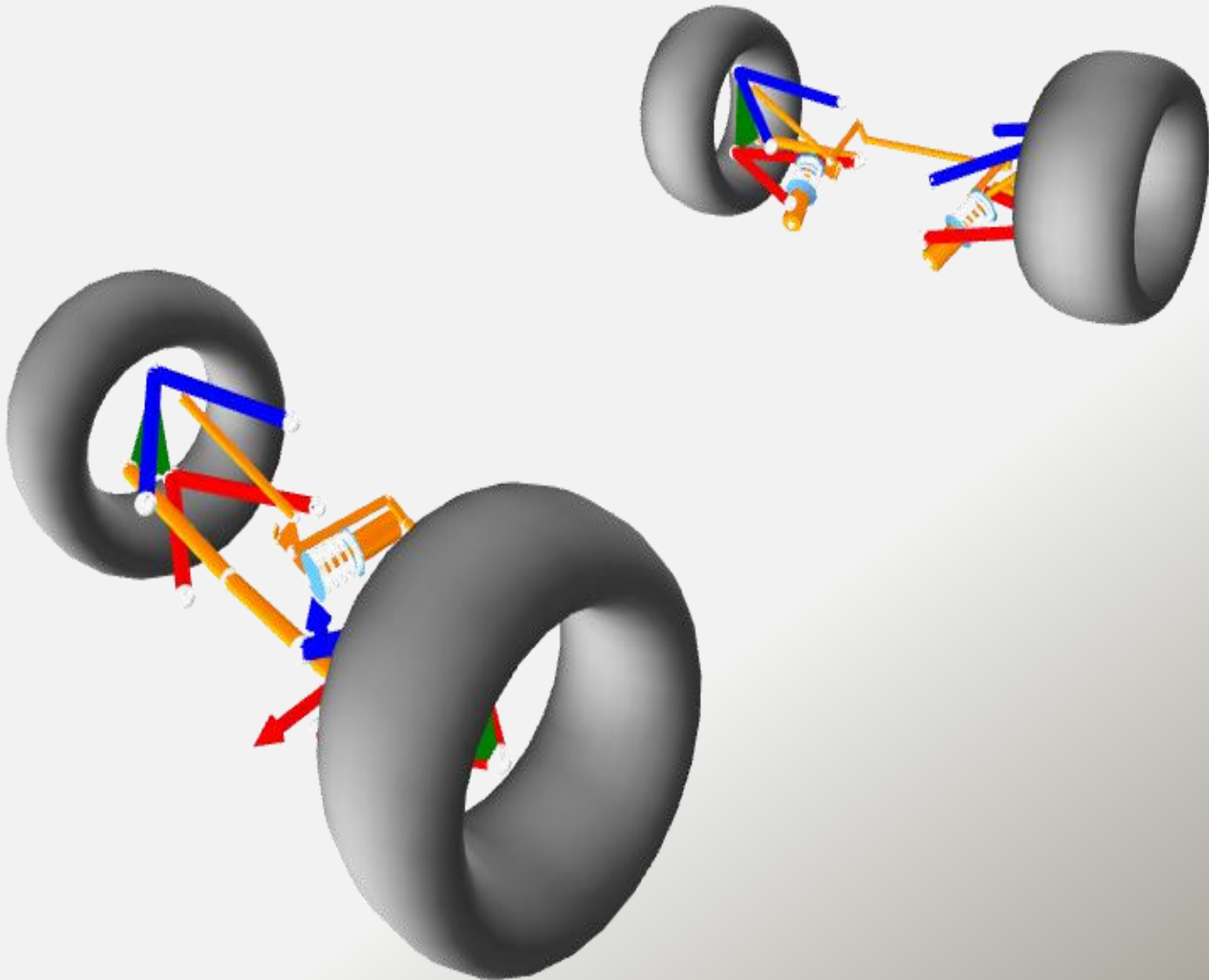
Prepared for Formula Students Teams by OptimumG
May 2015

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1. Study Description



Study Description

Kinematic investigation of generic FSAE car using OptimumKinematics software

Benefits of using OptimumKinematics

- Rapid iteration through kinematic concepts
- Tools designed to gain deep understanding of implications
- Advanced simultaneous motion simulation

Compliance and Limitations

OptimumKinematics does not account for compliance

Experience shows compliance amplifies kinematic issues

Common sources of compliance include

- Tire (largest contribution)
- Bushings
- Rim
- Suspension Elements
- Chassis

Good quality kinematics **critical** as a starting point

Vehicle Description

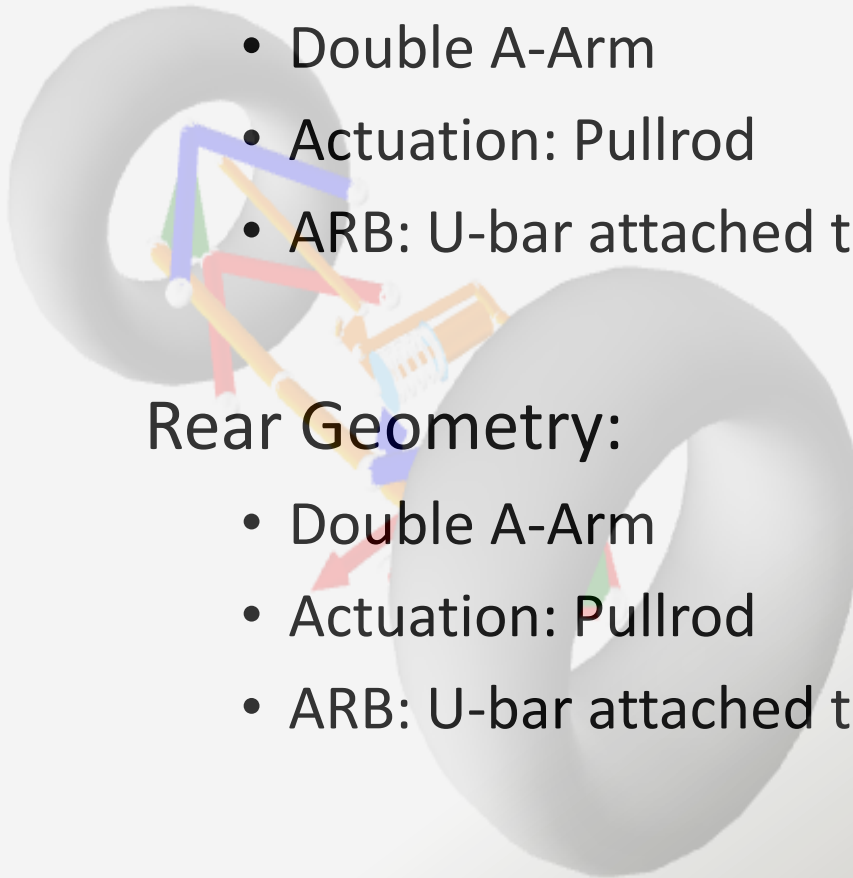
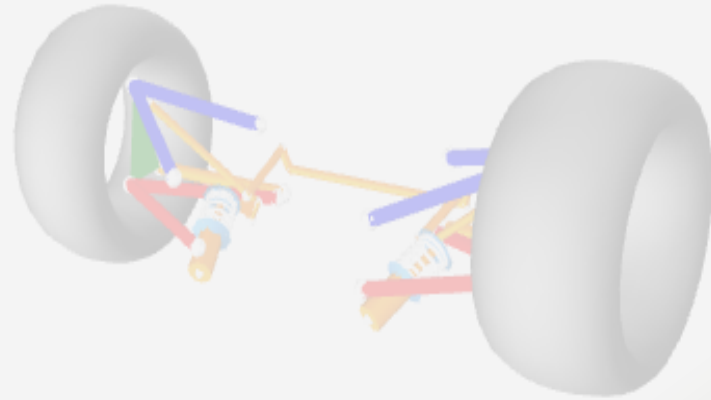
Generic FSAE

Front Geometry:

- Double A-Arm
- Actuation: Pullrod
- ARB: U-bar attached to rocker

Rear Geometry:

- Double A-Arm
- Actuation: Pullrod
- ARB: U-bar attached to rocker



Assumed Values

In absence of missing data this information has been assumed for the following analysis

Sprung Mass [kg]	212	Sprung Mass Pitch Inertia [kg m ²]	43
SM Position(x,y,z) [mm]	-796,0,173.6	Sprung Mass Roll Inertia [kg m ²]	20
Non Sprung Mass [kg]	20 F, 24 R	Front Mass Distribution %	48.4
NSM FL (x,y,z) [mm]	0,460,240	F Spring Rate [N/mm]	52.5
NSM FR (x,y,z) [mm]	0,-460,240	R Spring Rate [N/mm]	190.0
NSM RL (x,y,z) [mm]	-1550,460,260	F ARB Stiffness [N/mm]	224.9
NSM RR (x,y,z) [mm]	-1550,-460,260	R ARB Stiffness [N/mm]	103.5

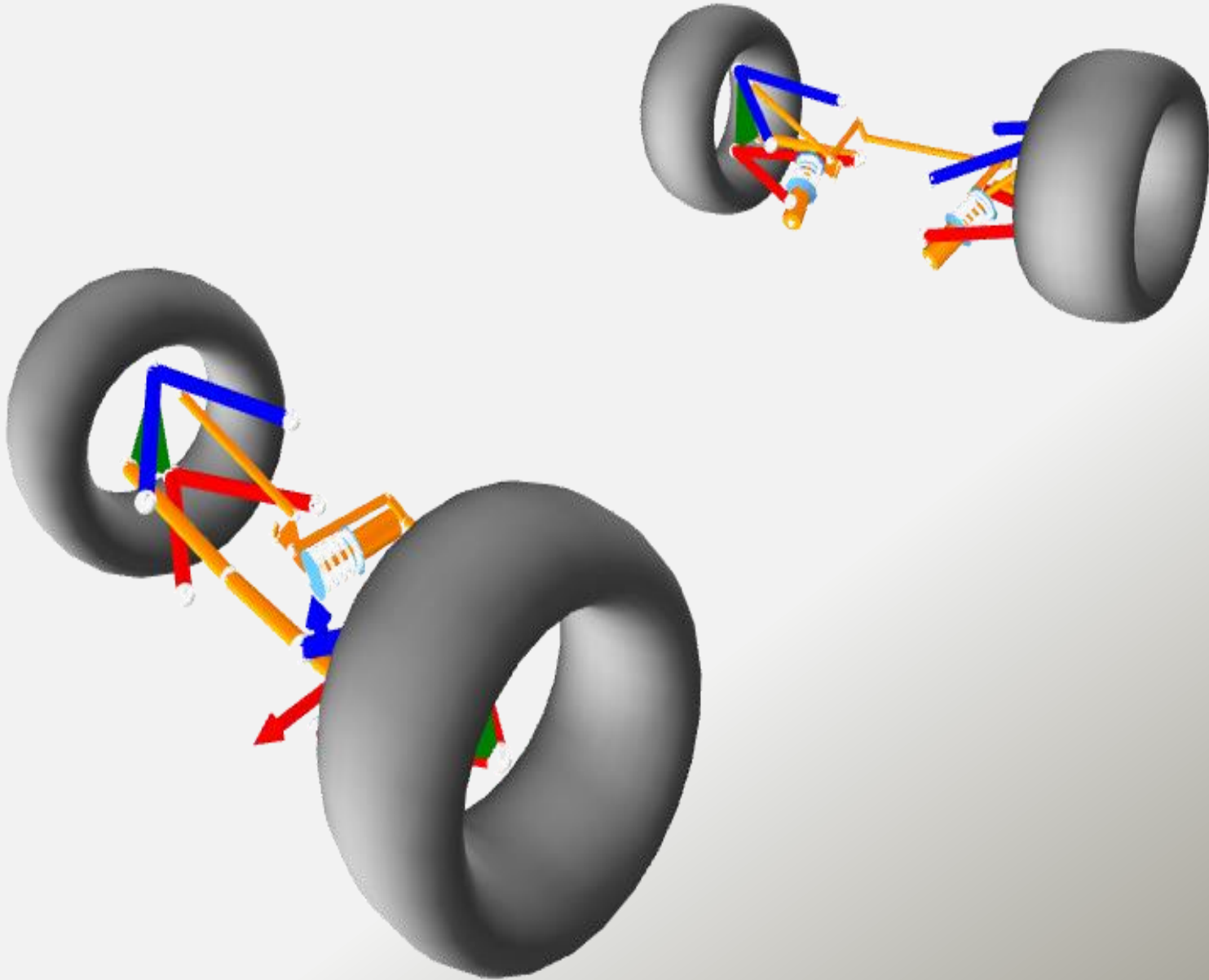
All coordinates are referenced to front axle origin as defined in model

Text Color Convention

Observations and comments related
to car suspension design

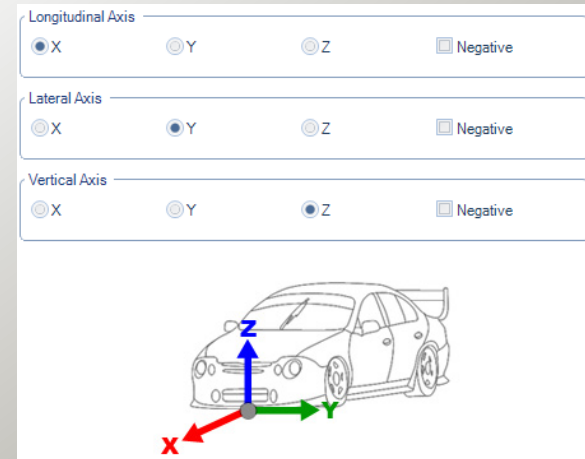
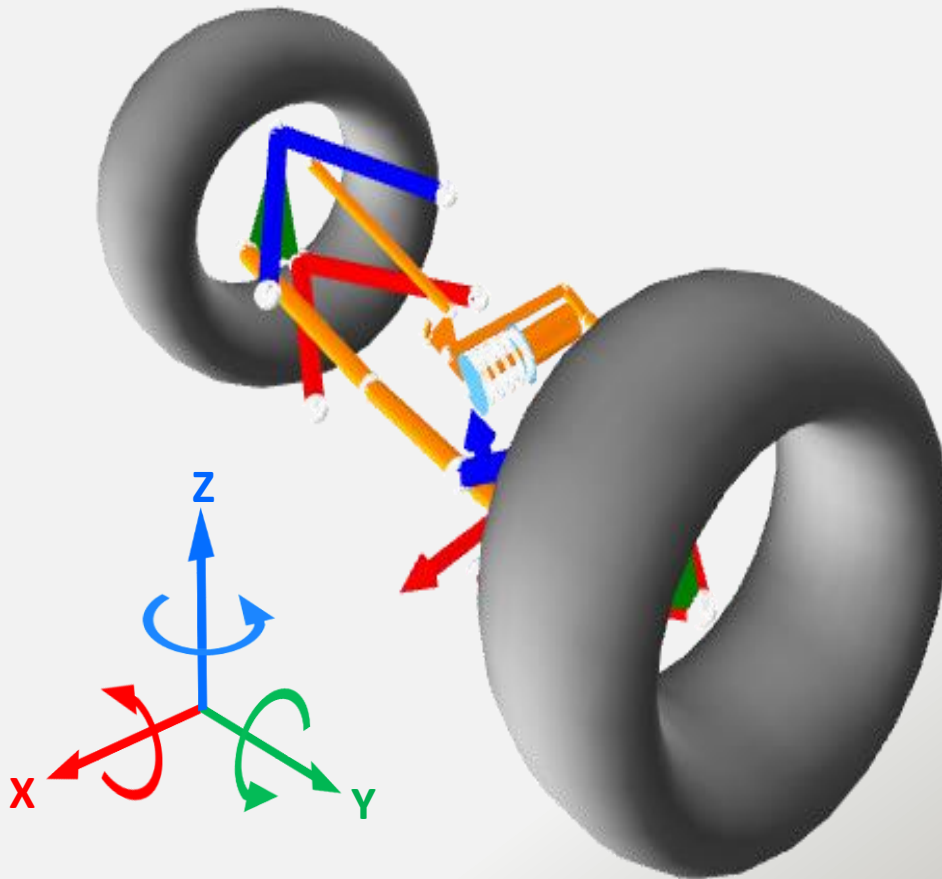
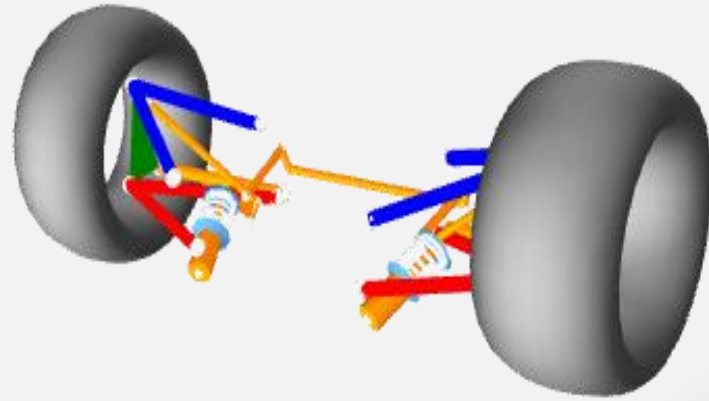
Comments and explanations related
to OptimumKinematics

2. Sign Convention Definitions



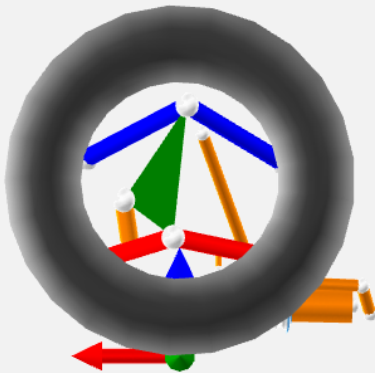
Coordinate System

OptimumKinematics allows different sign conventions to be chosen to suit the user



Motion: Heave

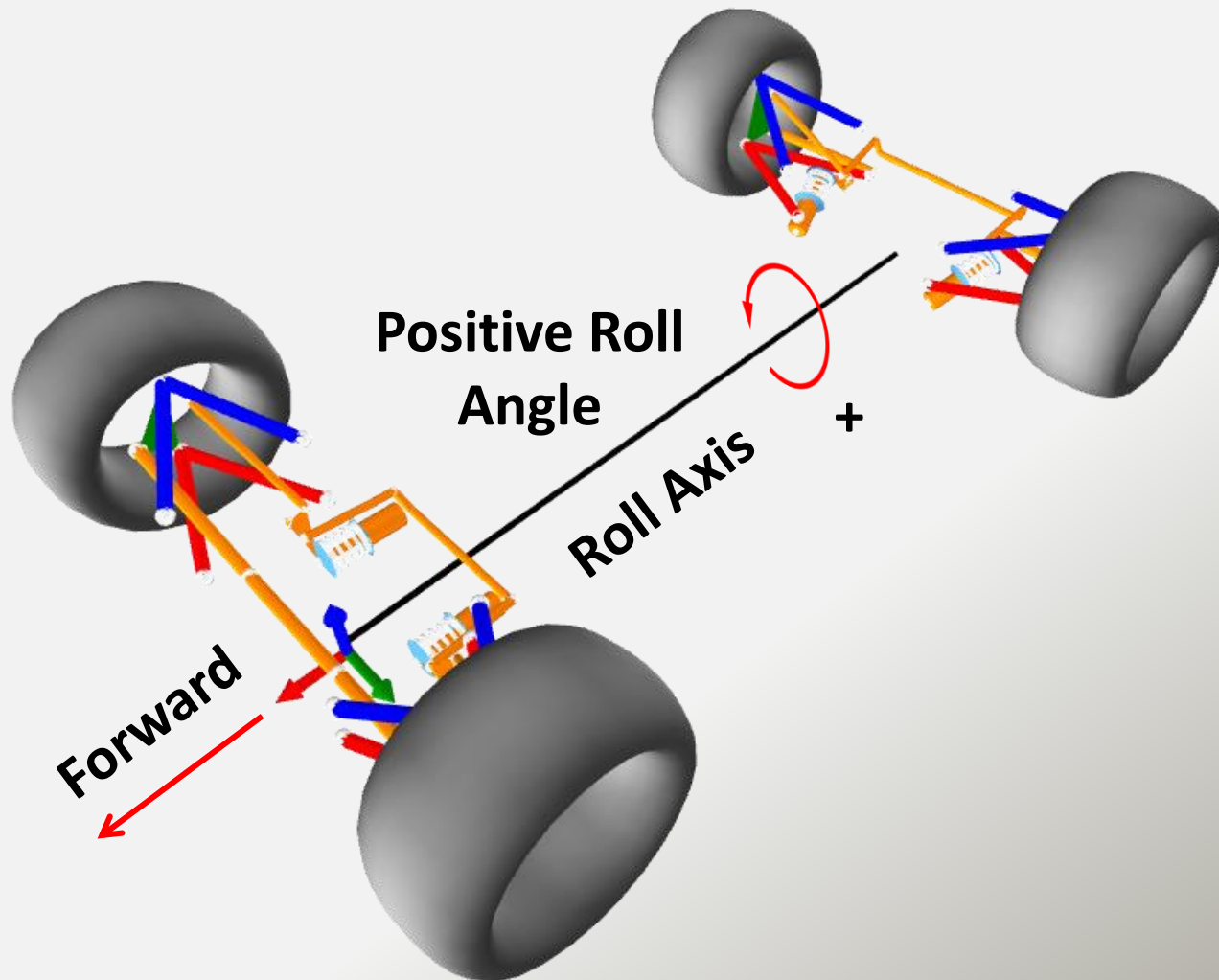
Left Side View



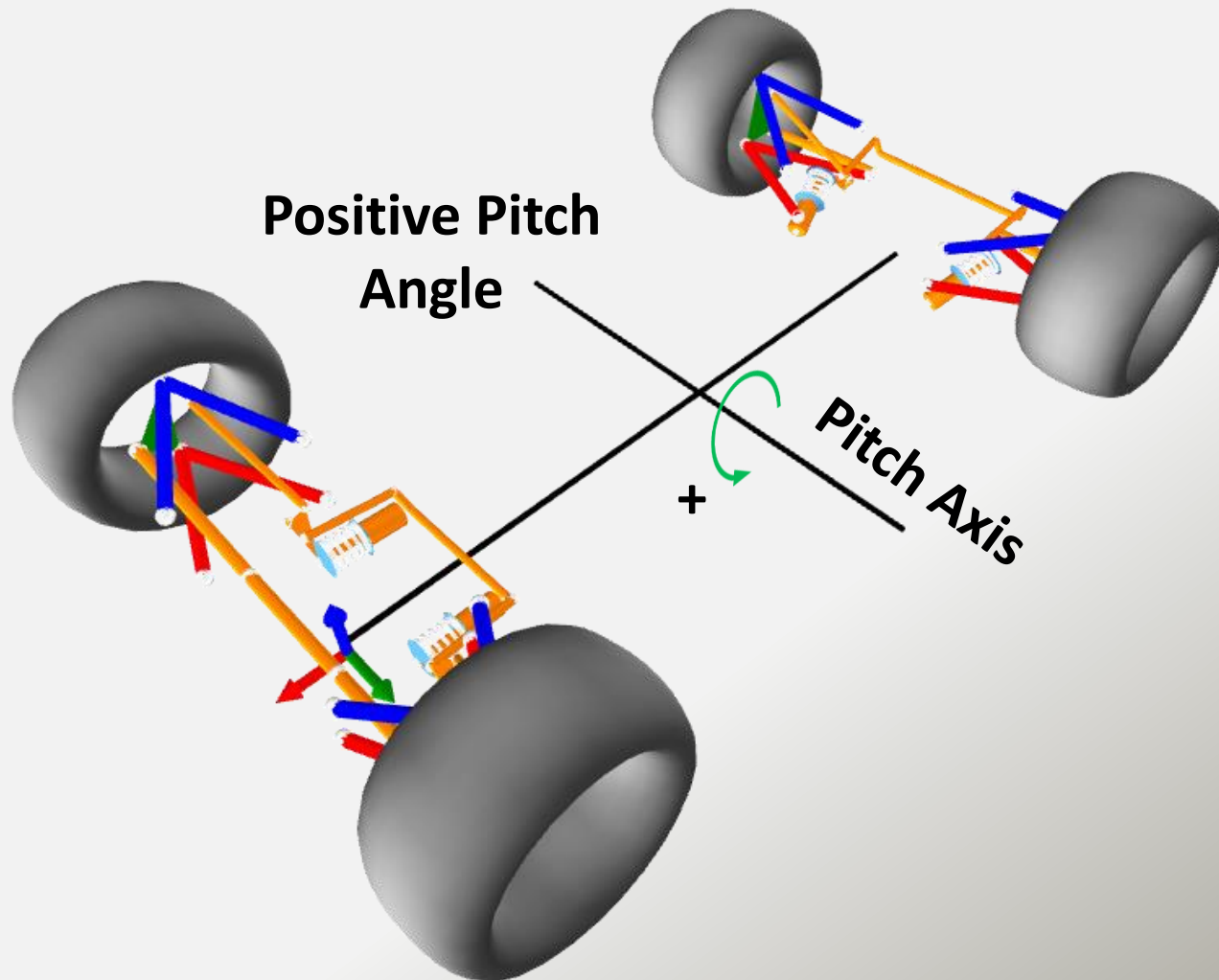
**Positive Heave
(Chassis moving
upwards)**



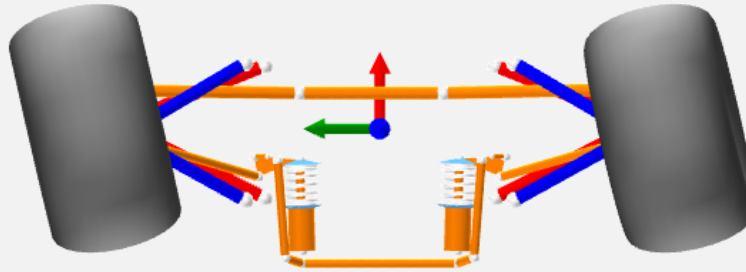
Motion: Roll



Motion: Pitch

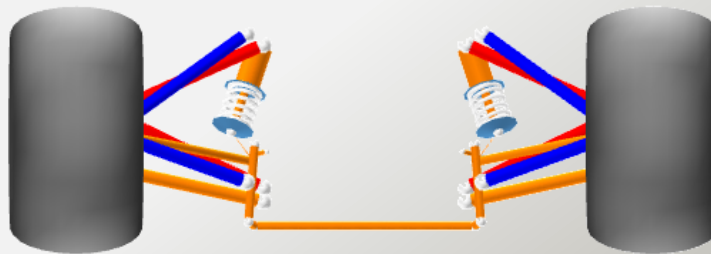


Motion: Steering



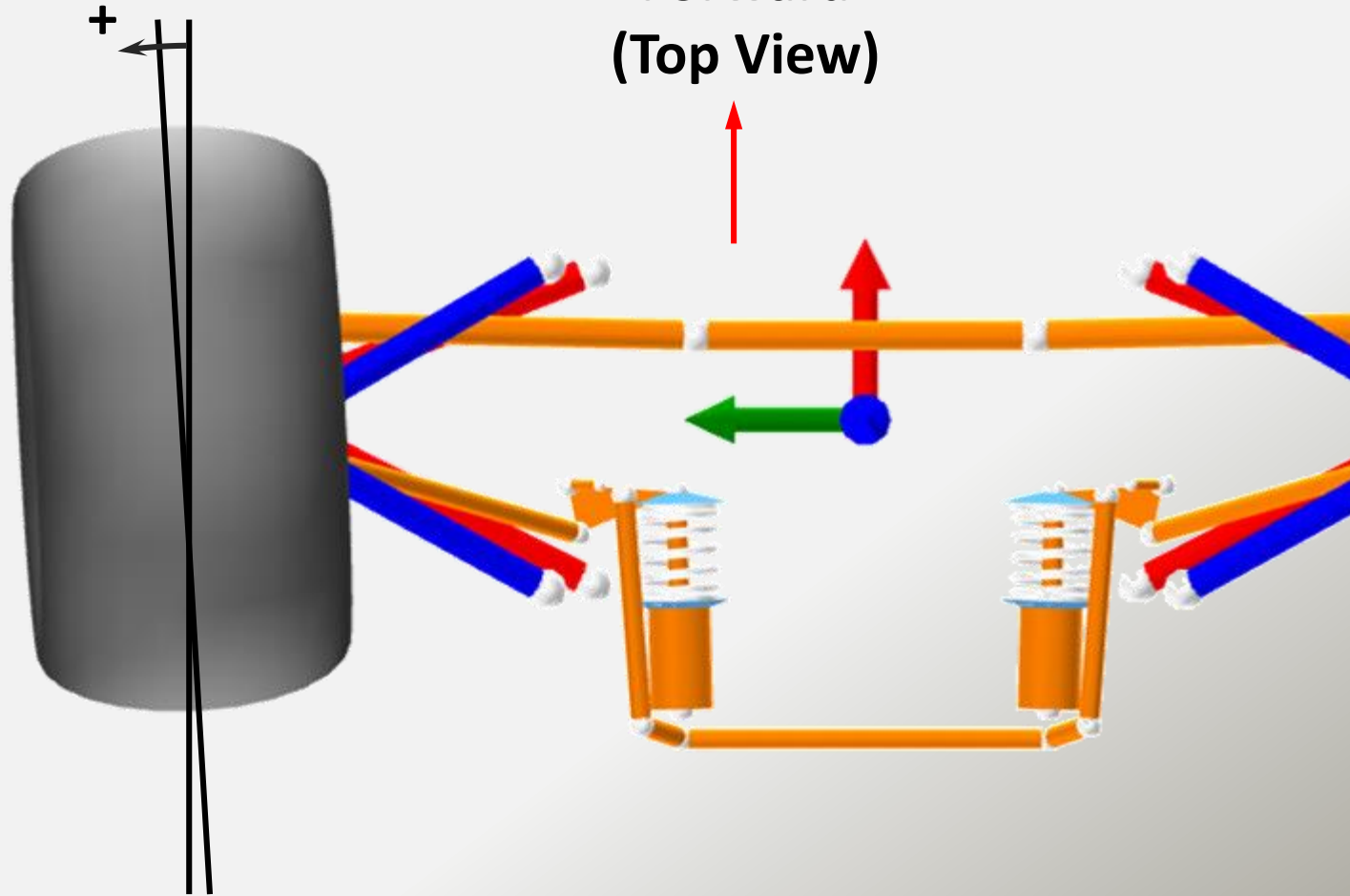
+

**Positive Steer Angle
(Steering wheel turning to the left)**



Toe Angle

**Positive Toe Angle
(Toe Out)**



Camber Angle

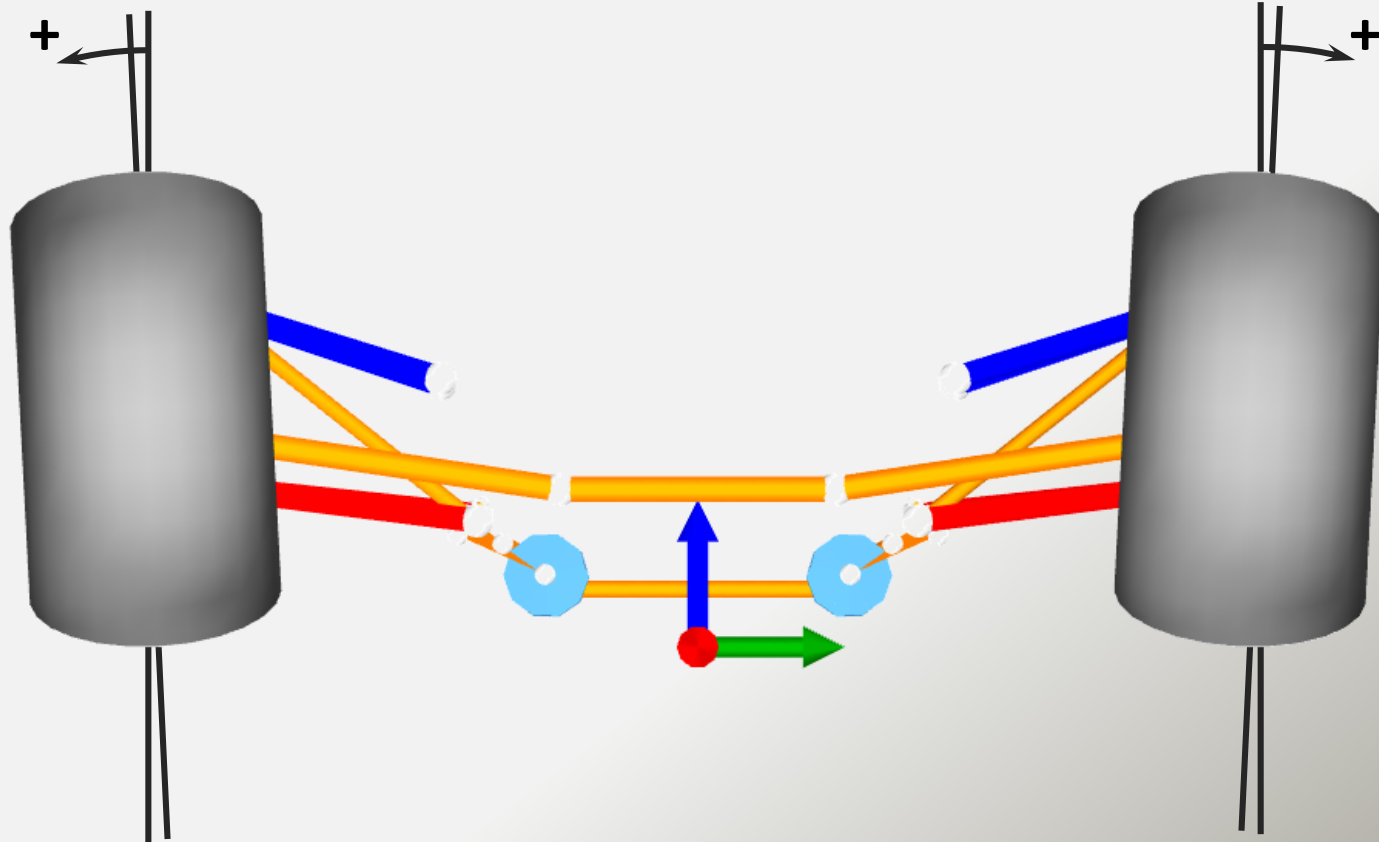
Positive Camber
Angle

+

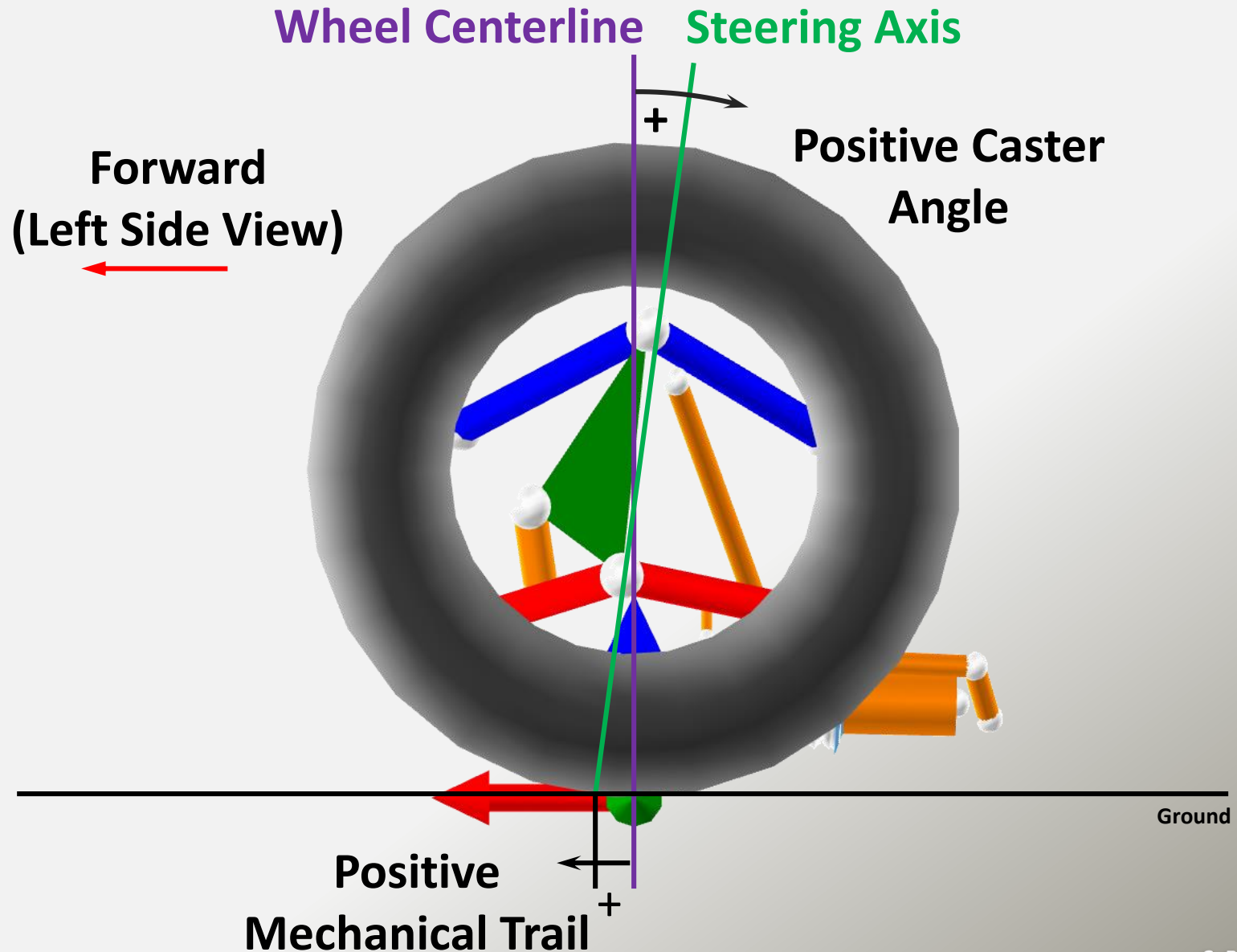
Front View

Positive Camber
Angle

+

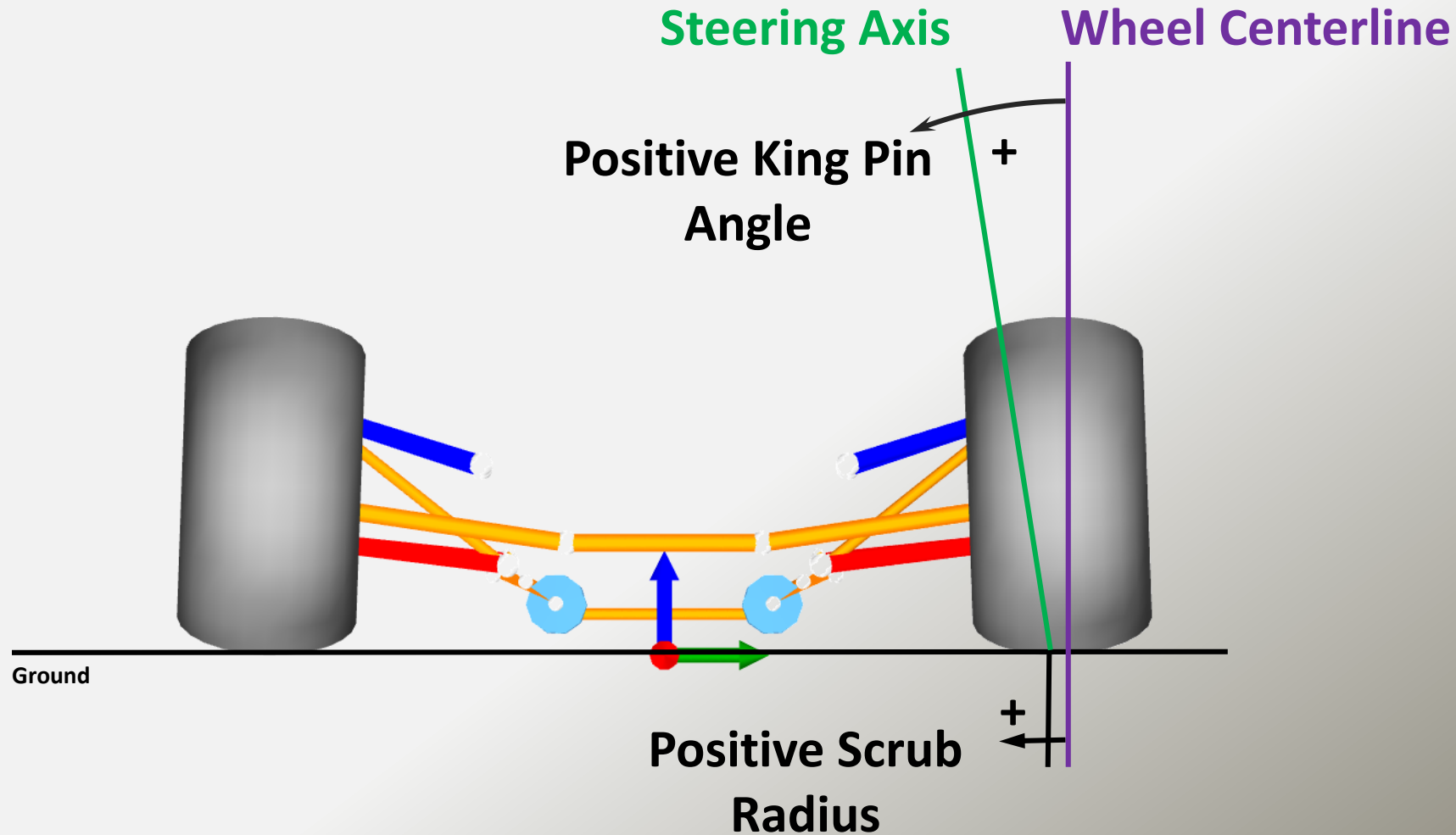


Caster and Mechanical Trail



Kingpin Angle and Scrub Radius

Front View



Ackermann Definition

Ackermann percentage is defined as a function of the inside steer angle, the outside steer angle, the front track and the vehicle wheelbase. The expressions are as follows:

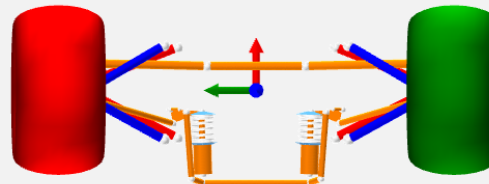
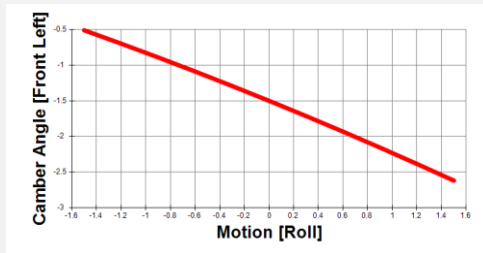
$$Ackermann = \tan^{-1} \left(\frac{wheelbase}{\frac{wheelbase}{\tan \delta_{outside}} - track_{front}} \right)$$

$$Ackermann_{percent} = \frac{\delta_{inside}}{Ackermann} \times 100$$

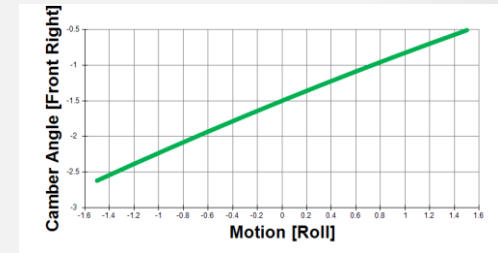
Plots Color Convention

Charts will be displayed using the following color code

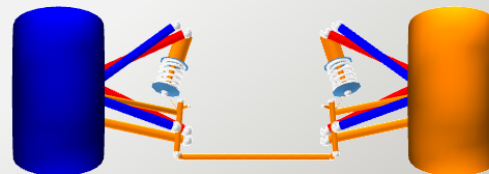
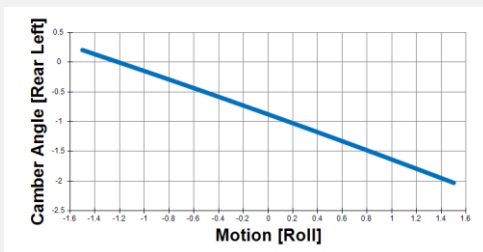
Front Left
Red



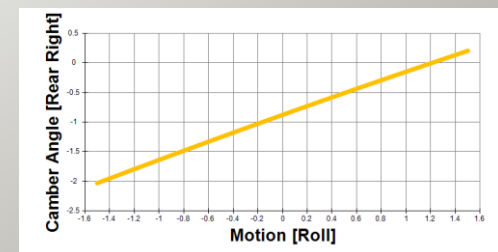
Front Right
Green



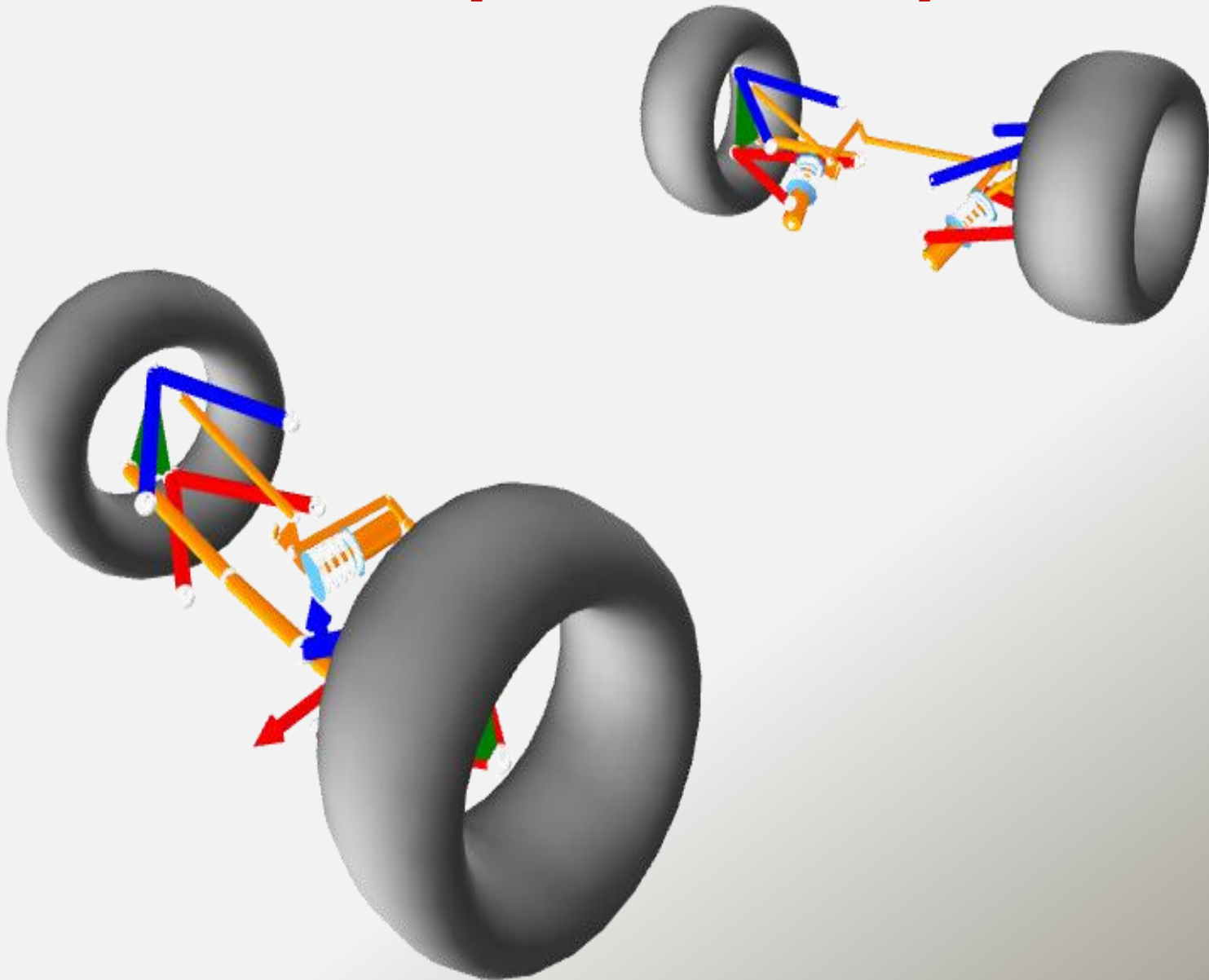
Rear Left
Blue



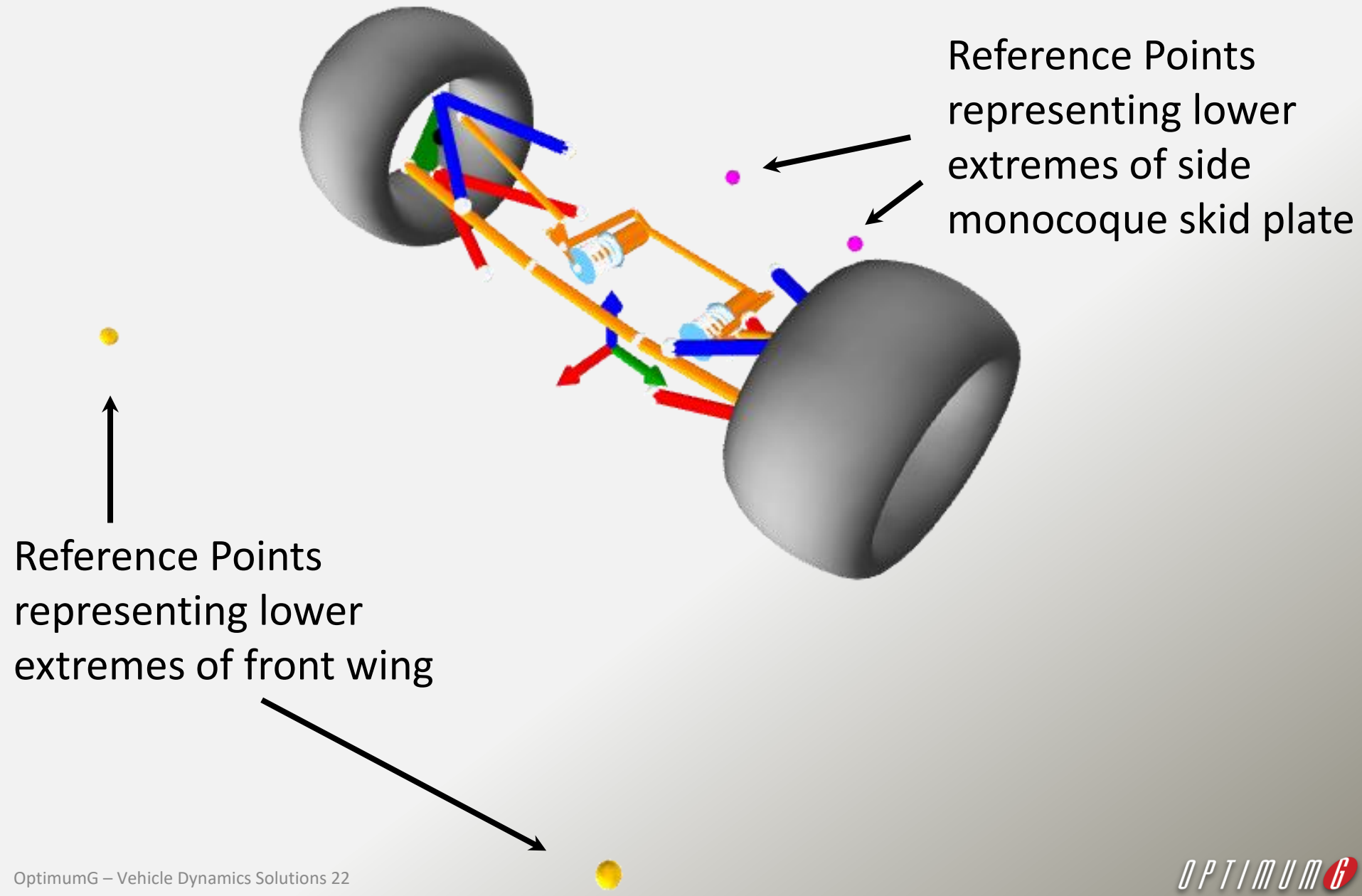
Rear Right
Orange



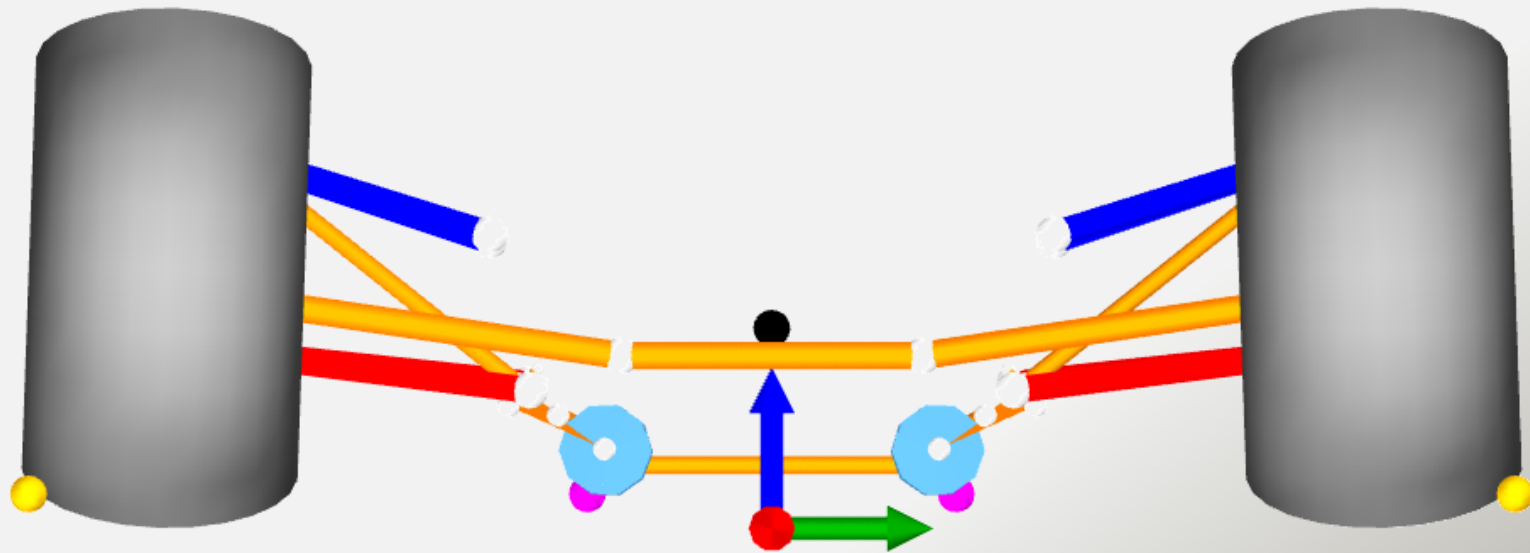
3. Suspension Layout



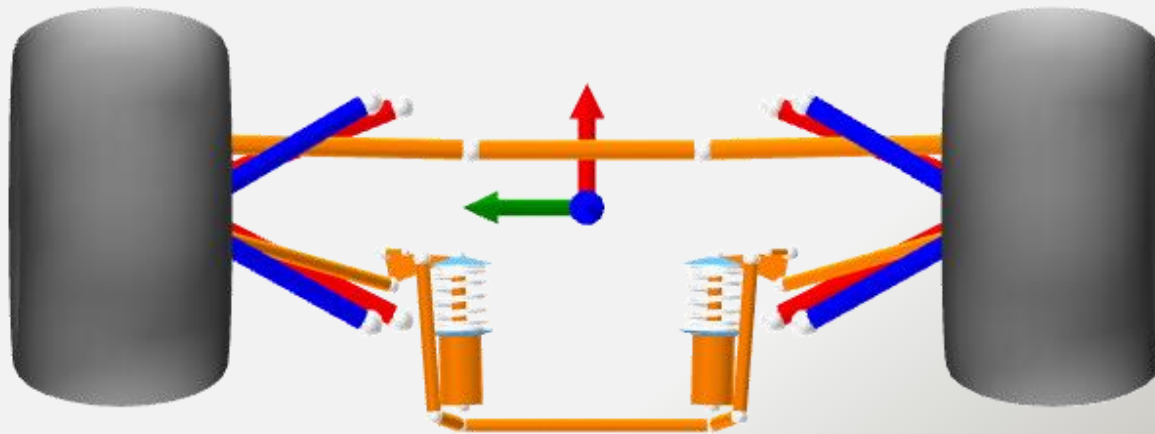
Front Suspension: Isometric View



Front Suspension: Front View

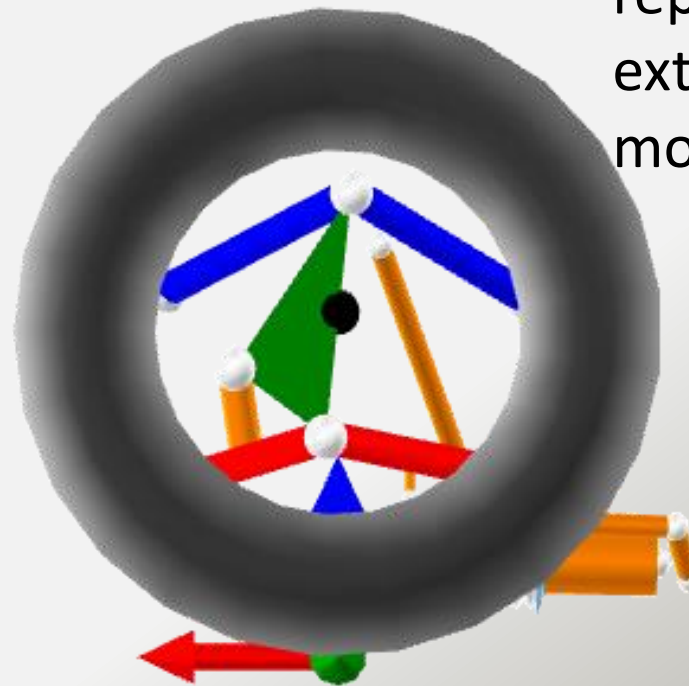
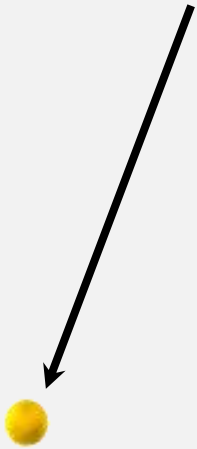


Front Suspension: Top View



Front Suspension: Left Side View

Reference point
representing lower
extreme of front splitter



Reference Points
representing lower
extremes of side
monocoque skid plate



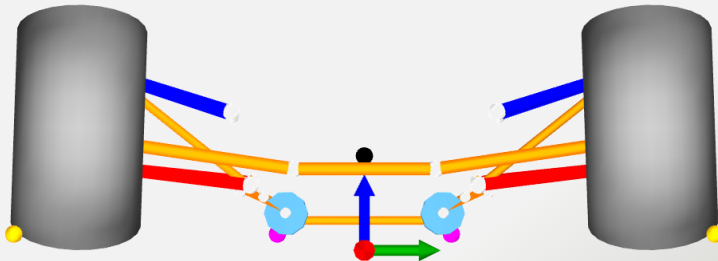
Front Suspension: Points Coordinates

Double A-Arm	Point Name	Left			Right		
		X	Y	Z	X	Y	Z
	CHAS_LowFor	114.500	210.000	120.000	114.500	-210.000	120.000
	CHAS_LowAft	-125.500	210.000	125.000	-125.500	-210.000	125.000
	CHAS_UppFor	119.500	245.000	255.000	119.500	-245.000	255.000
	CHAS_UppAft	-130.500	245.000	250.000	-130.500	-245.000	250.000
	UPRI_LowPnt	8.500	476.000	153.000	8.500	-476.000	153.000
	UPRI_UppPnt	-9.500	464.000	323.000	-9.500	-464.000	323.000
	CHAS_TiePnt	65.000	131.000	150.000	65.000	-131.000	150.000
	UPRI_TiePnt	72.500	476.590	200.840	72.500	-476.590	200.840
Push Pull	Point Name	Left			Right		
		X	Y	Z	X	Y	Z
	NSMA_PPAttPnt_L	-28.610	423.730	287.210	-28.610	-423.730	287.210
	CHAS_AttPnt_L	-222.000	141.000	65.520	-222.000	-141.000	65.520
	CHAS_RocAxi_L	-50.000	204.090	137.880	-50.000	-204.090	137.880
	CHAS_RocPiv_L	-50.000	228.710	106.360	-50.000	-228.710	106.360
	ROCK_RodPnt_L	-87.570	220.850	125.600	-87.570	-220.850	125.600
	ROCK_CoiPnt_L	-55.500	145.230	68.940	-55.500	-145.230	68.940
U-Bar	Point Name	Left			Right		
		X	Y	Z	X	Y	Z
	NSMA_UBarAttPnt_L	-57.440	185.430	97.930	-57.440	-185.430	97.930
	UBAR_AttPnt_L	-234.620	171.820	90.530	-234.620	-171.820	90.530
	CHAS_PivPnt_L	-245.010	141.000	55.020	-245.010	-141.000	55.020
Rack Pinion	Steering Ratio	85.788					
Wheels	Point Name	Left			Right		
	Half Track	525.000			525.000		
	Longitudinal Offset	0.000			0.000		
	Lateral Offset	0.000			0.000		
	Vertical Offset	0.000			0.000		
	Static Camber	-2.000			-2.000		
	Static Toe	0.000			0.000		
	Rim Diameter	254.000			254.000		
	Tire Diameter	0.000			0.000		
	Tire Width	240.000			240.000		

Front Suspension

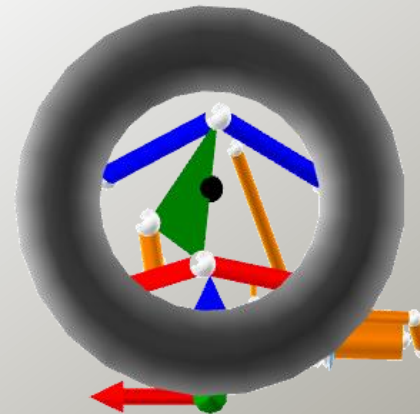
Static Values, Front View

Parameter Name	Value	Units
Track Width	1,050.0	mm
Scrub Radius	38.2	mm
Roll Center Height	28.3	mm
Swing Arm Length	921.3	mm
Camber	-2.0	degrees
Toe	0.0	degrees
King Pin Inclination	4.0	degrees



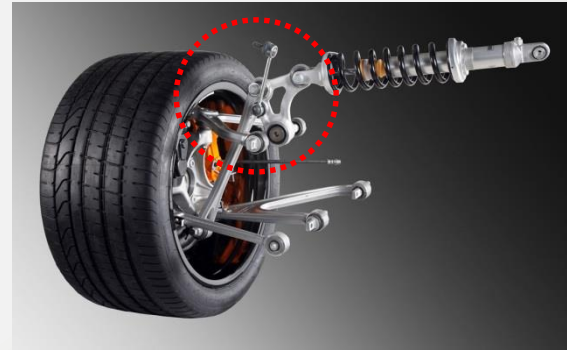
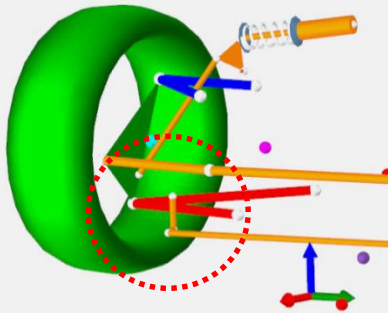
Static Values, Side View

Parameter Name	Value	Units
Wheel Base	1,550.0	mm
Mechanical Trail	24.7	mm
Swing Arm Length	4,247.7	mm
Caster Angle	6.0	degrees



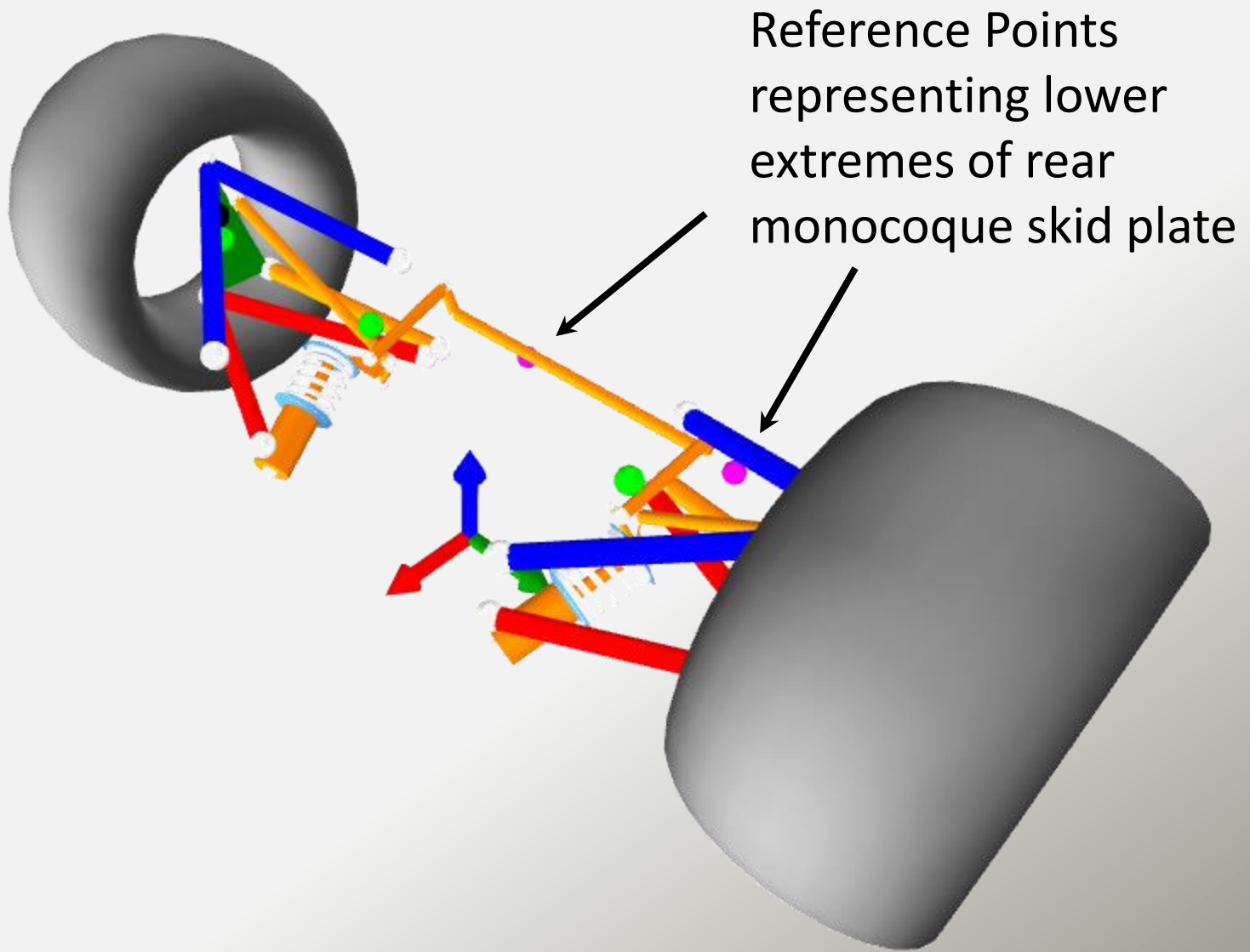
Front Suspension: Comments

- ARB attachment to lower A-arm should be considered carefully as it induces bending moments in the A-arm
- Since a rocker is used for the coilover, it should also be considered to attach the ARB to the rocker. Will result in higher structural efficiency.

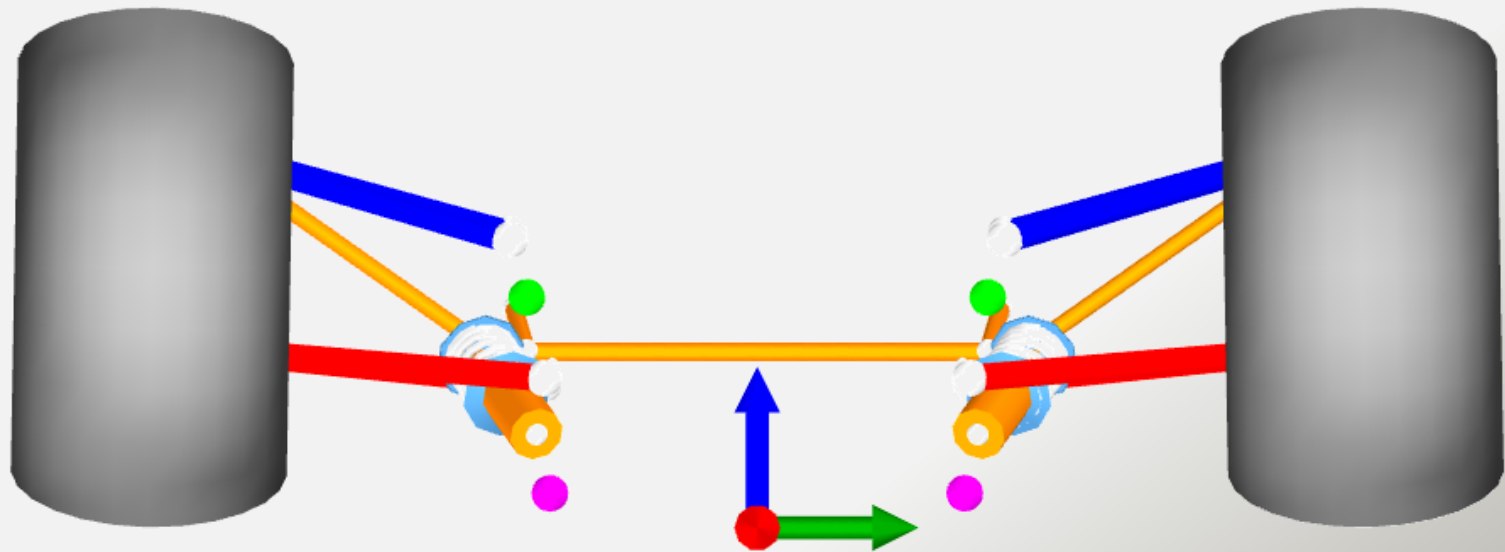


- Care should be taken with the Pushrod attachment to the lower A-arm. Lower outboard A-arm pivot, pushrod, rocker and damper should be in line and in same plane to avoid bending moments.
- Mechanical trail very high leading to high steering system loads

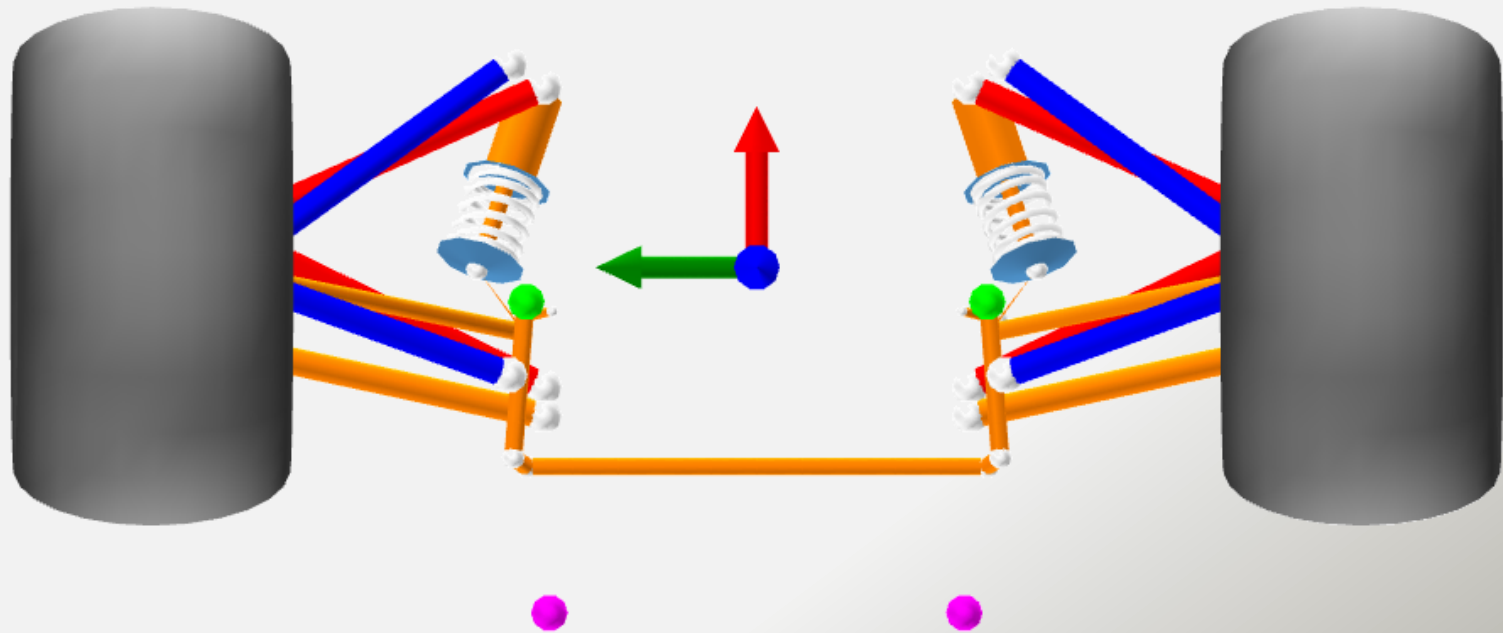
Rear Suspension: Isometric View



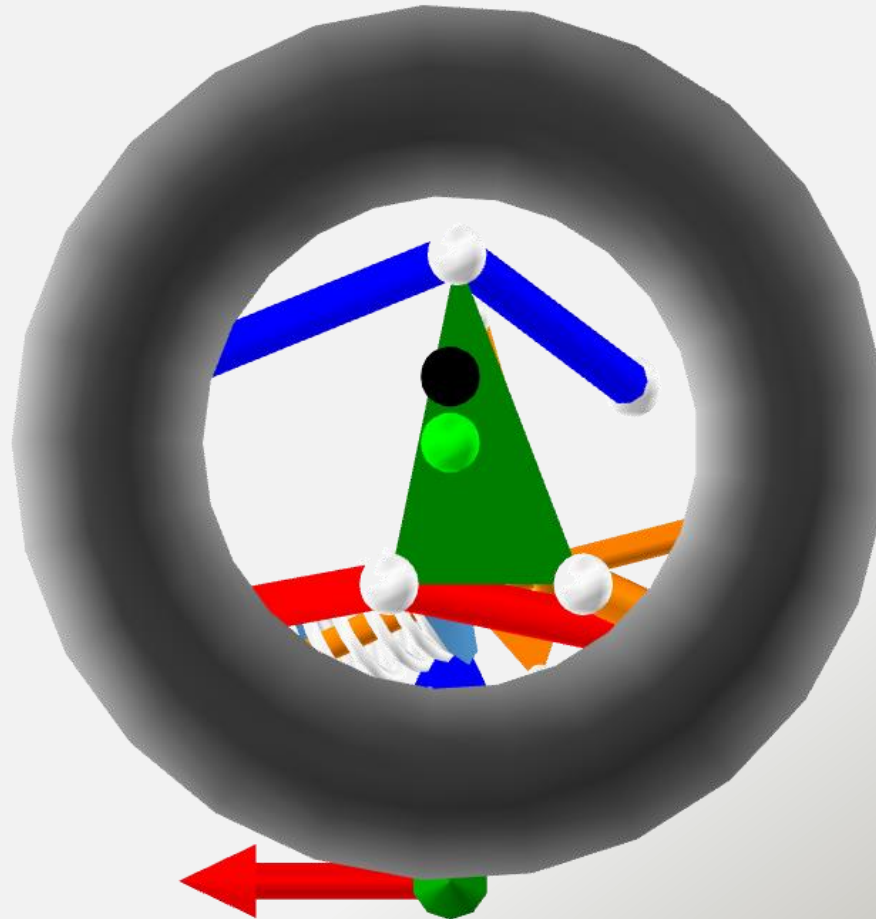
Rear Suspension: Front View



Rear Suspension: Top View



Rear Suspension: Left Side View



Reference Points
representing lower
extremes of rear
monocoque skid plate



Rear Suspension: Points Coordinates

Double A-Arm	Point Name	Left			Right		
		X	Y	Z	X	Y	Z
	CHAS_LowFor	156.500	185.000	130.000	156.500	-185.000	130.000
	CHAS_LowAft	-103.500	185.000	125.000	-103.500	-185.000	125.000
	CHAS_UppFor	176.500	215.000	250.000	176.500	-215.000	250.000
	CHAS_UppAft	-93.500	215.000	255.000	-93.500	-215.000	255.000
	UPRI_LowPnt	31.500	464.000	153.000	31.500	-464.000	153.000
	UPRI_UppPnt	-3.500	464.000	323.000	-3.500	-464.000	323.000
	CHAS_TiePnt	-128.500	185.000	125.000	-128.500	-185.000	125.000
	UPRI_TiePnt	-68.500	464.000	153.000	-68.500	-464.000	153.000

Push Pull	Point Name	Left			Right		
		X	Y	Z	X	Y	Z
	NSMA_AttPnt_L	-10.960	425.400	289.830	-10.960	-425.400	289.830
	CHAS_AttPnt_L	147.730	191.810	81.500	147.730	-191.810	81.500
	CHAS_RocAxi_L	-37.890	177.960	142.920	-37.890	-177.960	142.920
	CHAS_RocPiv_L	-45.740	208.710	101.730	-45.740	-208.710	101.730
	ROCK_RodPnt_L	-56.550	203.450	133.440	-56.550	-203.450	133.440
	ROCK_CoiPnt_L	-1.610	242.670	151.490	-1.610	-242.670	151.490

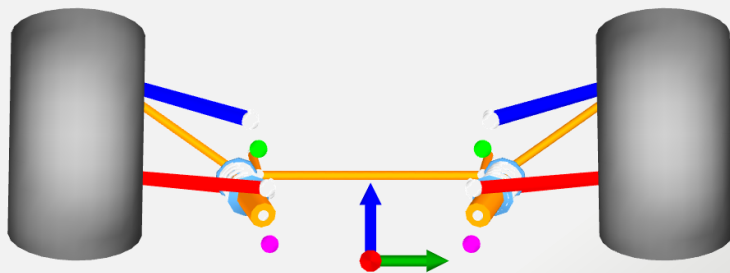
U-Bar	Point Name	Left			Right		
		X	Y	Z	X	Y	Z
	NSMA_UBarAttPnt_L	-24.600	200.350	153.940	-24.600	-200.350	153.940
	UBAR_AttPnt_L	-165.080	211.310	190.210	-165.080	-211.310	190.210
	CHAS_PivPnt_L	-172.880	199.990	152.670	-172.880	-199.990	152.670

Wheels	Point Name	Left		Right	
	Half Track	525.000		525.000	
	Longitudinal Offset	0.000		0.000	
	Lateral Offset	0.000		0.000	
	Vertical Offset	0.000		0.000	
	Static Camber	-1.000		-1.000	
	Static Toe	0.000		0.000	
	Rim Diameter	254.000		254.000	
	Tire Diameter	0.000		0.000	
	Tire Width	240.000		240.000	

Rear Suspension

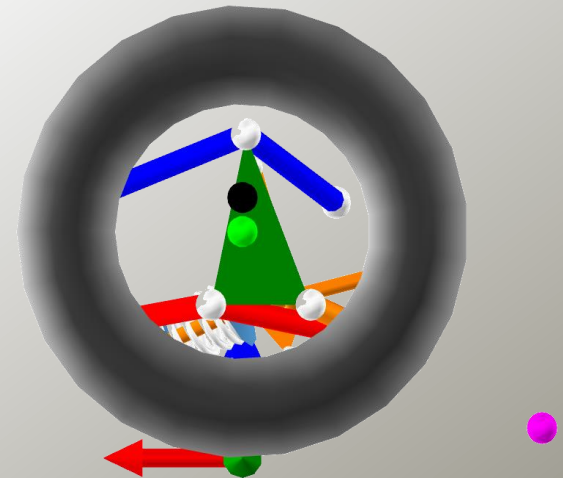
Static Values, Front View

Parameter Name	Value	Units
Track Width	1,050.0	mm
Scrub Radius	61.0	mm
Roll Center Height	37.2	mm
Swing Arm Length	972.5	mm
Camber	-1.0	degrees
Toe	0.0	degrees
King Pin Inclination	0	degrees



Static Values, Side View

Parameter Name	Value	Units
Wheel Base	1,550.0	mm
Mechanical Trail	63.0	mm
Swing Arm Length	4,816.5	mm
Caster Angle	11.6	degrees

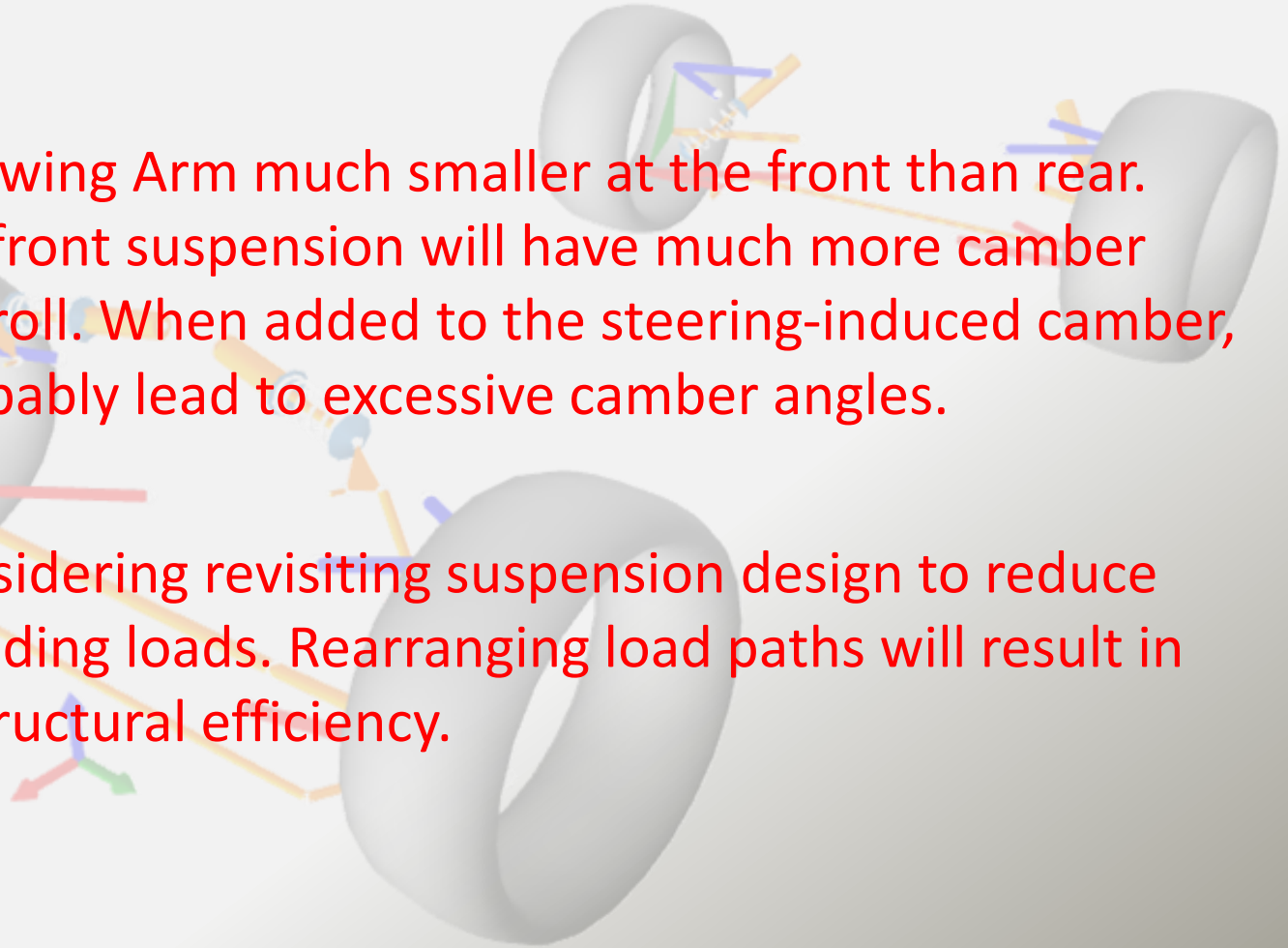


Rear Suspension: Comments

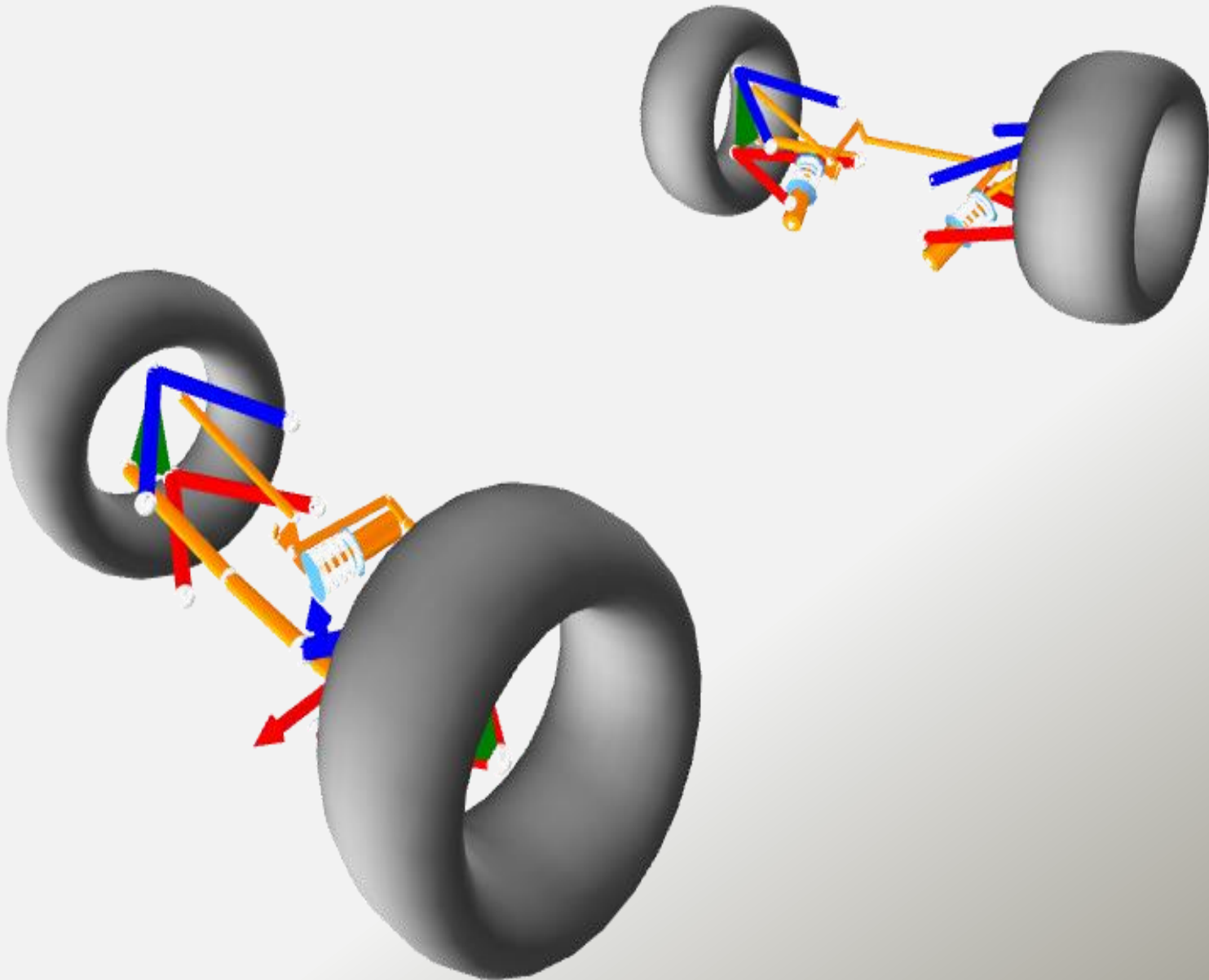
- ARB connection to the lower A-arm induces bending moments in A-arm as in the front suspension
- Coilover attachment to the lower A-arm should be aligned with axis formed by coilover attachment to the chassis and the lower A-arm outboard pickup point to minimize compliance.
- Mechanical trail high which will induce high loads into toe link

Overall Suspension Comments

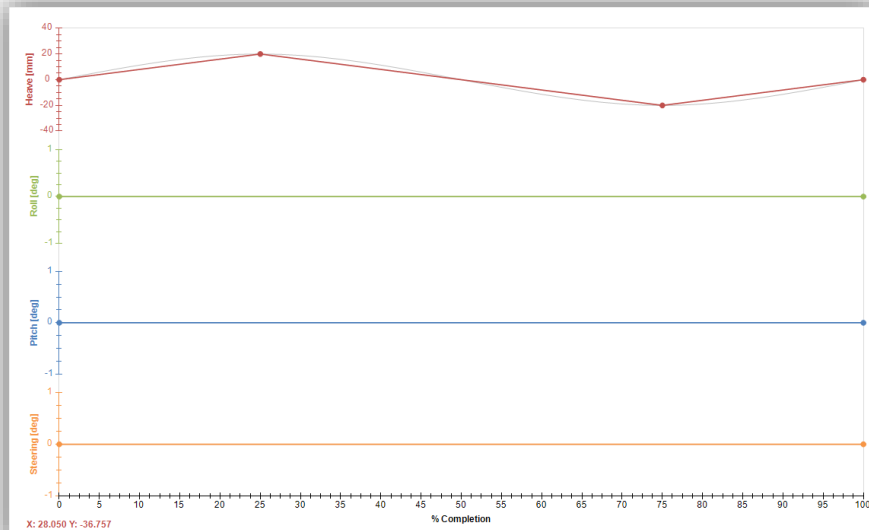
- Front view Swing Arm much smaller at the front than rear. This means front suspension will have much more camber variation in roll. When added to the steering-induced camber, this will probably lead to excessive camber angles.
- Suggest considering revisiting suspension design to reduce induced bending loads. Rearranging load paths will result in improved structural efficiency.



4. Input Motions



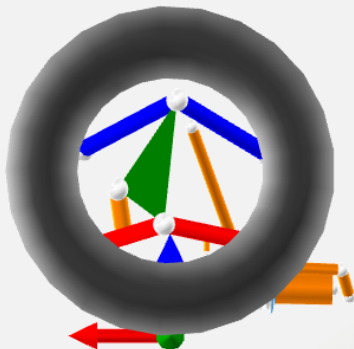
Input Motion: Pure Heave



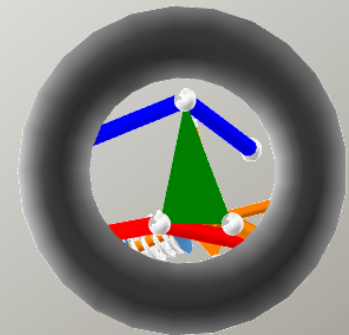
Points

☒ Heave ☐ Roll ☐ Pitch ☐ Steering

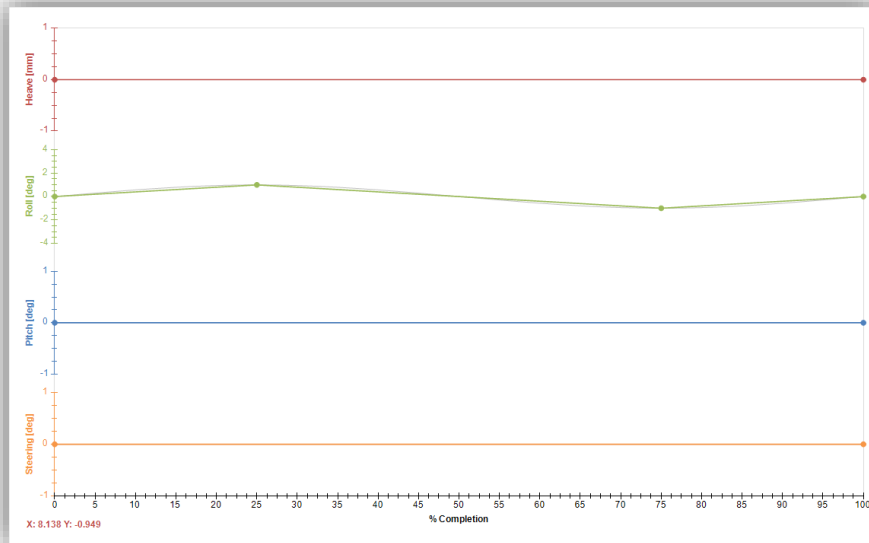
X	Y
0.000	0.000
25.000	20.000
75.000	-20.000
100.000	0.000



Positive Heave-
Chassis moving upwards



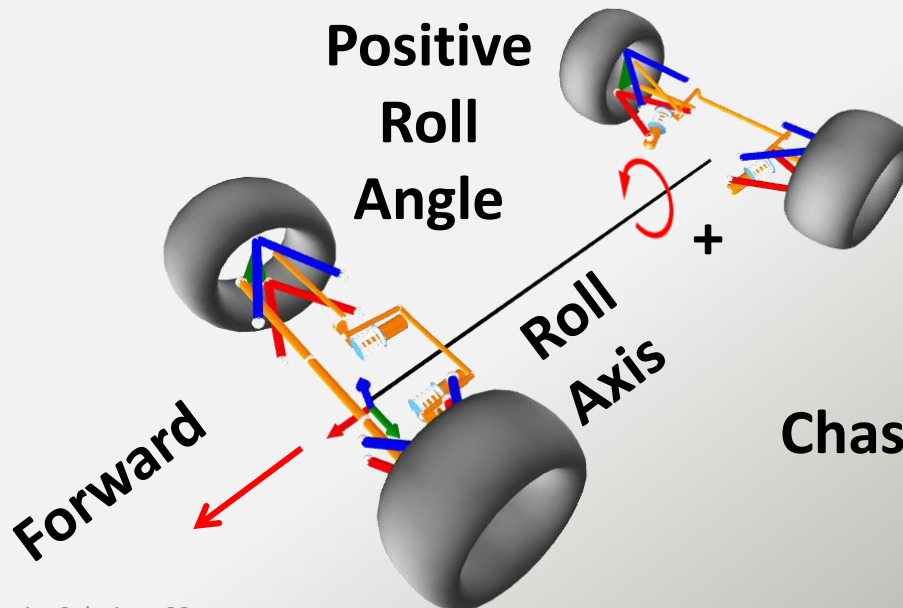
Input Motion: Pure Roll



Points

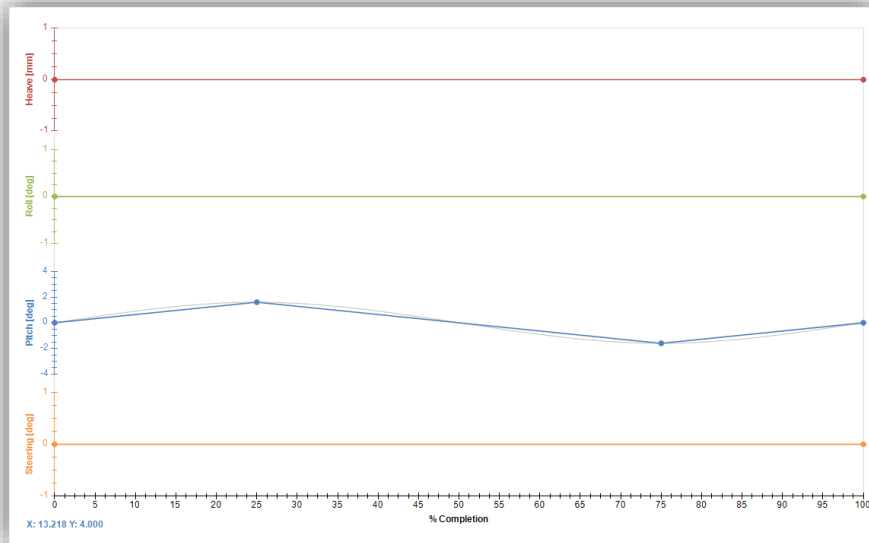
☐ Heave ☒ Roll ☐ Pitch ☐ Steering

X	Y
0.000	0.000
25.000	1.000
75.000	-1.000
100.000	0.000



**Positive Roll =
Chassis rolling to the right**

Input Motion: Pure Pitch



Points

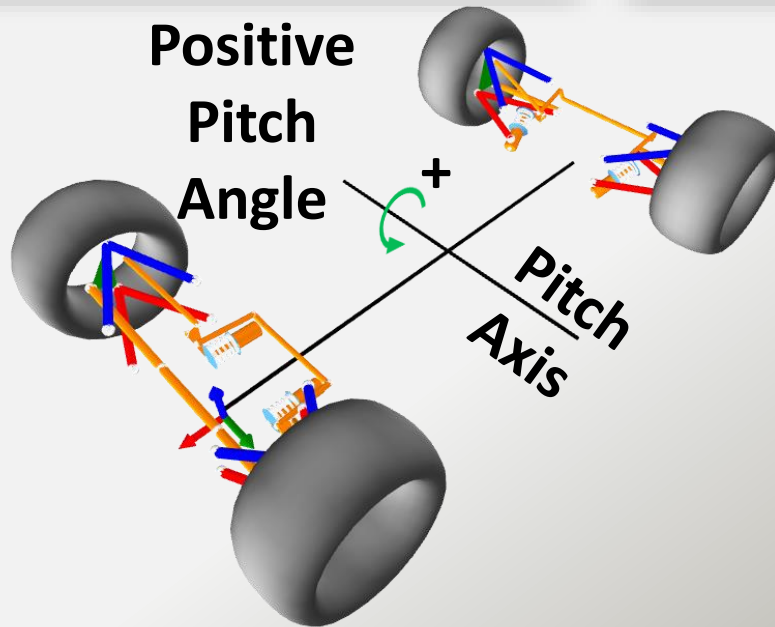
☐ Heave

☐ Roll

☒ Pitch

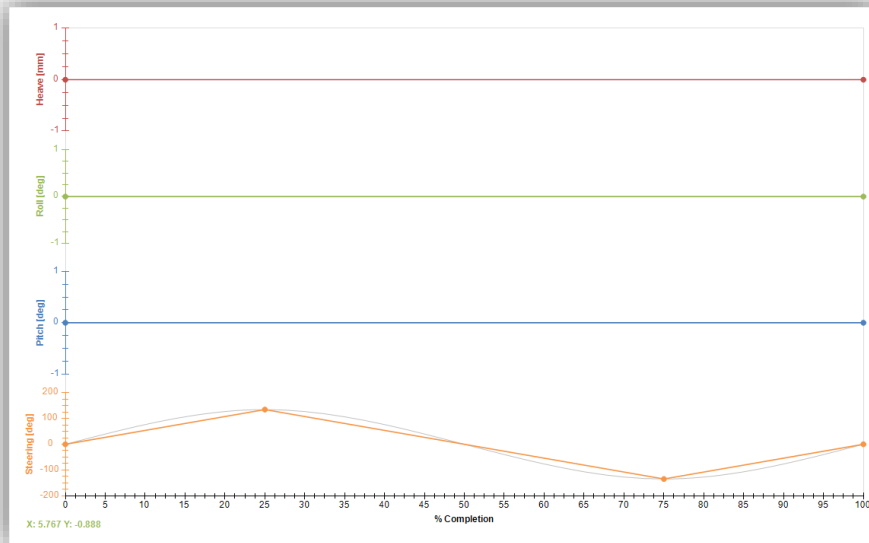
☐ Steering

X	Y
0.000	0.000
25.000	1.600
75.000	-1.600
100.000	0.000



**Positive Pitch =
Chassis pitching forward**

Input Motion: Pure Steer



Points

☐ Heave ☐ Roll ☐ Pitch ☒ Steering

X

Y

0.000

0.000

25.000

135.000

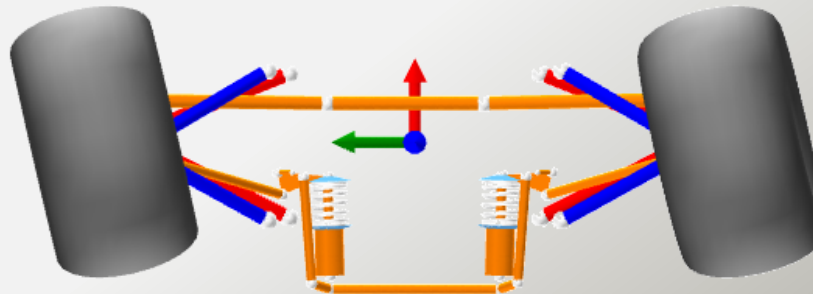
75.000

-135.000

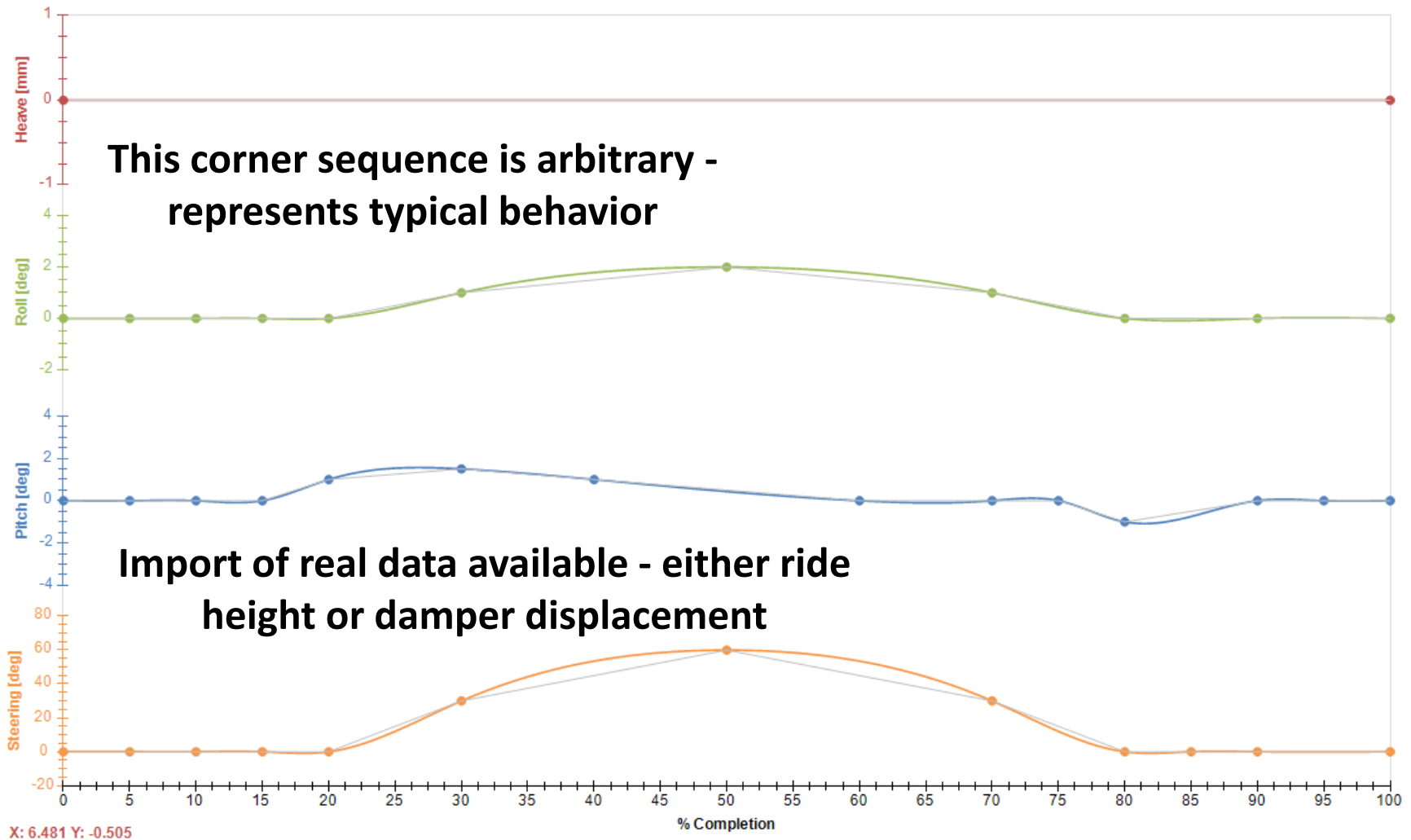
100.000

0.000

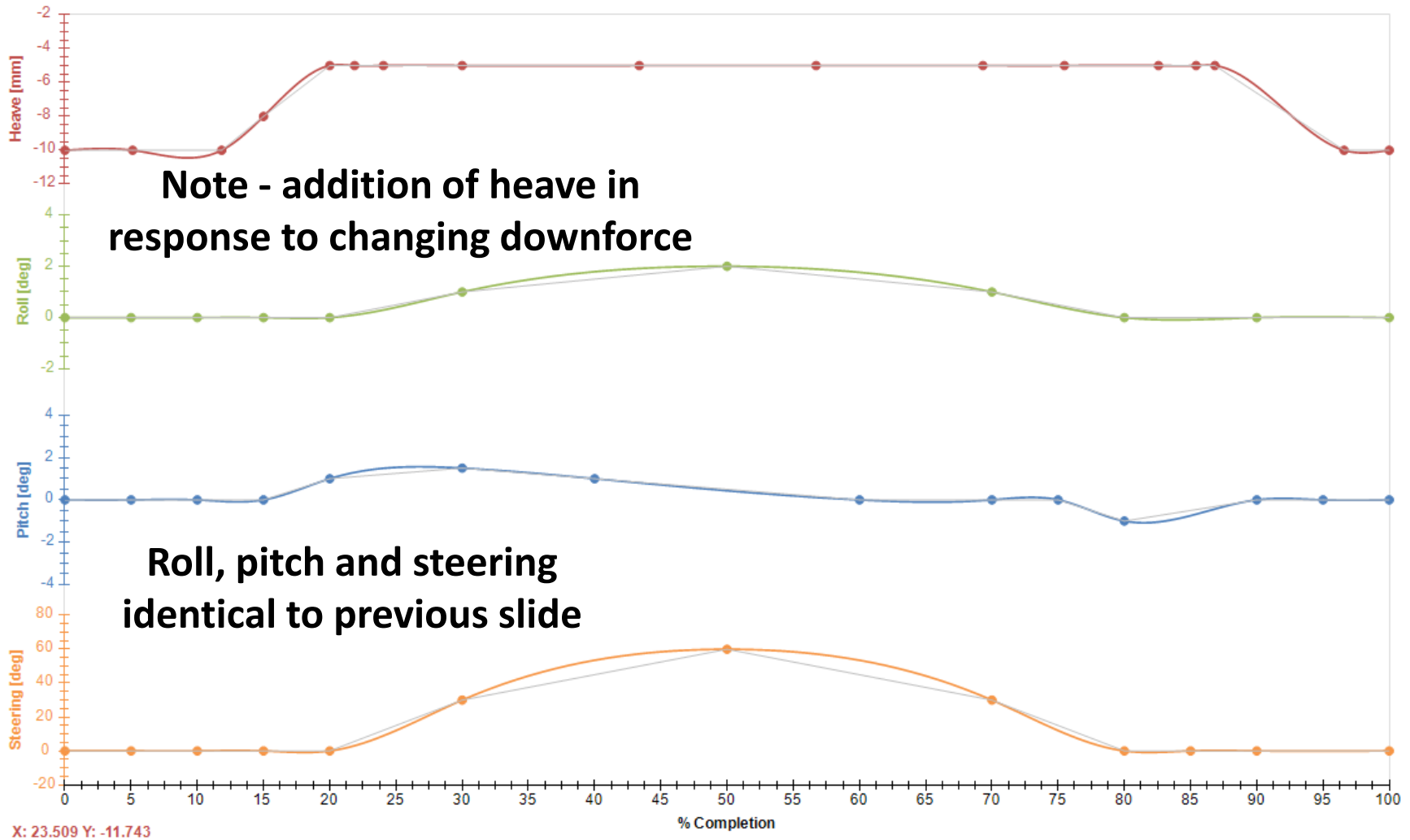
**Positive Steer-
Wheels turning left**



Input Motion: Corner Without Downforce



Input Motion: Corner With Downforce



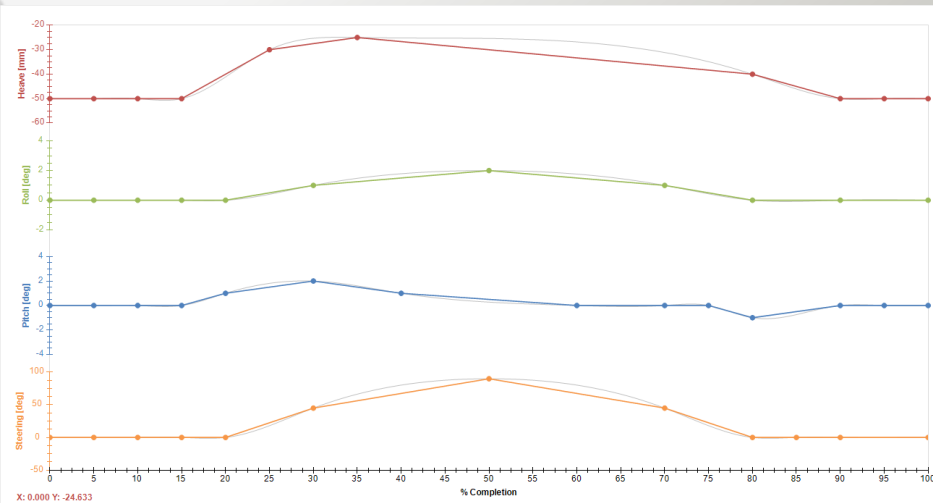
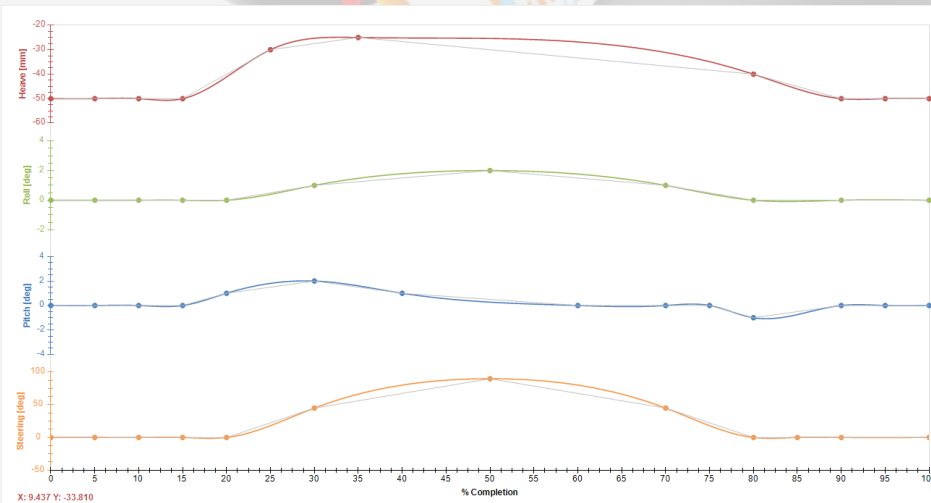
Cubic Spline Feature

Smooth out motion input: optional

▢ Default Parameters	
Number of Steps	20
▢ Interpolation	
Cubic Spline	☒ True
▢ Overrides Parameters	
Number of Steps	100
Overrides Number of Steps	☒ True

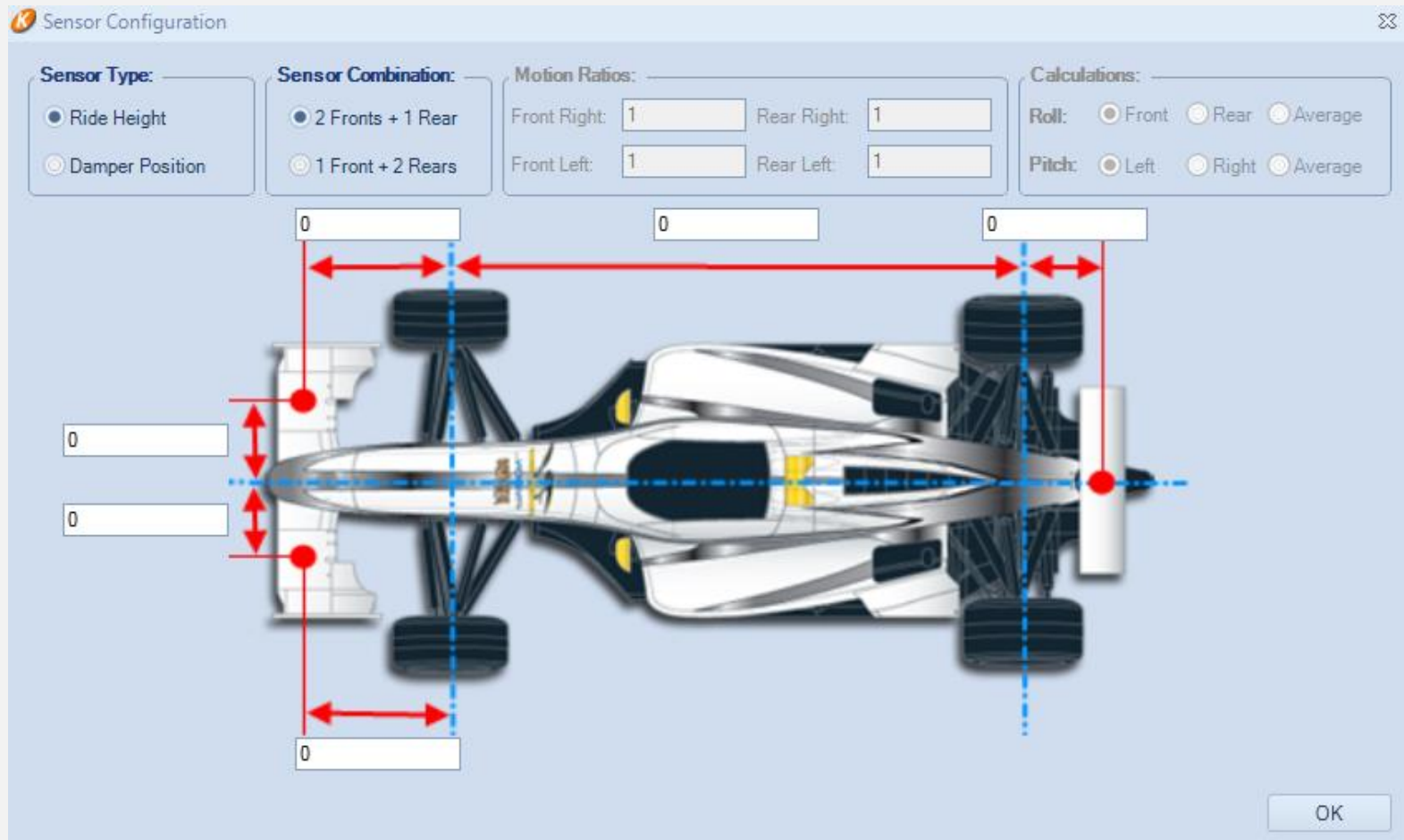
Cubic Interpolation

Linear Interpolation



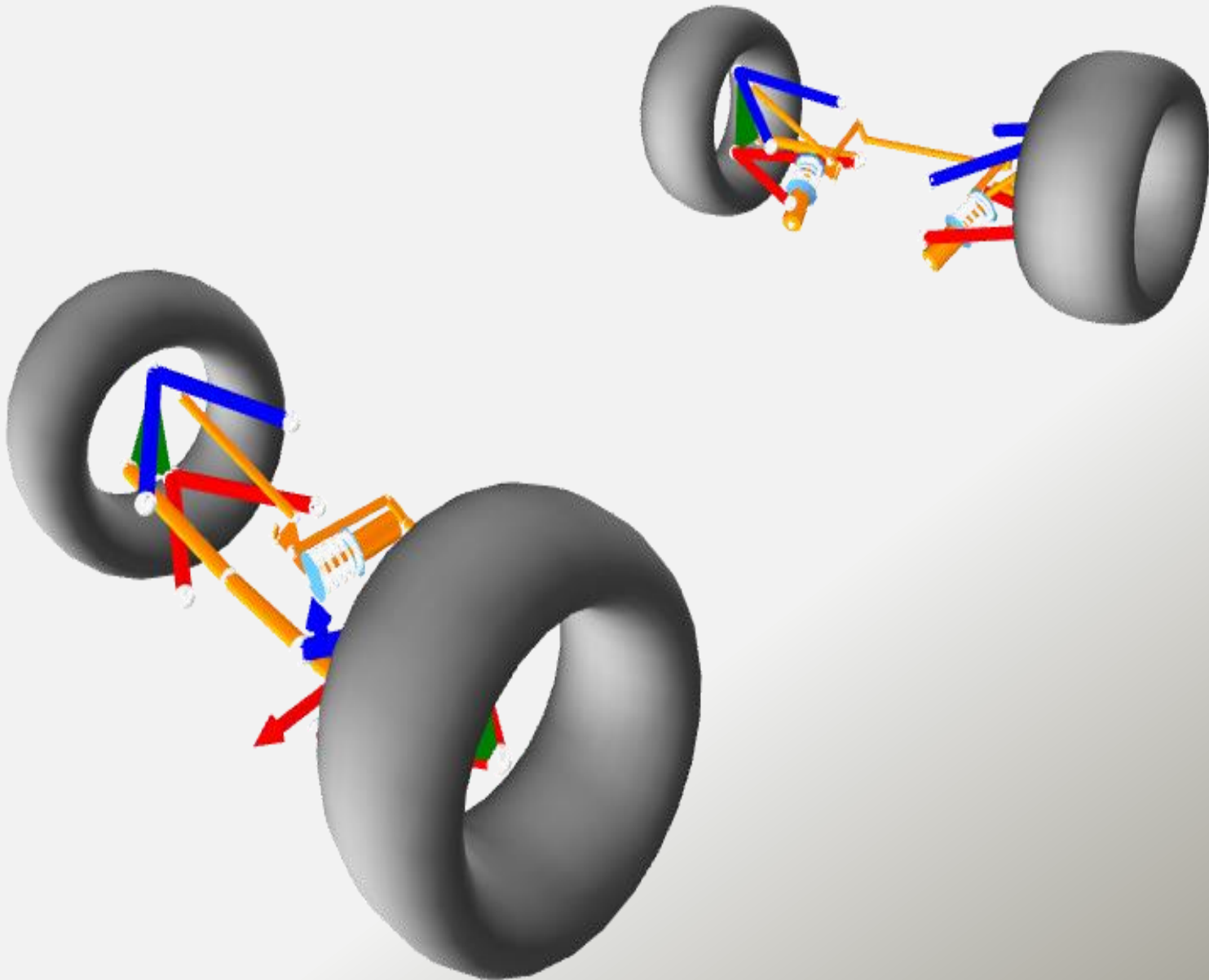
Input Motion: Import Data

Import either damper displacement or ride height sensor data. Can then playback kinematics based on actual data



Note- compliance neglected and motion ratios for input data constant

5. Output Options



Basic Simulation Outputs

- Wheel Orientation:

- Camber
- Toe

- Vehicle:

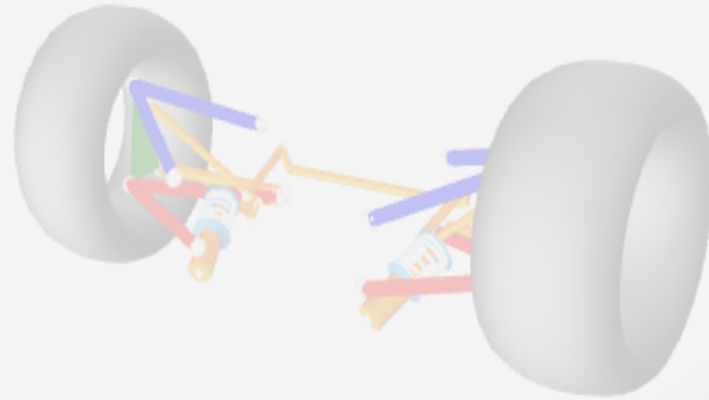
- Half-Track
- Ground Clearance
- Wheel Rates
- Spring Motion Ratio
- ARB Motion Ratio

- Steering Geometry:

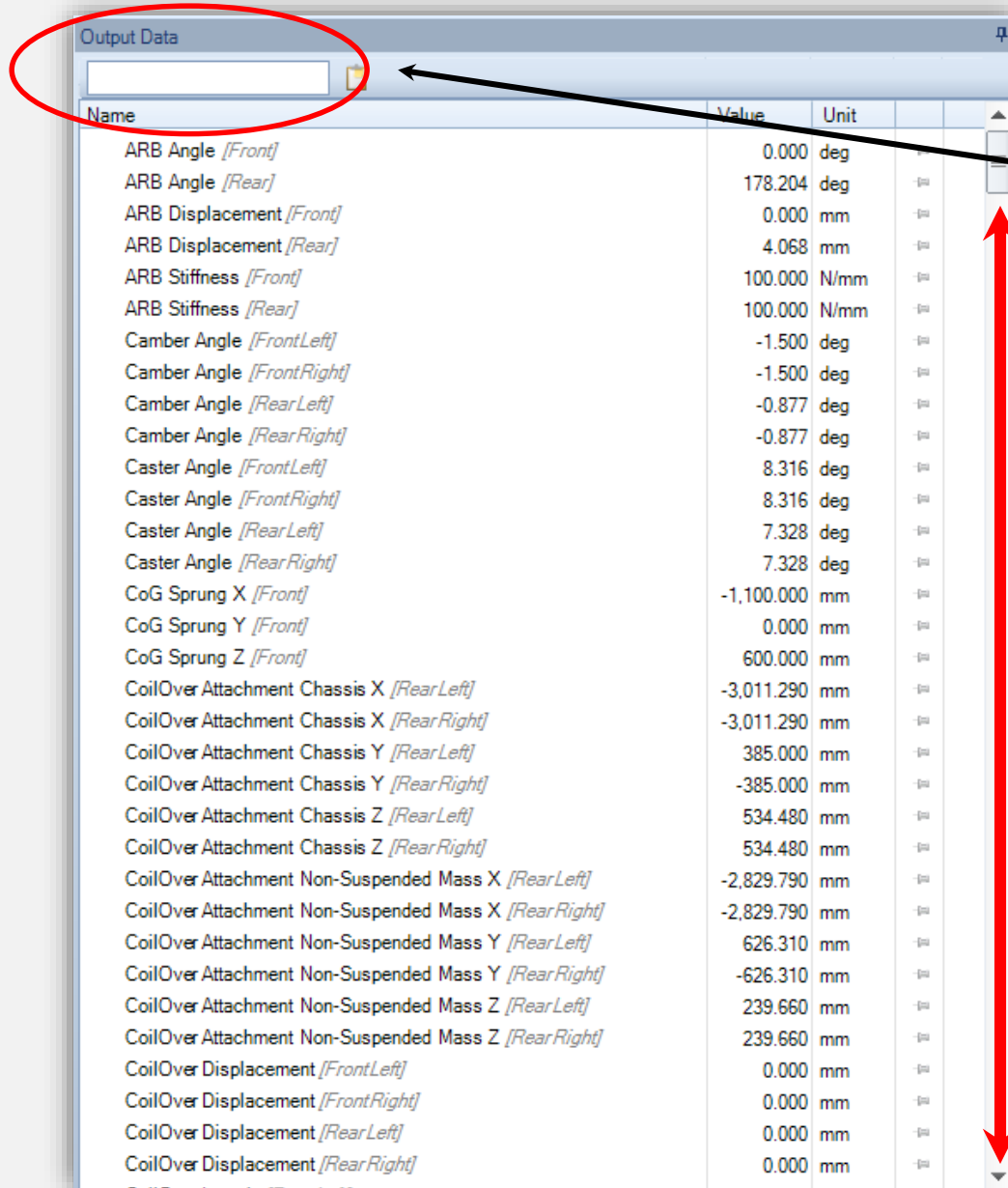
- Caster Angle
- Mechanical Trail
- Scrub Radius
- Steering Angle

- Drive Shaft Length
- 1st Magic Number
- Instant Center Angles
- Roll Center Migration
- Pitch Center Migration

- Ackermann Percentage
- Steering Ratio



Advanced Simulation Outputs



Name	Value	Unit
ARB Angle [Front]	0.000	deg
ARB Angle [Rear]	178.204	deg
ARB Displacement [Front]	0.000	mm
ARB Displacement [Rear]	4.068	mm
ARB Stiffness [Front]	100.000	N/mm
ARB Stiffness [Rear]	100.000	N/mm
Camber Angle [FrontLeft]	-1.500	deg
Camber Angle [FrontRight]	-1.500	deg
Camber Angle [RearLeft]	-0.877	deg
Camber Angle [RearRight]	-0.877	deg
Caster Angle [FrontLeft]	8.316	deg
Caster Angle [FrontRight]	8.316	deg
Caster Angle [RearLeft]	7.328	deg
Caster Angle [RearRight]	7.328	deg
CoG Sprung X [Front]	-1,100.000	mm
CoG Sprung Y [Front]	0.000	mm
CoG Sprung Z [Front]	600.000	mm
CoilOver Attachment Chassis X [RearLeft]	-3,011.290	mm
CoilOver Attachment Chassis X [RearRight]	-3,011.290	mm
CoilOver Attachment Chassis Y [RearLeft]	385.000	mm
CoilOver Attachment Chassis Y [RearRight]	-385.000	mm
CoilOver Attachment Chassis Z [RearLeft]	534.480	mm
CoilOver Attachment Chassis Z [RearRight]	534.480	mm
CoilOver Attachment Non-Suspended Mass X [RearLeft]	-2,829.790	mm
CoilOver Attachment Non-Suspended Mass X [RearRight]	-2,829.790	mm
CoilOver Attachment Non-Suspended Mass Y [RearLeft]	626.310	mm
CoilOver Attachment Non-Suspended Mass Y [RearRight]	-626.310	mm
CoilOver Attachment Non-Suspended Mass Z [RearLeft]	239.660	mm
CoilOver Attachment Non-Suspended Mass Z [RearRight]	239.660	mm
CoilOver Displacement [FrontLeft]	0.000	mm
CoilOver Displacement [FrontRight]	0.000	mm
CoilOver Displacement [RearLeft]	0.000	mm
CoilOver Displacement [RearRight]	0.000	mm

Search bar very useful due to large number of output variables

Only small sample of available outputs shown

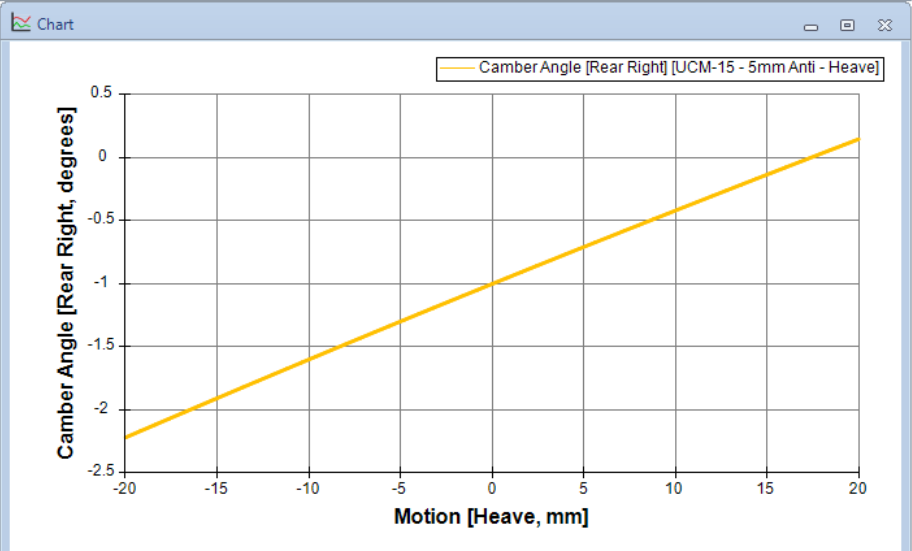
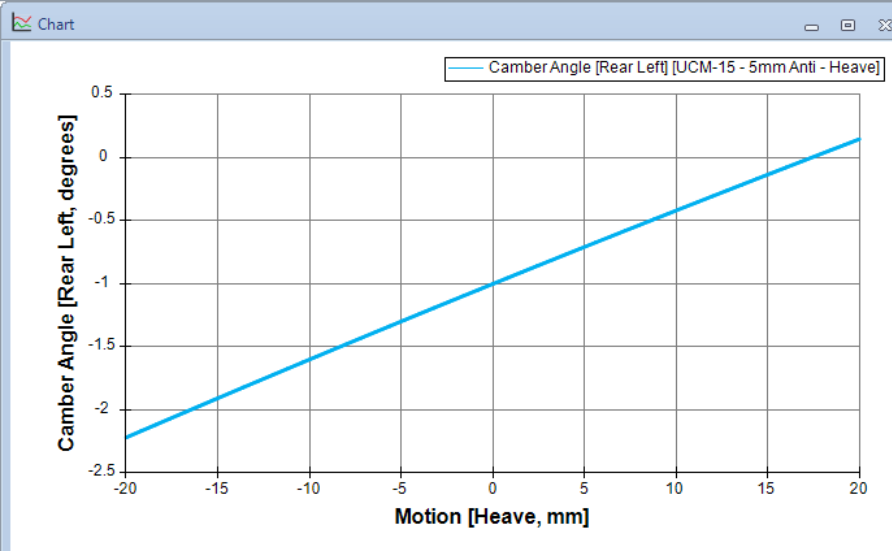
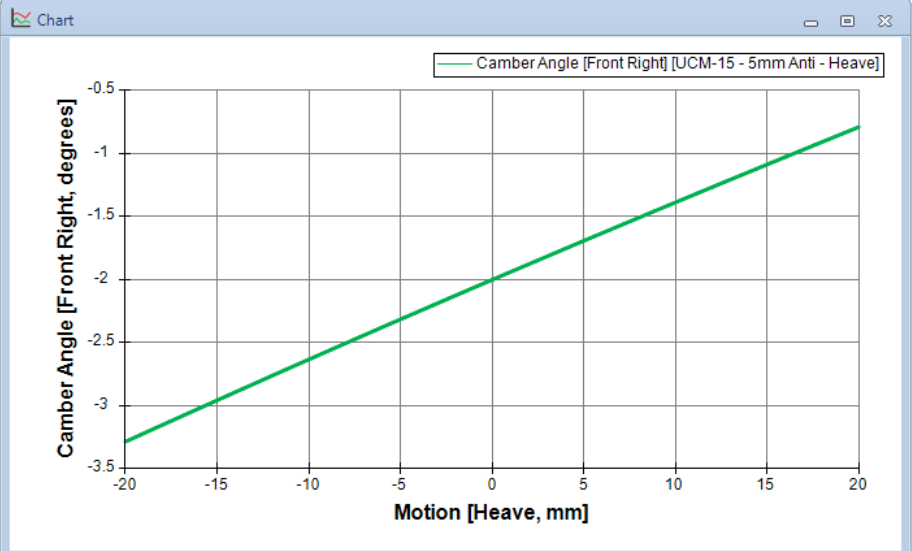
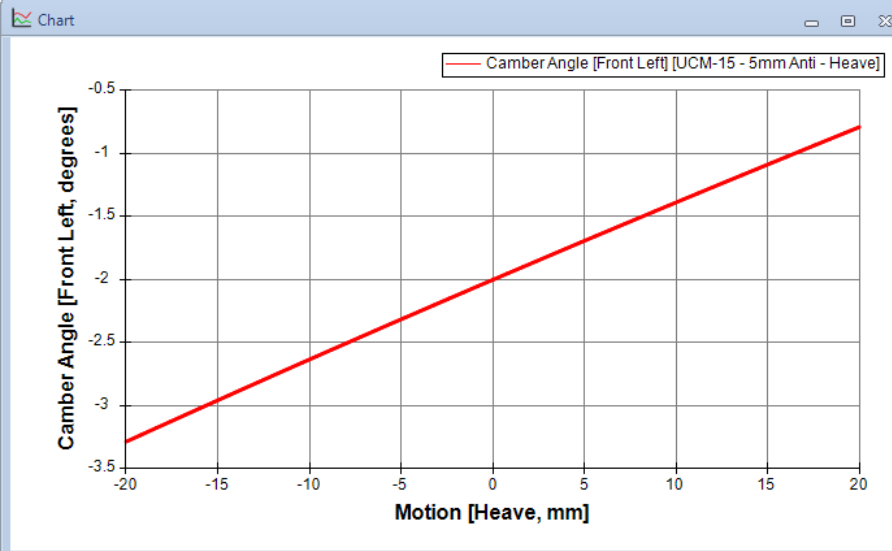
Visualizing Simulation Outputs

- OptimumKinematics offers four ways of visualizing outputs:
 - Table
 - Chart
 - 3D View
 - Worksheets
- A worksheet can be created to group relevant tables, charts and 3D views.

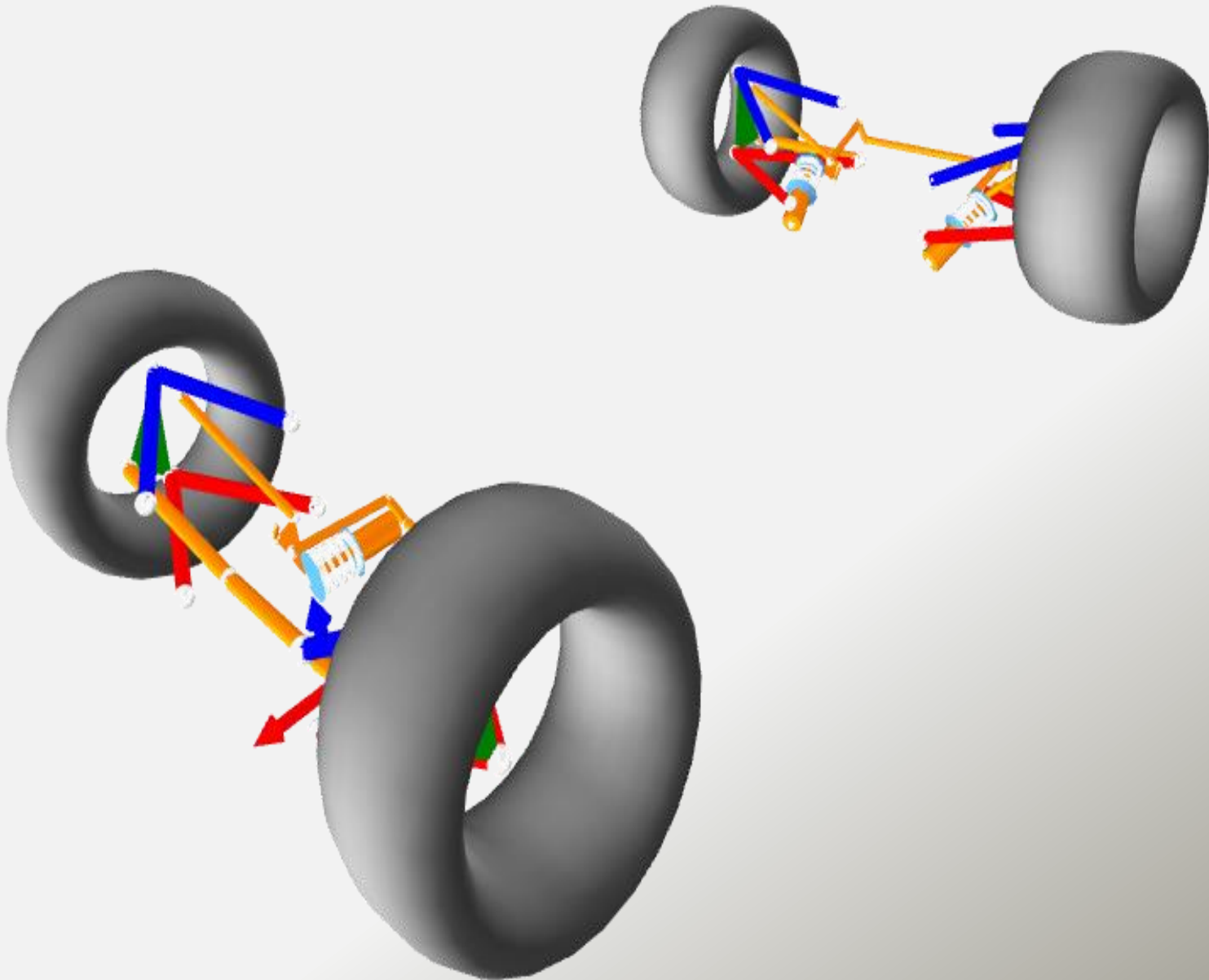
Tables

Table						
Input Data						
Quick Search						
☐ Lower A-Arm Chassis Fore X [Front Left] ☐ Lower A-Arm Chassis Fore Y [Front Left] ☐ Lower A-Arm Chassis Fore Z [Front Left] ☐ Lower A-Arm Chassis Aft X [Front Left] ☐ Lower A-Arm Chassis Aft Y [Front Left] ☐ Lower A-Arm Chassis Aft Z [Front Left] ☐ Upper A-Arm Chassis Fore X [Front Left] ☐ Upper A-Arm Chassis Fore Y [Front Left] ☐ Upper A-Arm Chassis Fore Z [Front Left] ☐ Upper A-Arm Chassis Aft X [Front Left] ☐ Upper A-Arm Chassis Aft Y [Front Left]						
Quick Search ☐ Compare						
UCM-15 UCM-15 Result ☒ UCM-15 - 5mm Anti - Heave ☐ UCM-15 - 5mm Anti - Roll ☐ UCM-15 - 5mm Anti - Pitch ☐ UCM-15 - 5mm Anti - Steering ☐ UCM-15 - 5mm Anti - Corner - No DF ☐ UCM-15 - 5mm Anti - Corner - With DF Bump Steer Iteration ☐ New Heave ☐ New Roll ☐ New Pitch ☐ New Steering ☐ New Corner - No DF ☐ New Corner - With DF Track MR 1-1 - Roll A - Pitch A Track MR 1.2-0.8 - Roll A - Pitch A Track MR 1.2-0.8 - Roll F - Pitch A Track MR 1-1 - Roll F - Pitch A Track MR 1-1 - Roll R - Pitch A Track FSAE Track FSAE Skidpad ☐ FSAE Motion ☐ Absolute Ride Heights Pictures ☐ Steering						
	Camber Angle [Front Left] UCM-15 - 5mm Anti - Heave	Half Track [Front Left] UCM-15 - 5mm Anti - Heave	Caster Angle [Front Left] UCM-15 - 5mm Anti - Heave	Scrub Radius [Front Left] UCM-15 - 5mm Anti - Heave	FL Wing Lower Corner Z [Front] UCM-15 - 5mm Anti - Heave	
Maximum Value	-0.788	525.470	6.314	38.242	50.000	
Minimum Value	-3.284	523.300	5.777	38.028	10.000	
Average Value	-2.012	524.795	6.044	38.179	30.000	
Start Value	-2.000	525.000	6.044	38.200	30.000	
End Value	-2.000	525.000	6.044	38.200	30.000	
Max Absolute Value	3.284	525.470	6.314	38.242	50.000	
Variance Value	0.514	0.419	0.024	0.004	132.119	
Std Deviation Value	0.717	0.647	0.154	0.063	11.494	
Step [0]	-2.000	525.000	6.044	38.200	30.000	
Step [1]	-1.950	524.956	6.033	38.204	30.800	
Step [2]	-1.901	524.910	6.023	38.208	31.600	
Step [3]	-1.851	524.862	6.012	38.211	32.400	
Step [4]	-1.802	524.812	6.001	38.215	33.200	
Step [5]	-1.752	524.760	5.990	38.218	34.000	
Step [6]	-1.703	524.706	5.980	38.221	34.800	
Step [7]	-1.654	524.650	5.969	38.224	35.600	
Step [8]	-1.605	524.592	5.958	38.226	36.400	
Step [9]	-1.556	524.532	5.948	38.228	37.200	
Step [10]	-1.507	524.470	5.937	38.231	38.000	
Step [11]	-1.459	524.406	5.926	38.233	38.800	
Step [12]	-1.410	524.340	5.916	38.234	39.600	
Step [13]	-1.362	524.272	5.905	38.236	40.400	
Step [14]	-1.313	524.202	5.894	38.237	41.200	
Step [15]	-1.265	524.130	5.883	38.239	42.000	
Step [16]	-1.217	524.056	5.873	38.240	42.800	
Step [17]	-1.169	523.980	5.862	38.241	43.600	
Step [18]	-1.121	523.902	5.851	38.241	44.400	
Step [19]	-1.073	523.822	5.841	38.242	45.200	
Step [20]	-1.026	523.740	5.830	38.242	46.000	
Step [21]	-0.978	523.656	5.819	38.242	46.800	
Step [22]	-0.930	523.570	5.809	38.242	47.600	
Step [23]	-0.883	523.482	5.798	38.242	48.400	
Step [24]	-0.836	523.392	5.787	38.241	49.200	
Step [25]	-0.788	523.300	5.777	38.241	50.000	

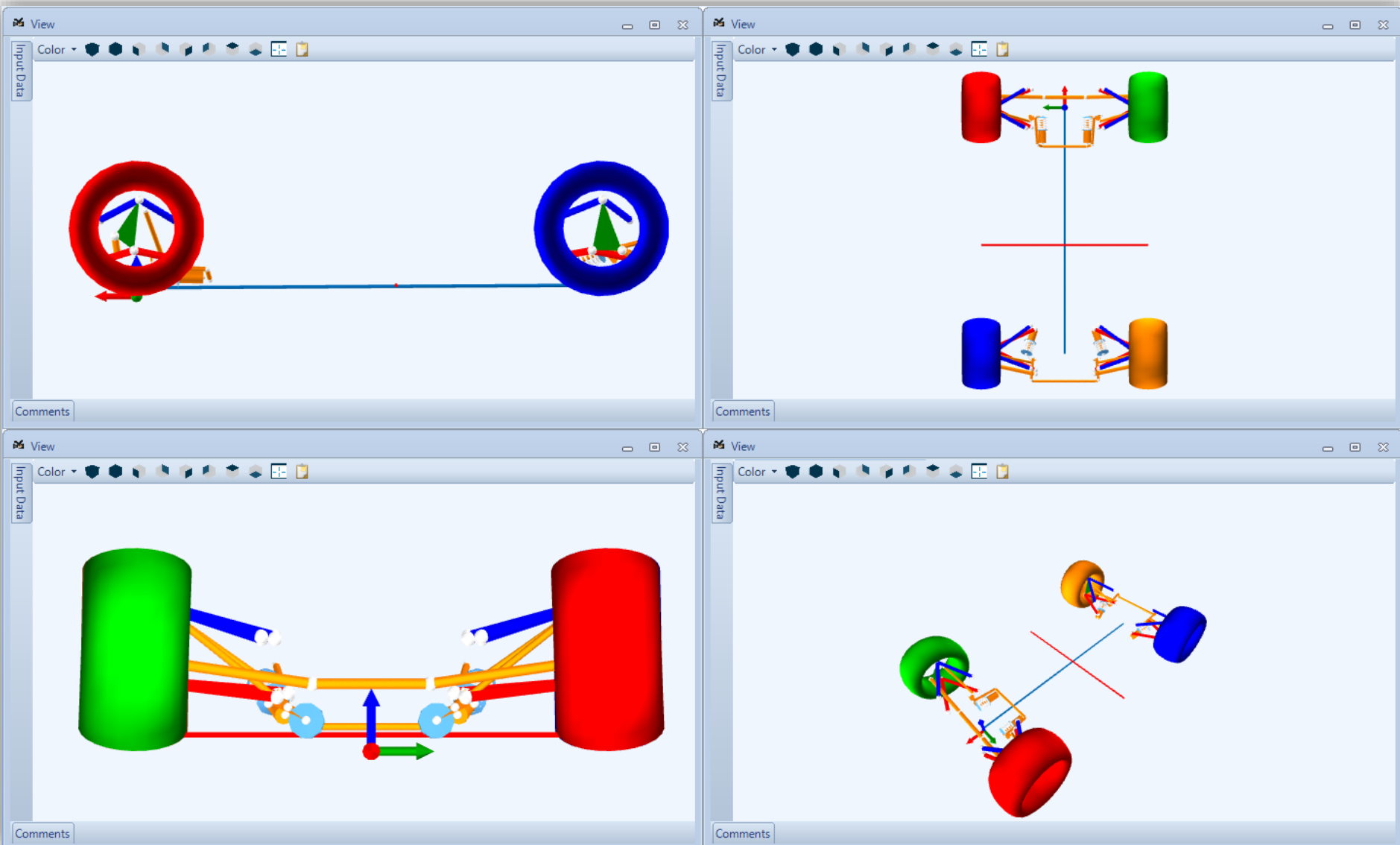
Charts



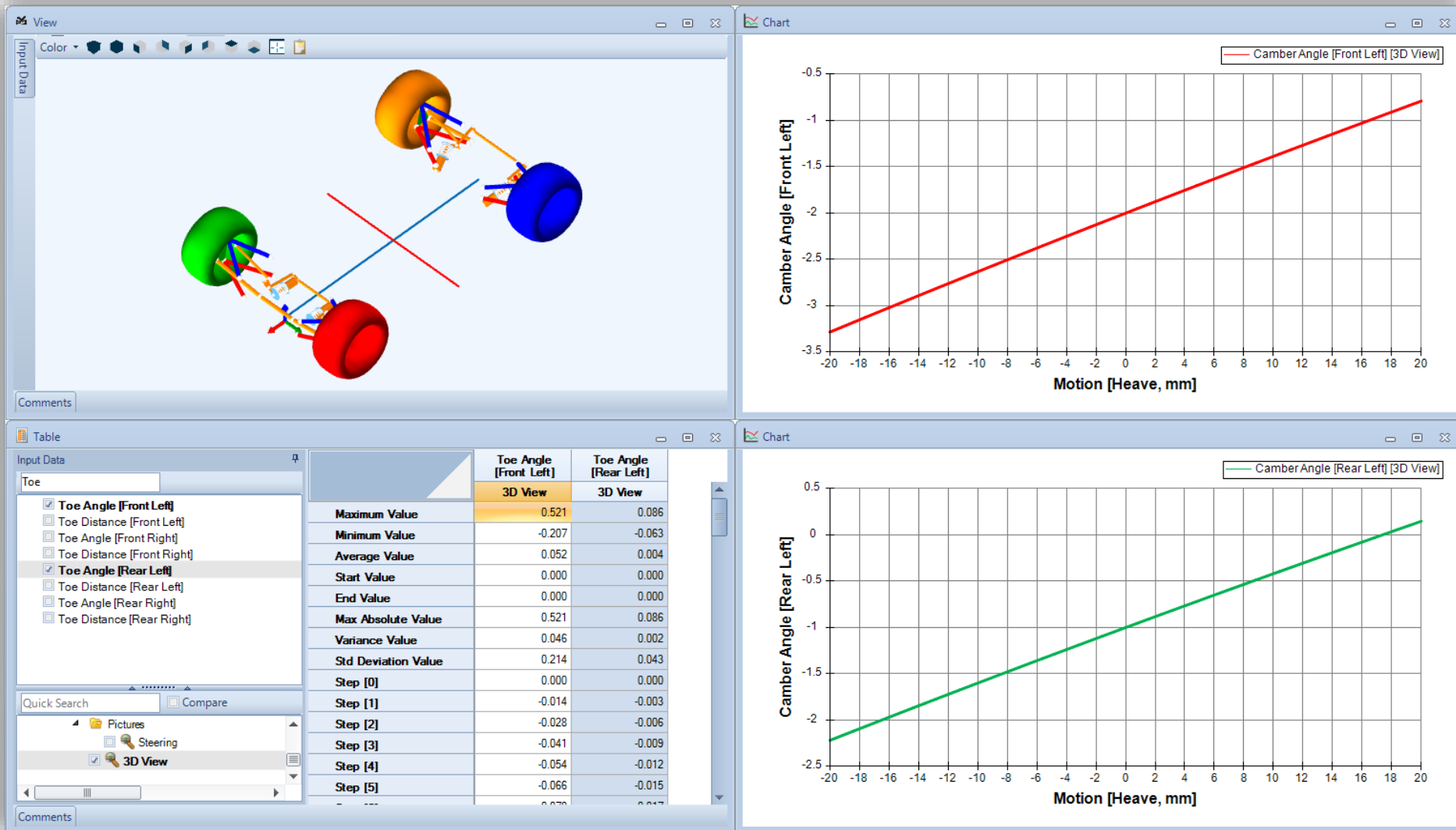
Three Dimensional View



Three Dimensional View



Worksheet



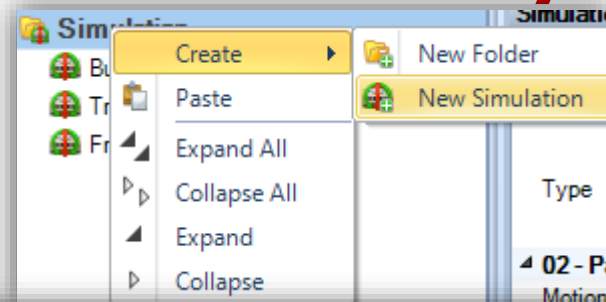
Creating an Iterative Study

OptimumKinematics allows any input parameter to be varied across any combination of simulations. This allows the effect of varying a parameter on the kinematics to be visualized.

An example will be shown where the vertical (Z) attachment point of the outer tie rod on the front left upright will be varied, attempting to reduce bump steer in heave.

Creating an Iterative Study

In the simulation
tab, create new
simulation

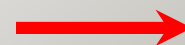


	Front Suspension Double A-Arm Tierod Left Upright Z
Default Values	200.840
Iteration 1	195.840
Iteration 2	205.840
Iteration 3	200.840

Select Multiple
Iterations



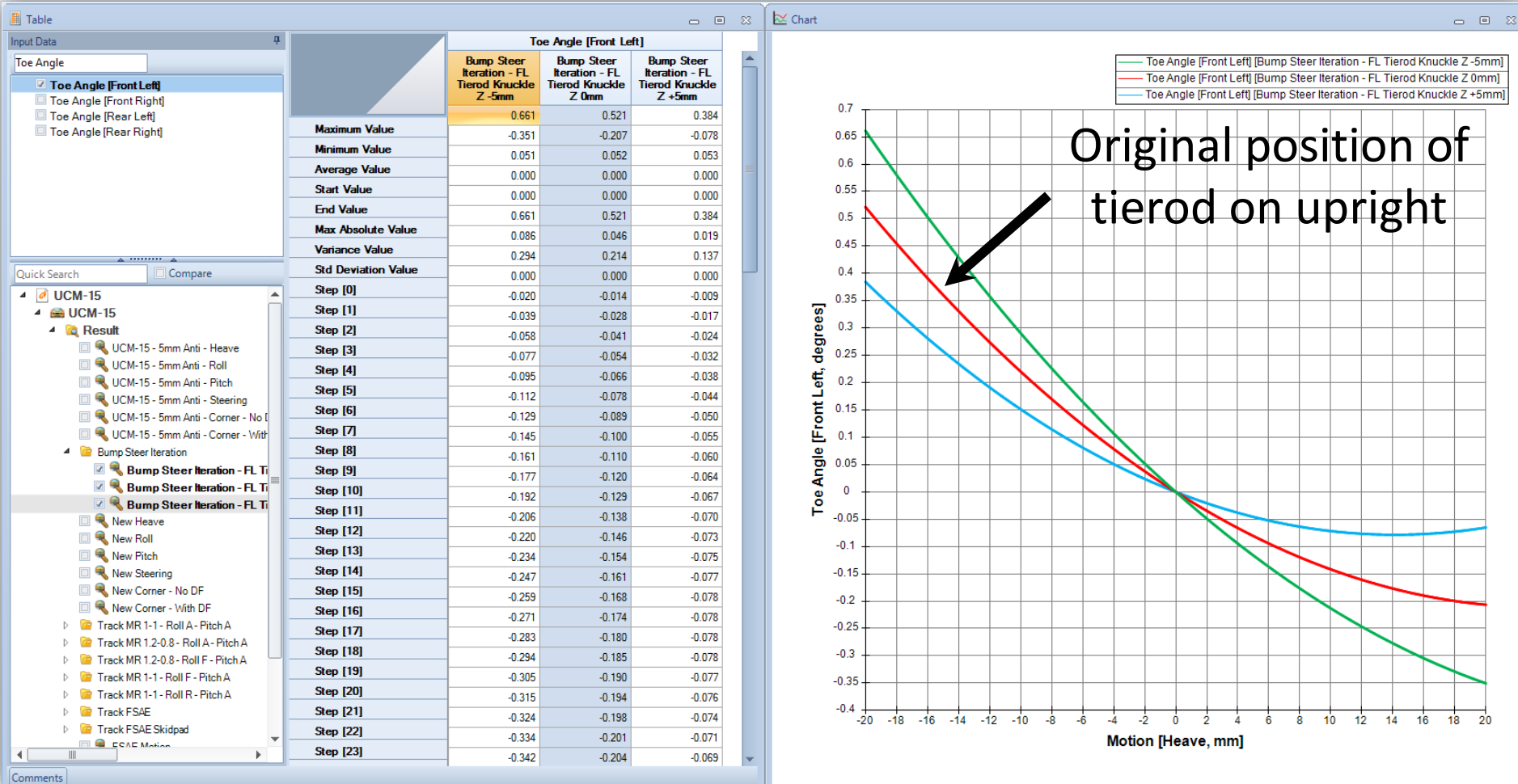
Define Parameter



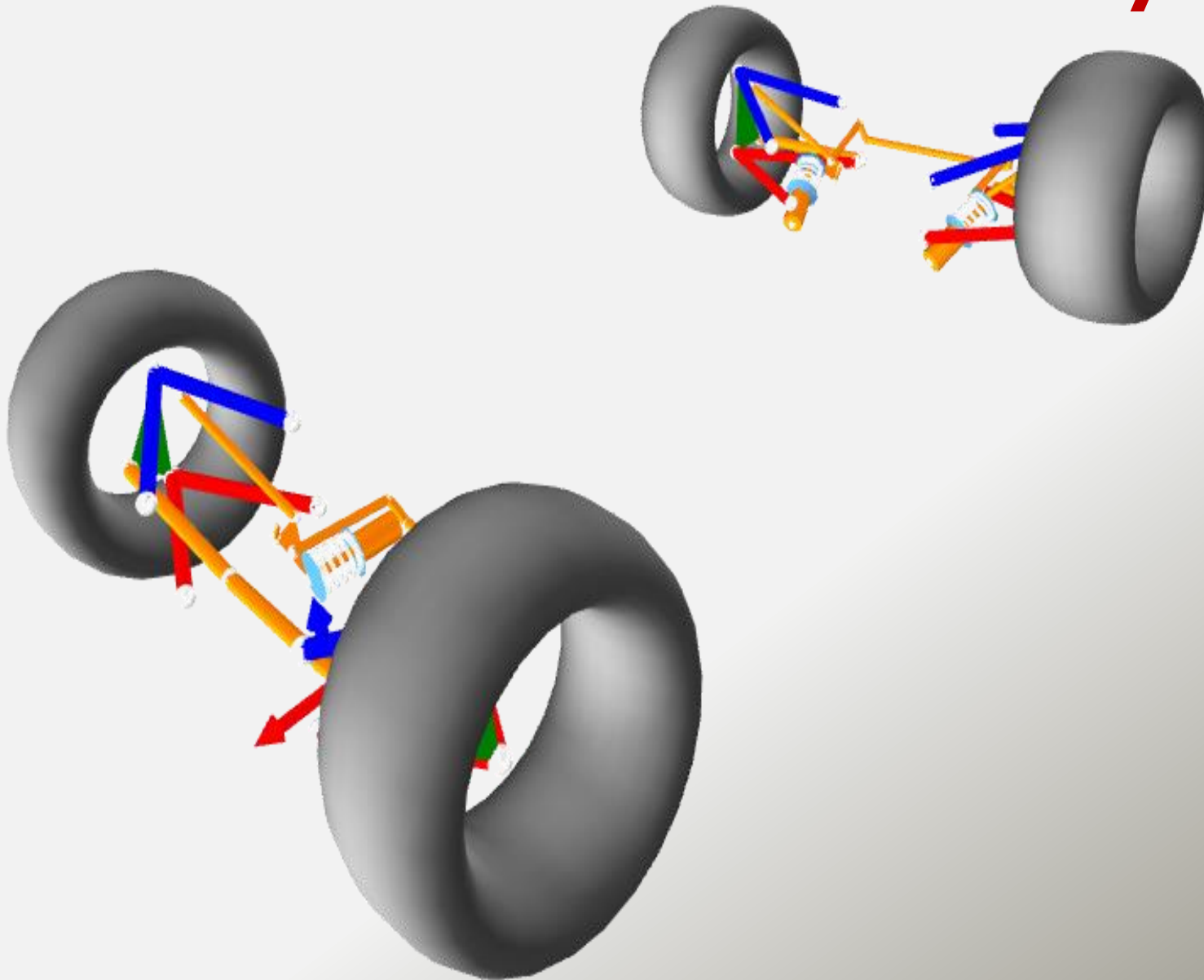
Add Number and
Value of Iterations as
Required

Creating an Iterative Study

Results can be displayed as a table or plot



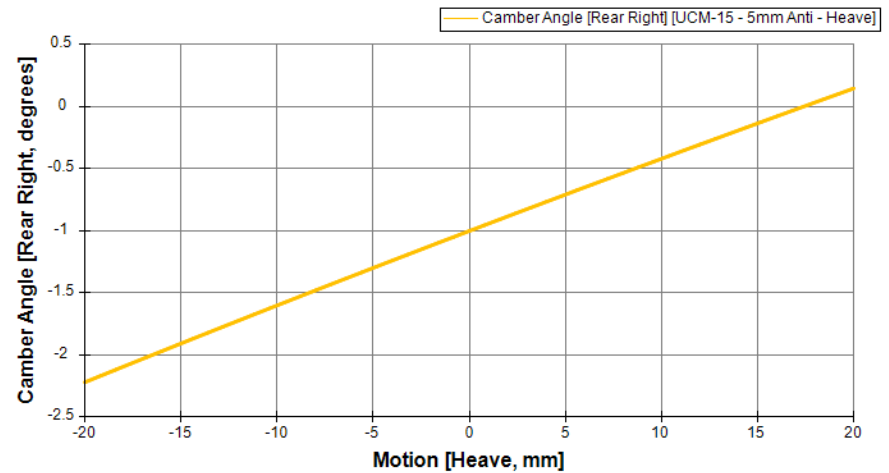
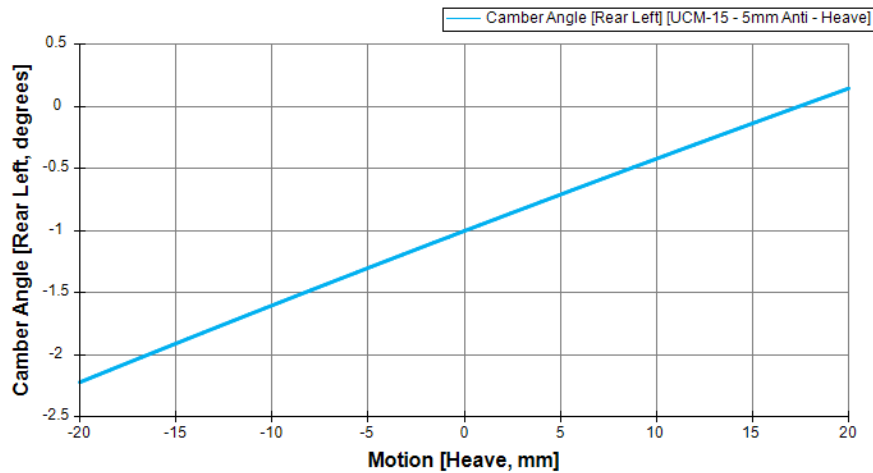
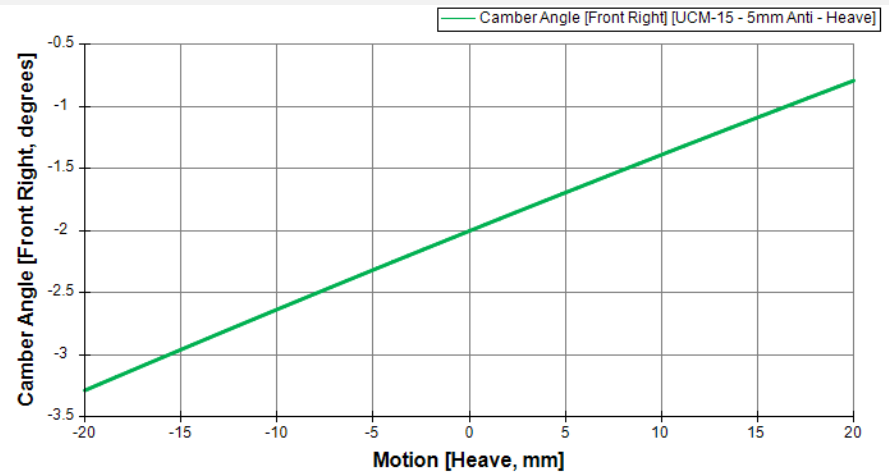
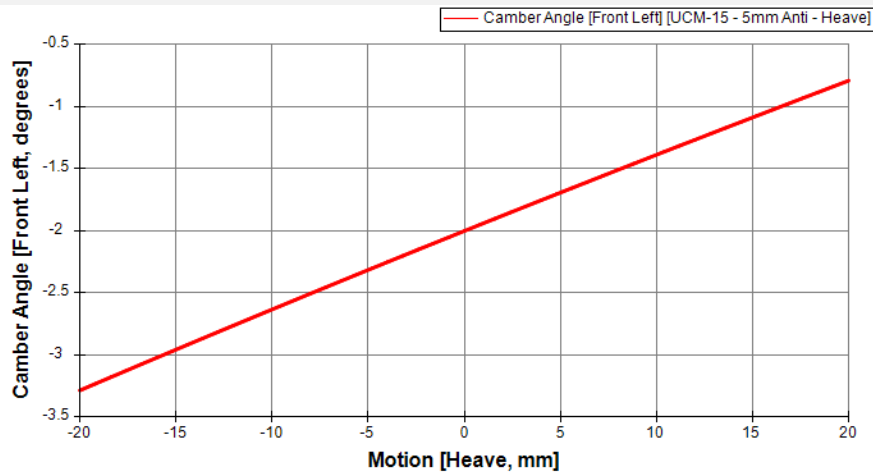
6. Car Kinematics Analysis



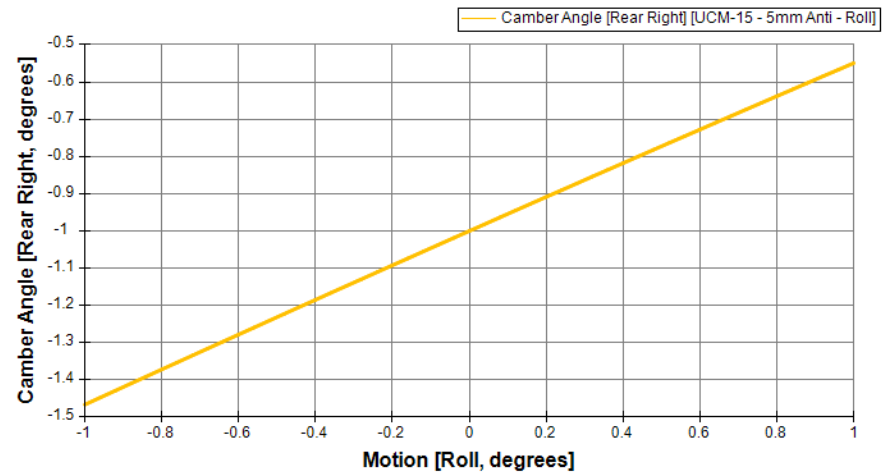
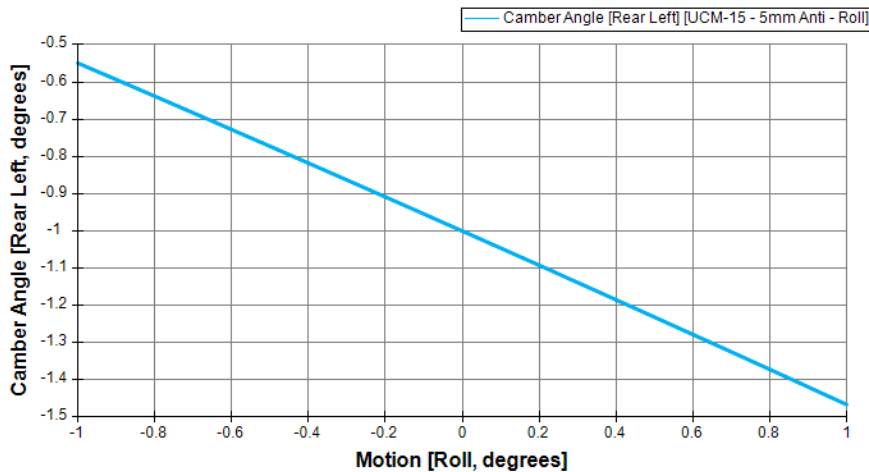
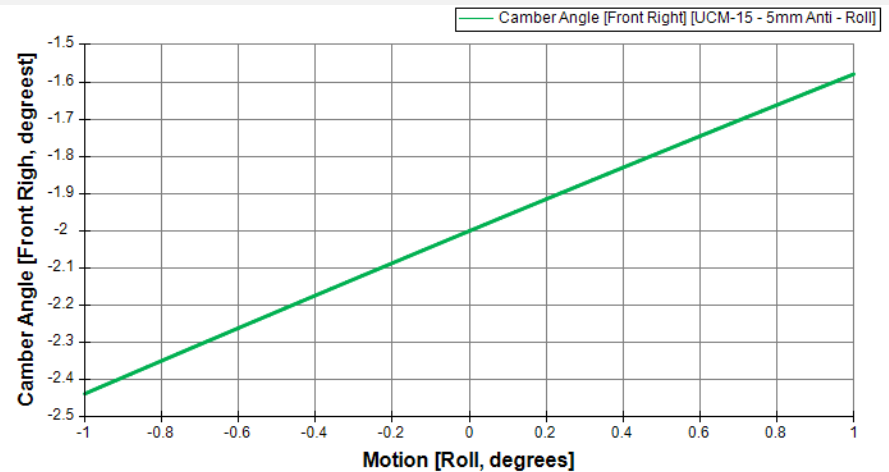
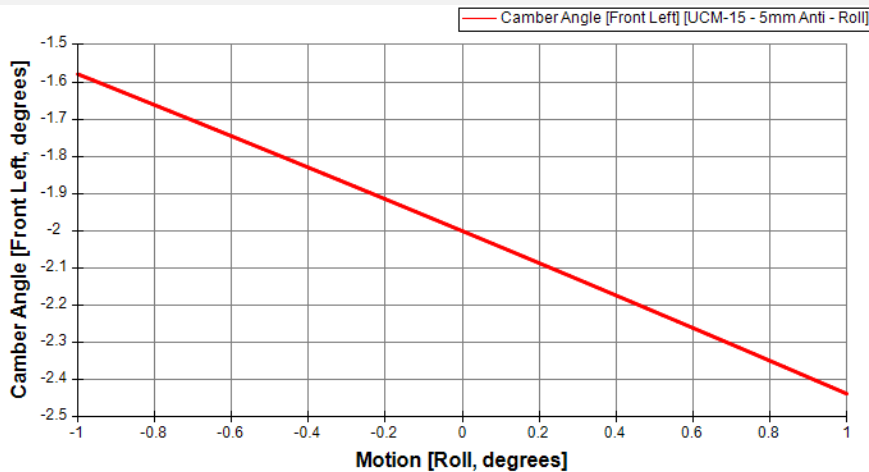
Camber Angle

- Camber angle is directly related to the grip generated by the tire, both lateral and longitudinal grip. Therefore it must be ensured that the vehicle maintains a suitable camber angle throughout the range vehicle of operation.
- It is important to keep in mind that the camber angle has great influence on tire temperature and wear

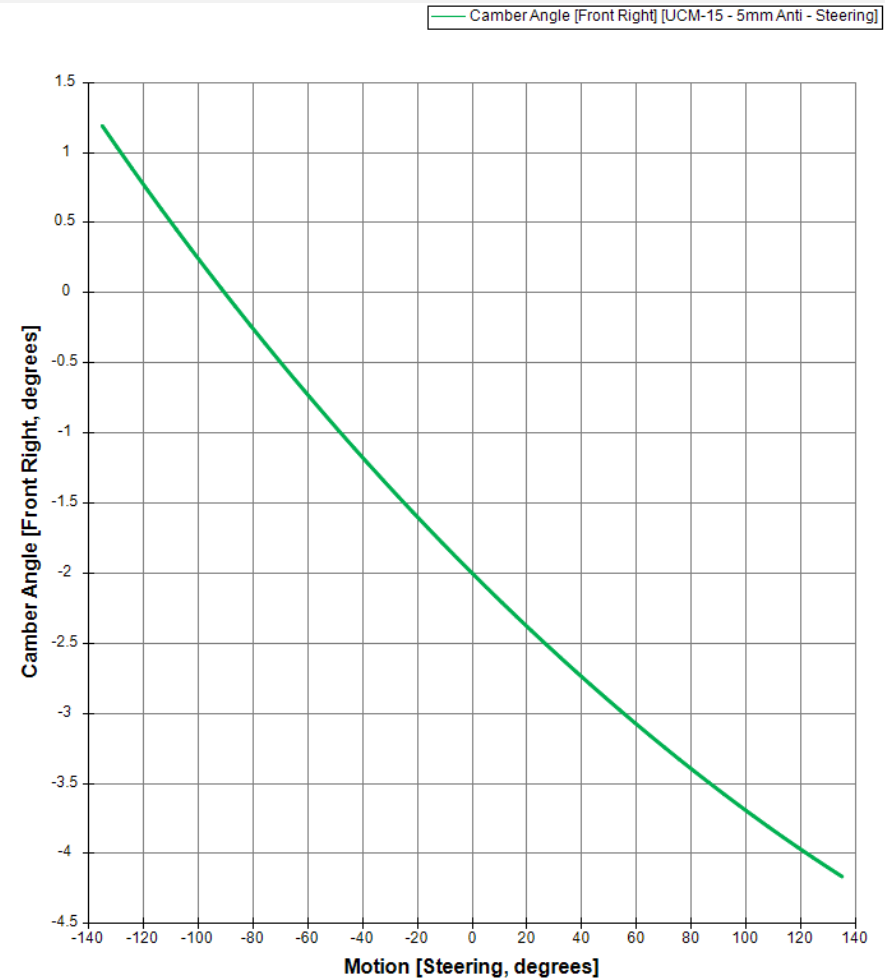
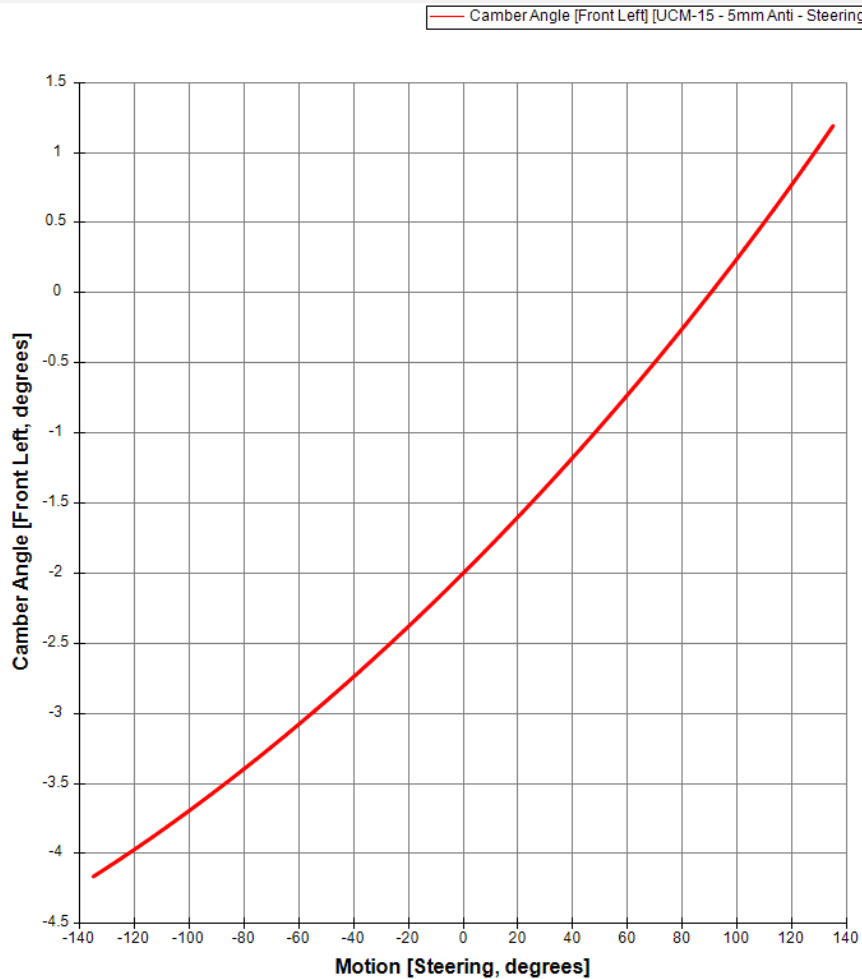
Camber Angle - Heave



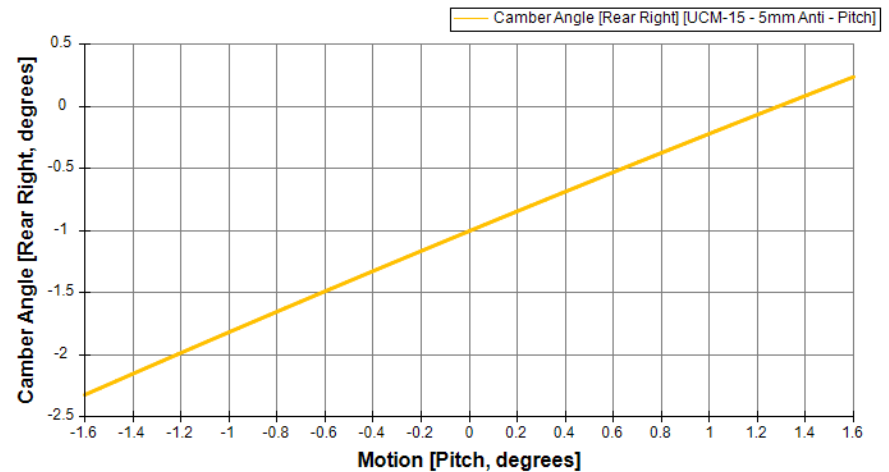
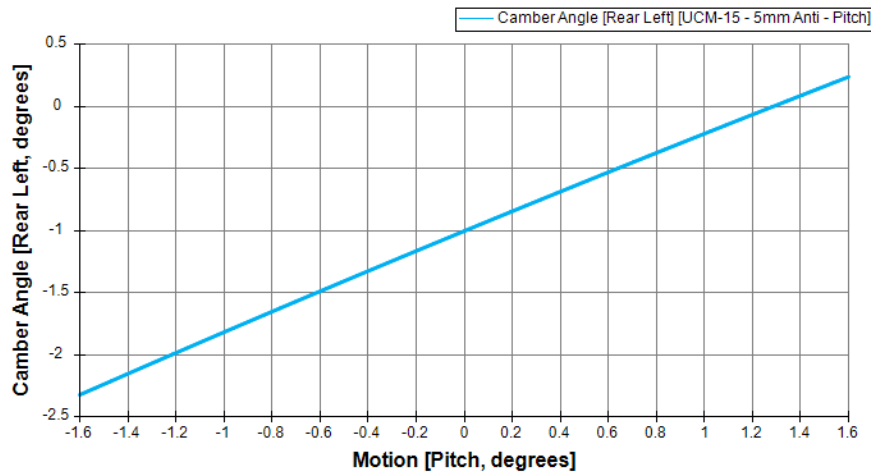
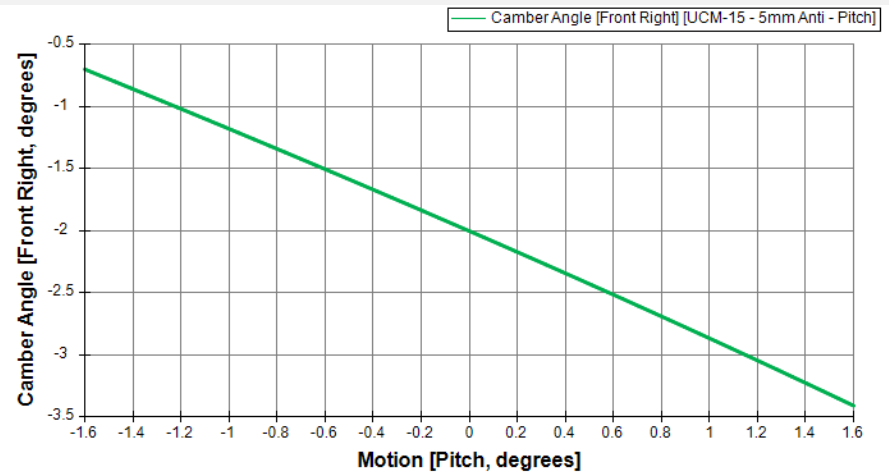
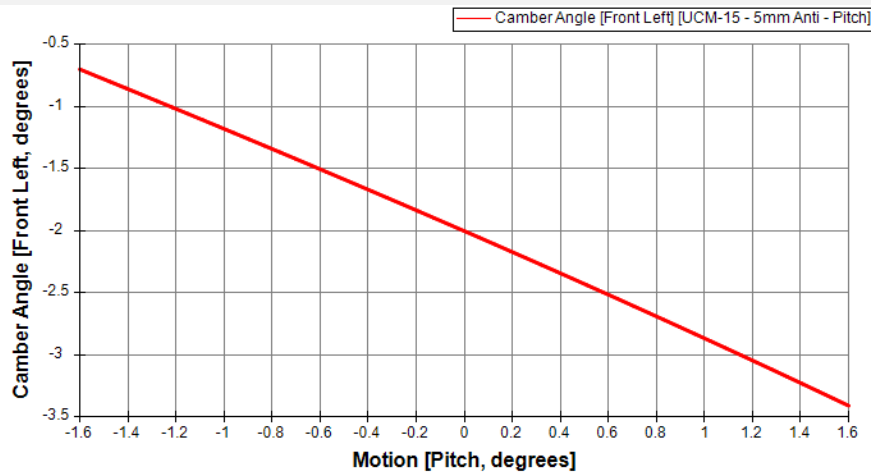
Camber Angle -Roll



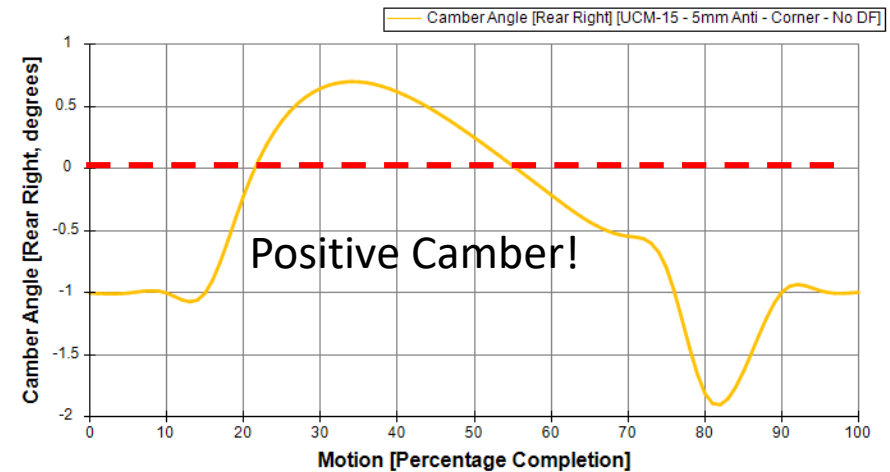
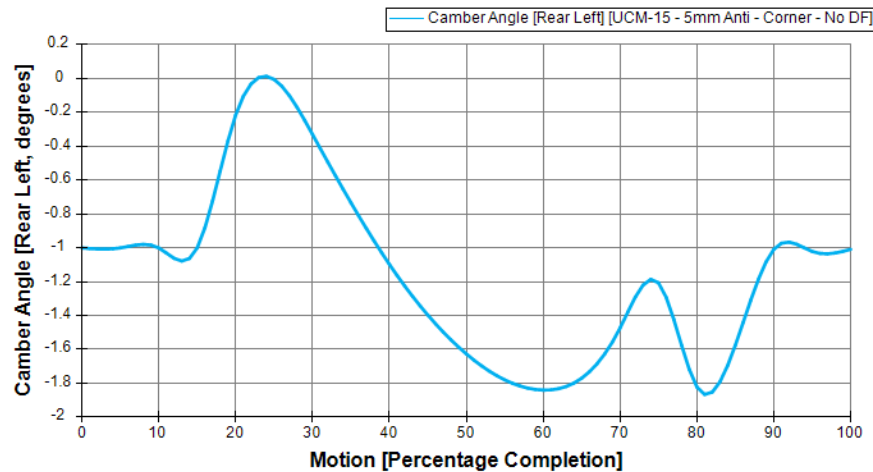
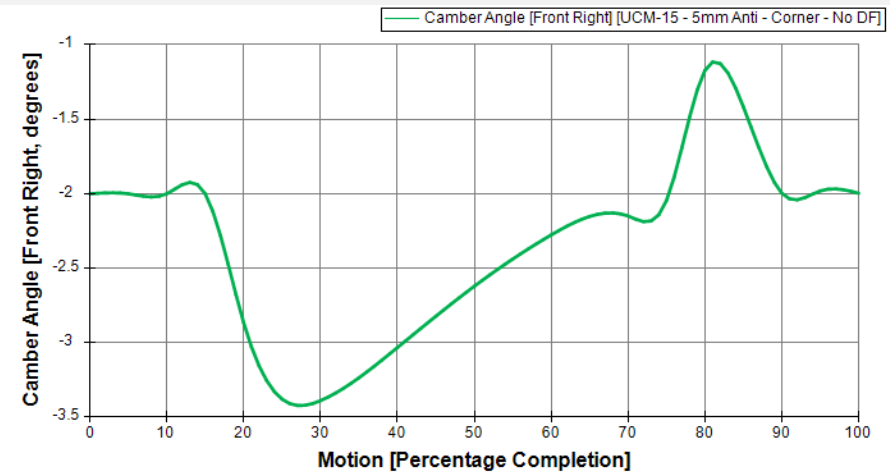
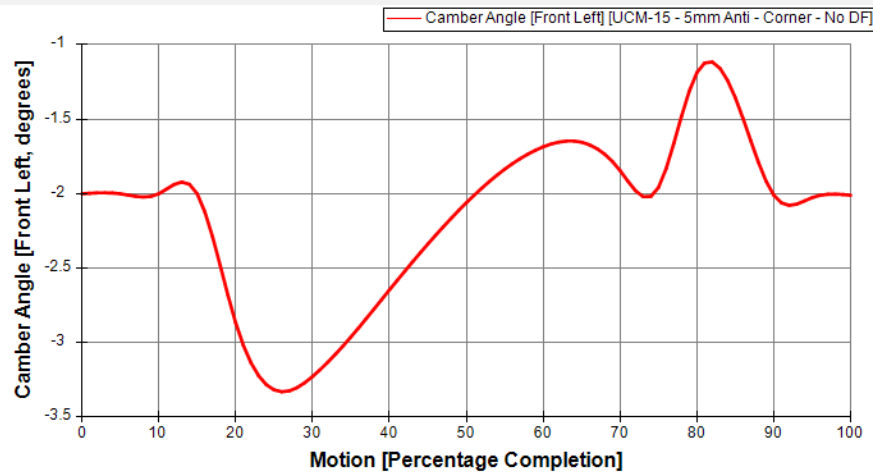
Camber Angle - Steering



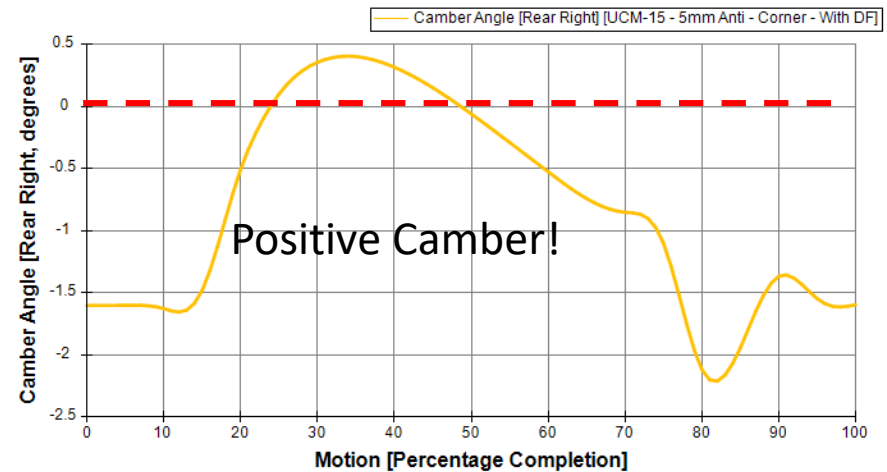
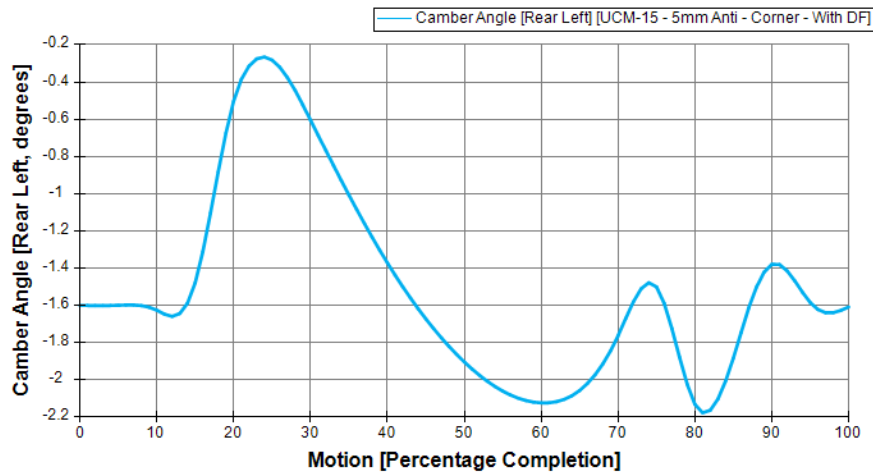
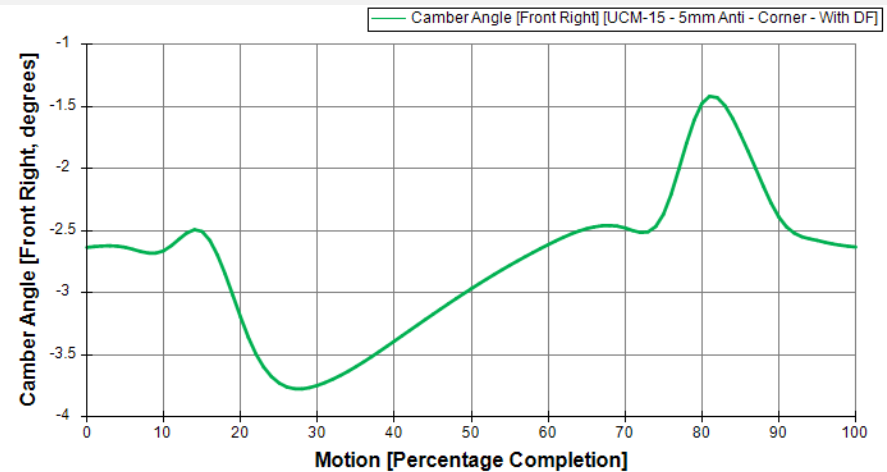
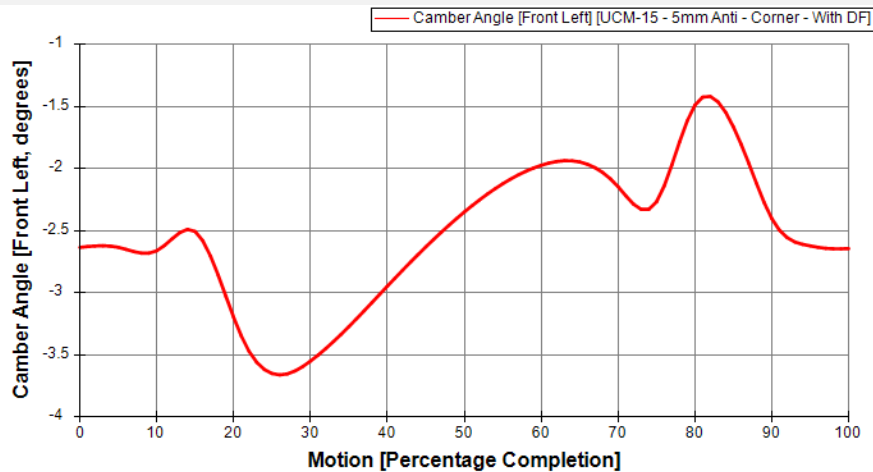
Camber Angle - Pitch



Camber Angle - Corner Without Downforce



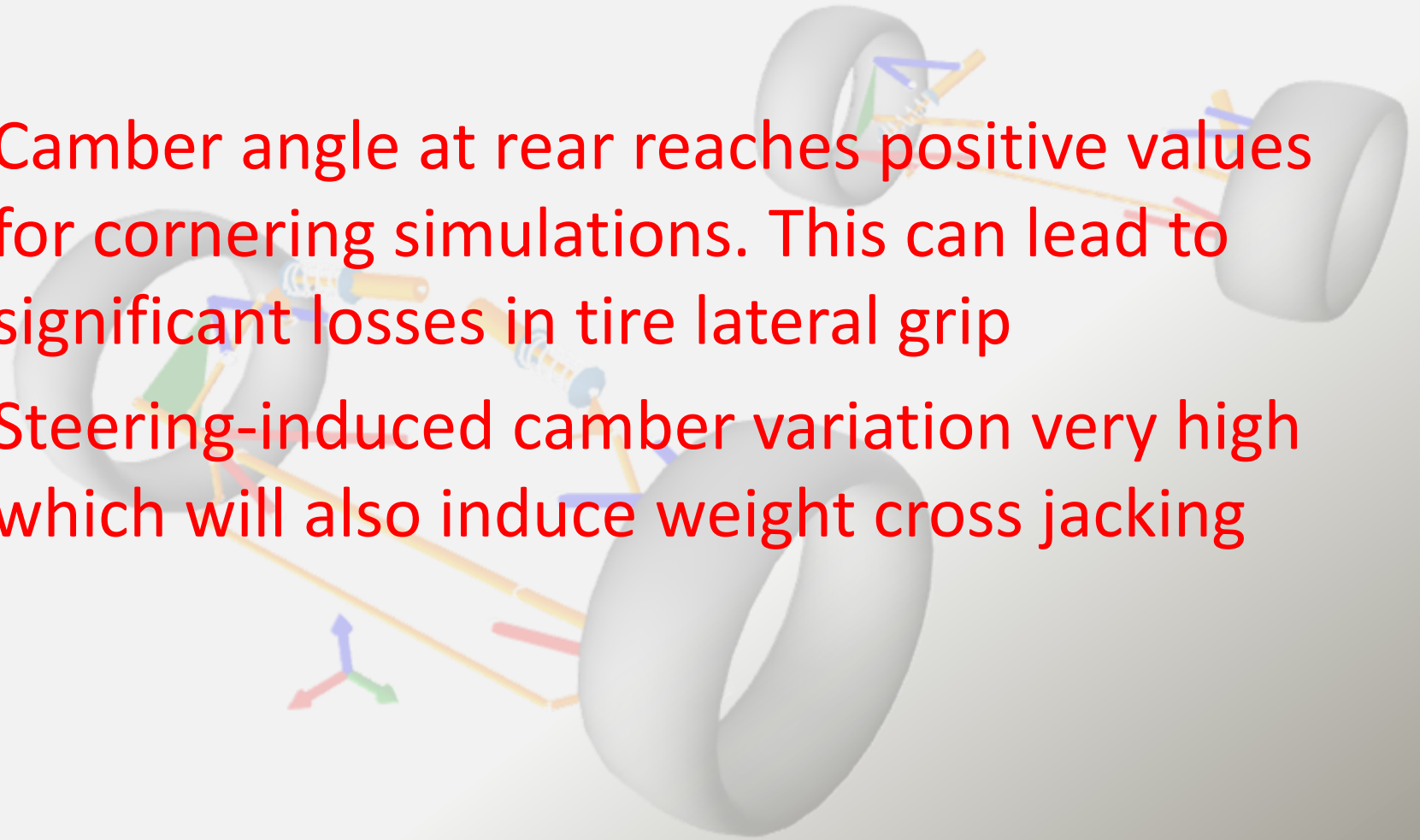
Camber Angle - Corner With Downforce



Positive Camber!

Camber Angle – Comments

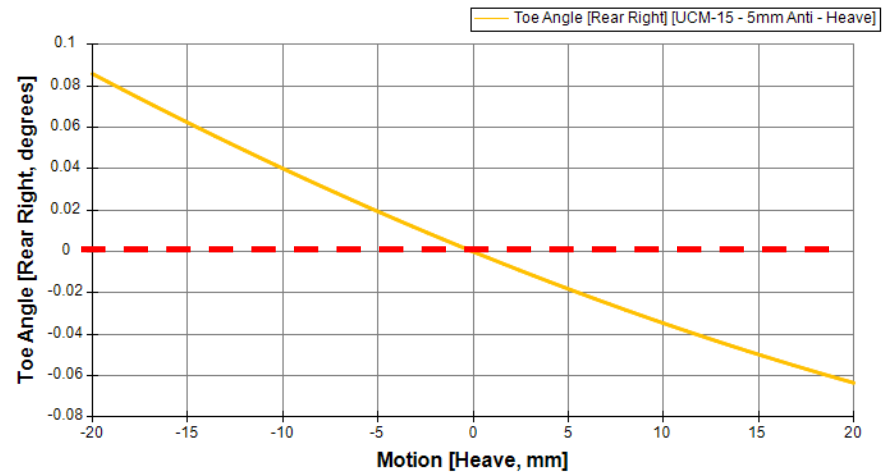
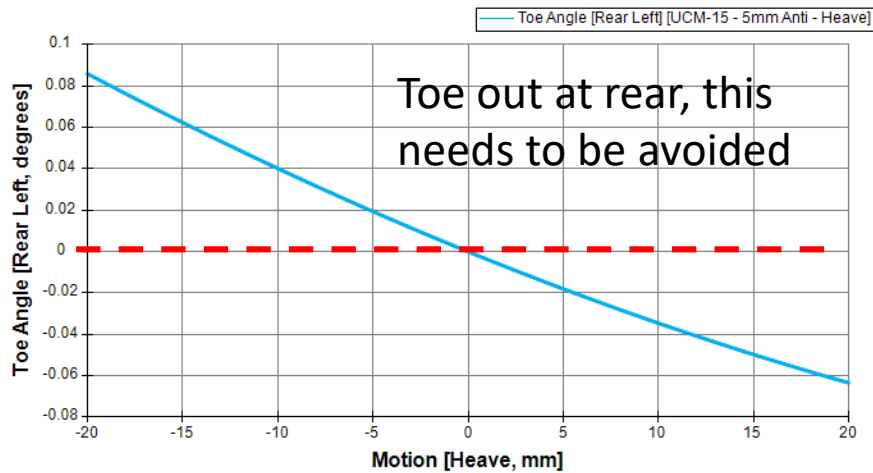
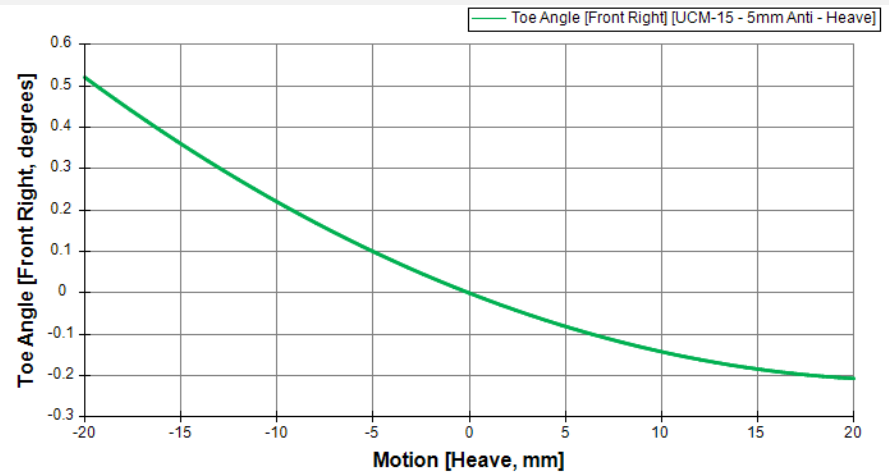
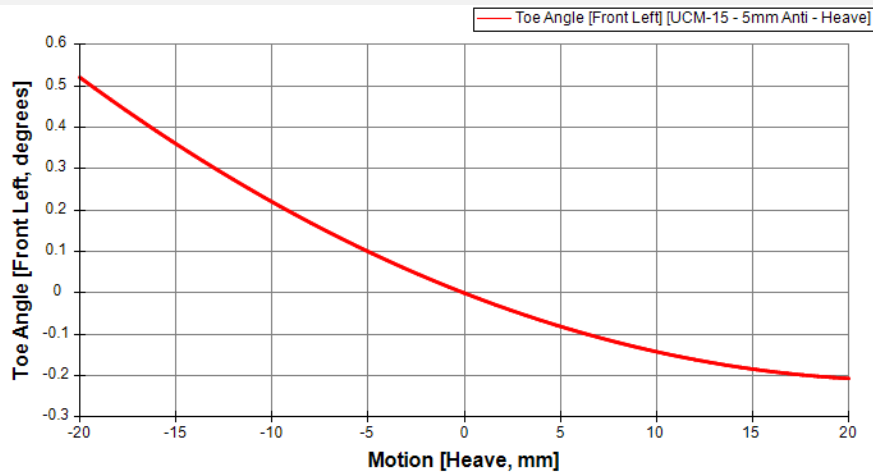
- Camber angle at rear reaches positive values for cornering simulations. This can lead to significant losses in tire lateral grip
- Steering-induced camber variation very high which will also induce weight cross jacking



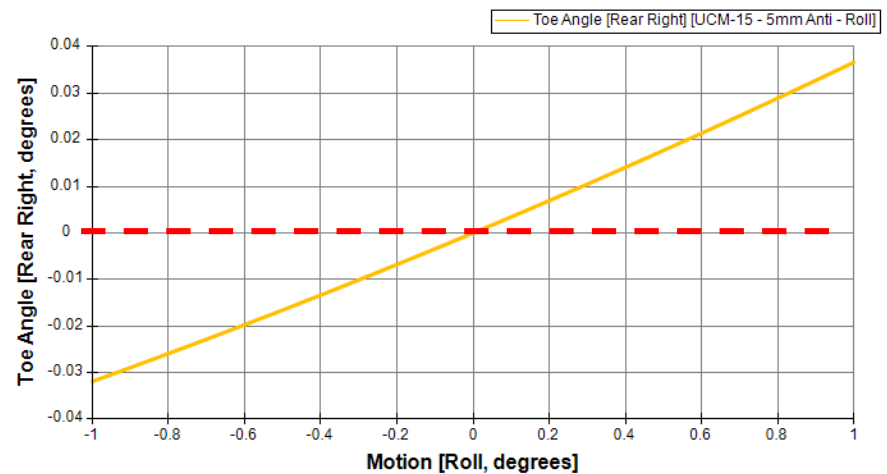
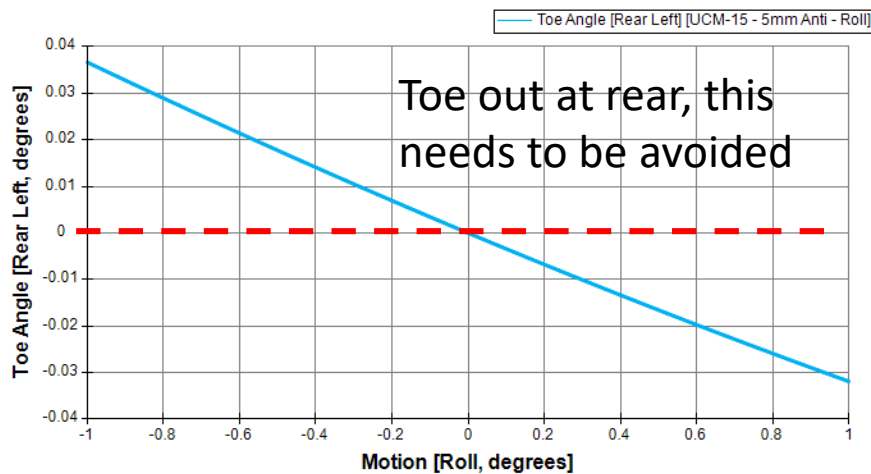
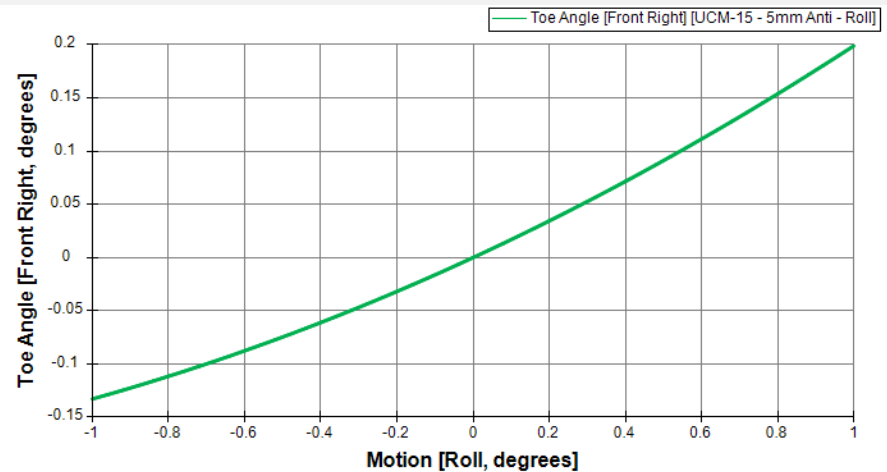
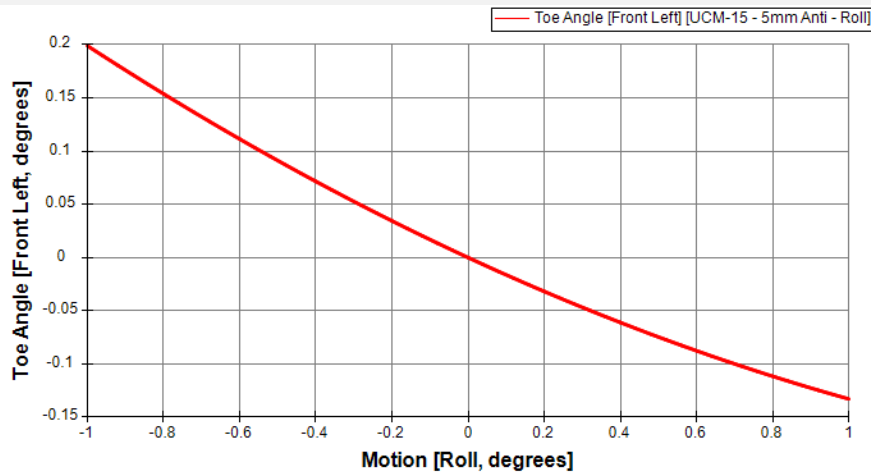
Toe Angle

- Variation of toe angle with the suspension motion will induce additional slip angle in the tire that is not controlled by the driver which will influence the lateral force developed by the tires
- Stability issues can appear if toe angle is not controlled well over the suspension displacement

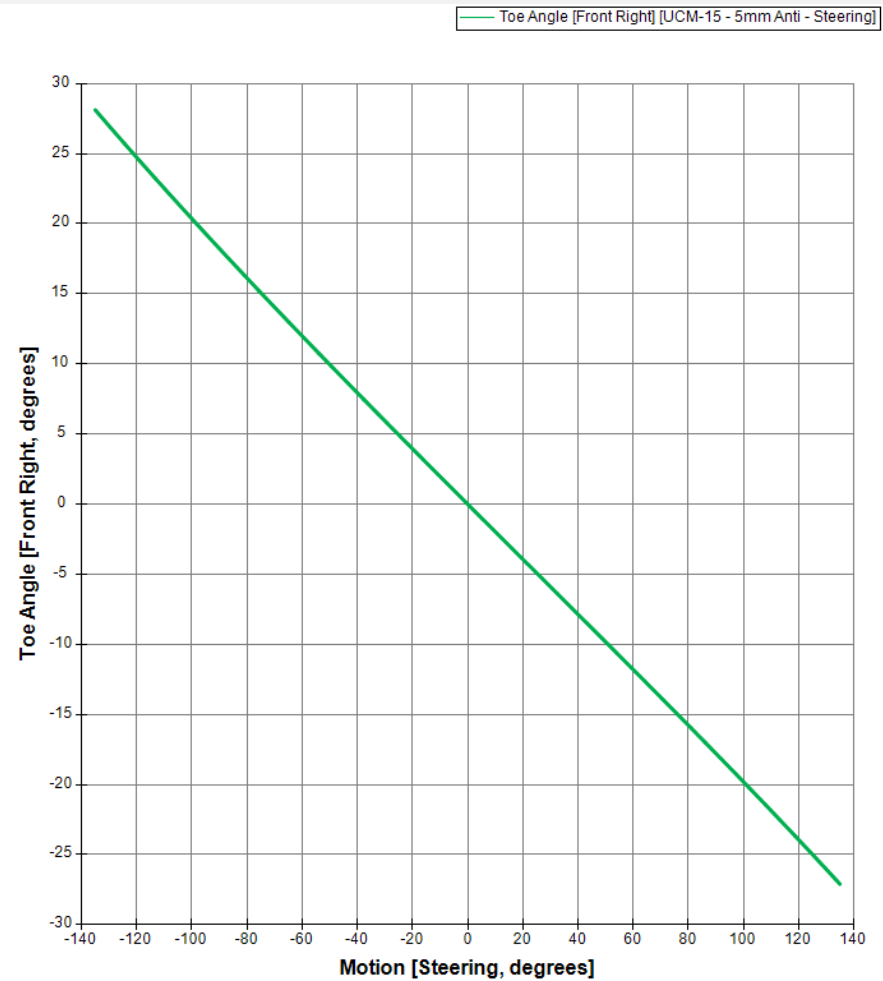
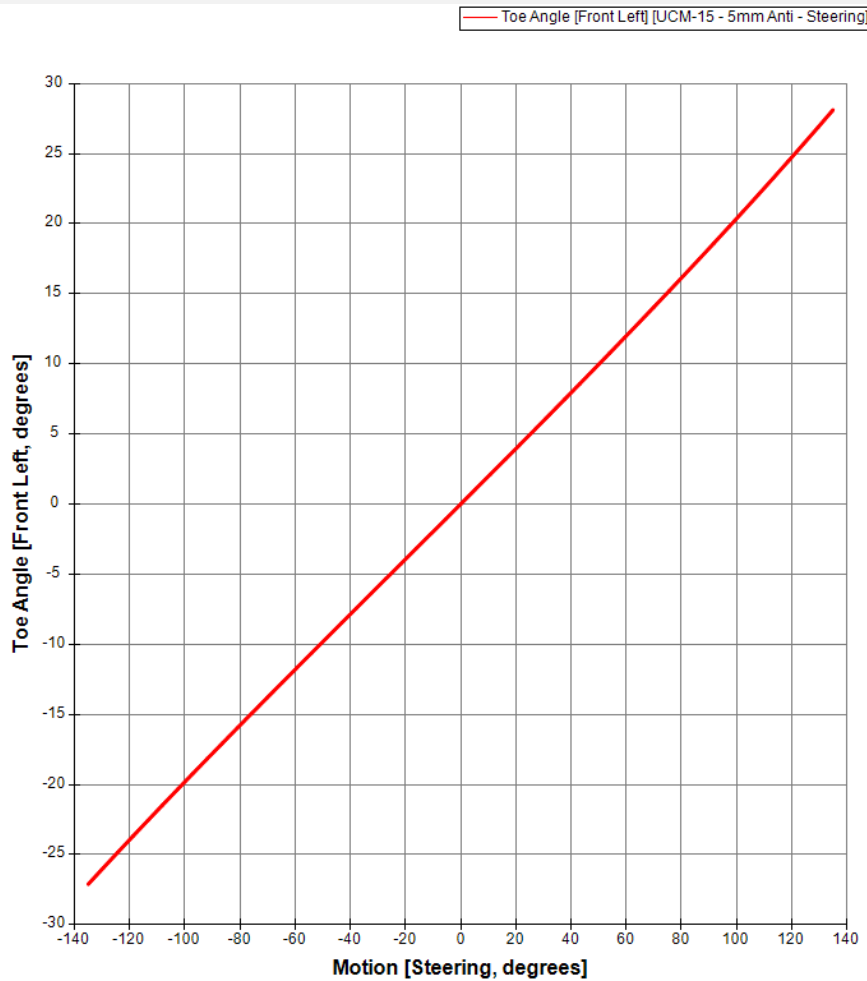
Toe Angle - Heave



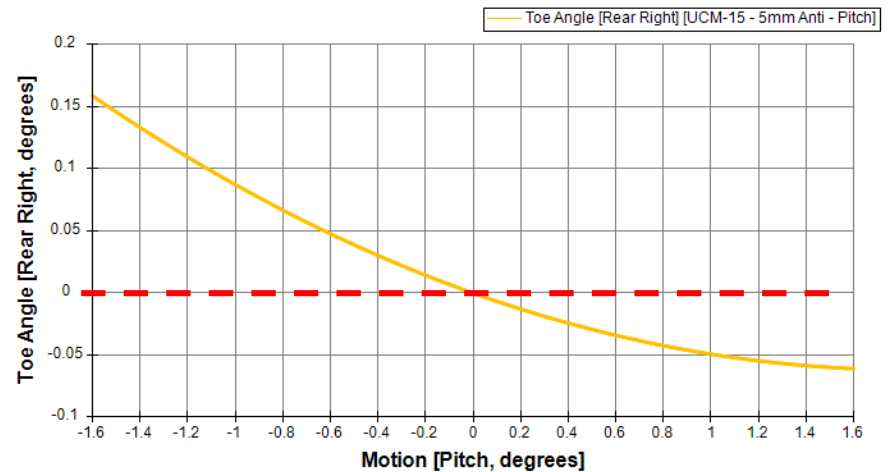
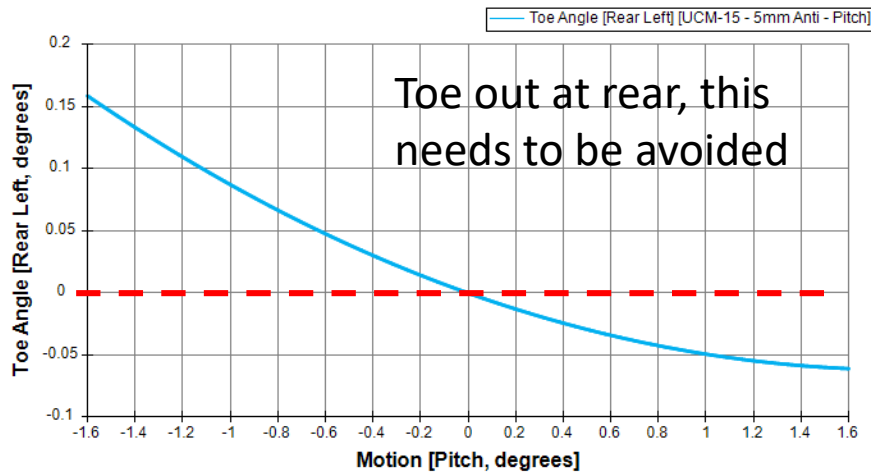
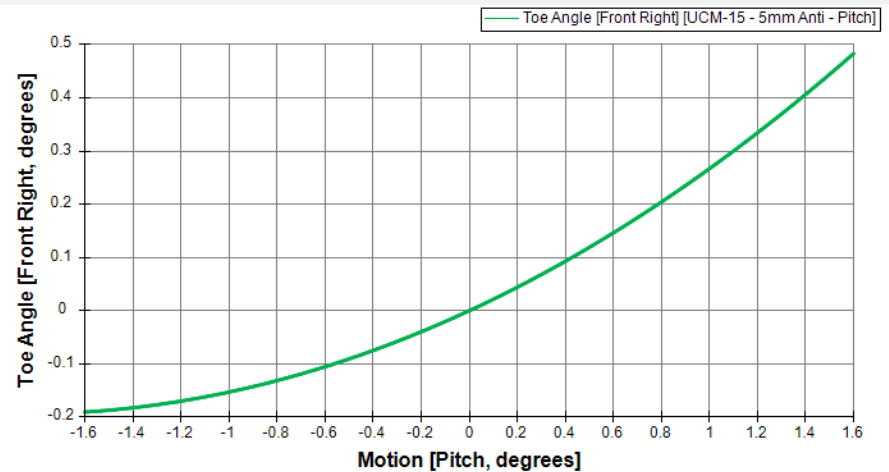
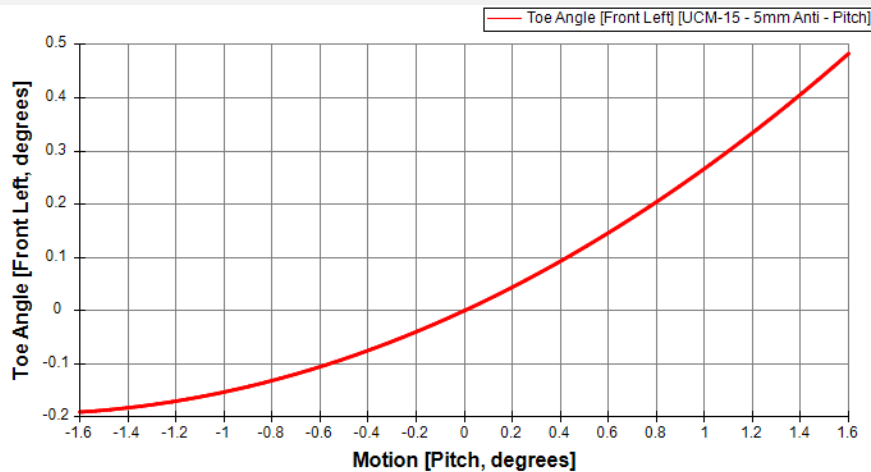
Toe Angle - Roll



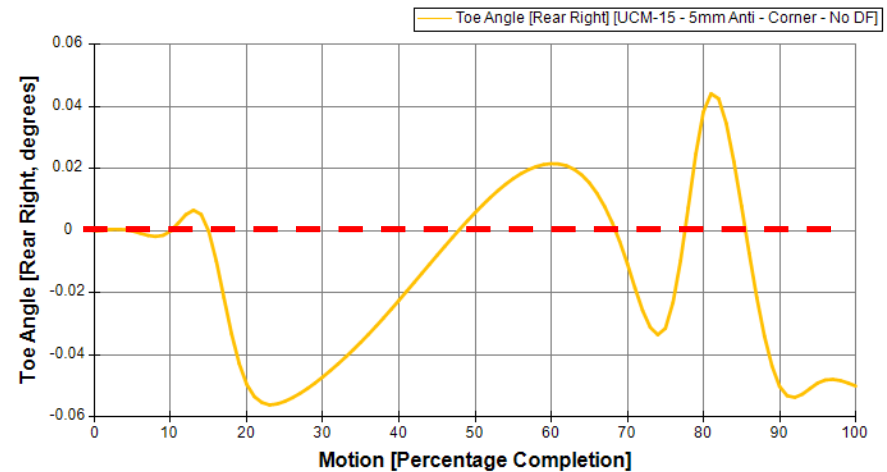
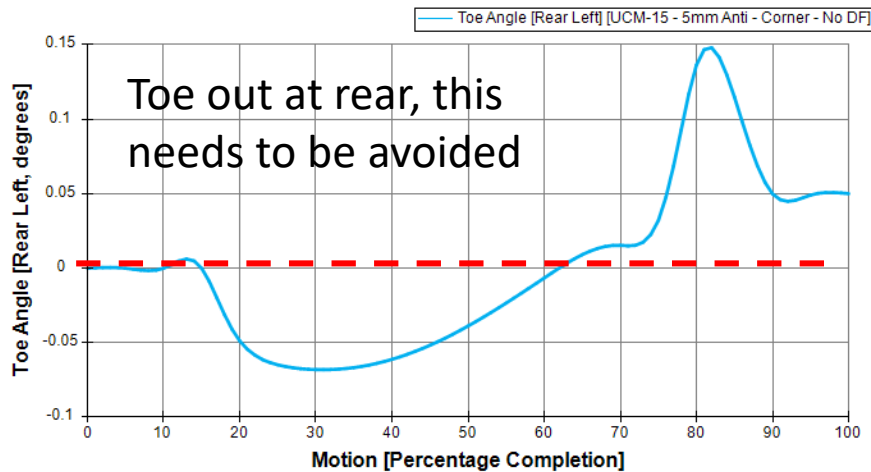
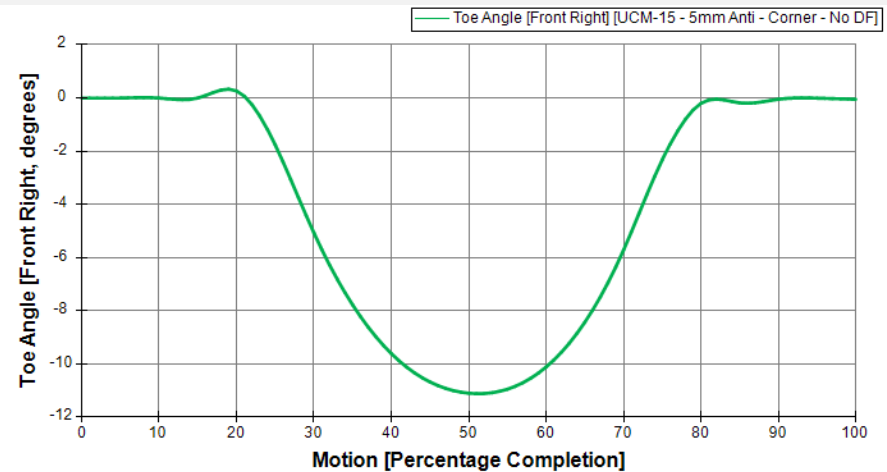
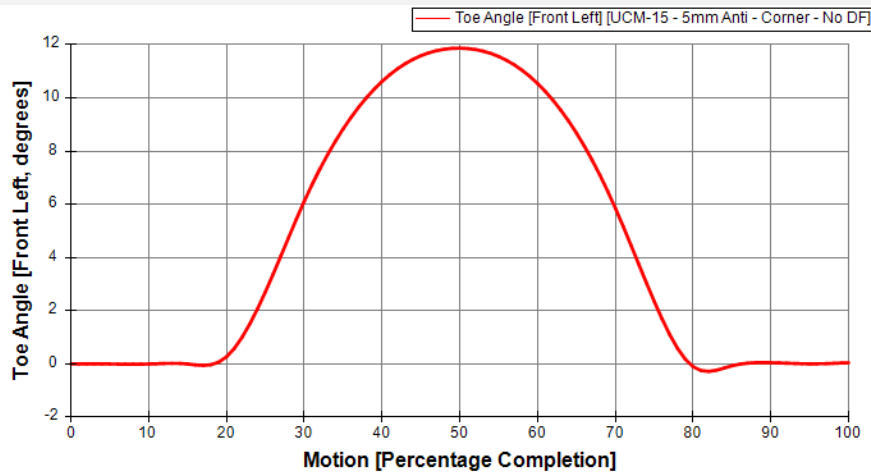
Toe Angle - Steering



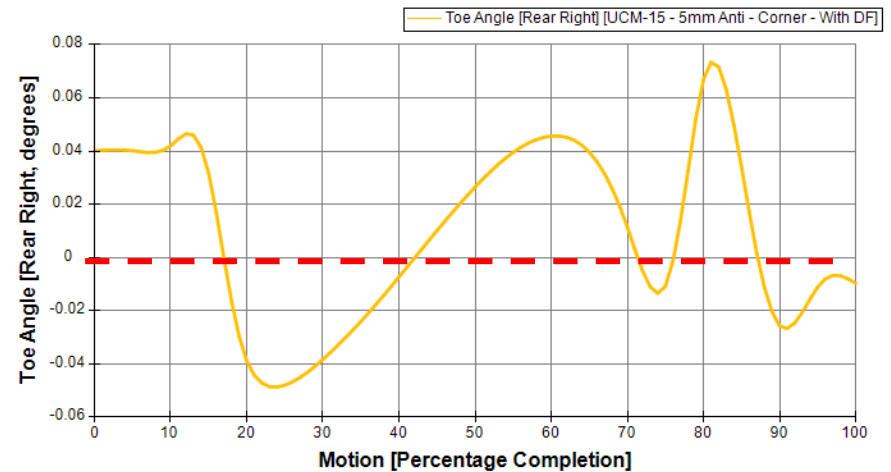
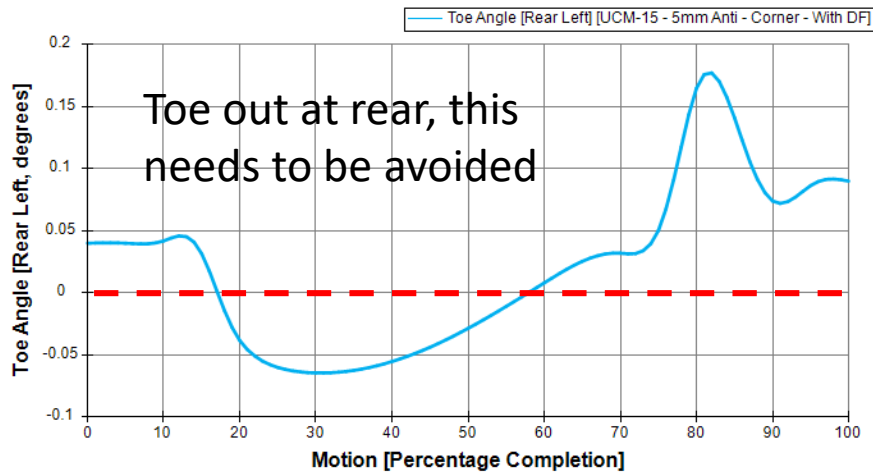
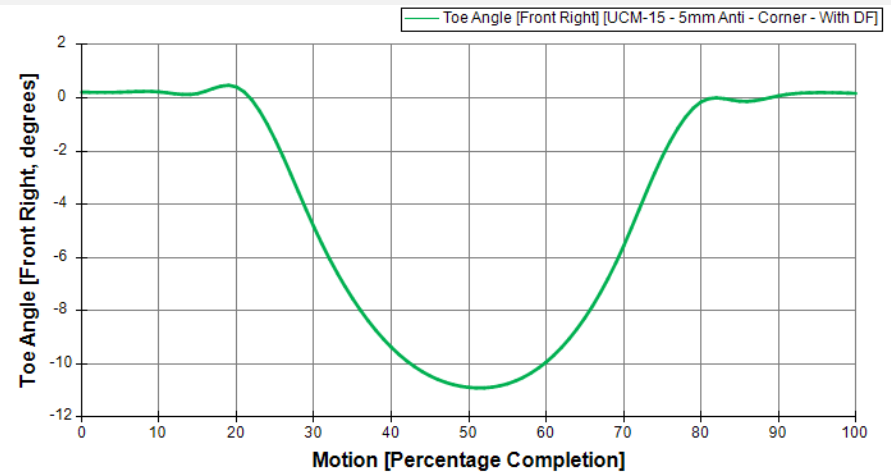
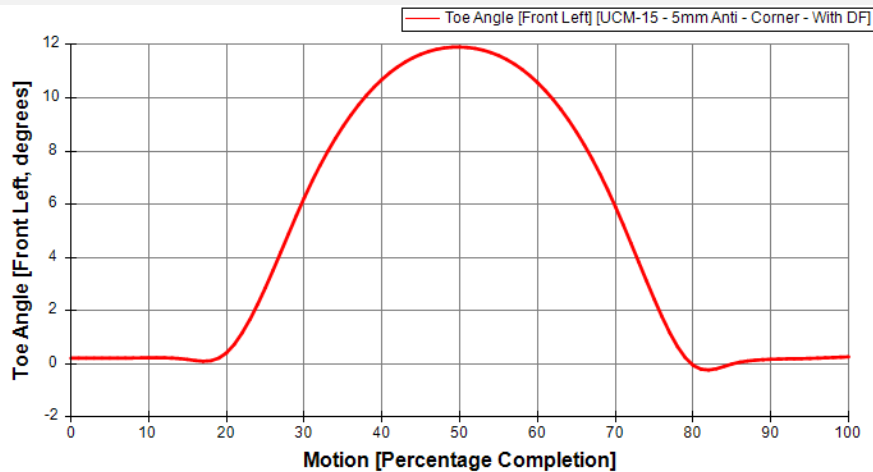
Toe Angle - Pitch



Toe Angle - Corner Without Downforce

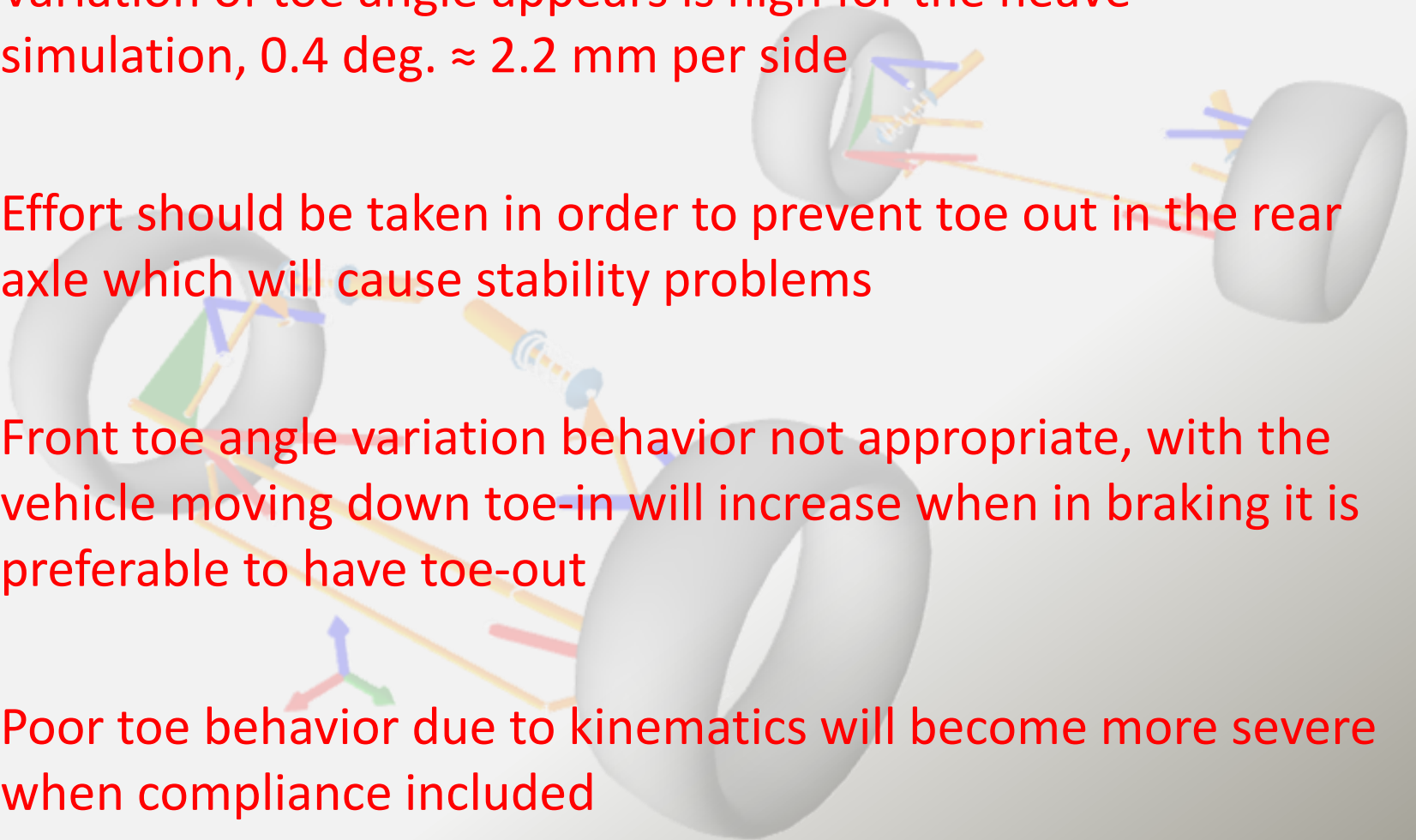


Toe Angle - Corner With Downforce



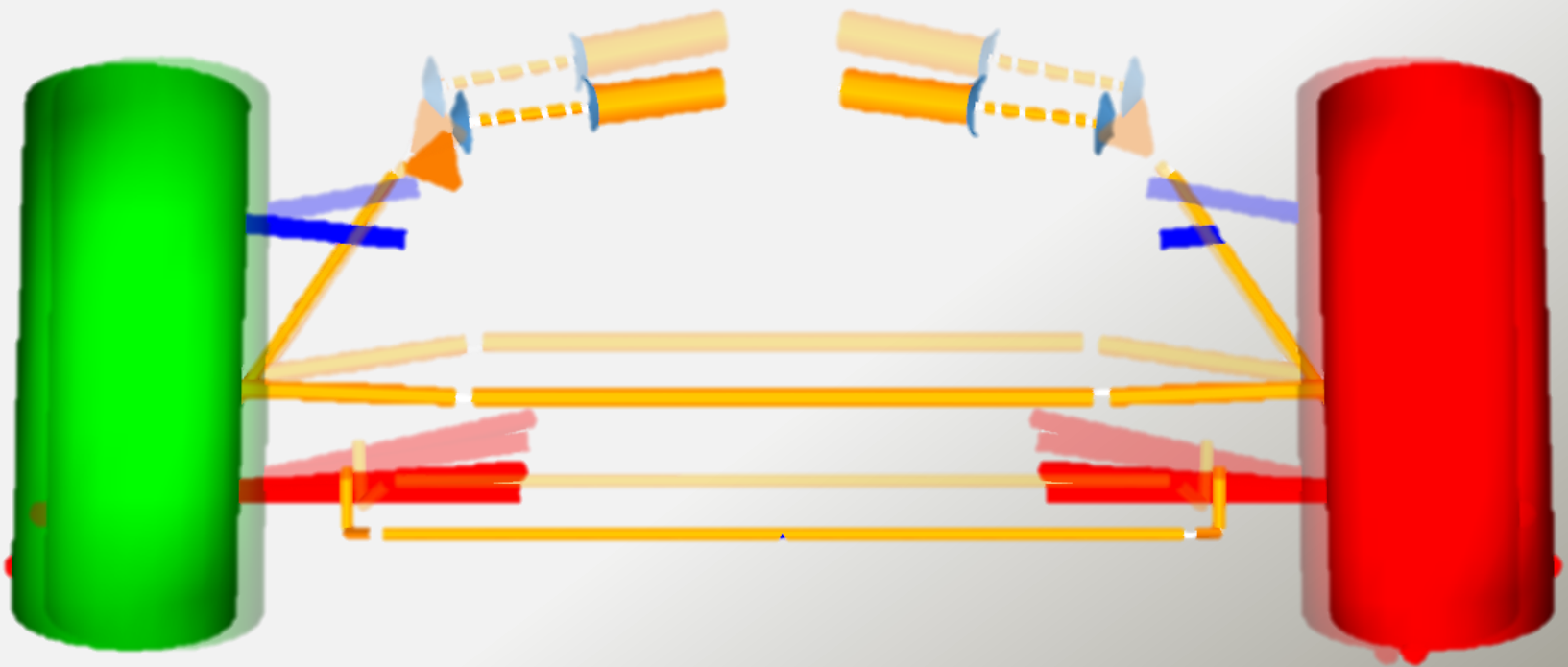
UPDATE: Toe Angle

- Variation of toe angle appears is high for the heave simulation, 0.4 deg. $\approx$ 2.2 mm per side
- Effort should be taken in order to prevent toe out in the rear axle which will cause stability problems
- Front toe angle variation behavior not appropriate, with the vehicle moving down toe-in will increase when in braking it is preferable to have toe-out
- Poor toe behavior due to kinematics will become more severe when compliance included

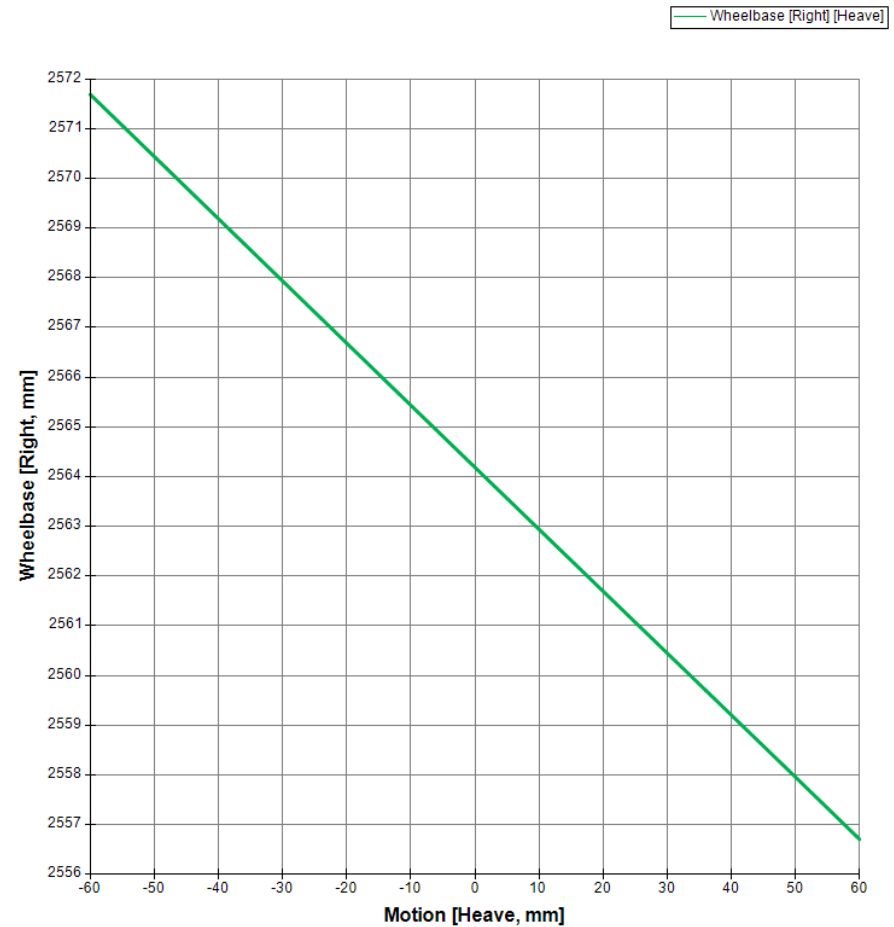
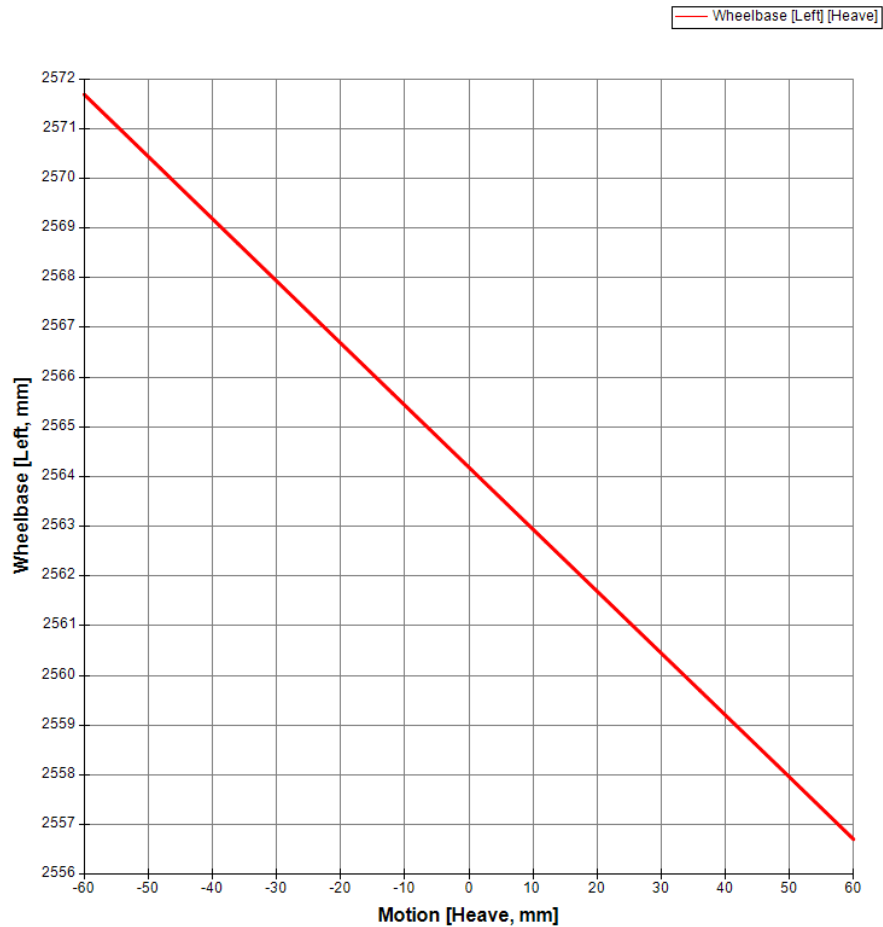


Wheelbase & Half-Track

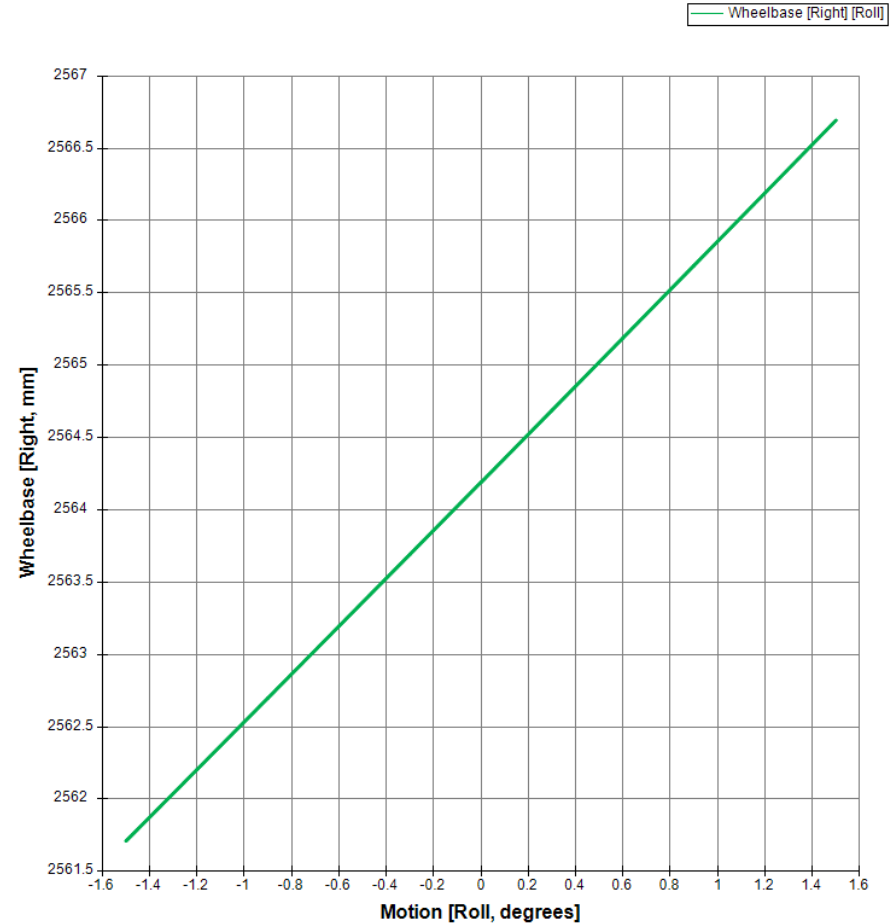
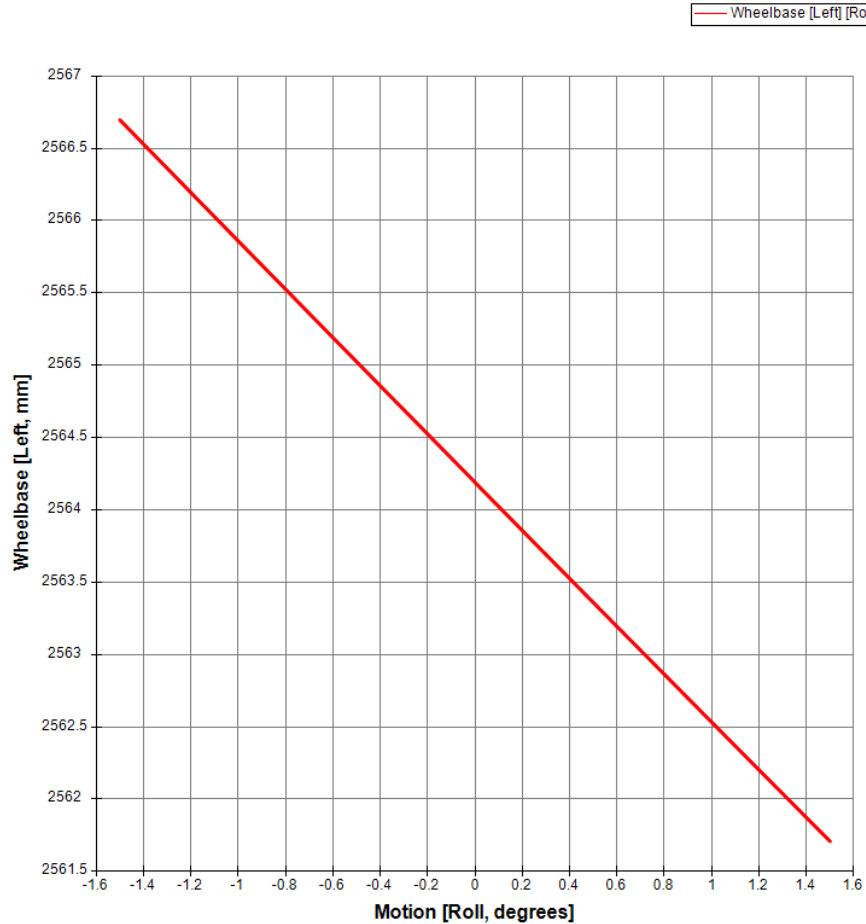
- Significant wheelbase and half-track variation contributes to an increase in tire temperature which can lead to heavy tire wear in operation



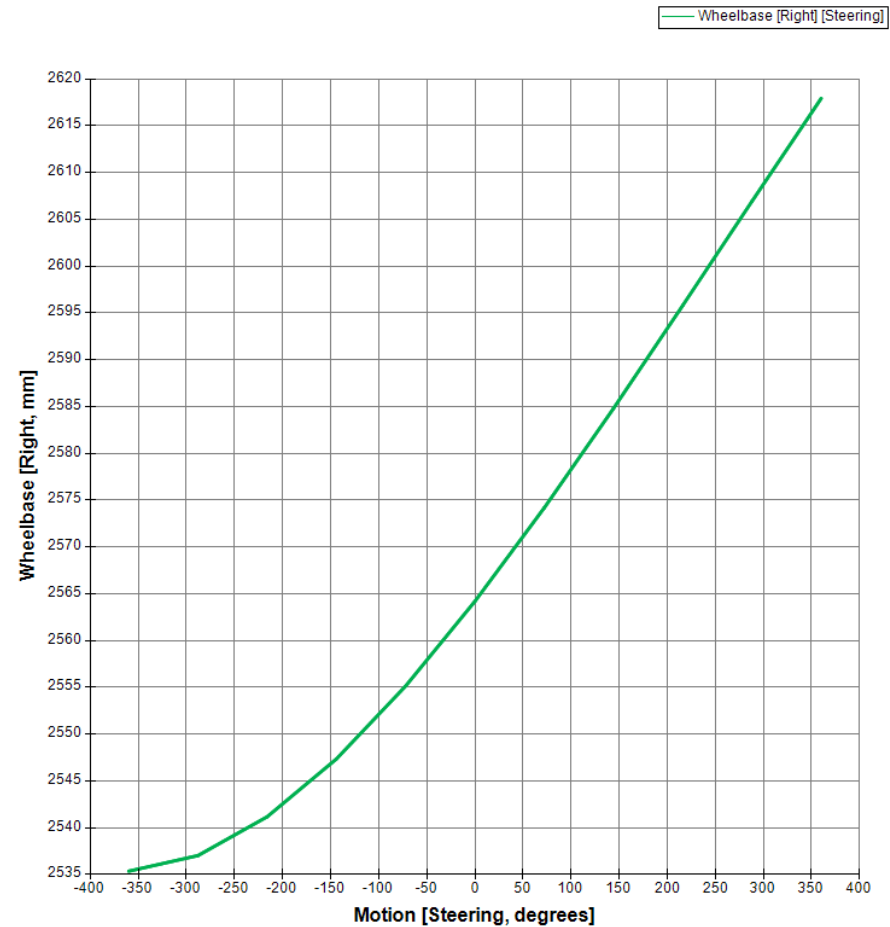
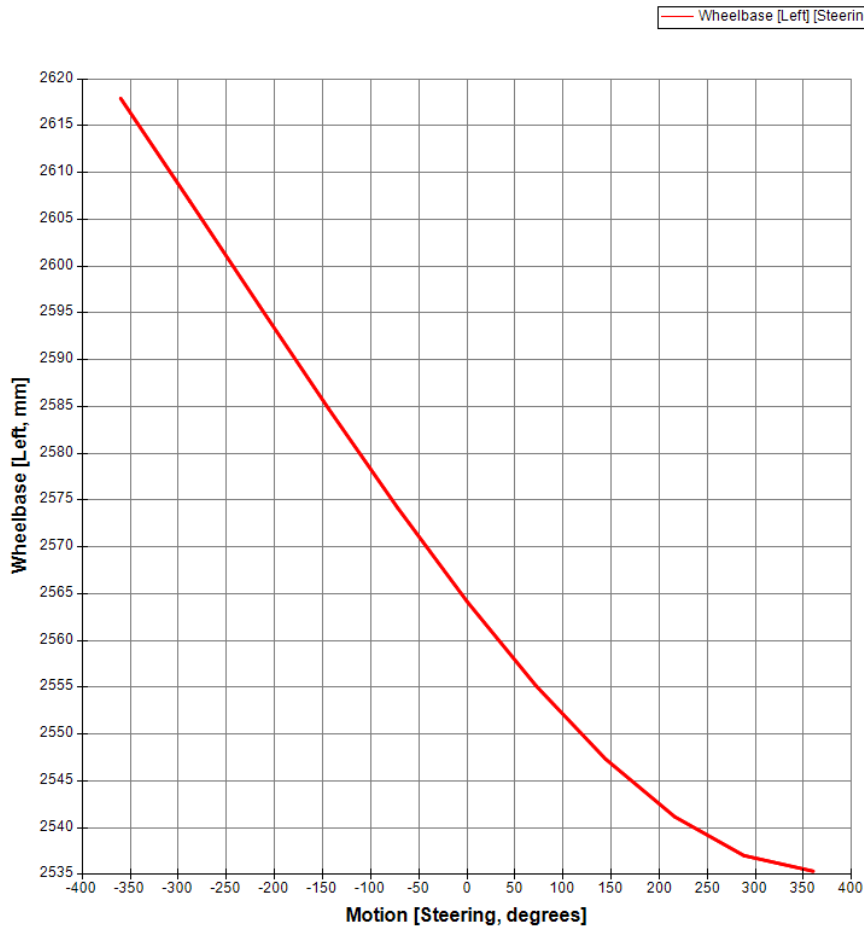
Wheelbase – Heave



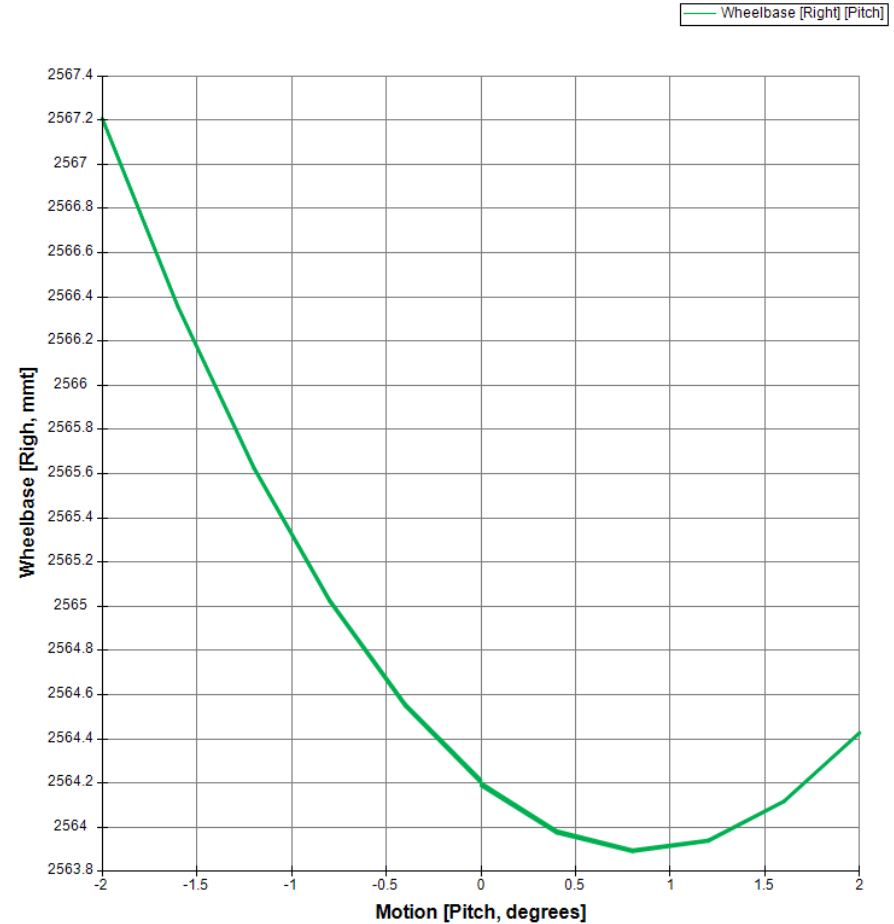
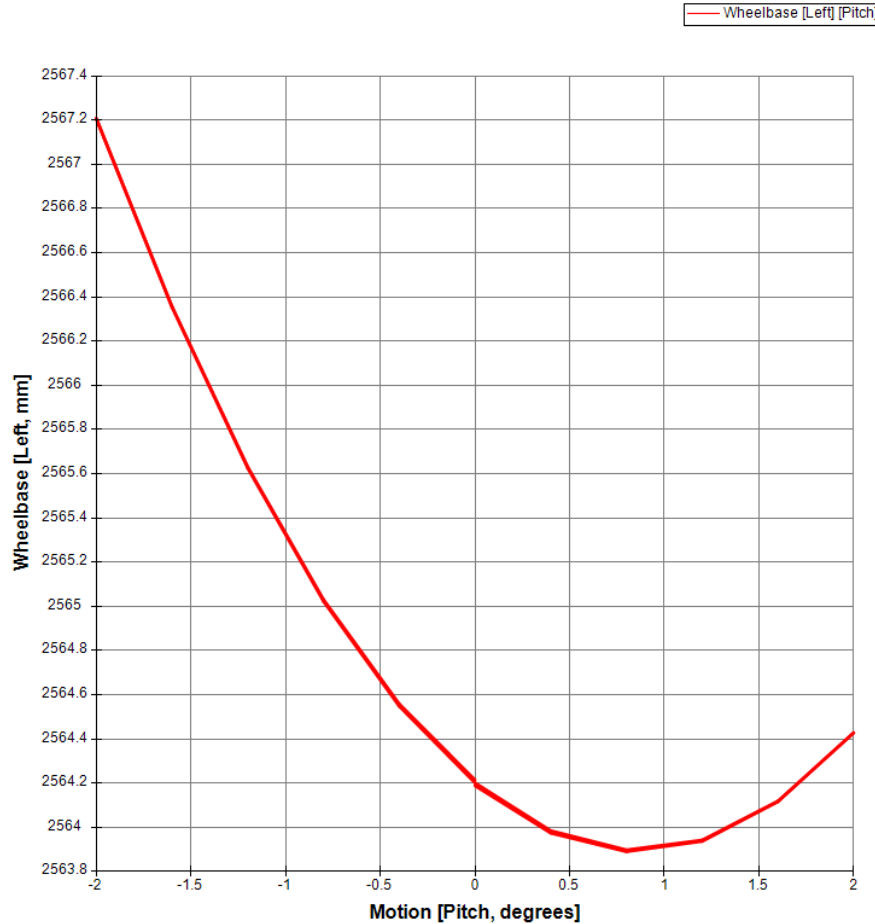
Wheelbase – Roll



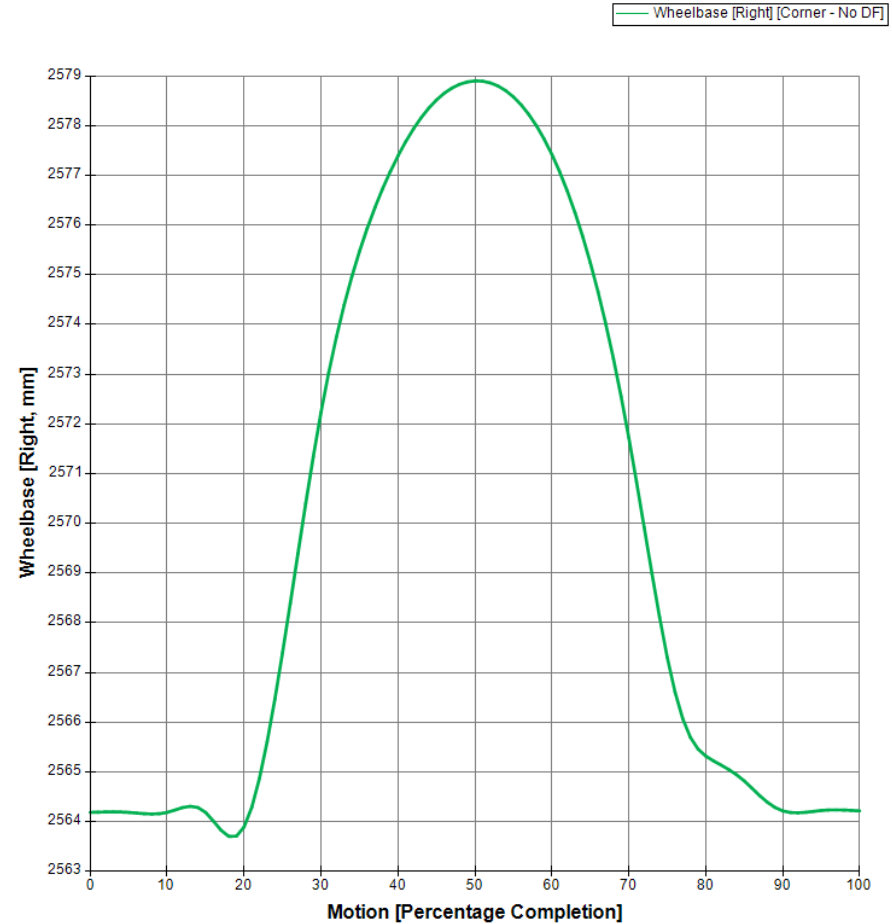
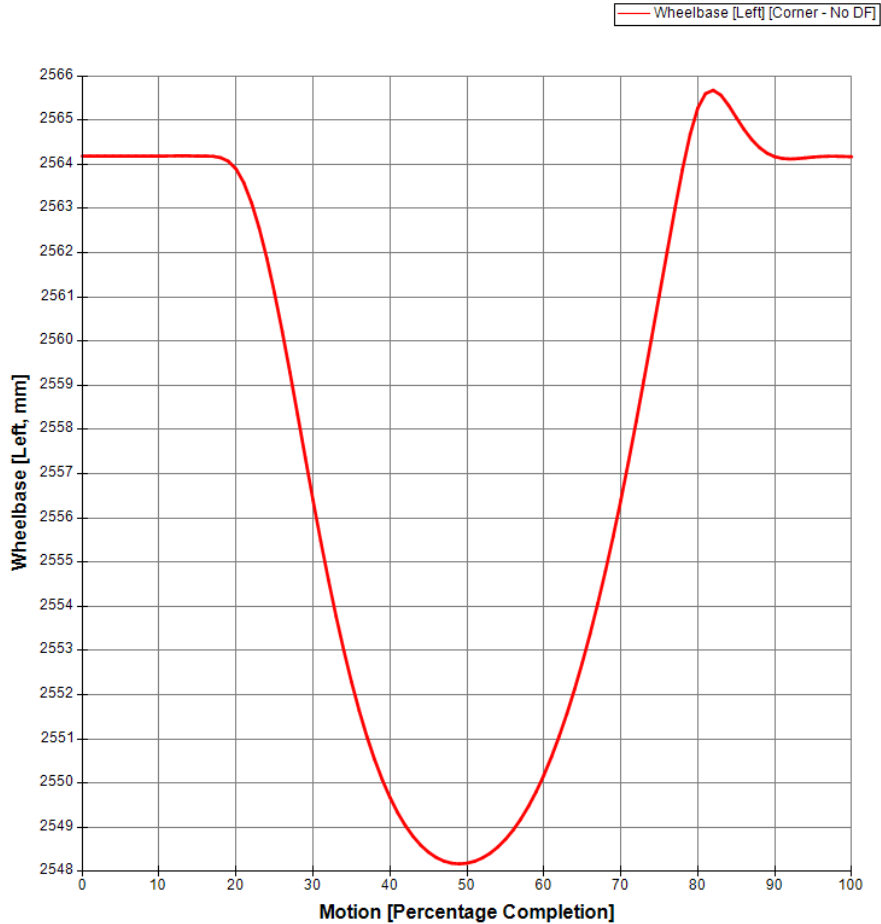
Wheelbase – Steering



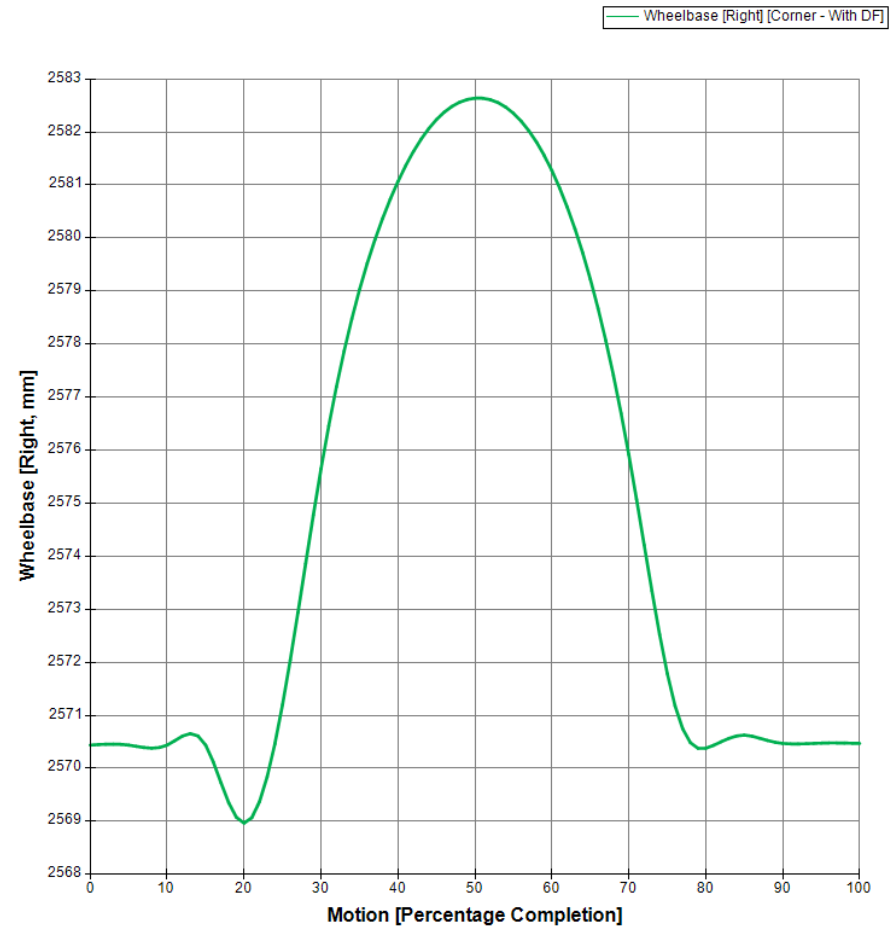
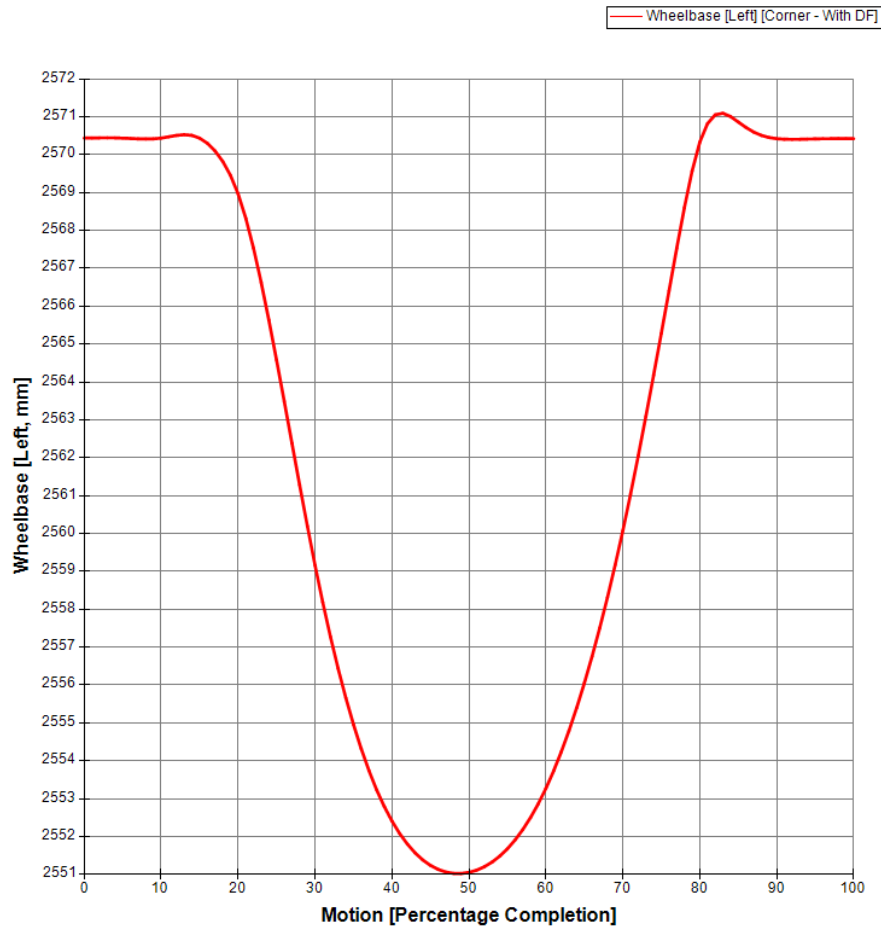
Wheelbase – Pitch



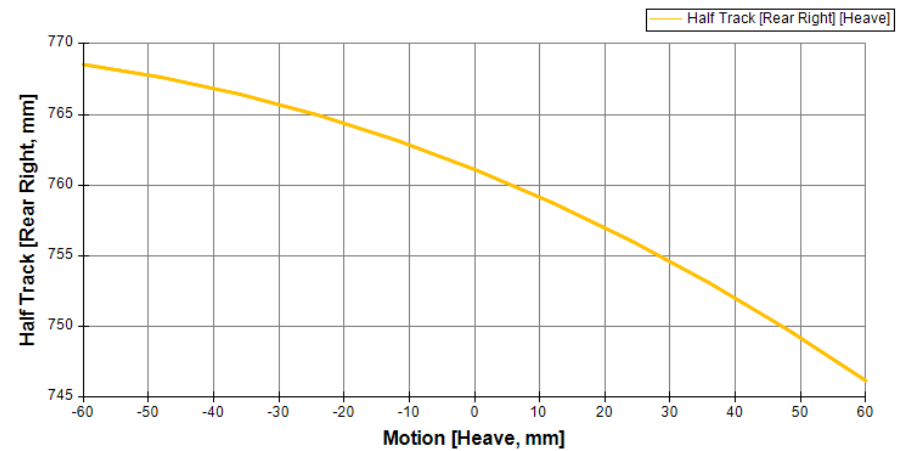
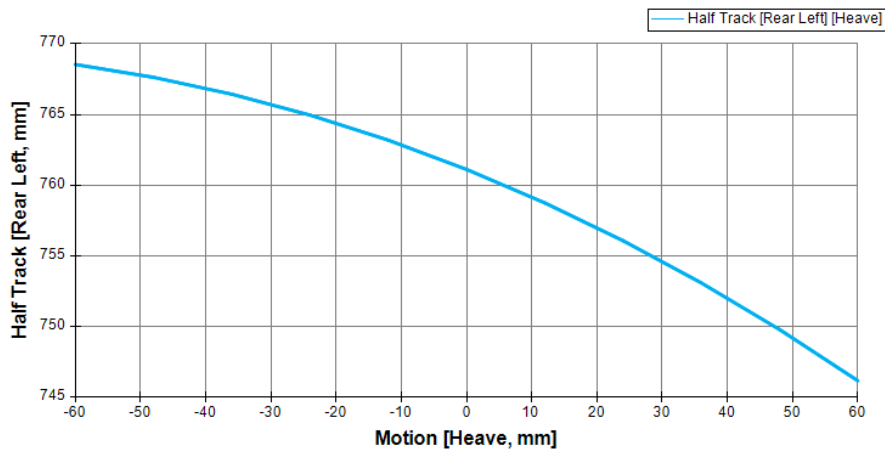
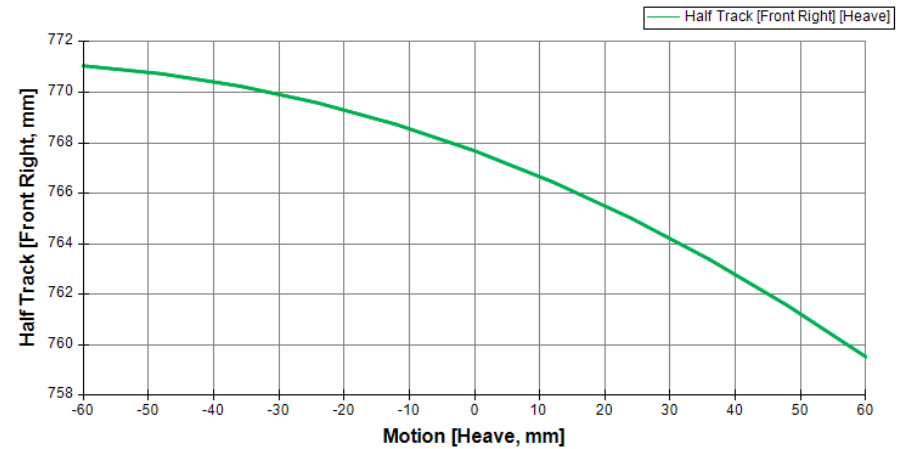
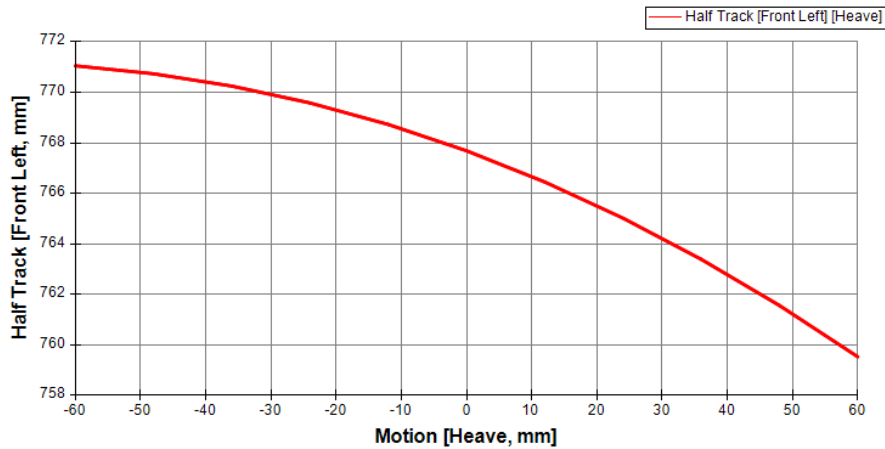
Wheelbase – Corner No DF



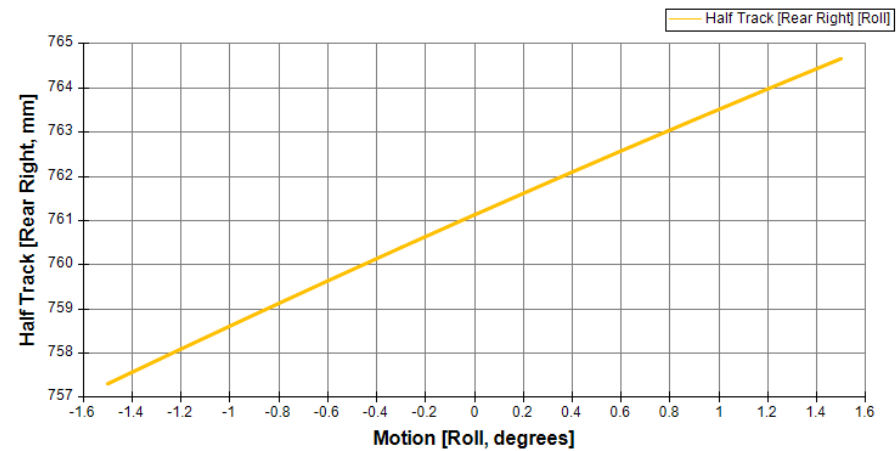
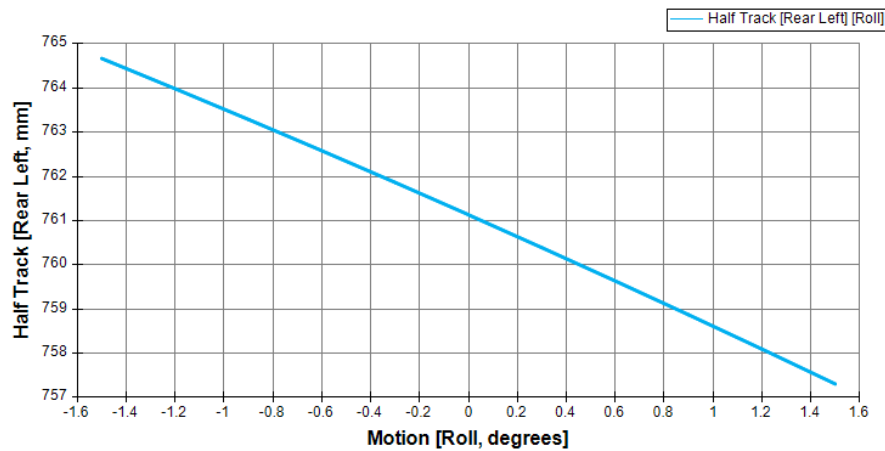
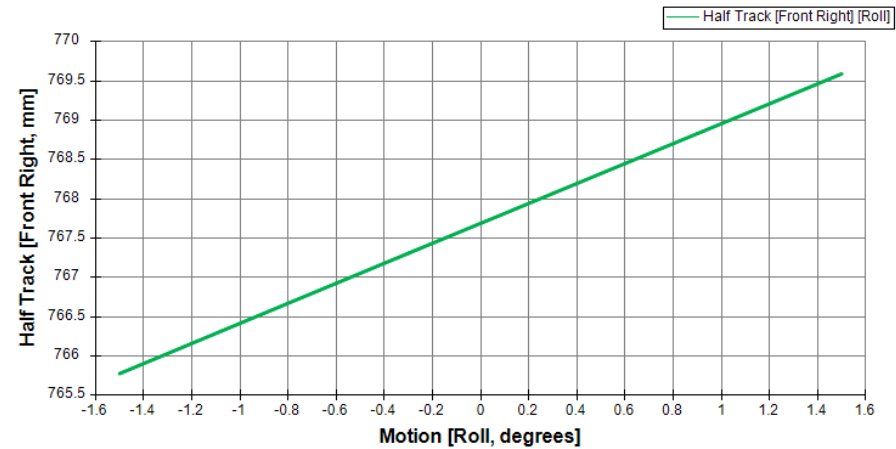
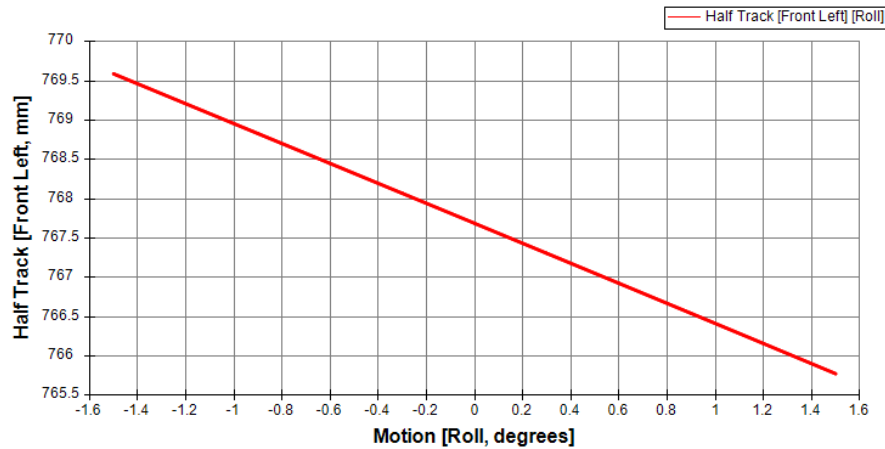
Wheelbase – Corner With DF



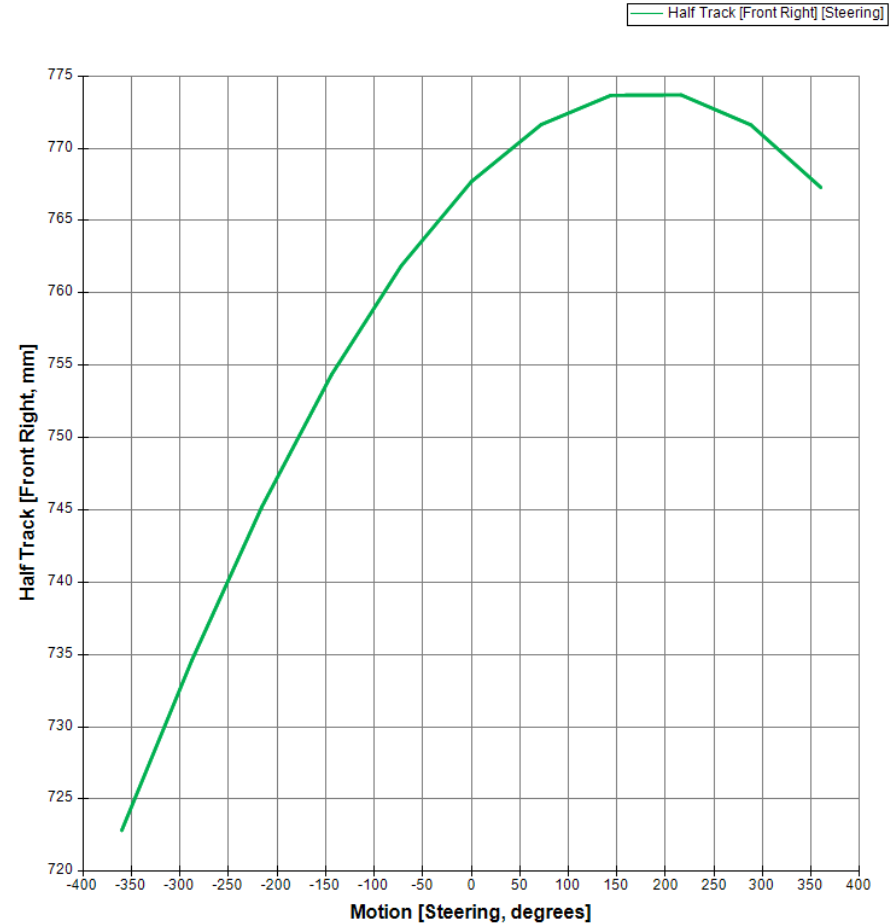
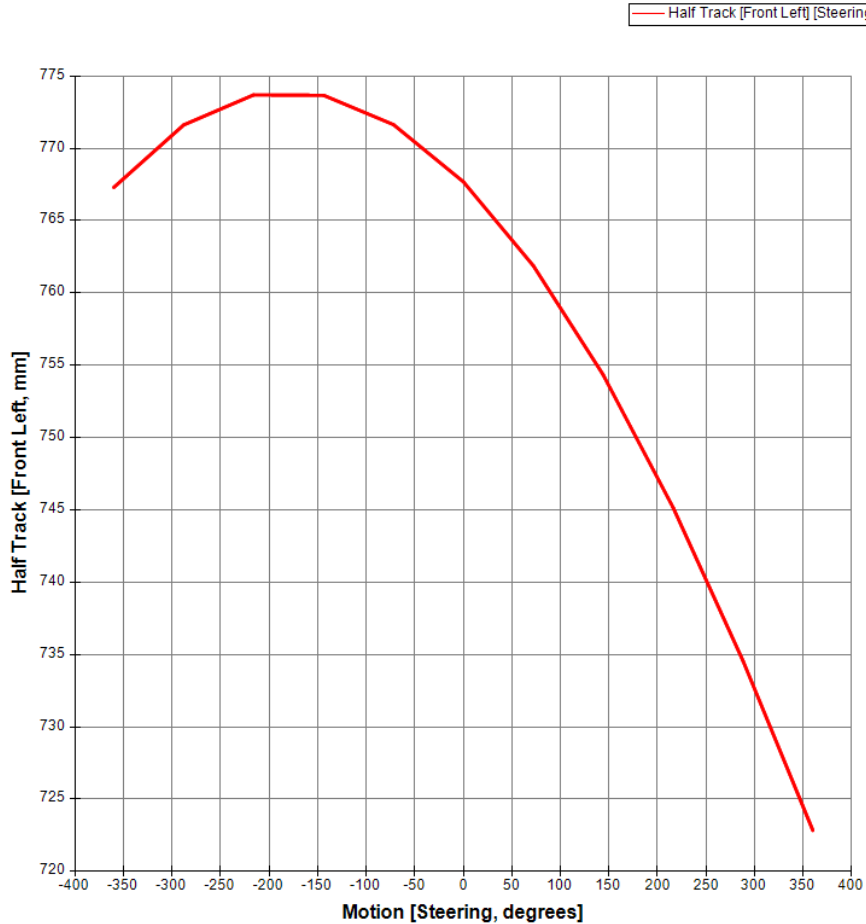
Half-Track – Heave



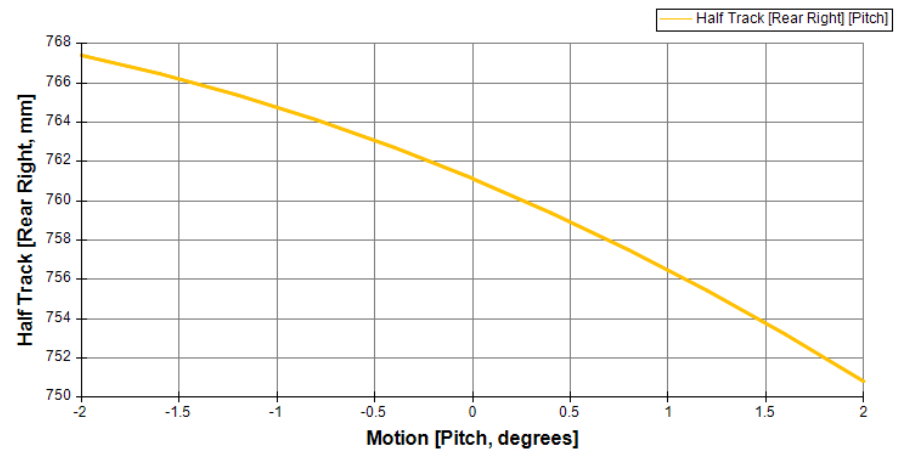
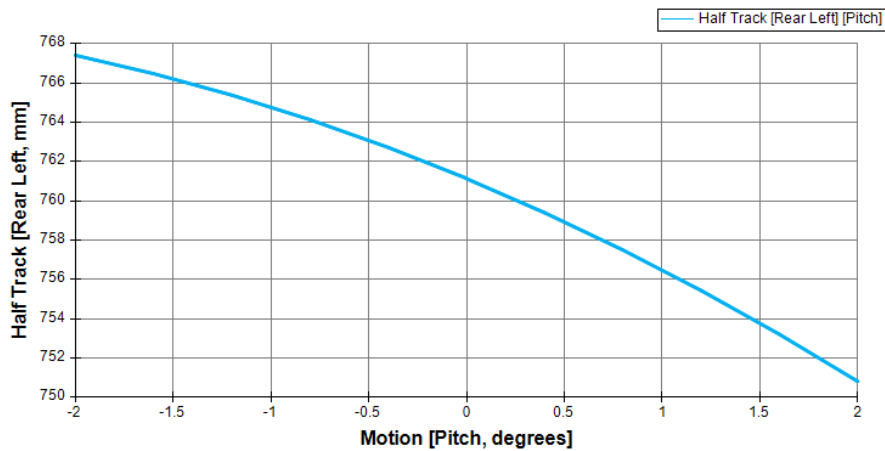
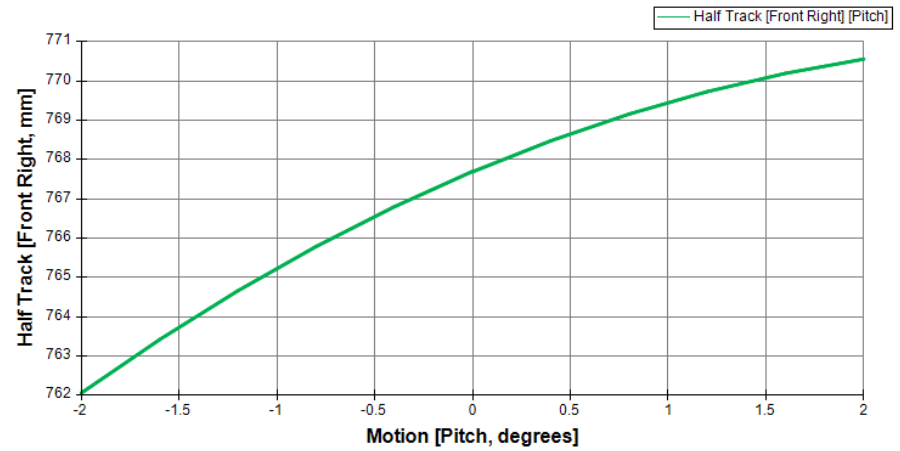
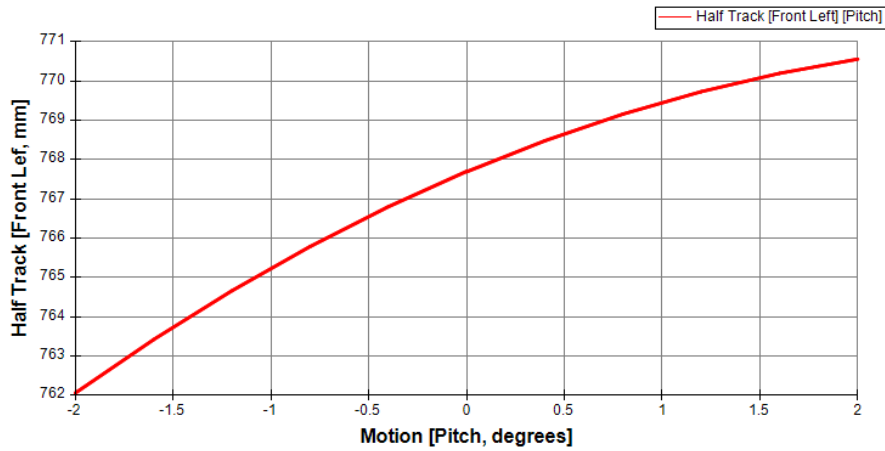
Half-Track – Roll



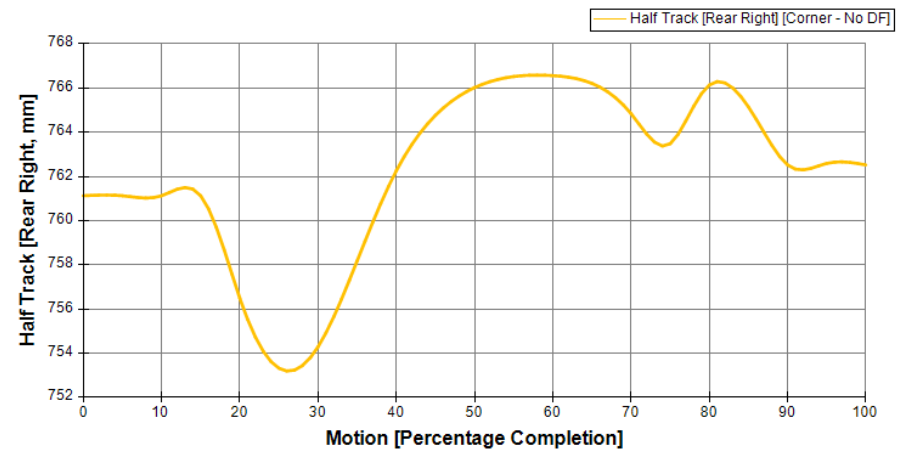
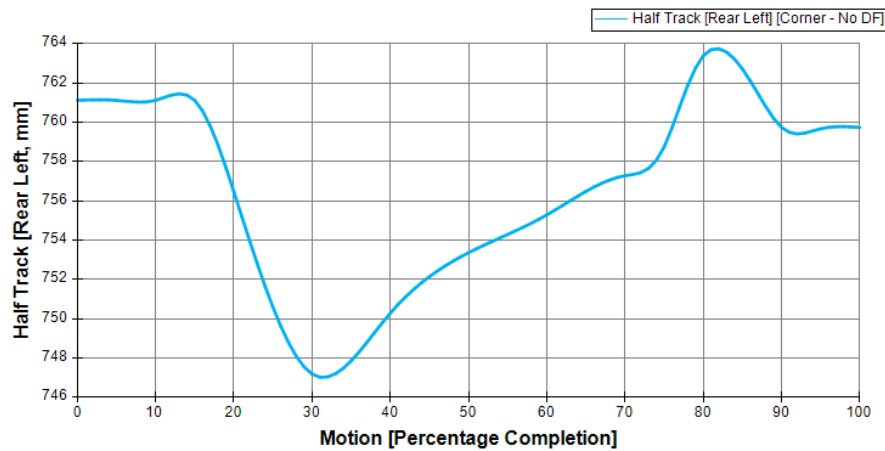
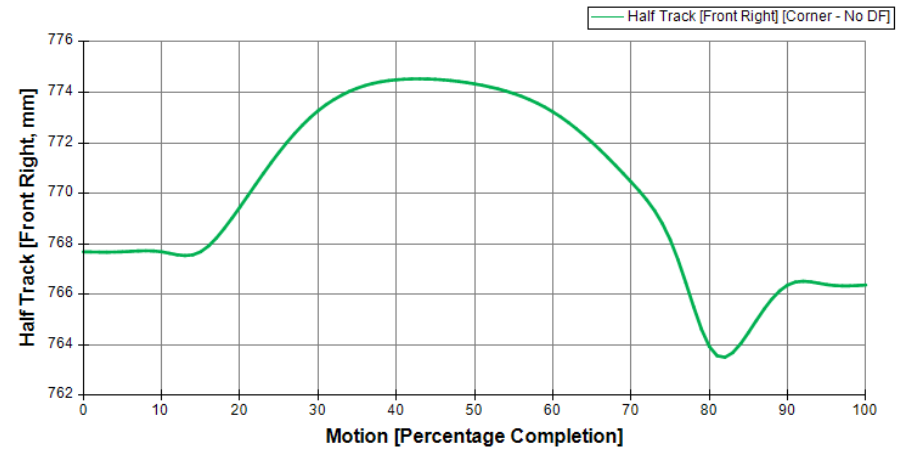
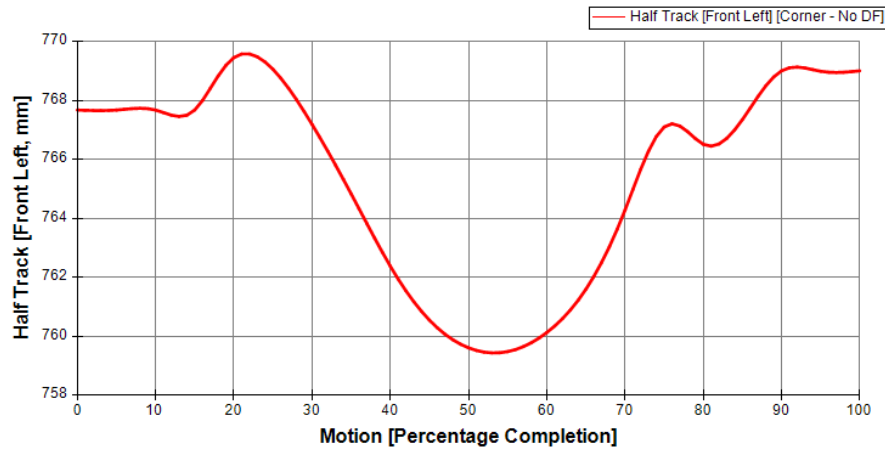
Half-Track – Steering



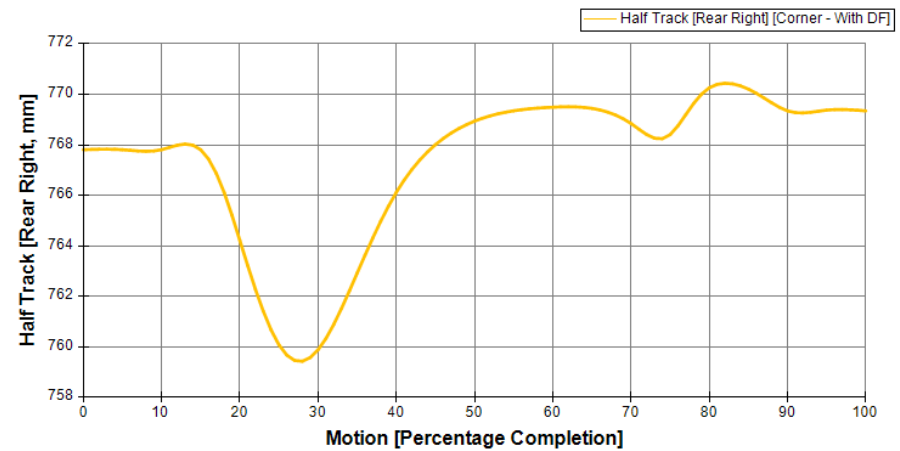
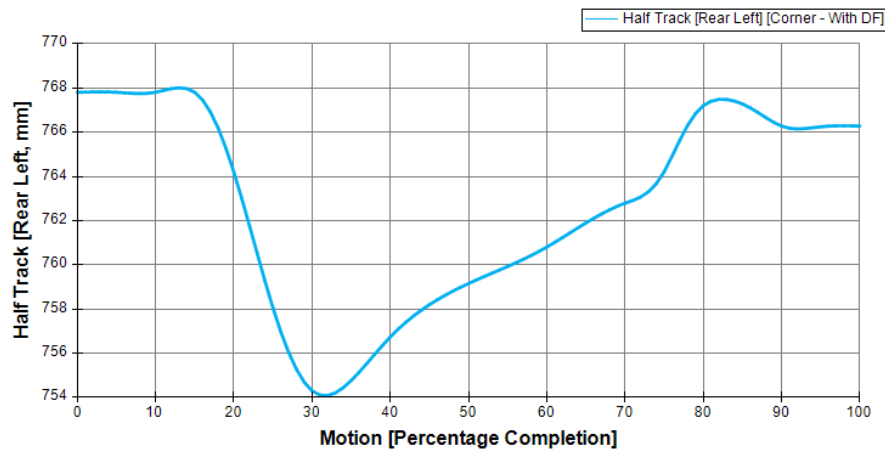
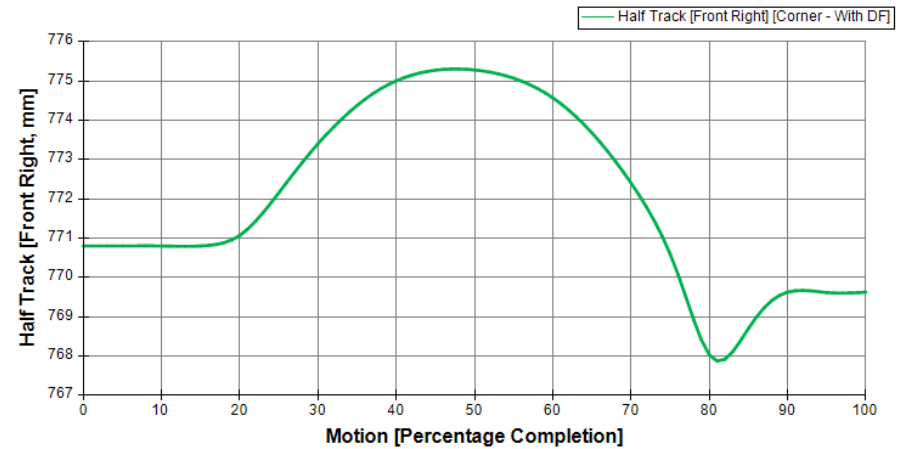
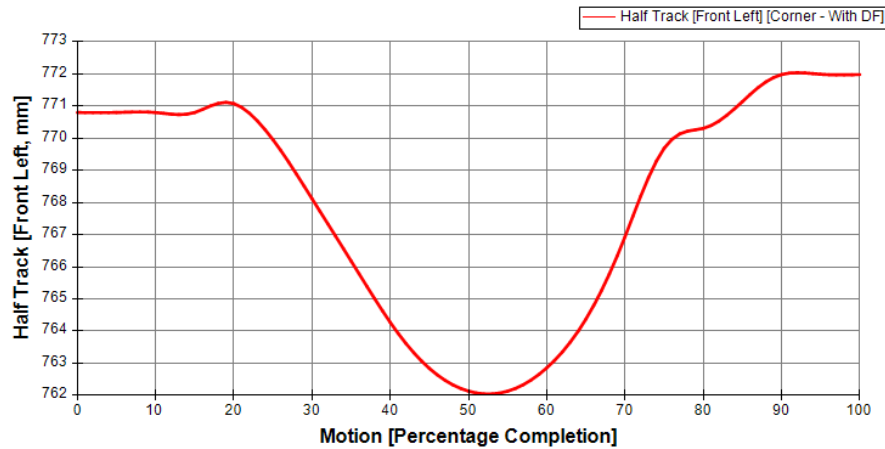
Half-Track – Pitch



Half-Track – Corner No DF

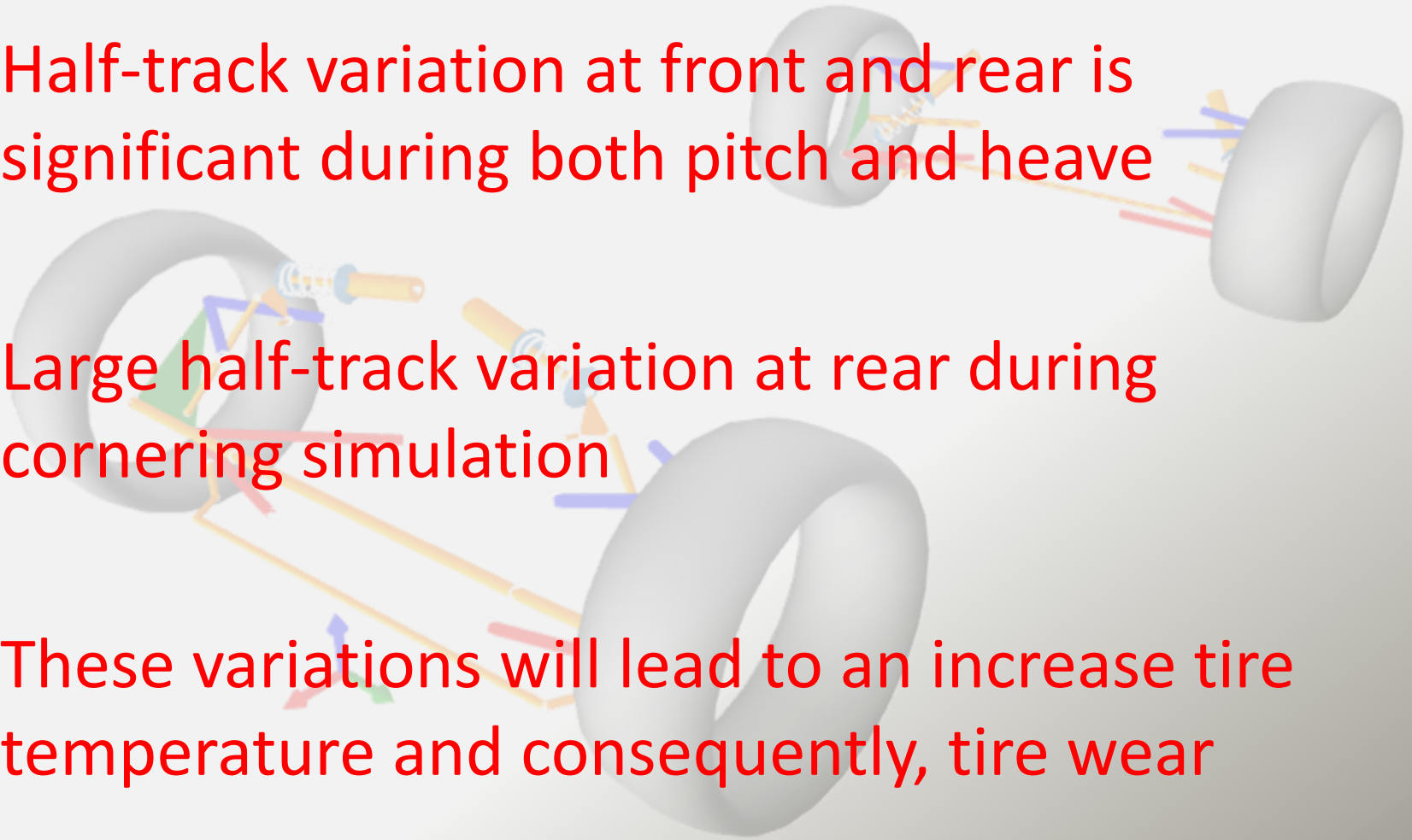


Half-Track – Corner DF

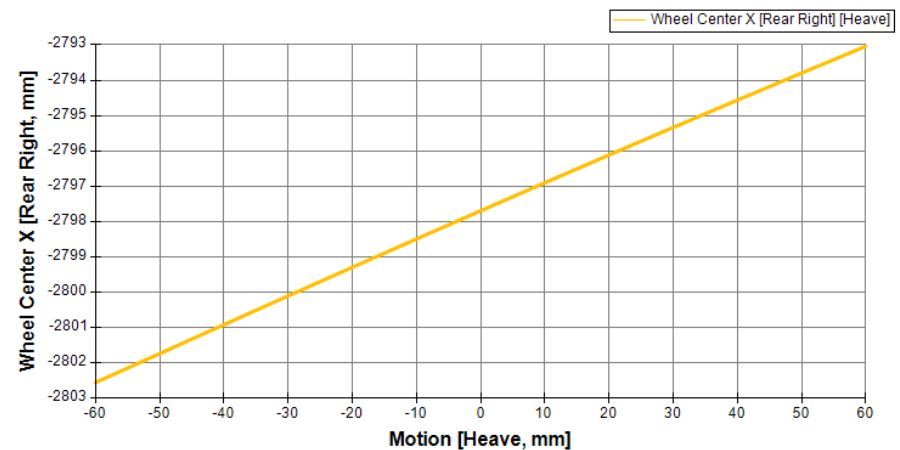
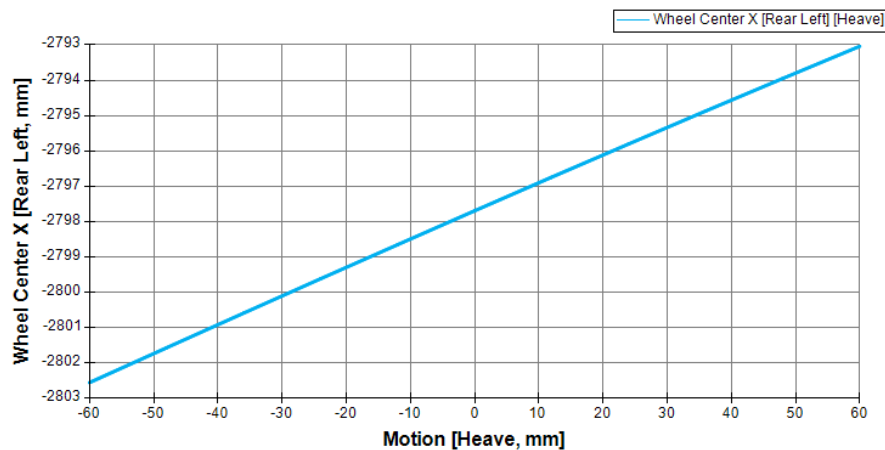
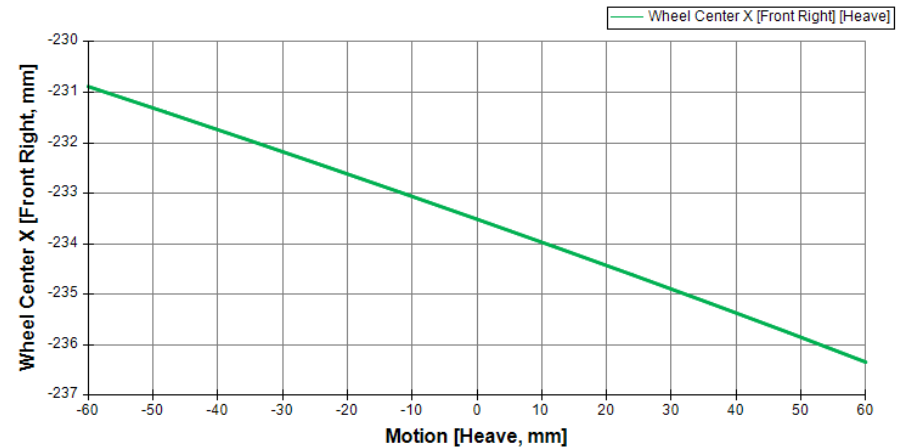
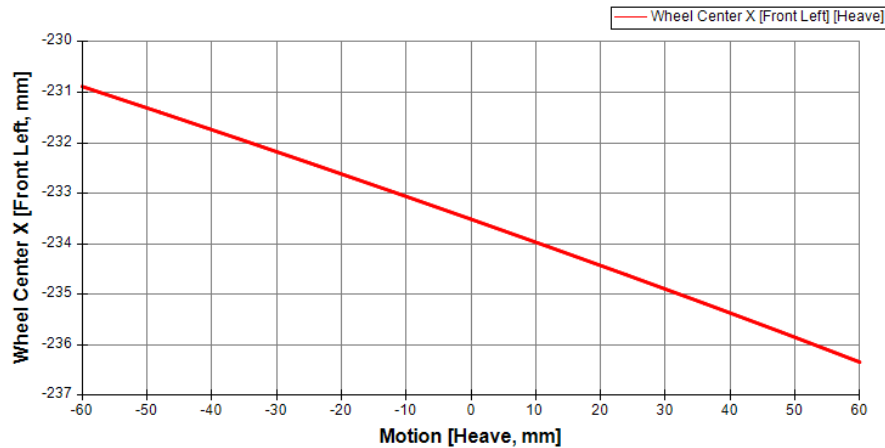


Wheelbase & Half-Track – Comments

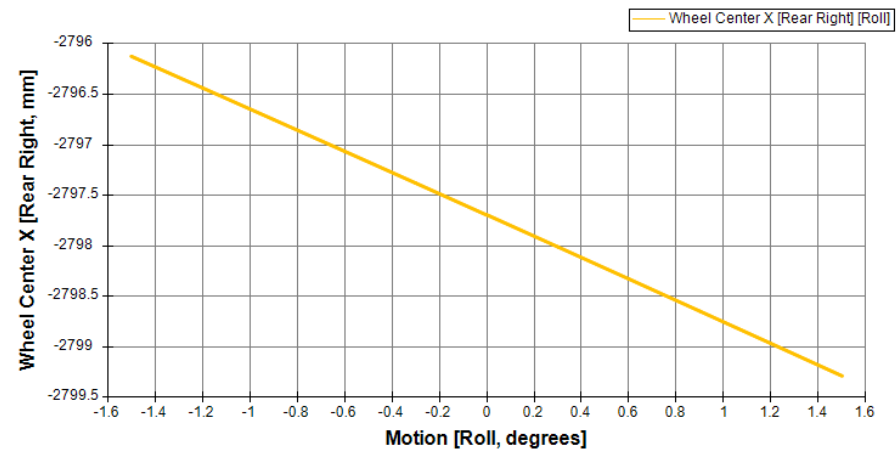
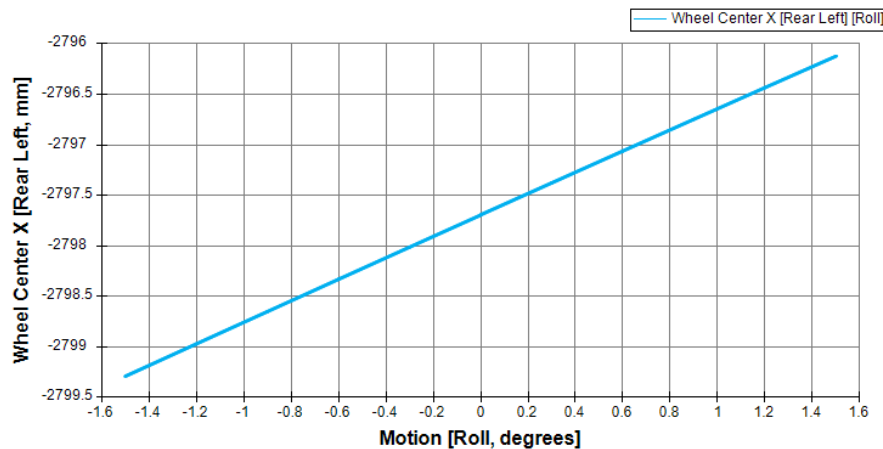
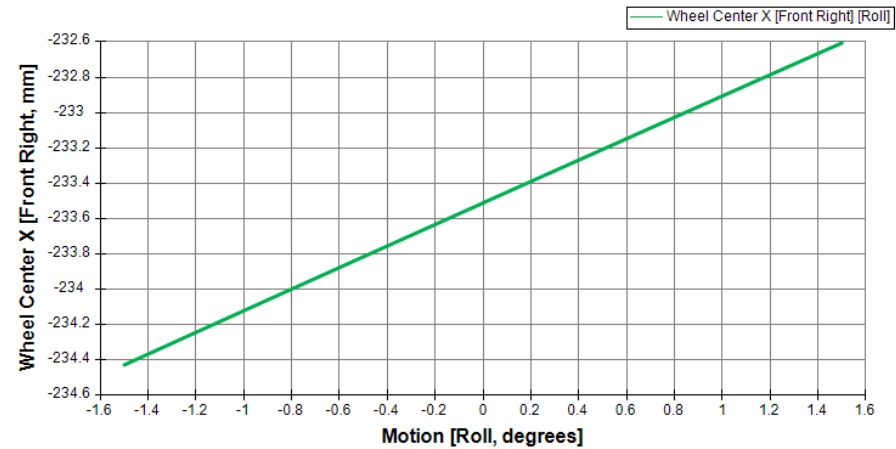
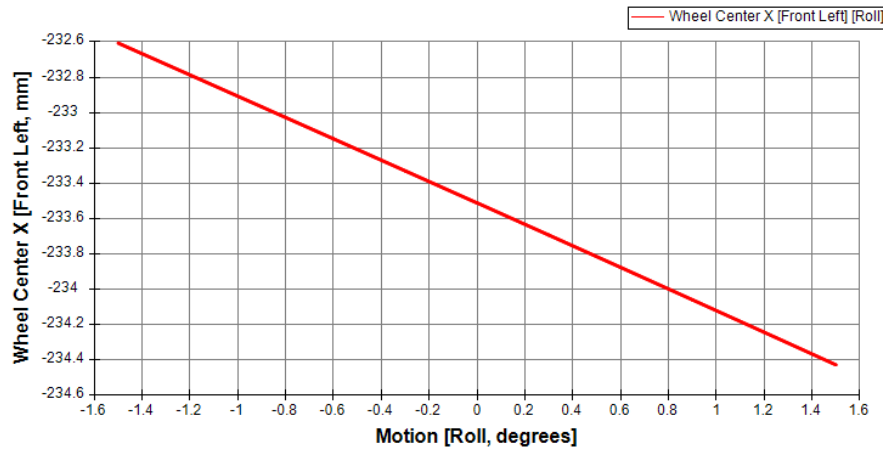
- Half-track variation at front and rear is significant during both pitch and heave
- Large half-track variation at rear during cornering simulation
- These variations will lead to an increase tire temperature and consequently, tire wear



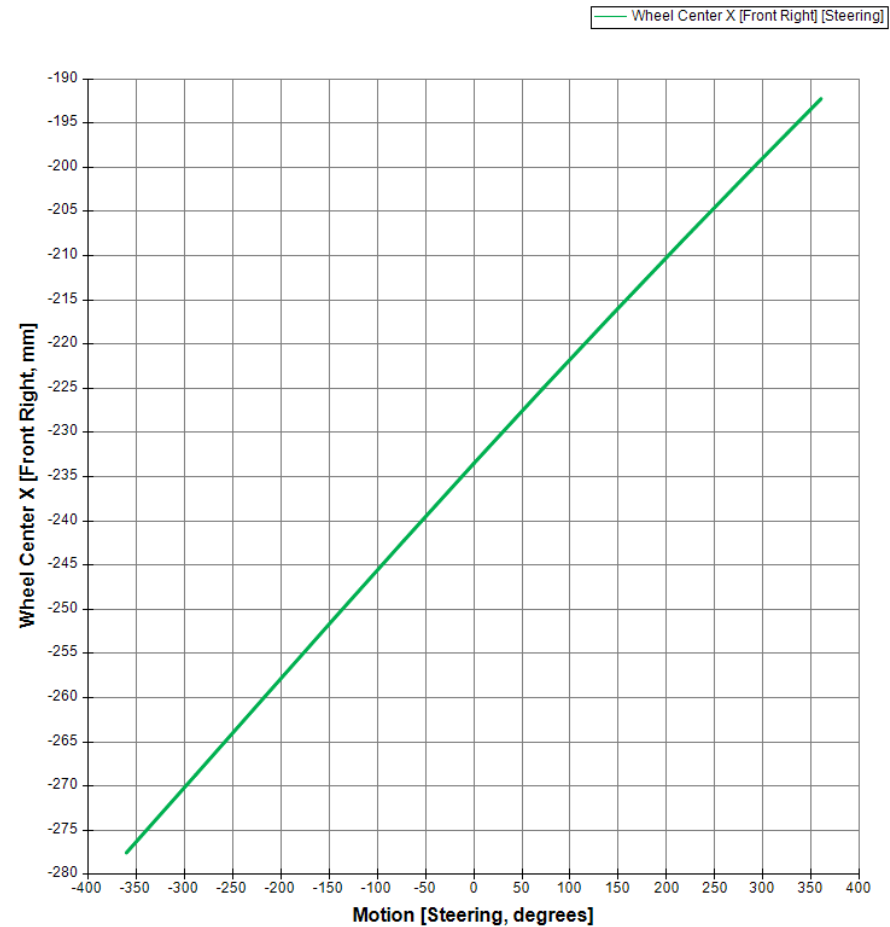
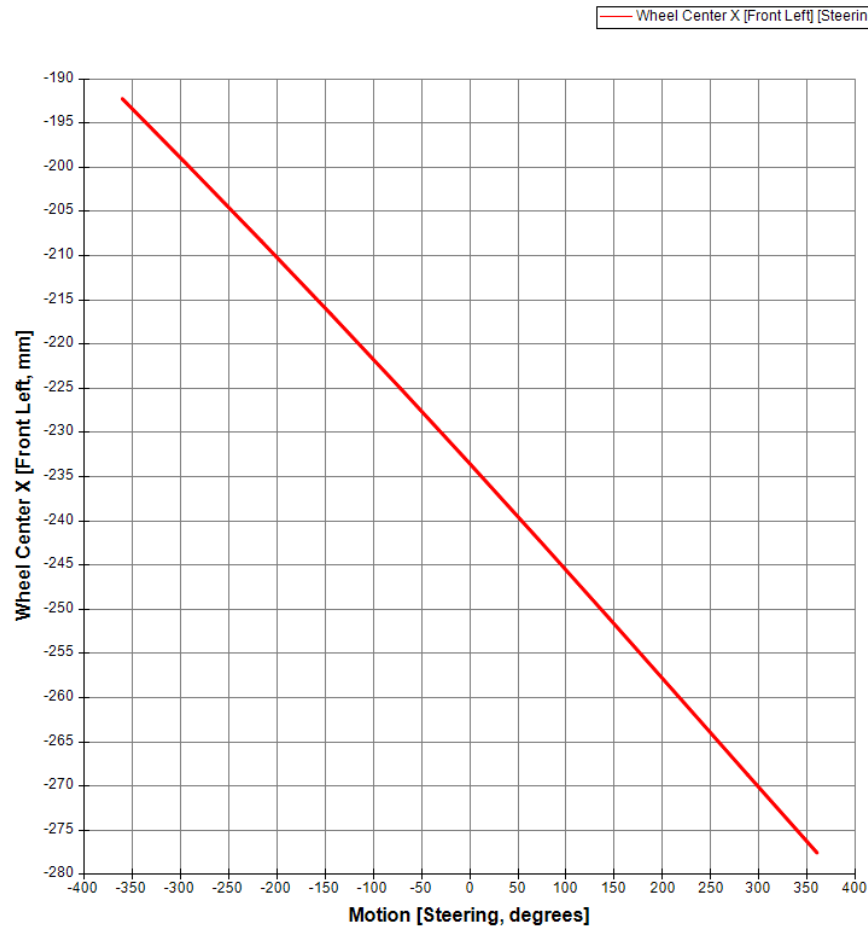
Wheel Center X Coordinate – Heave



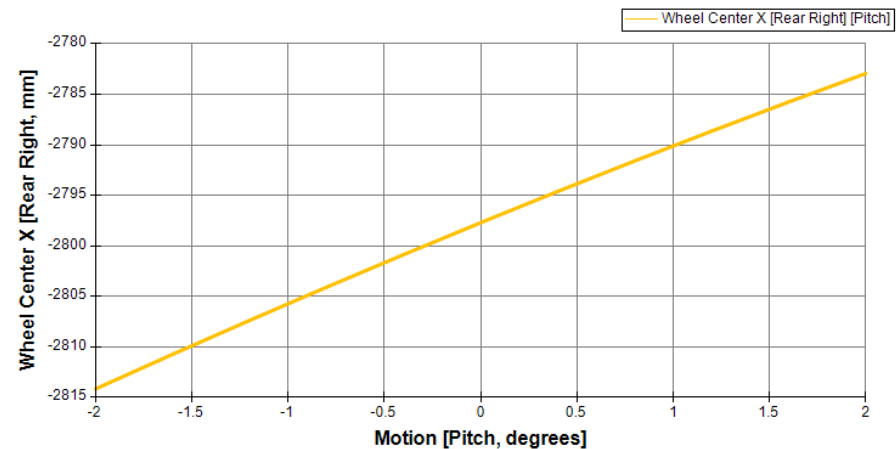
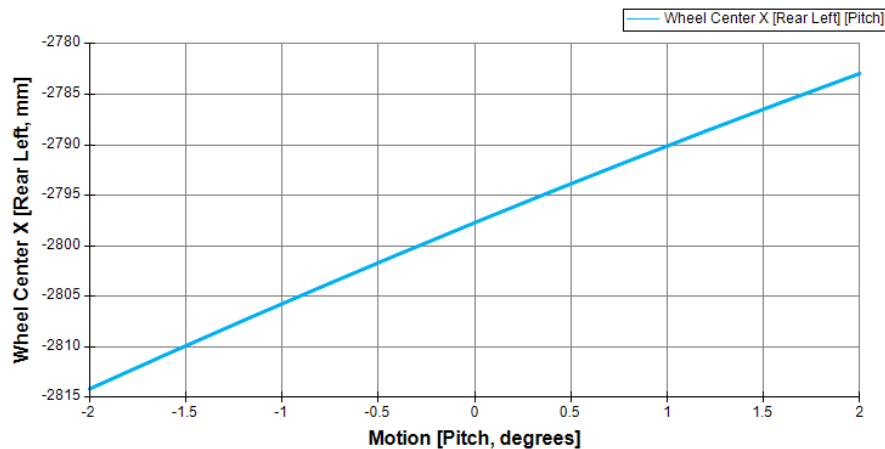
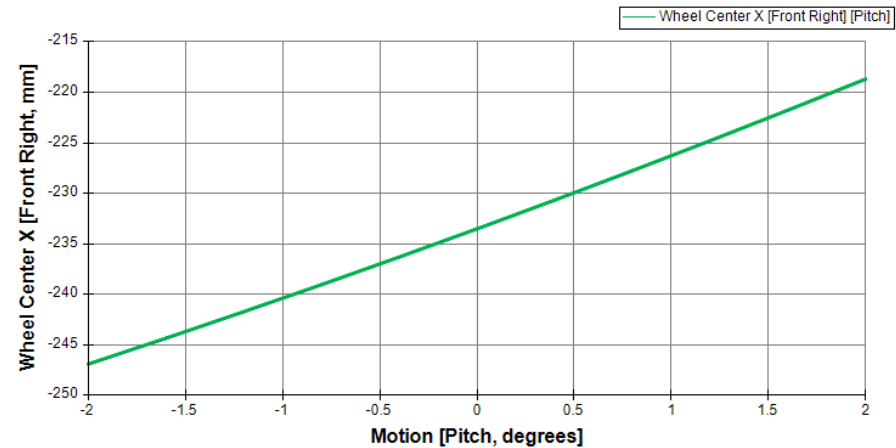
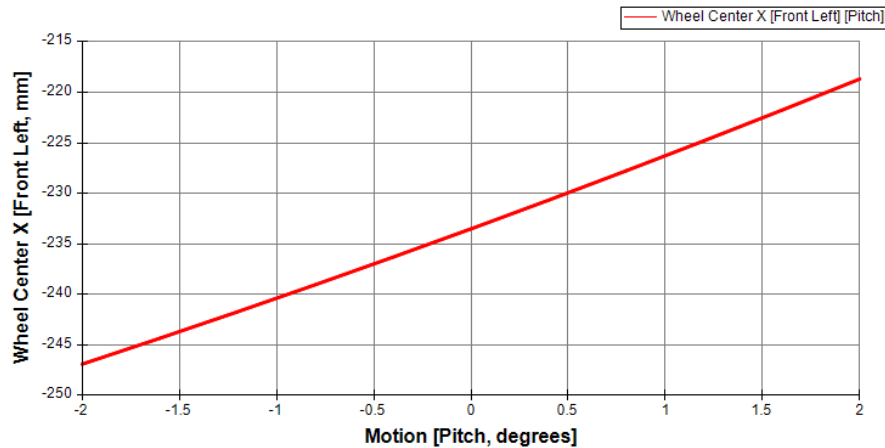
Wheel Center X Coordinate – Roll



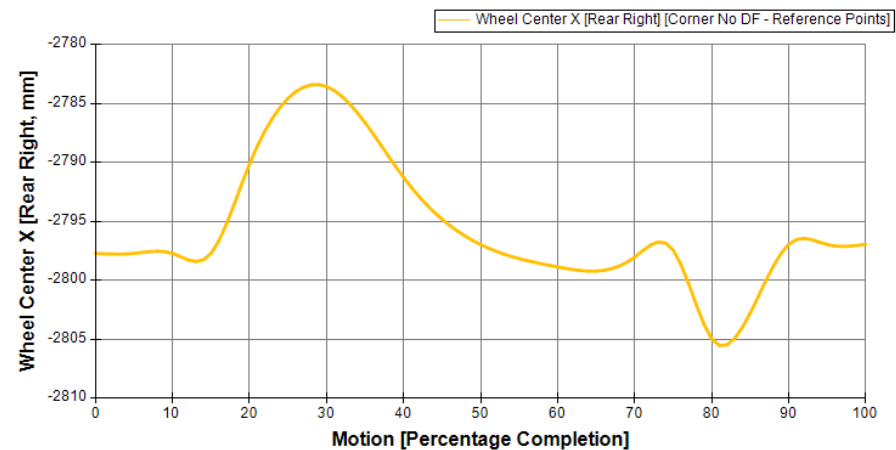
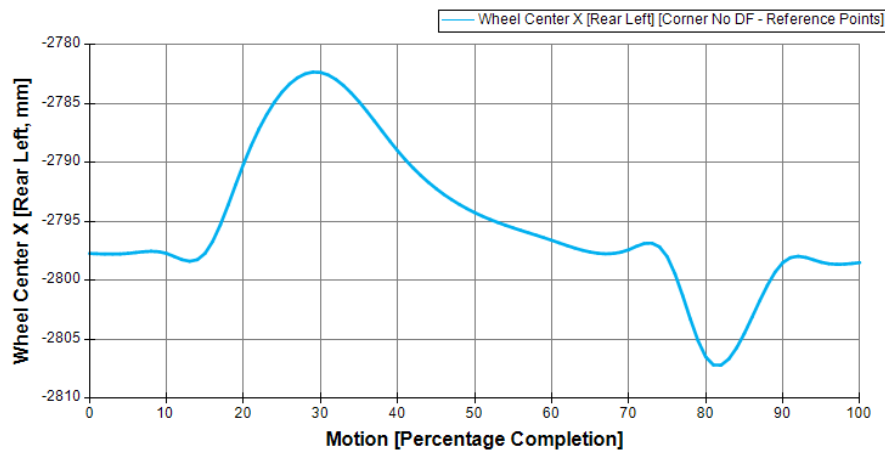
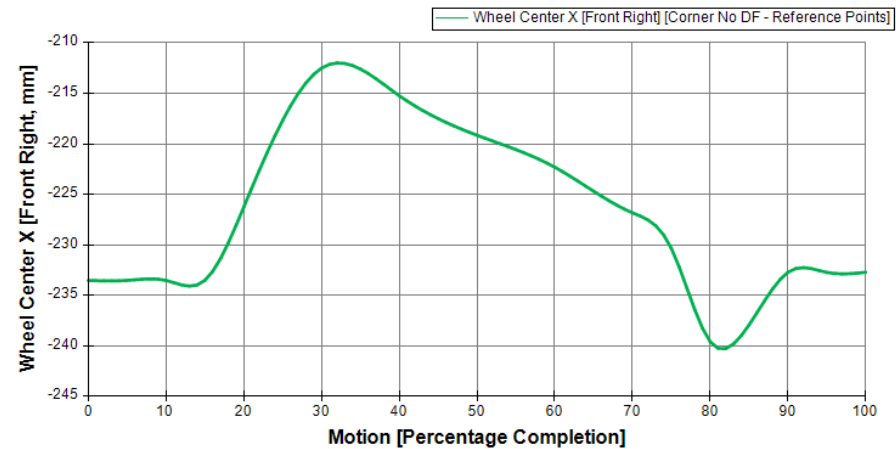
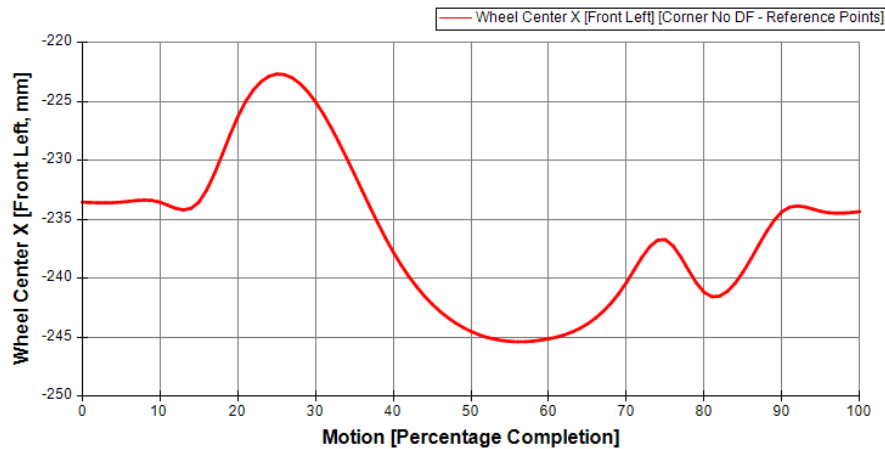
Wheel Center X Coordinate – Steering



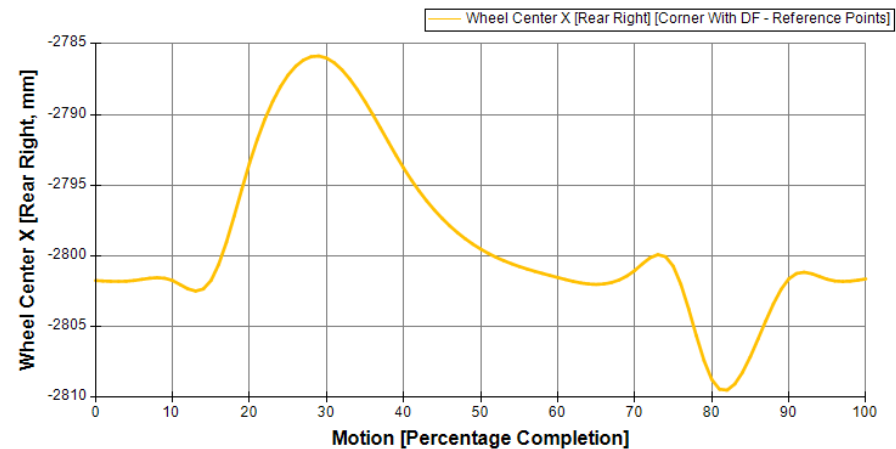
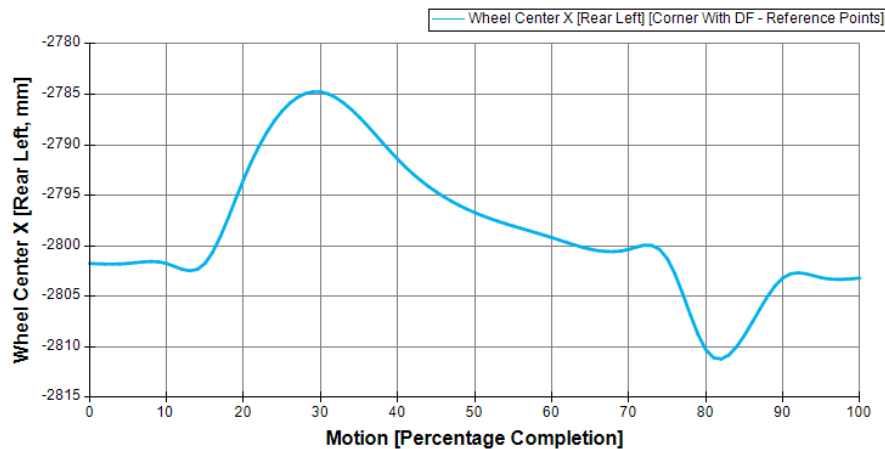
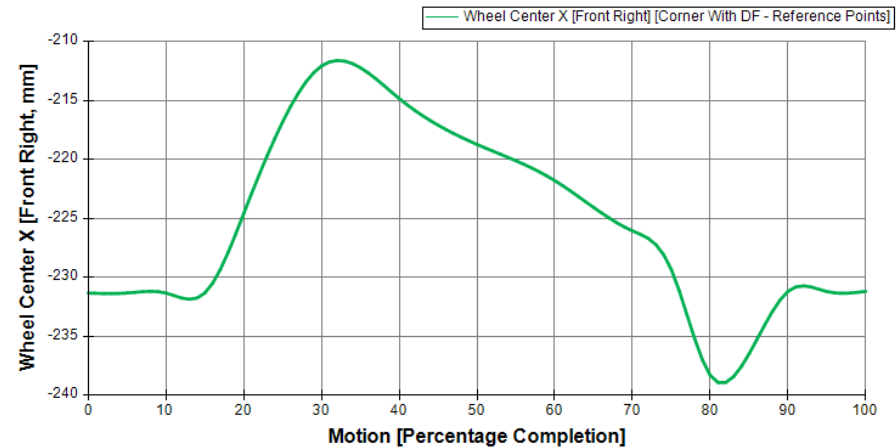
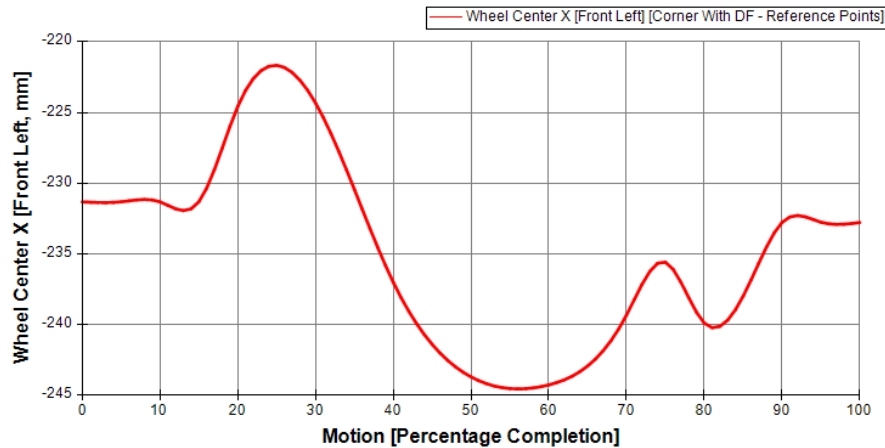
Wheel Center X Coordinate – Pitch



Wheel Center X Coordinate – Corner No DF

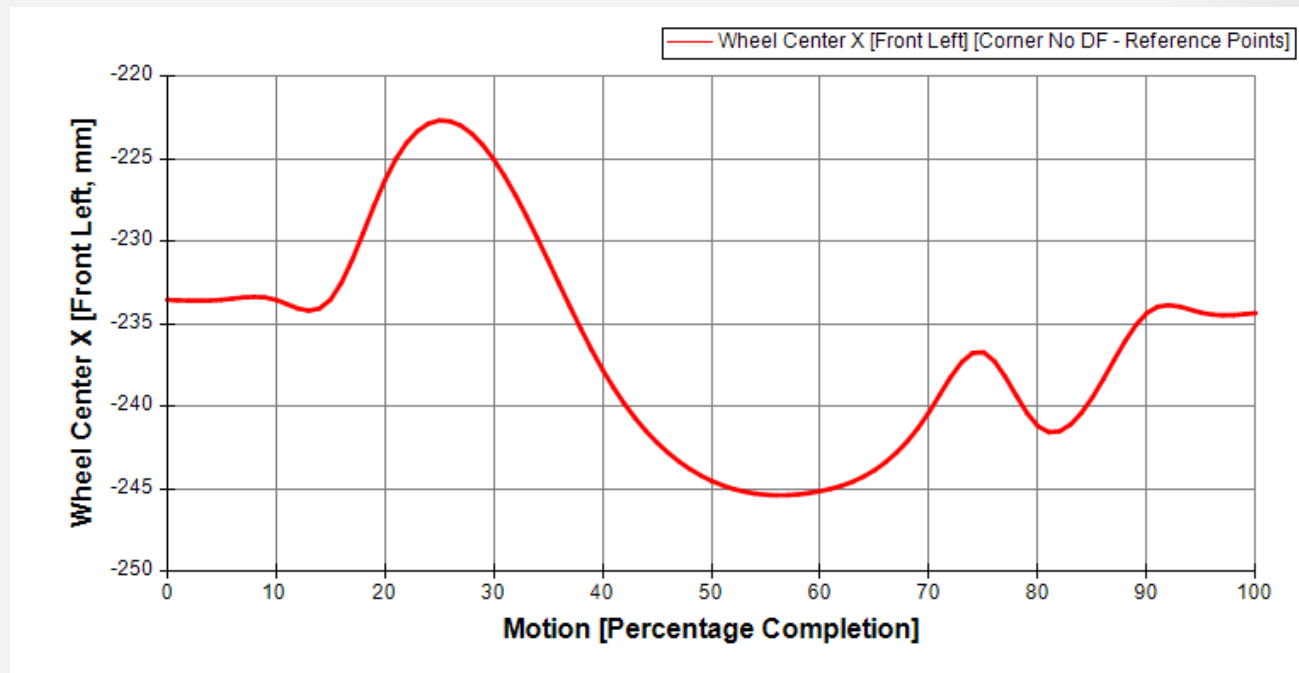


Wheel Center X Coordinate – Corner DF



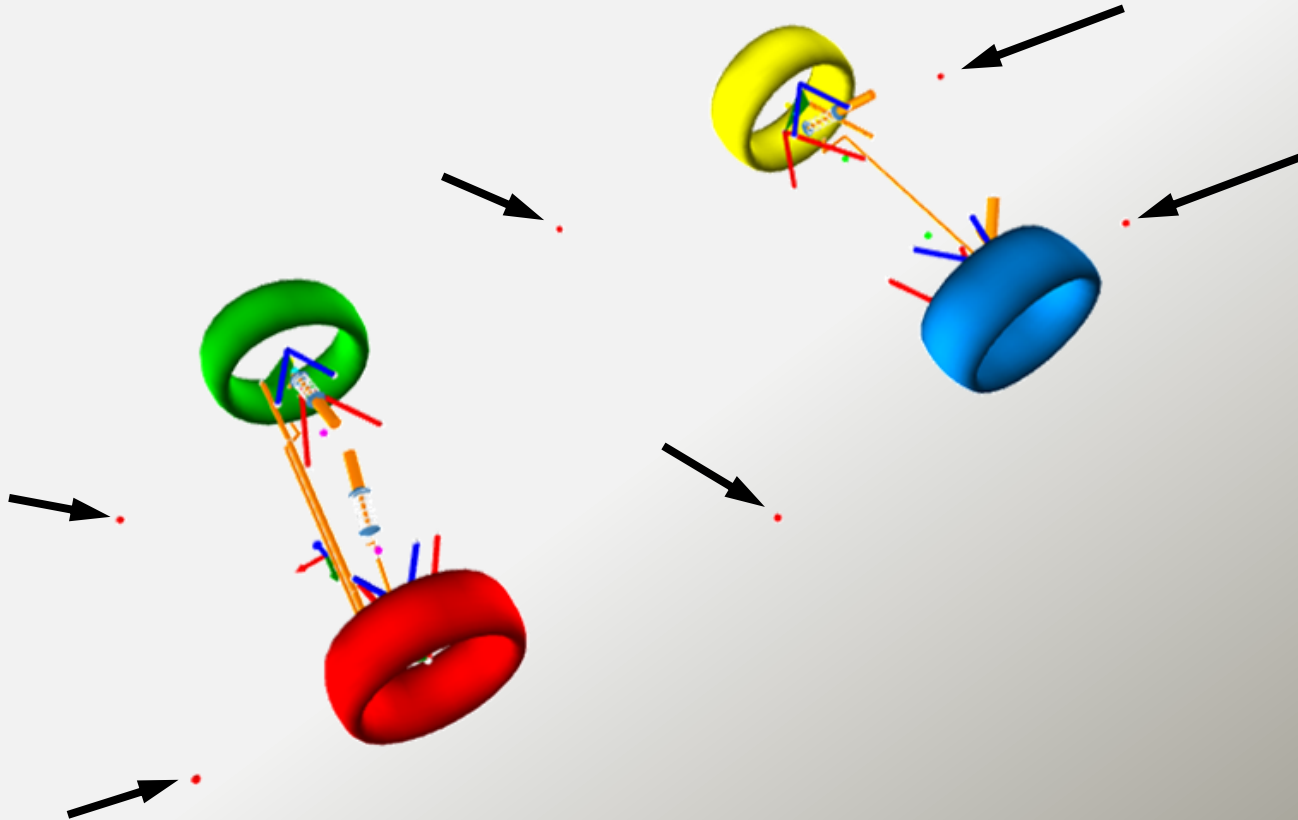
Wheel Center X Coordinate– Comments

Migration of Wheel X Center Coordinate can be used to indicate whether front or rear axle is dominant in the change in wheelbase.

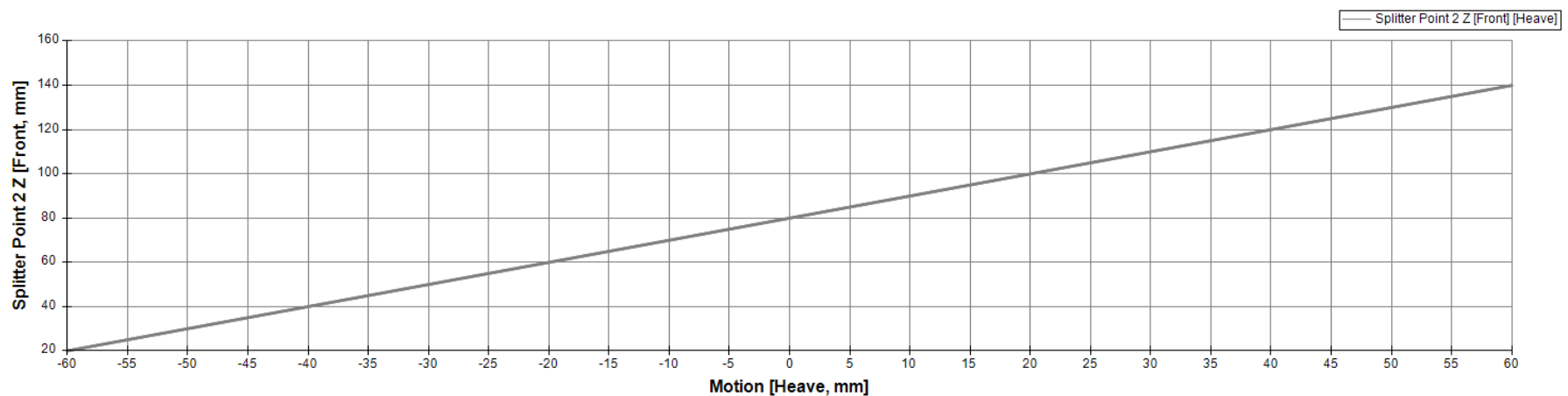
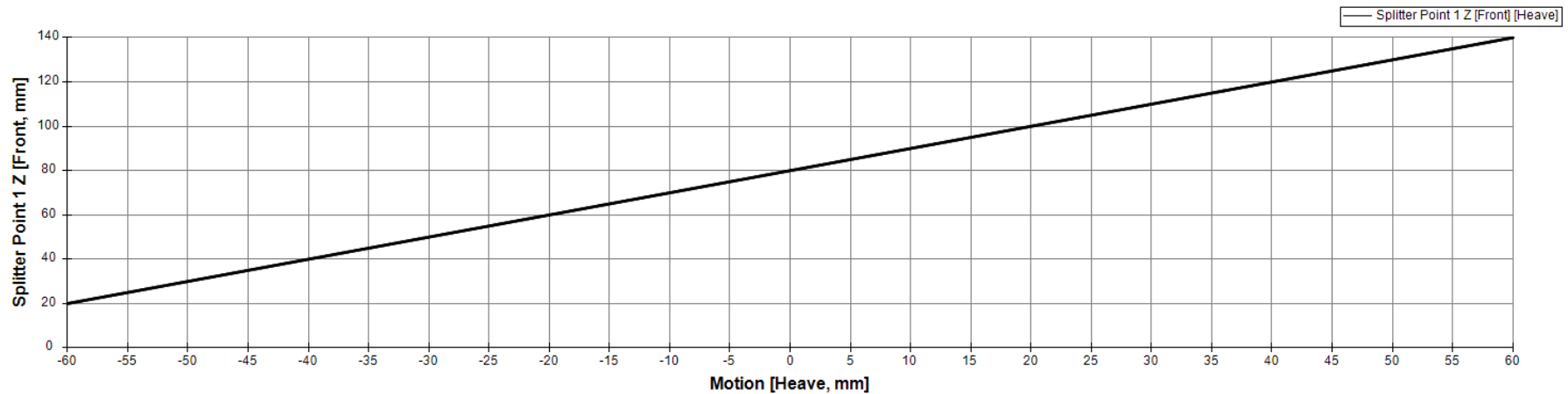


Ground Clearance

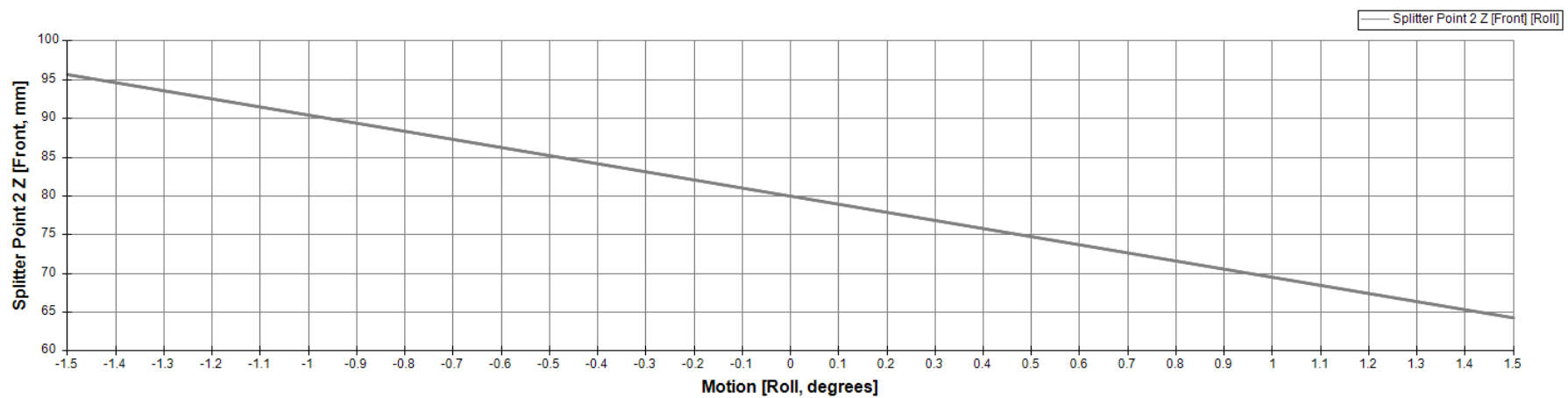
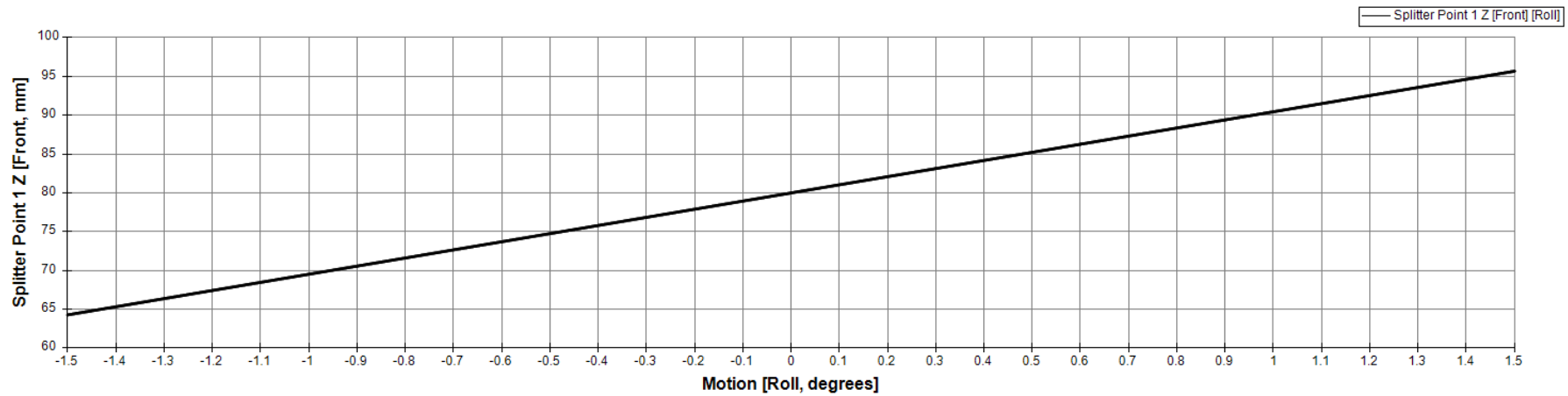
In order to inspect if the vehicle will come in contact with the ground in any point during the simulation we can specify reference points attached to the sprung mass that represent a component of the vehicle, like the front splitter for example.



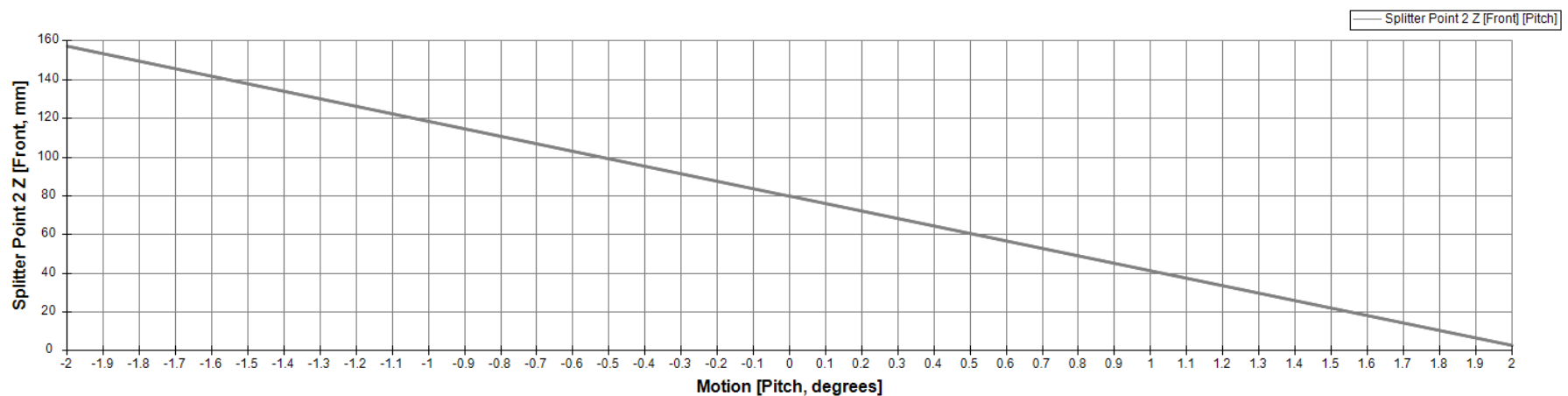
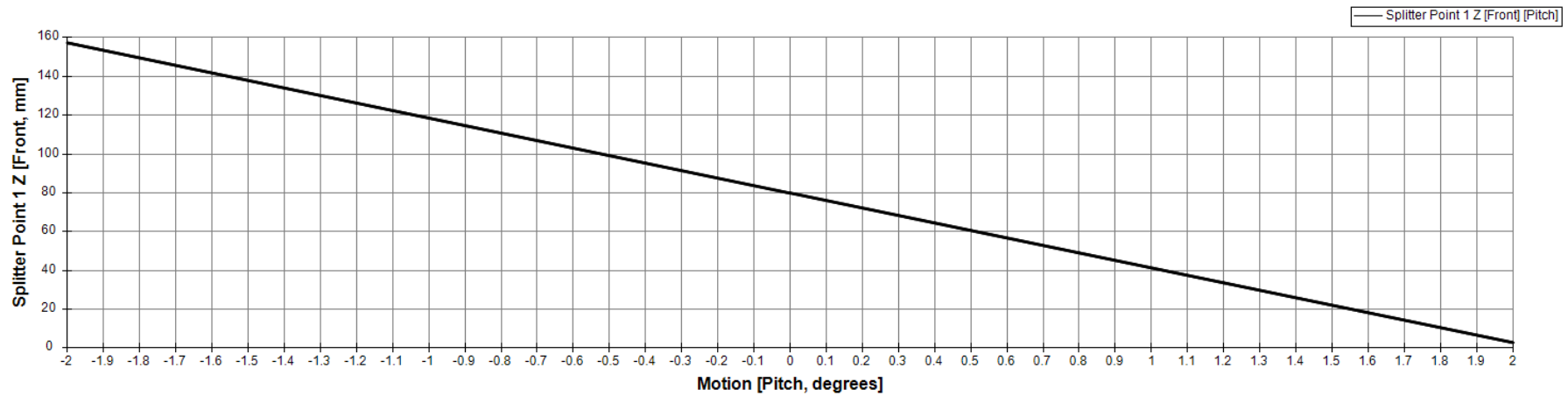
Ground Clearance Front – Heave



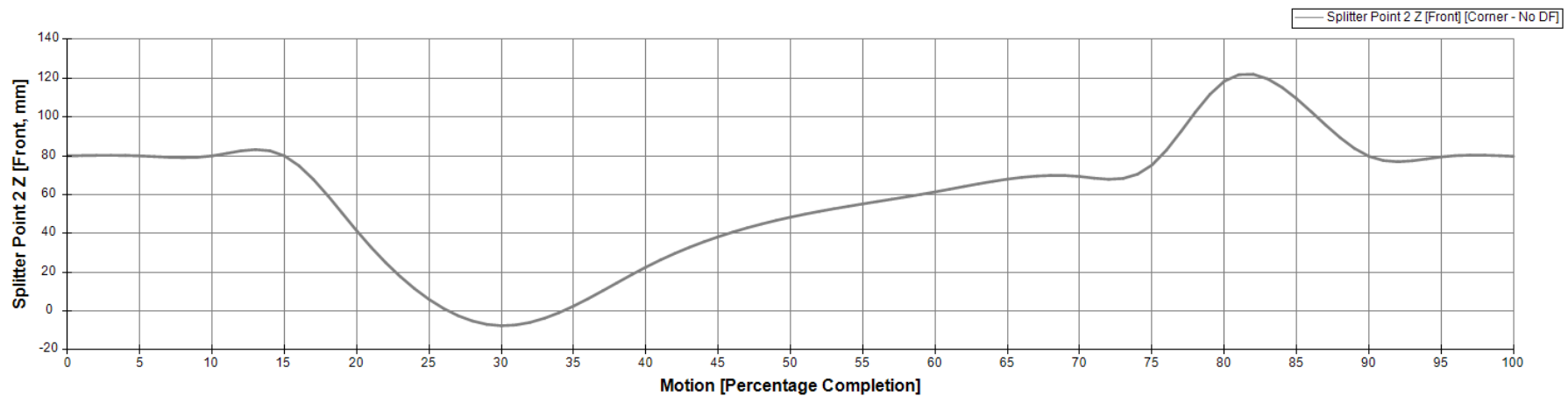
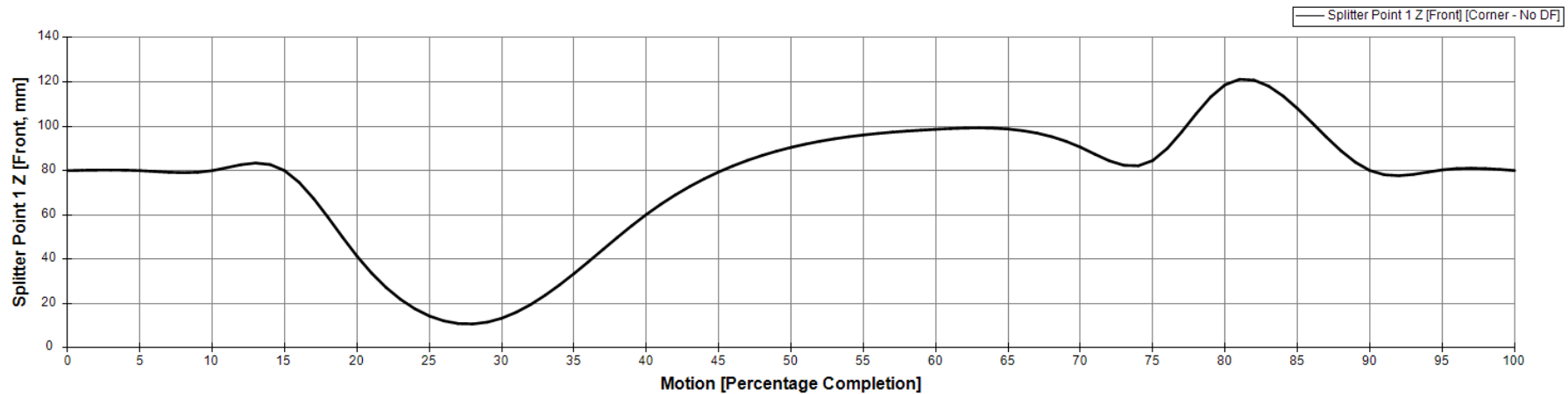
Ground Clearance Front – Roll



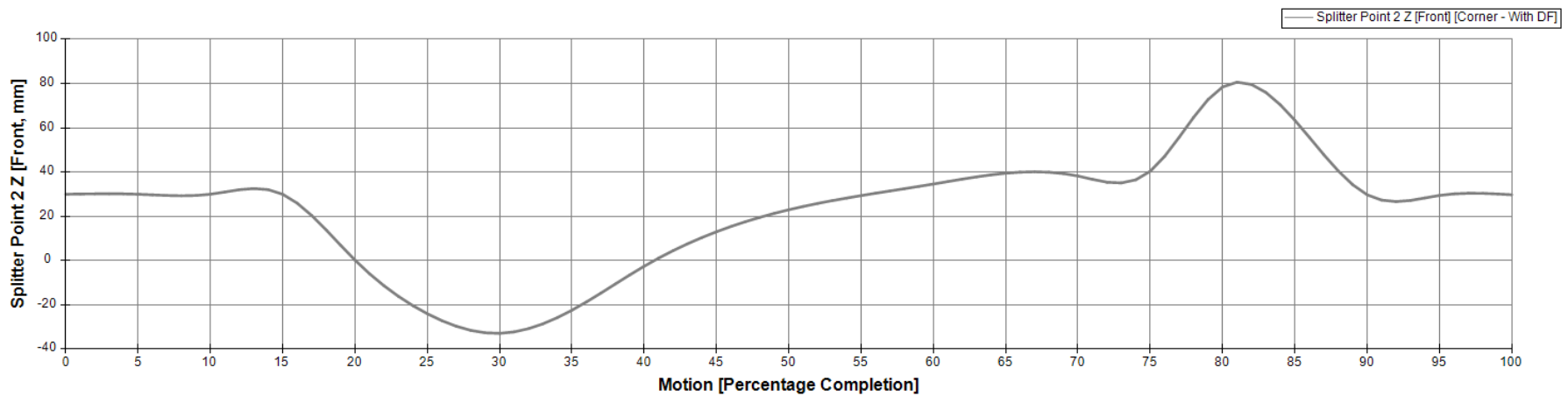
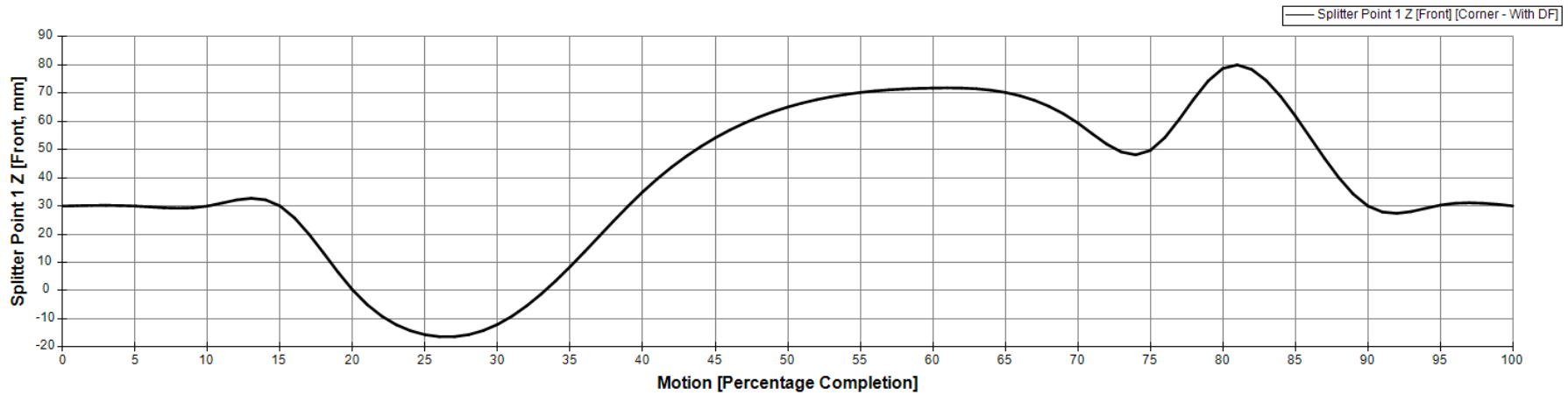
Ground Clearance Front – Pitch



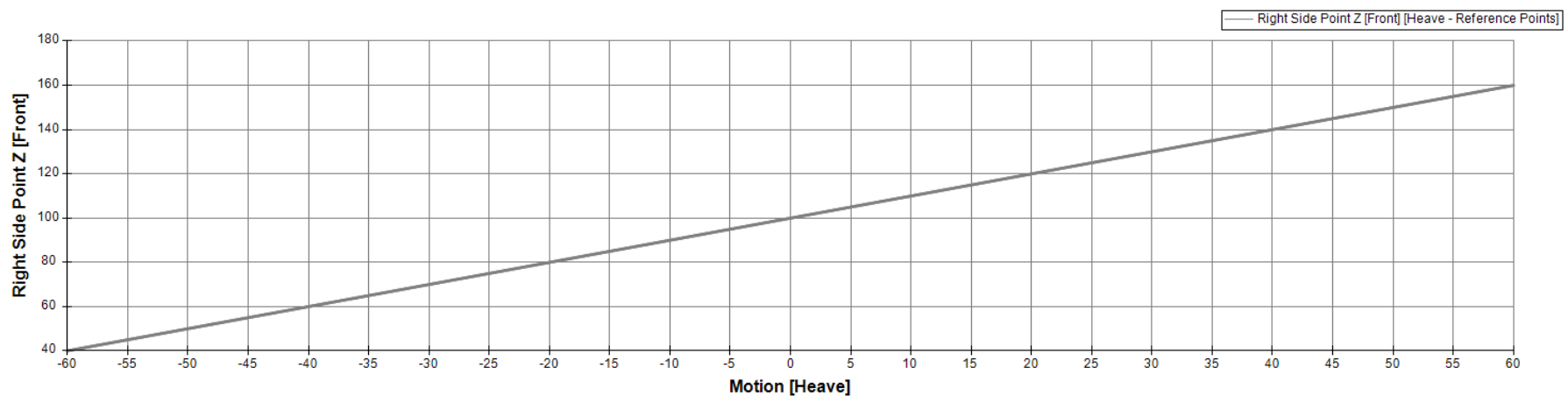
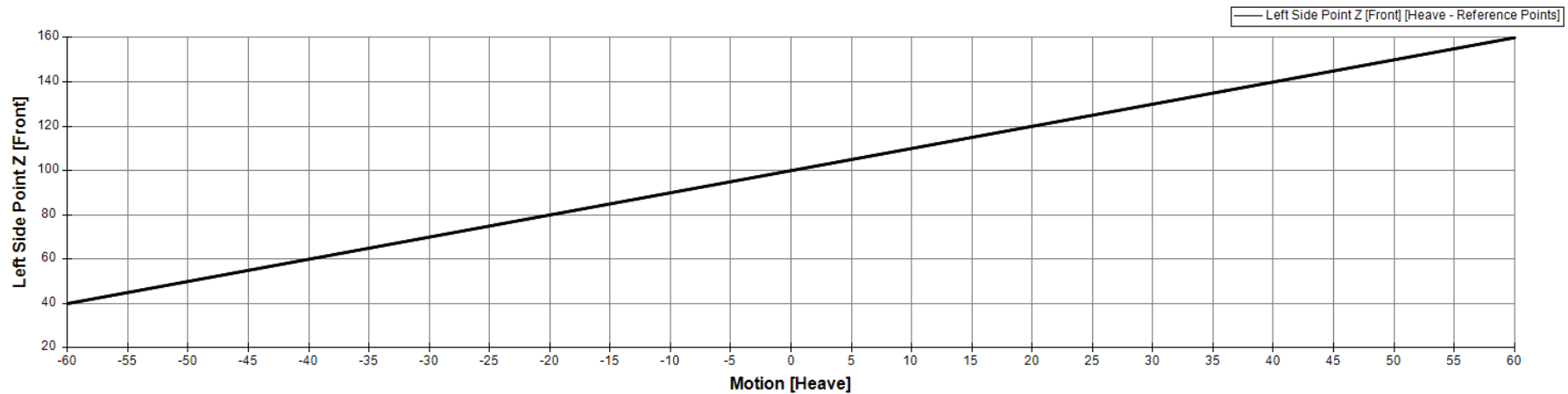
Ground Clearance Front – Corner No DF



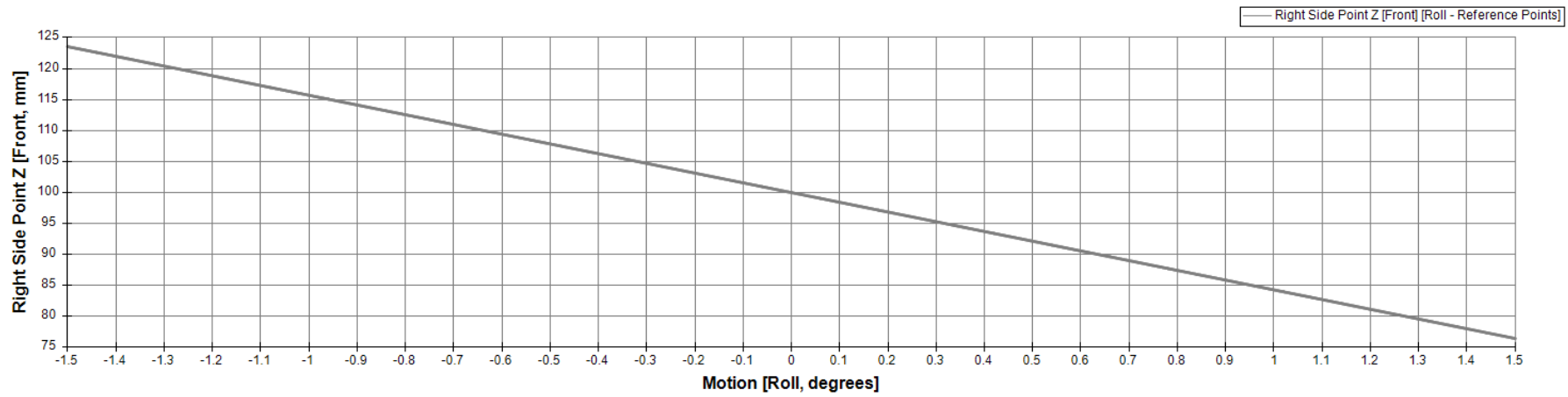
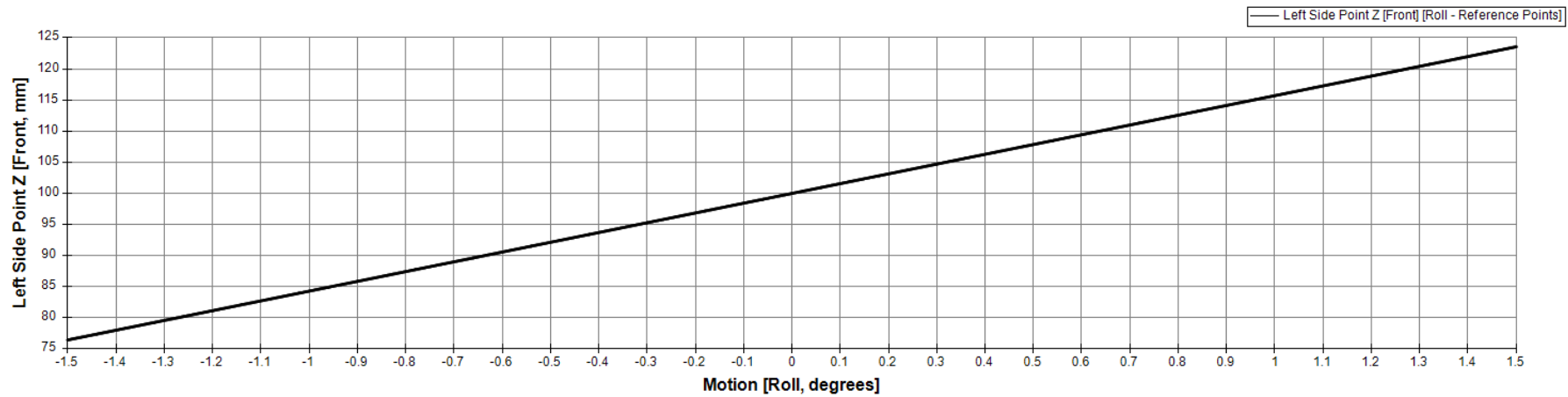
Ground Clearance Front – Corner DF



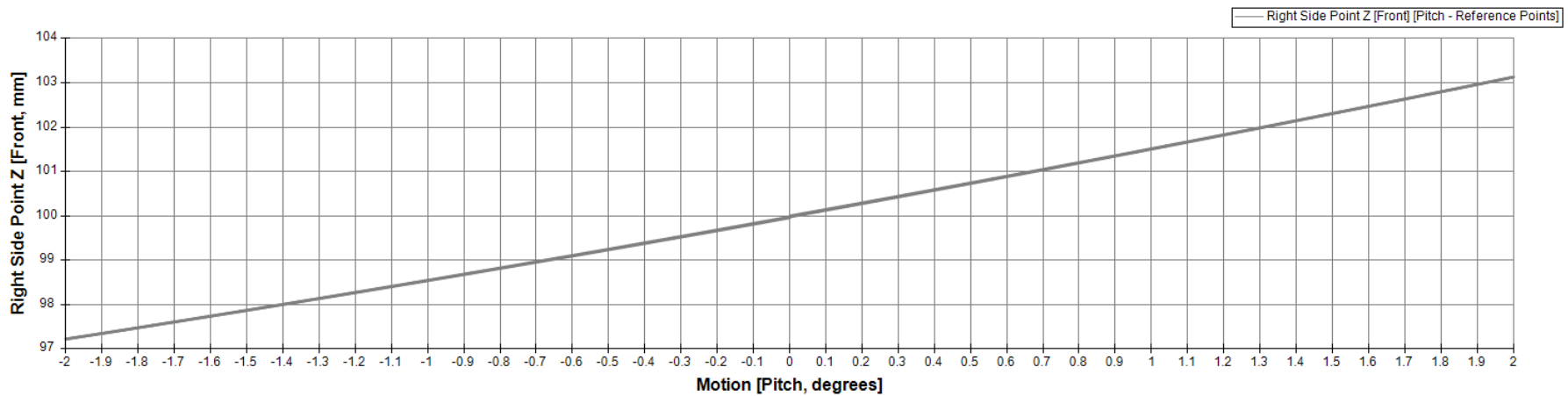
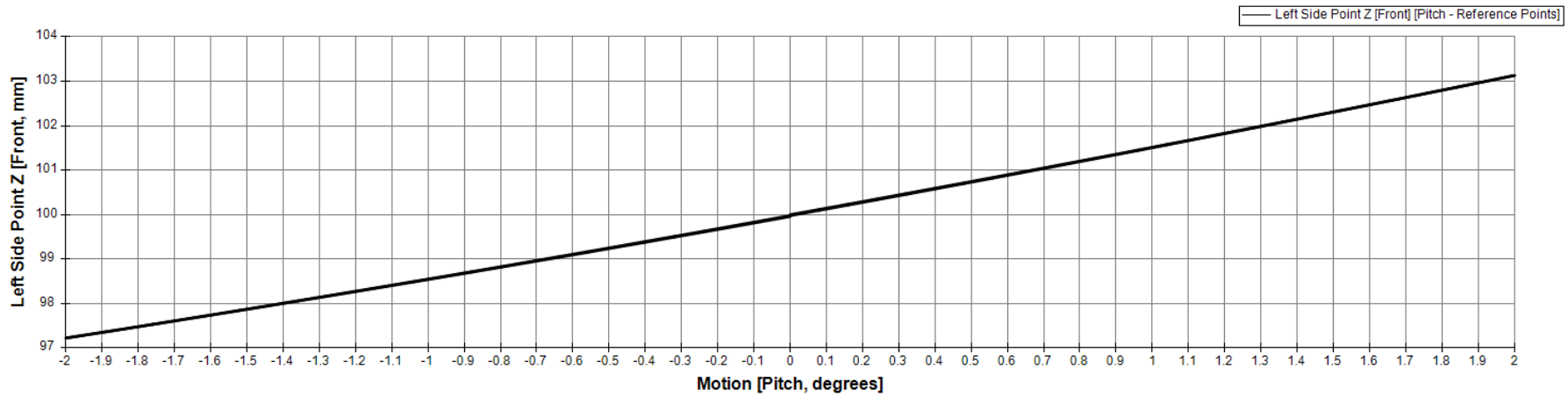
Ground Clearance Side – Heave



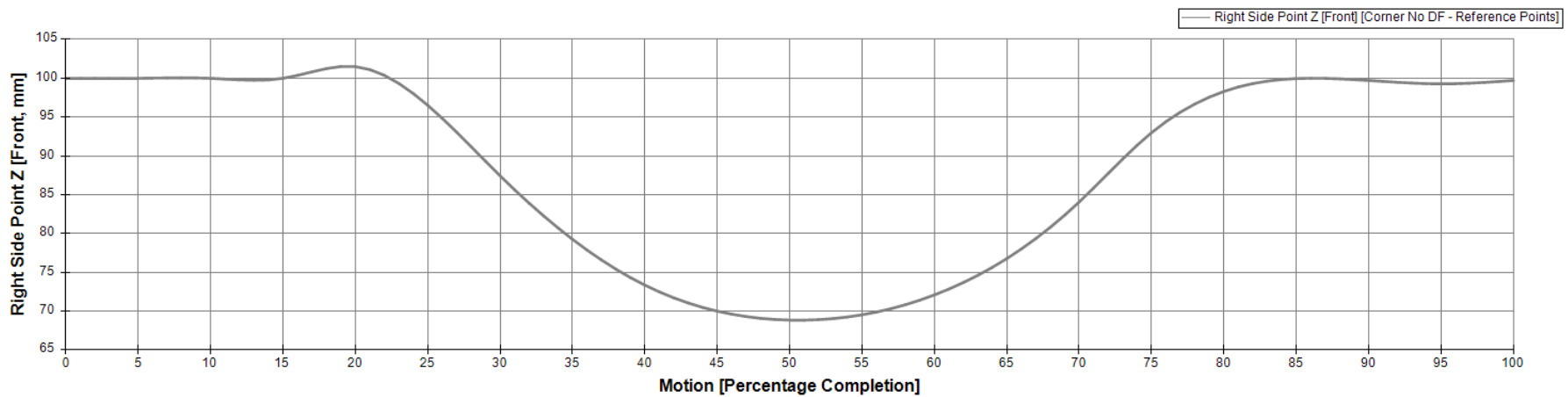
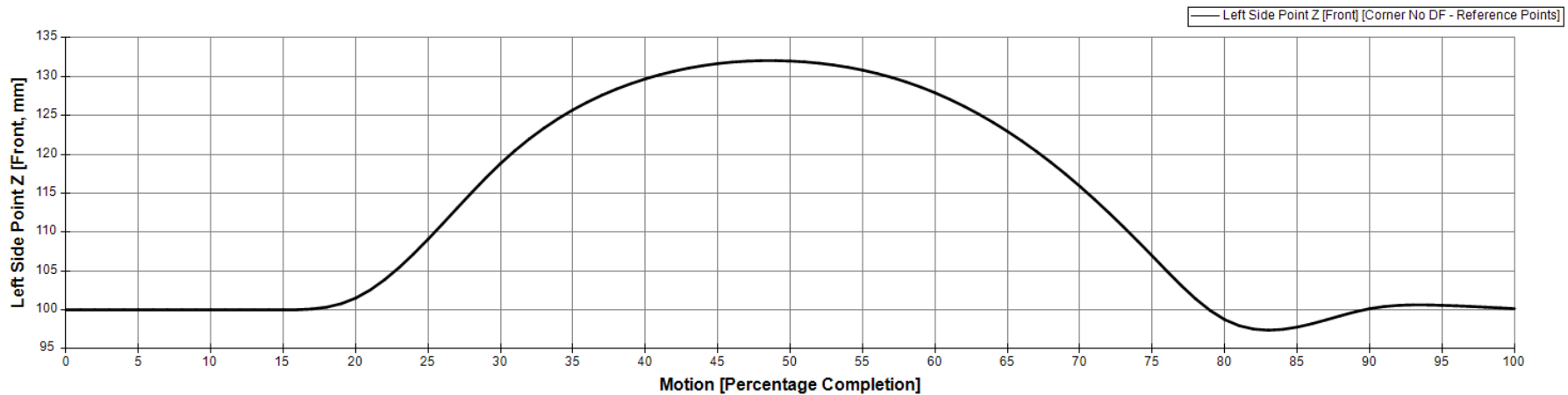
Ground Clearance Side – Roll



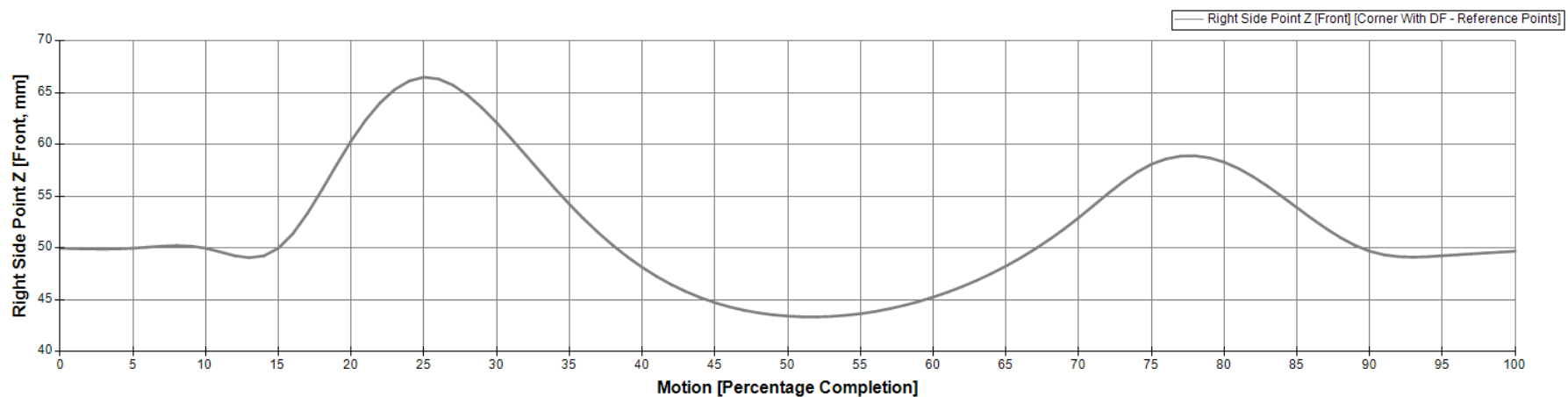
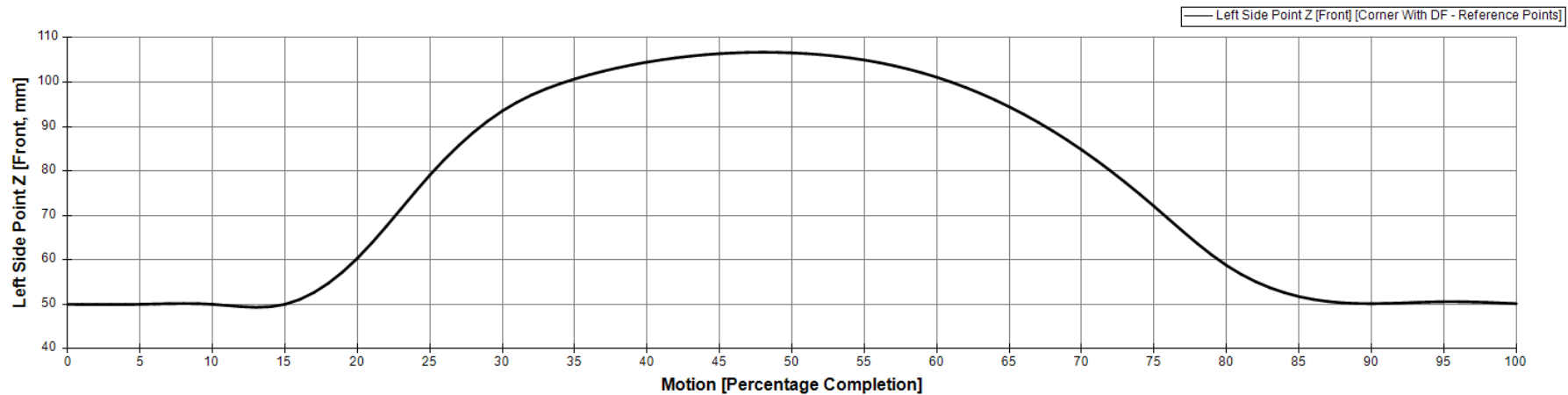
Ground Clearance Side – Pitch



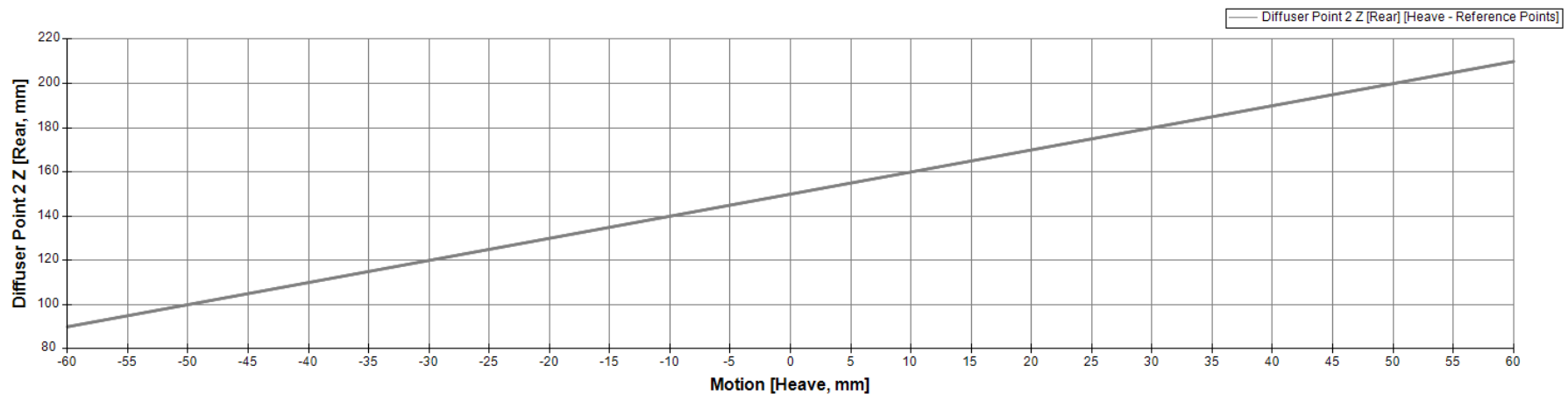
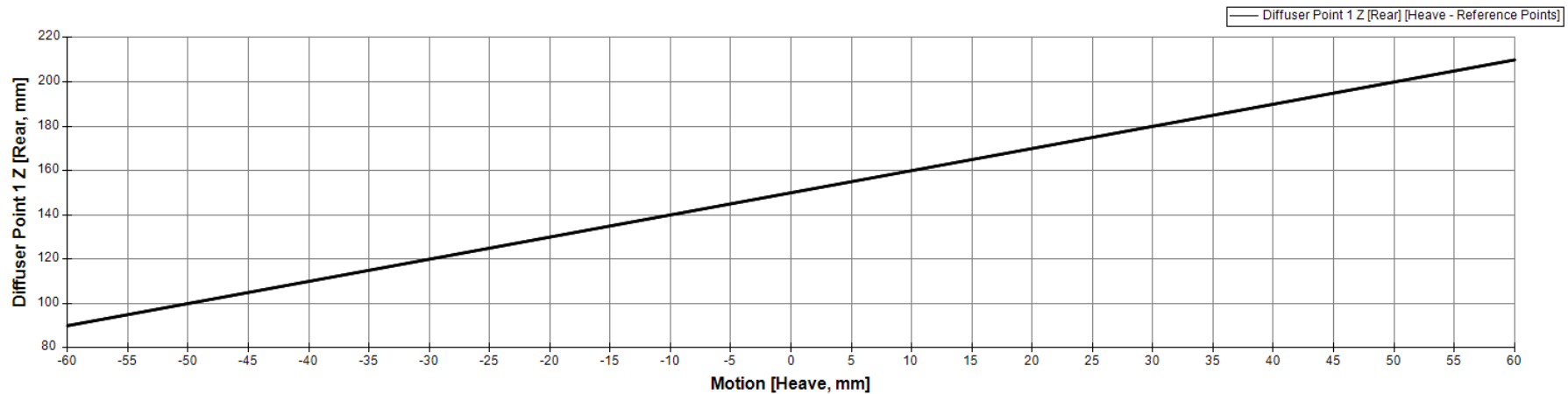
Ground Clearance – Corner No DF



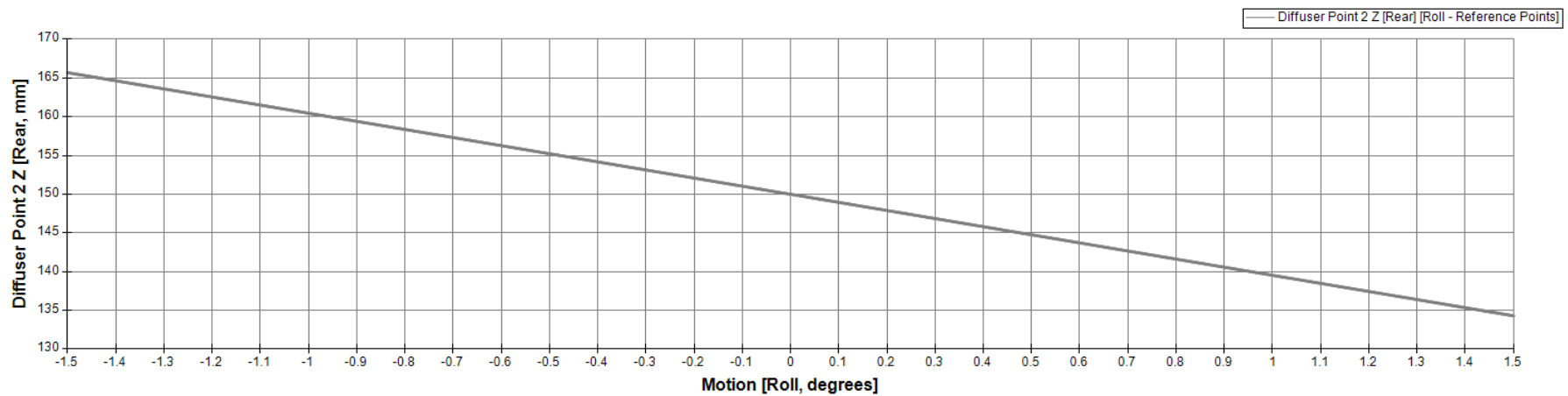
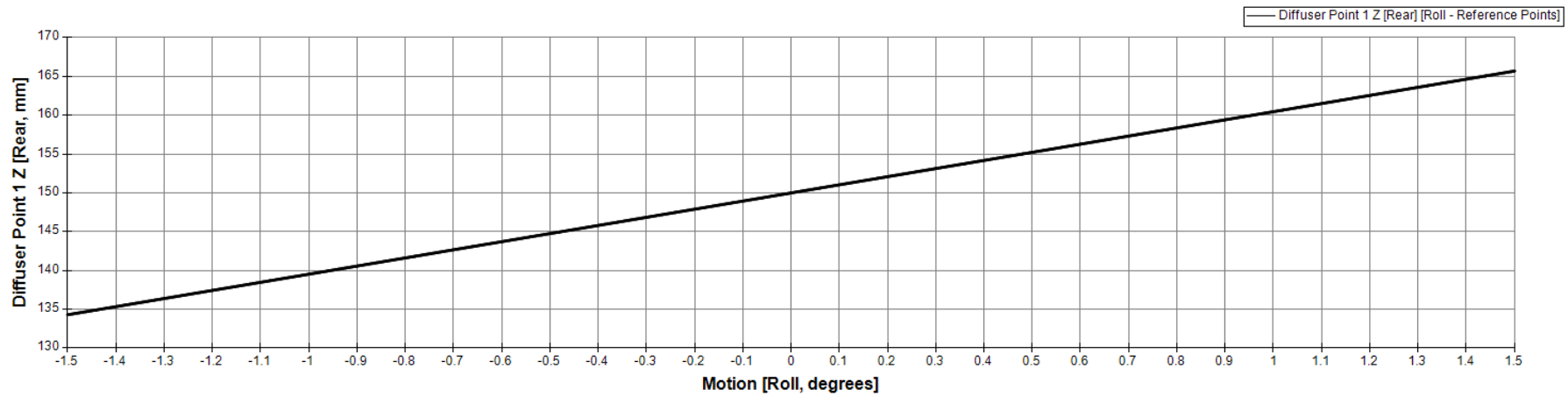
Ground Clearance – Corner DF



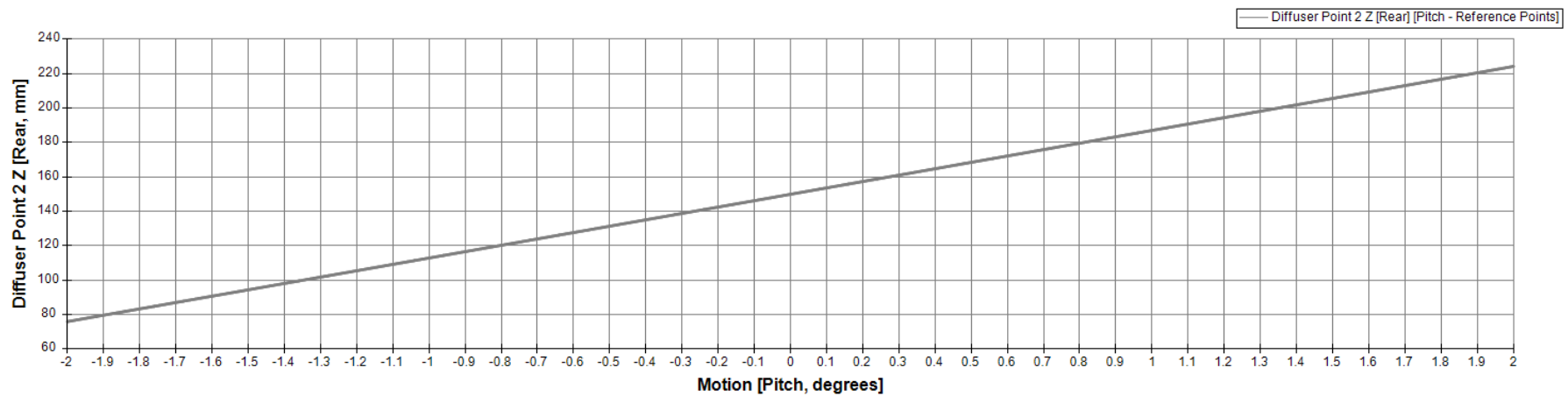
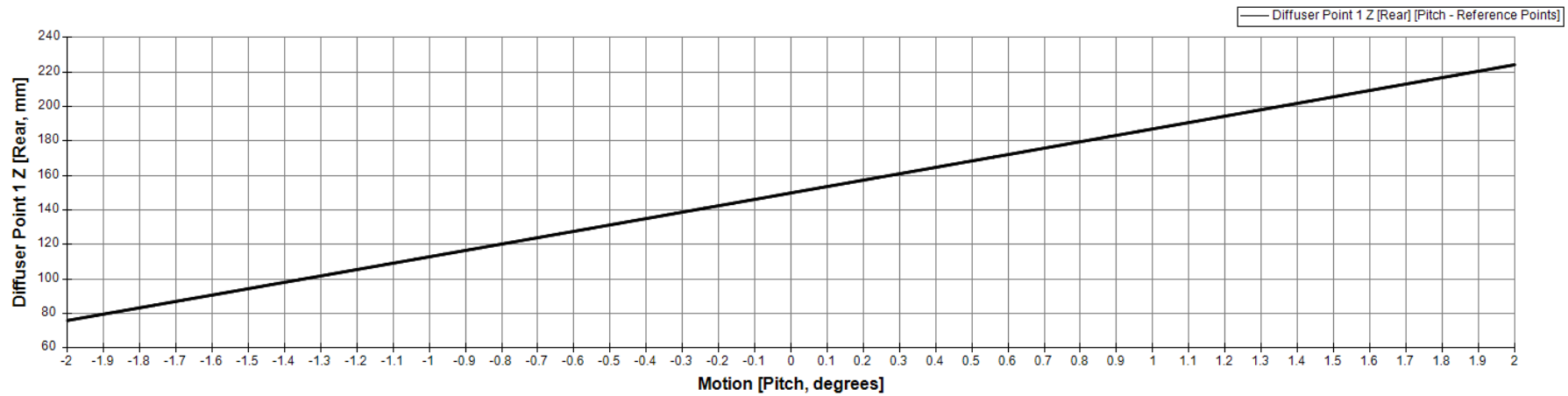
Ground Clearance Rear – Heave



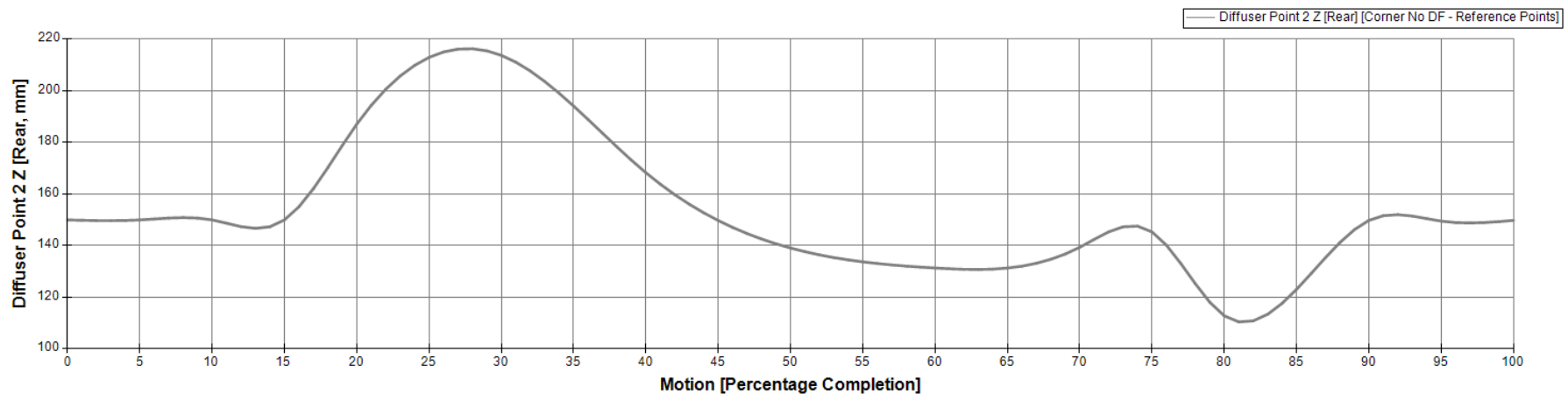
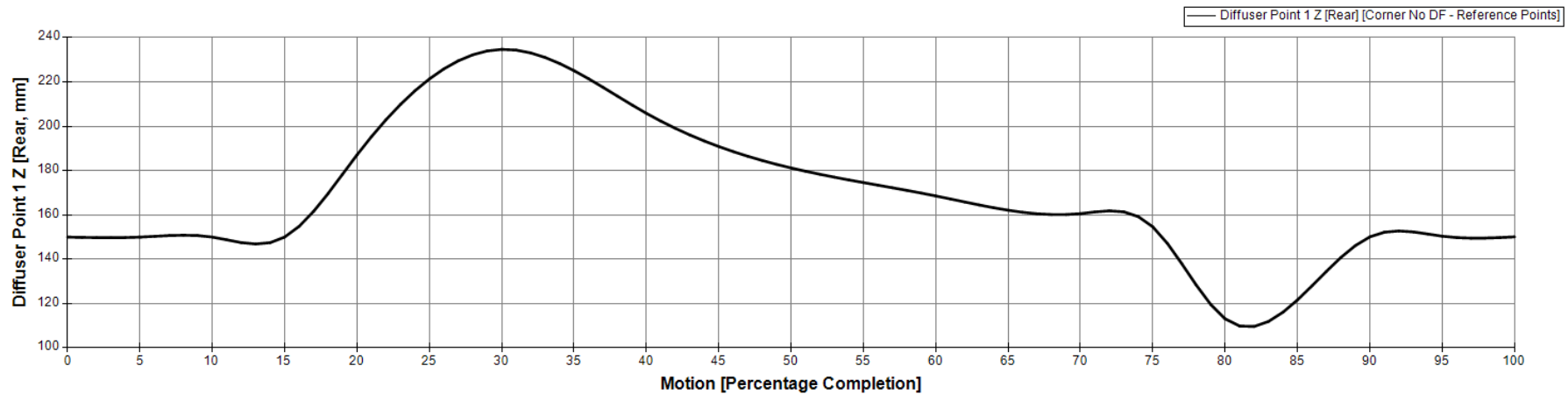
Ground Clearance Rear – Roll



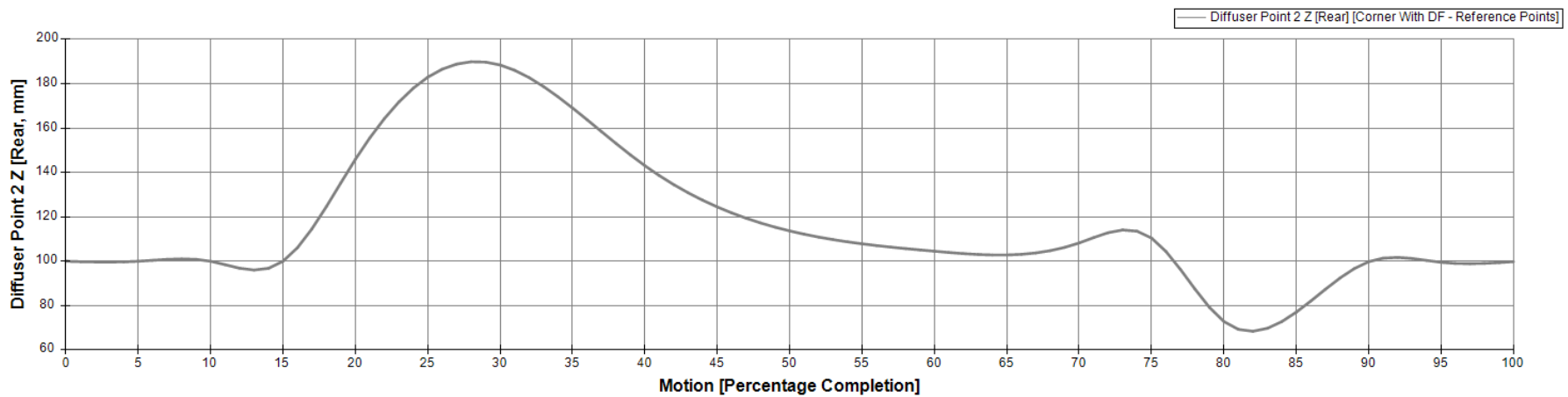
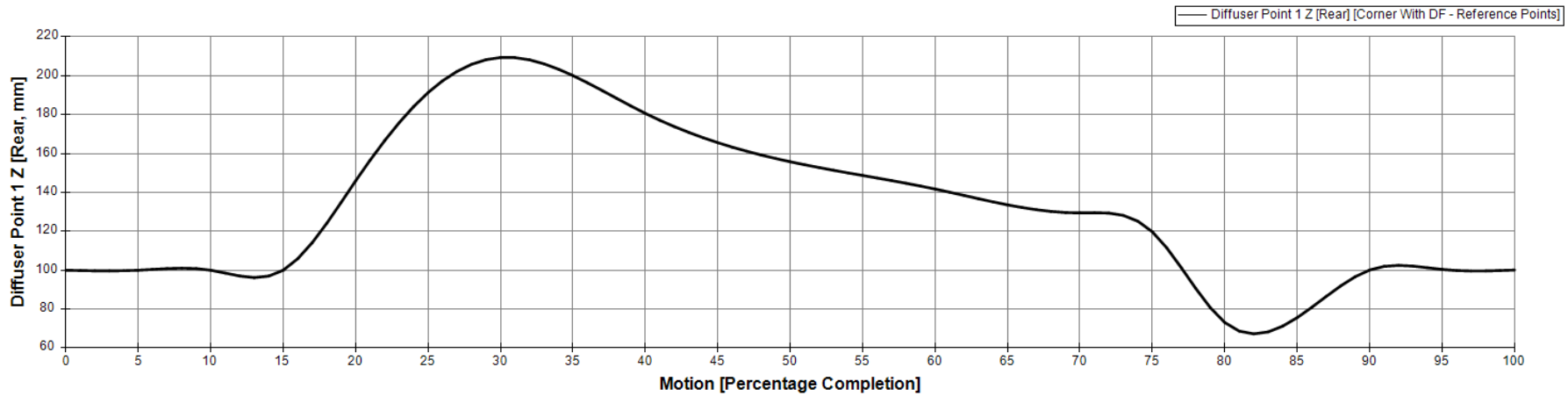
Ground Clearance Rear – Pitch



Ground Clearance Rear – Corner No DF

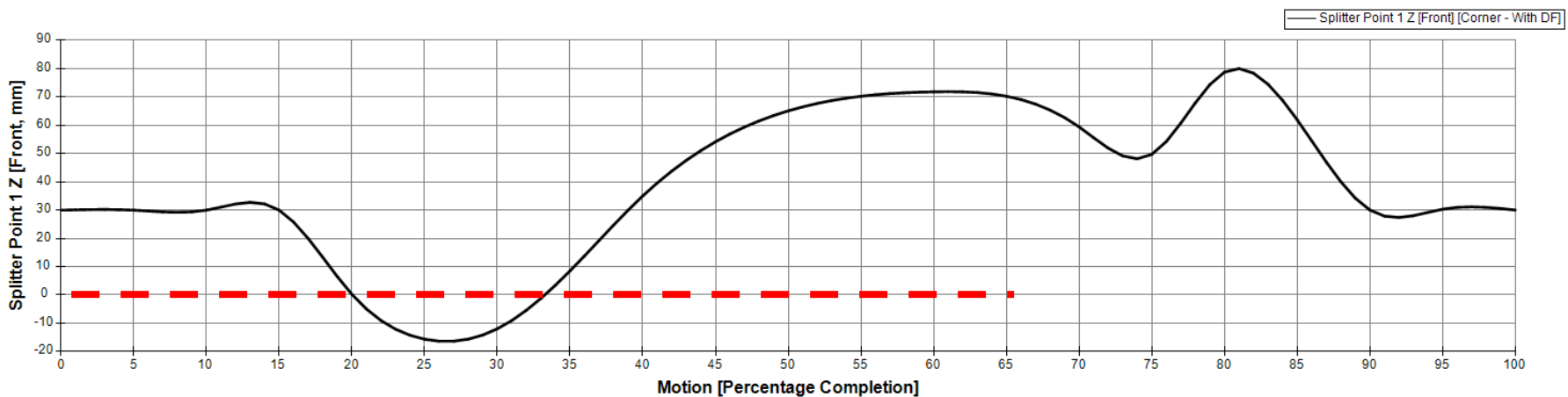


Ground Clearance Rear – Corner DF

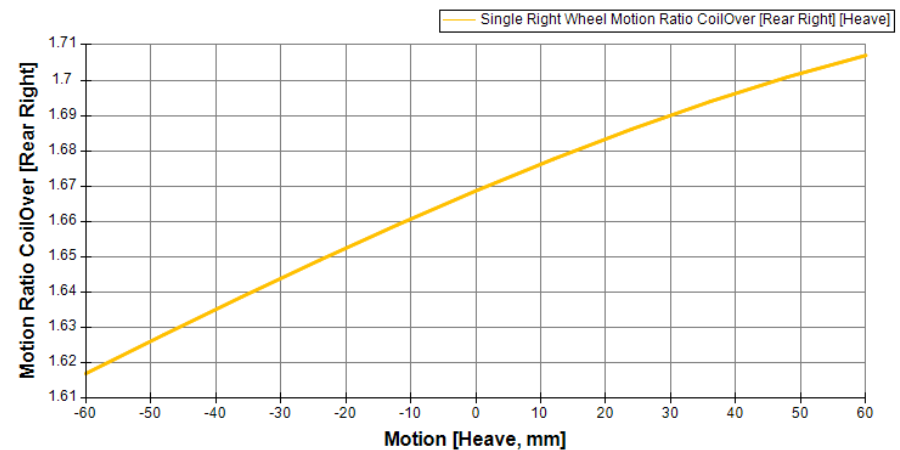
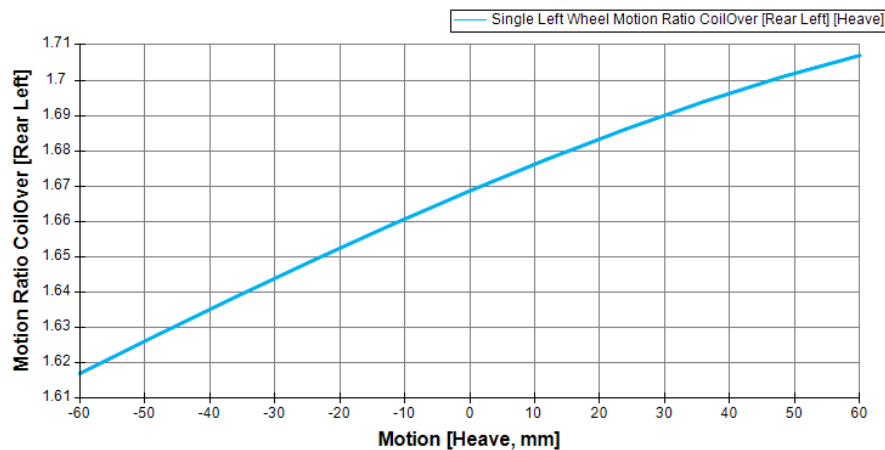
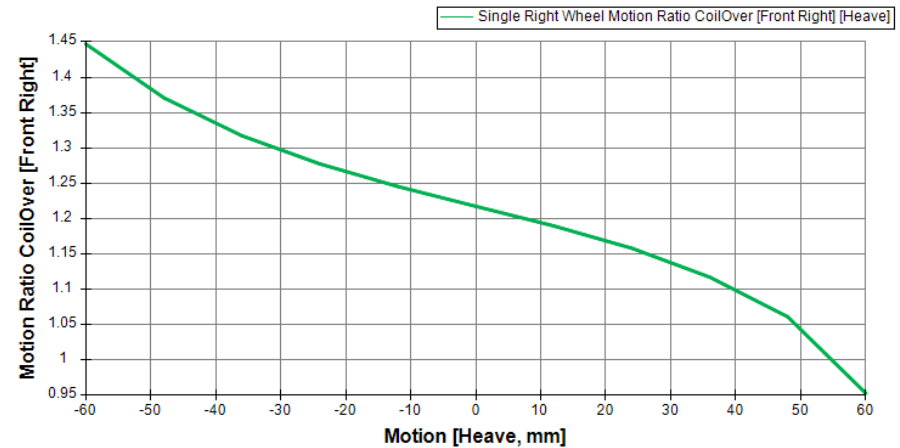
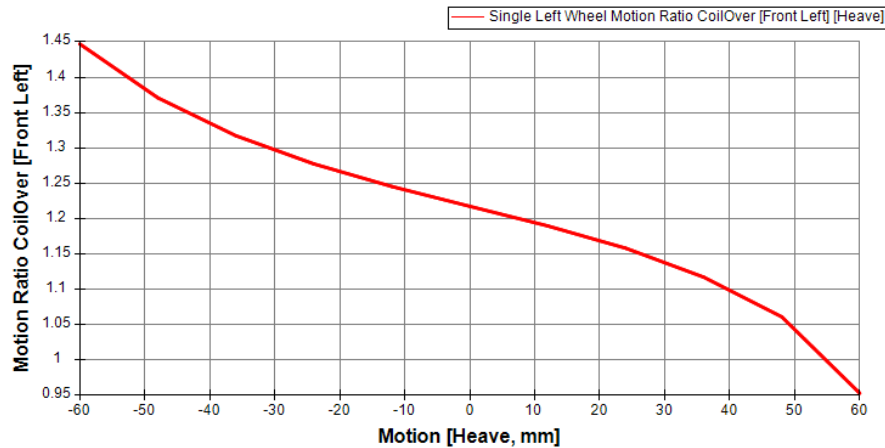


Ground Clearance – Comments

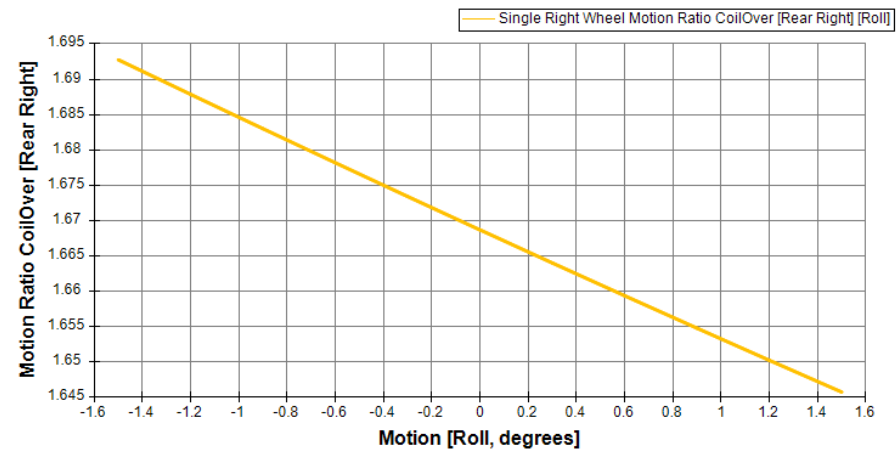
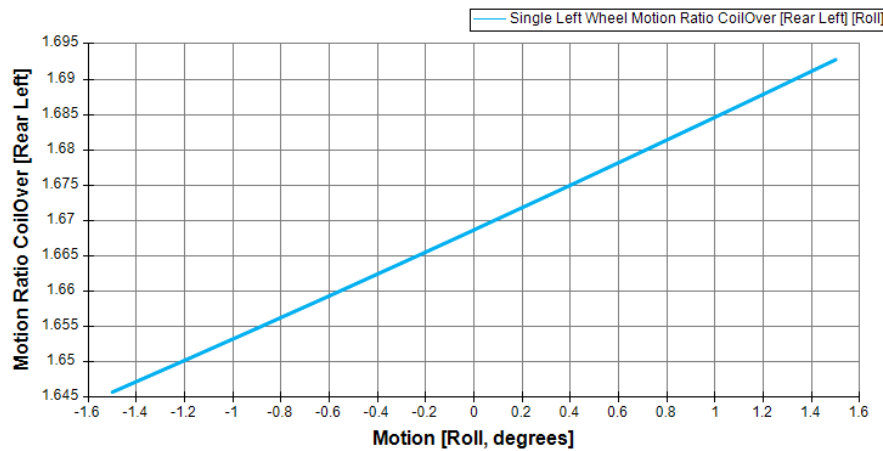
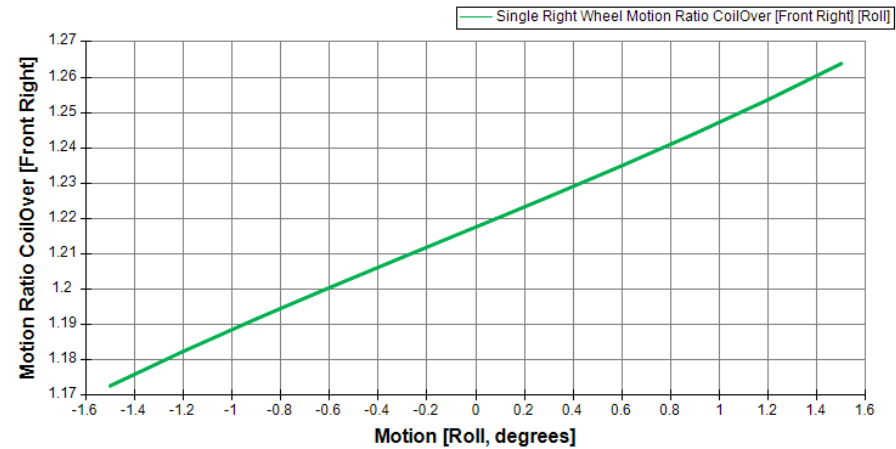
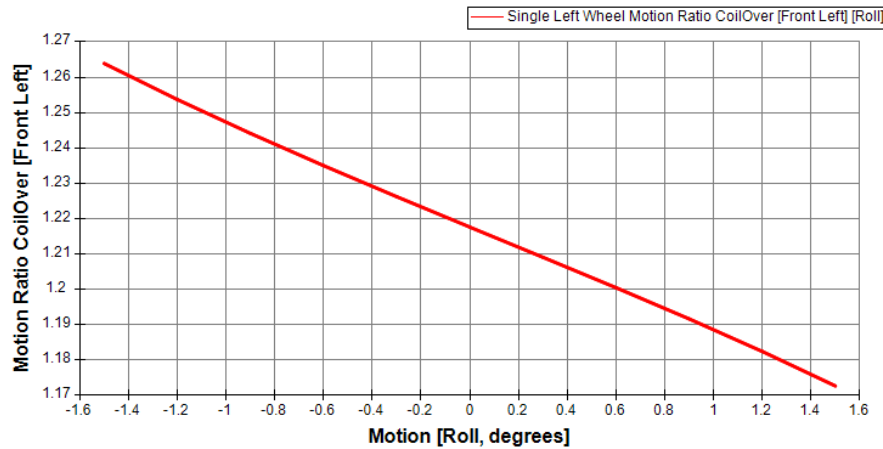
For the chosen front reference points, the zero is crossed in the cornering simulation which means that the design would have to be revised to ensure no contact with the road for this motion. Note this is a simplified steady state analysis without tire or suspension compliance and dynamic (damper and inertia) effects.



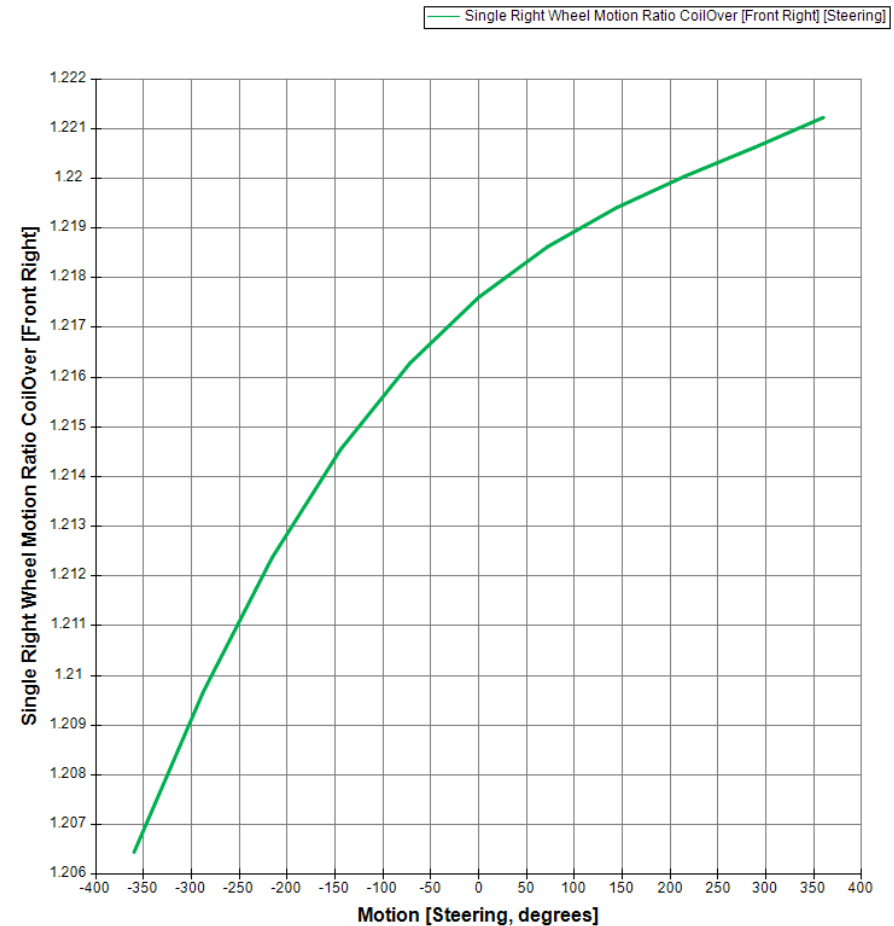
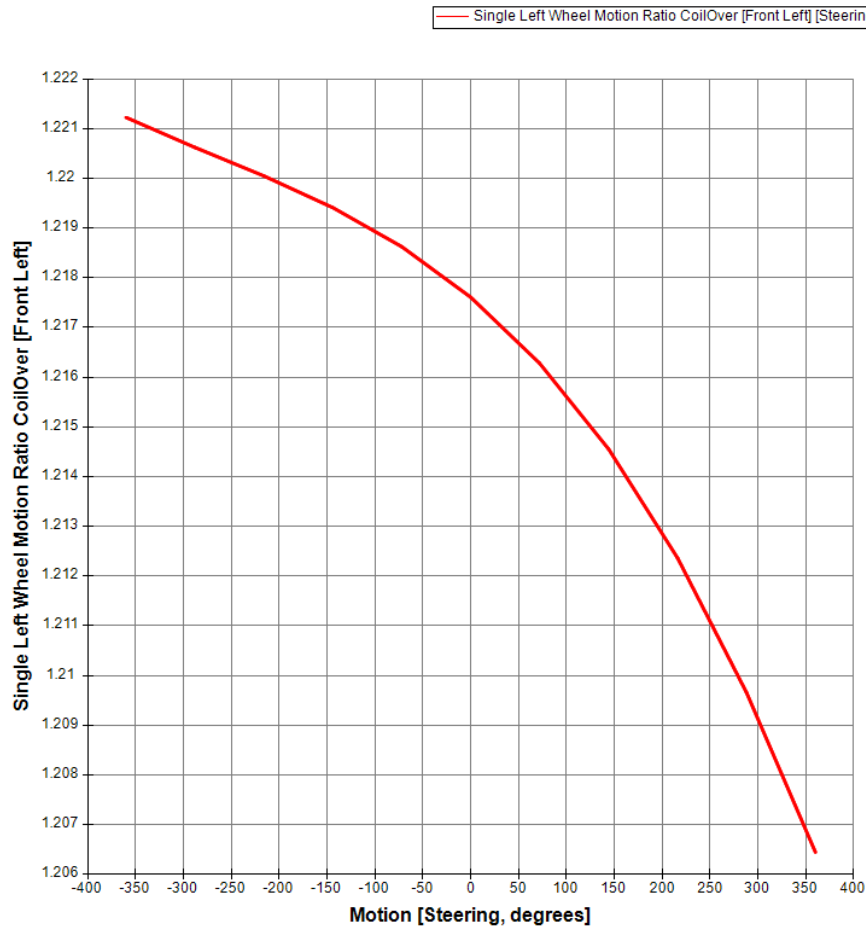
Spring Motion Ratio – Heave



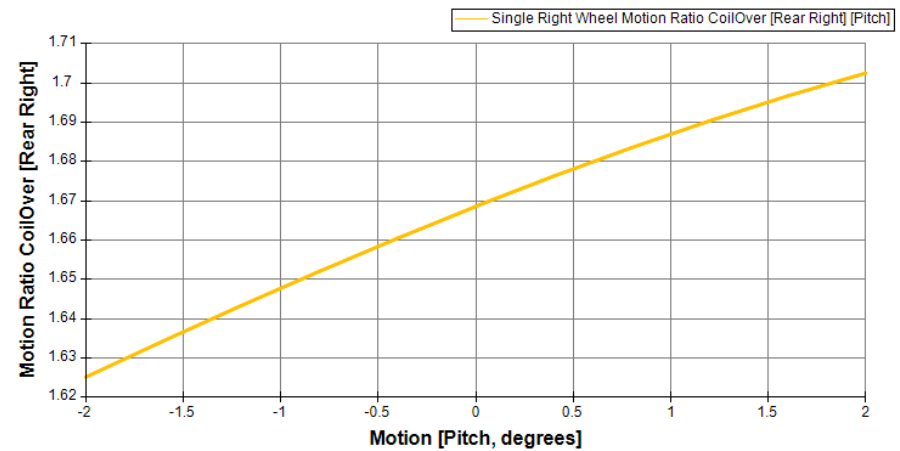
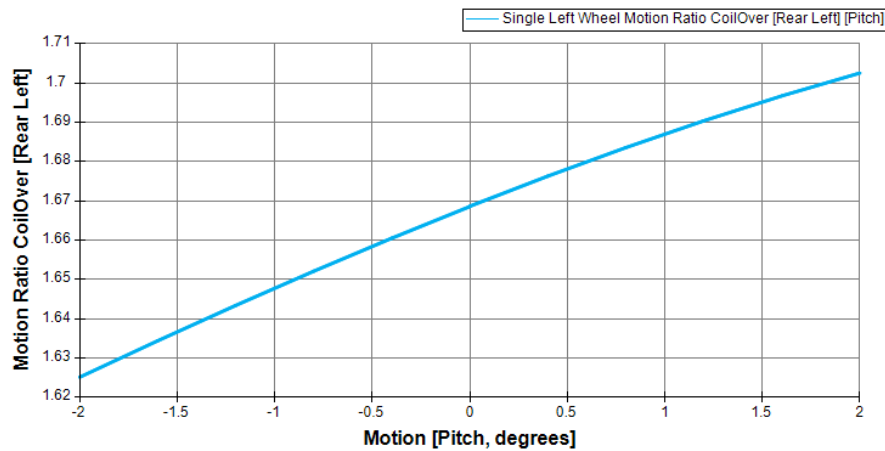
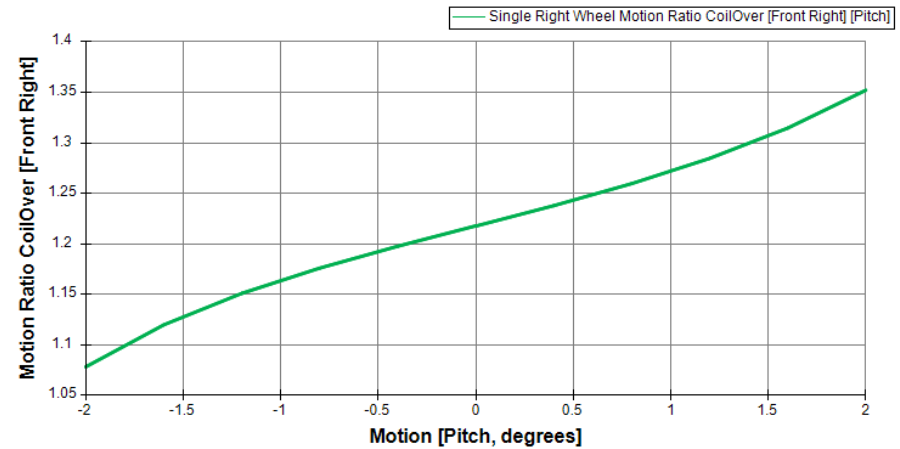
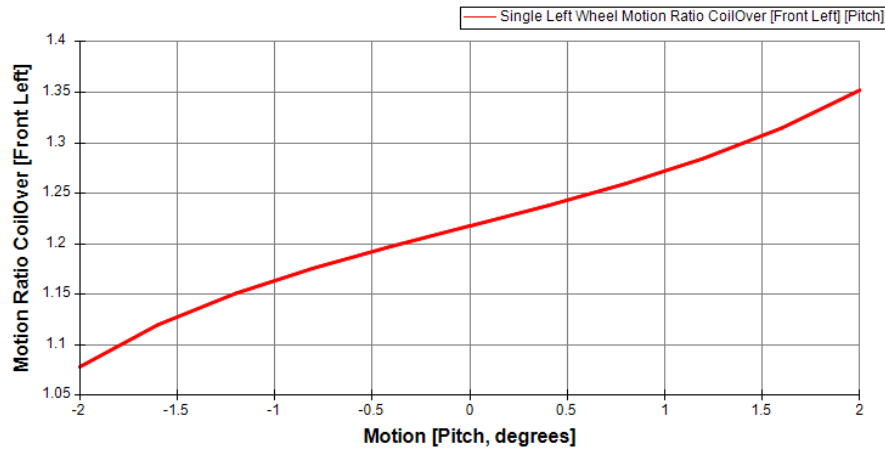
Spring Motion Ratio – Roll



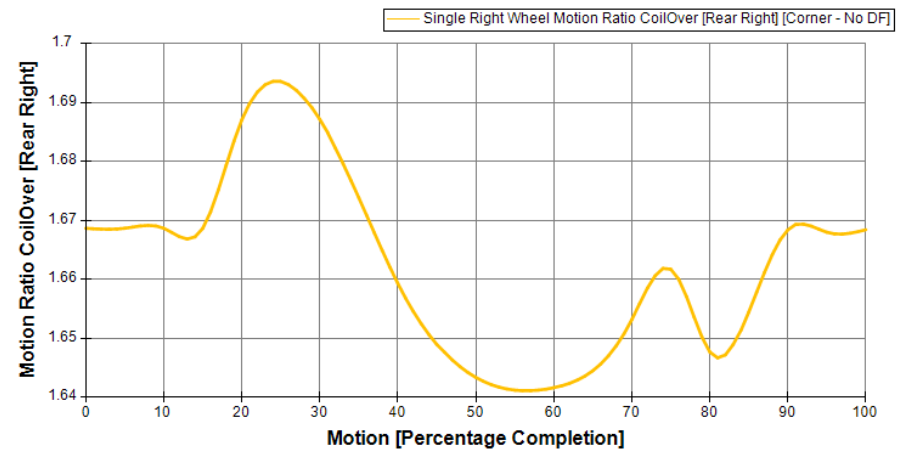
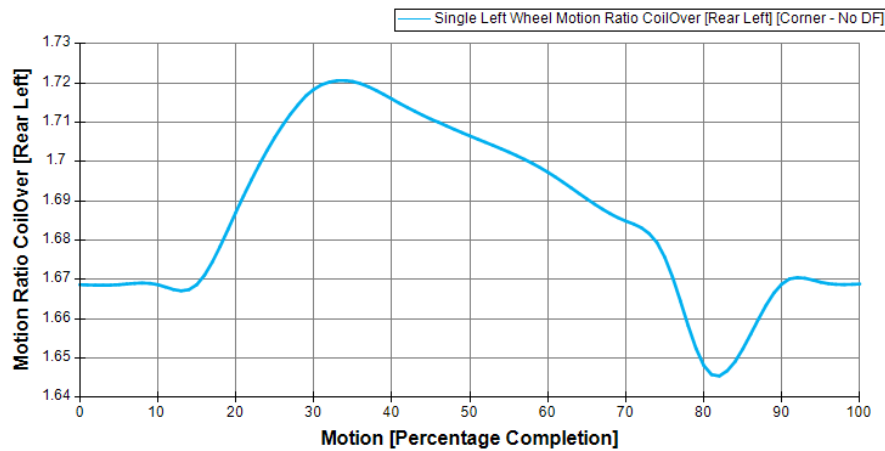
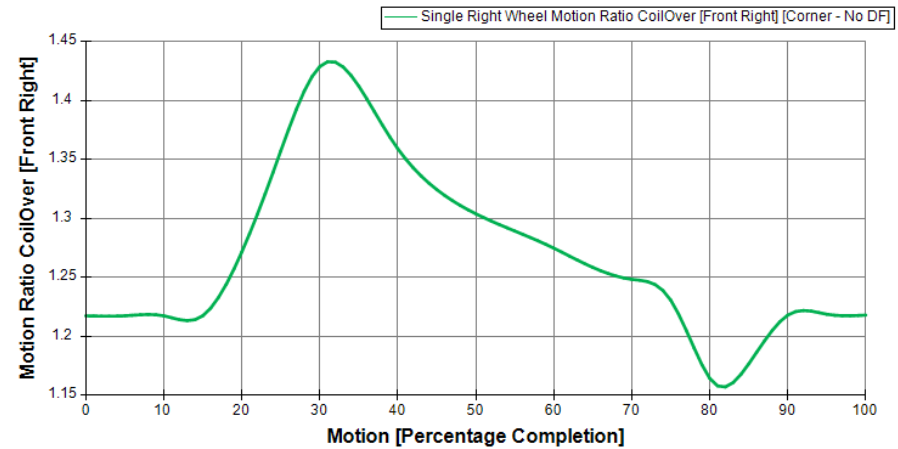
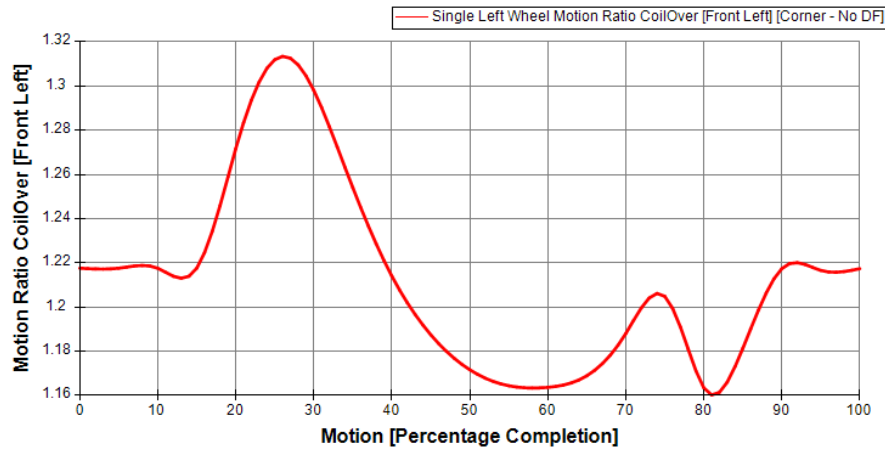
Spring Motion Ratio – Steering



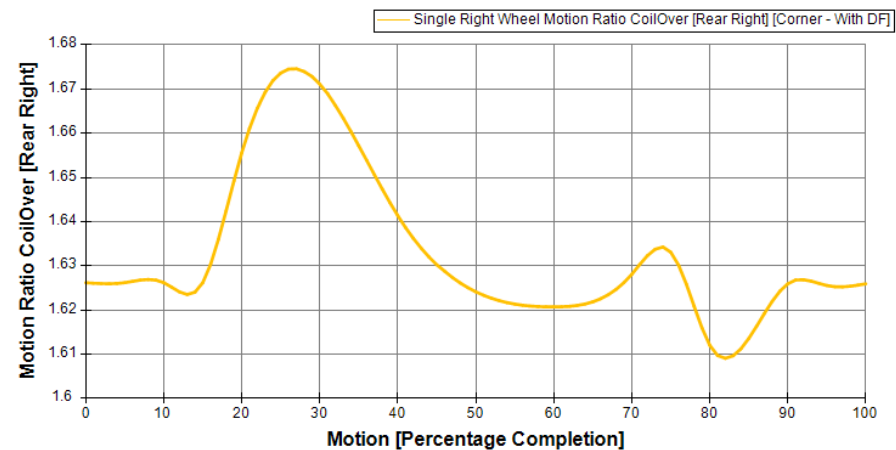
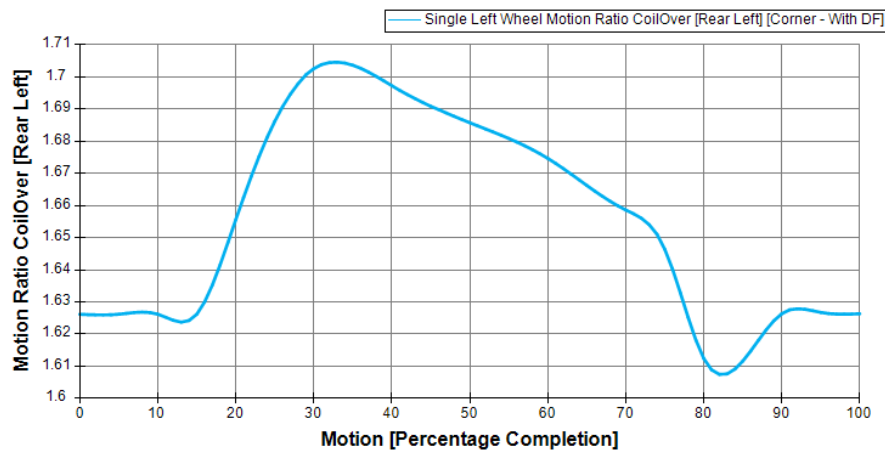
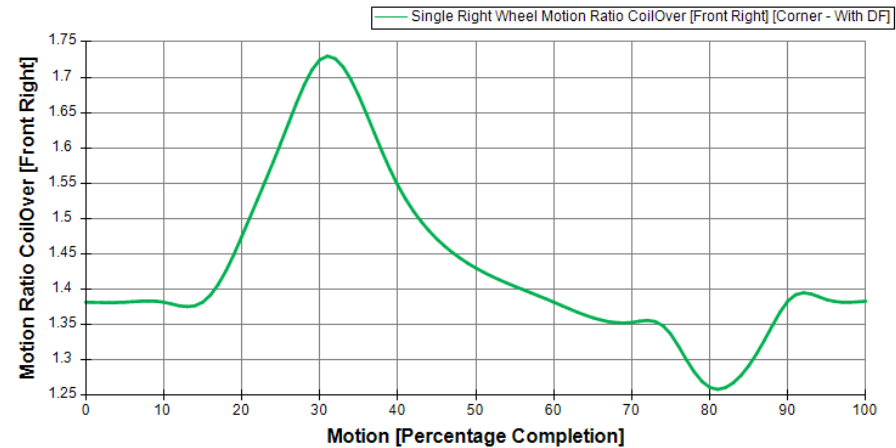
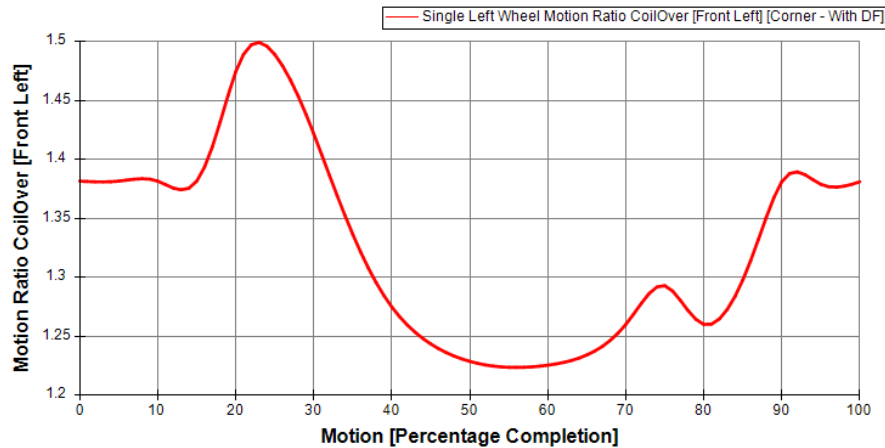
Spring Motion Ratio – Pitch



Spring Motion Ratio – Corner No DF

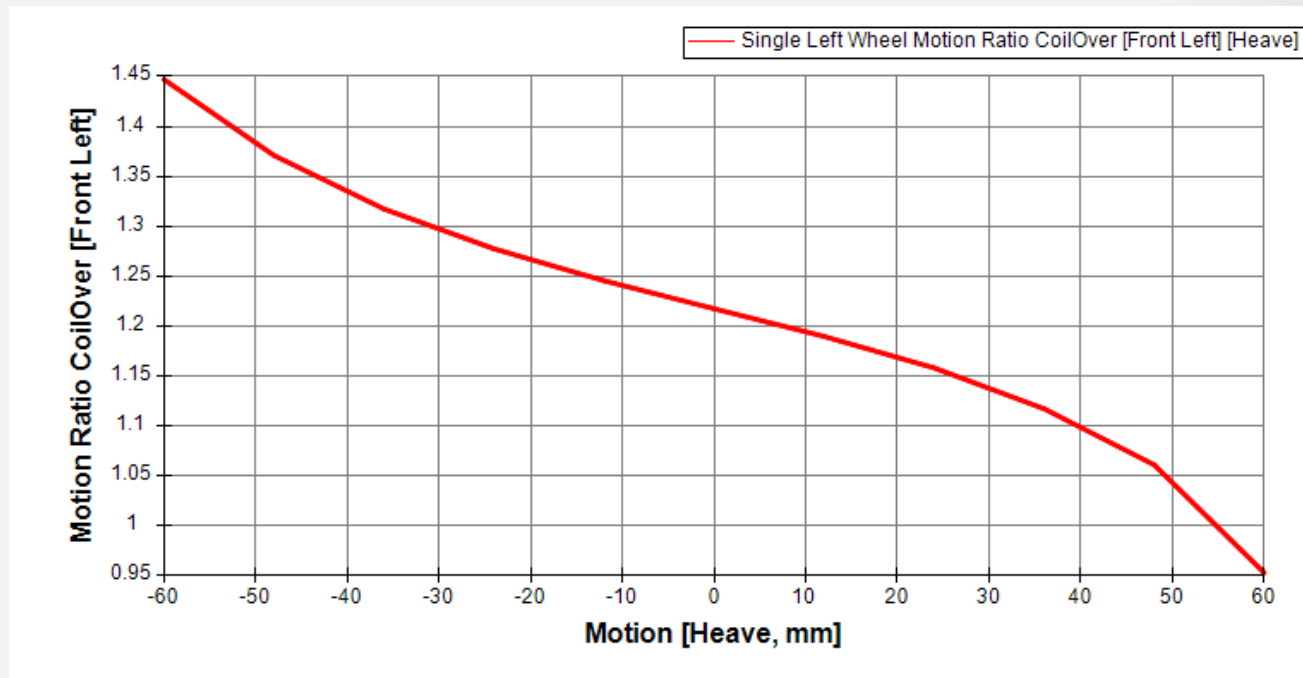


Spring Motion Ratio – Corner DF

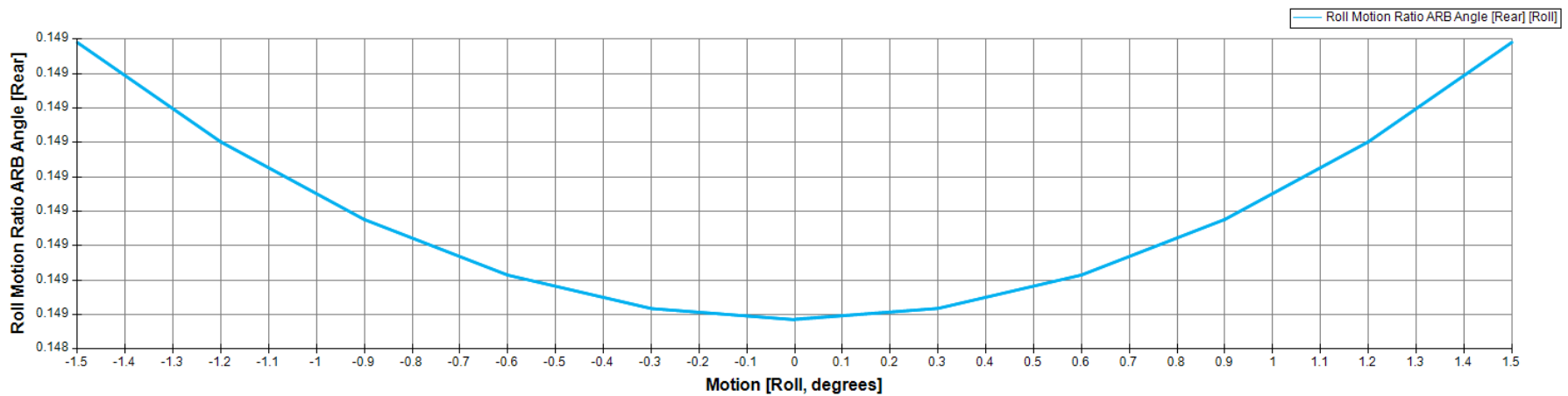
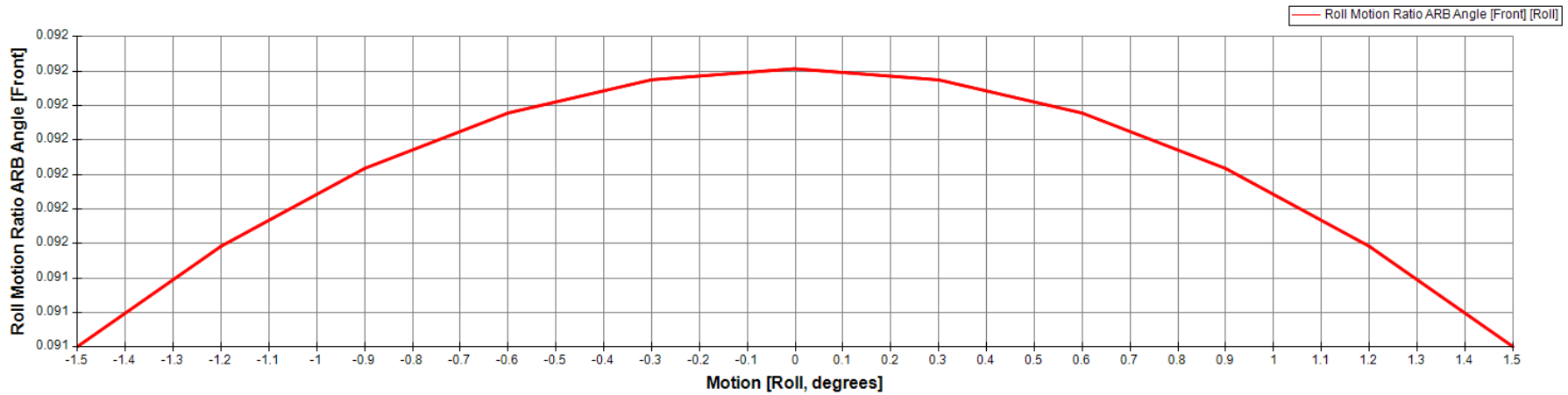


Spring Motion Ratio – Comments

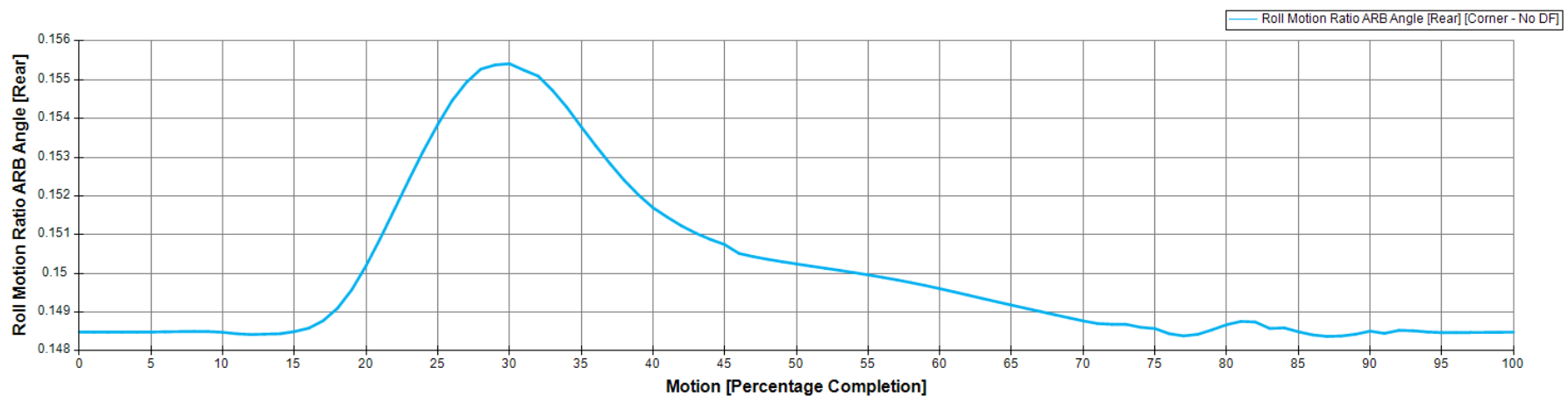
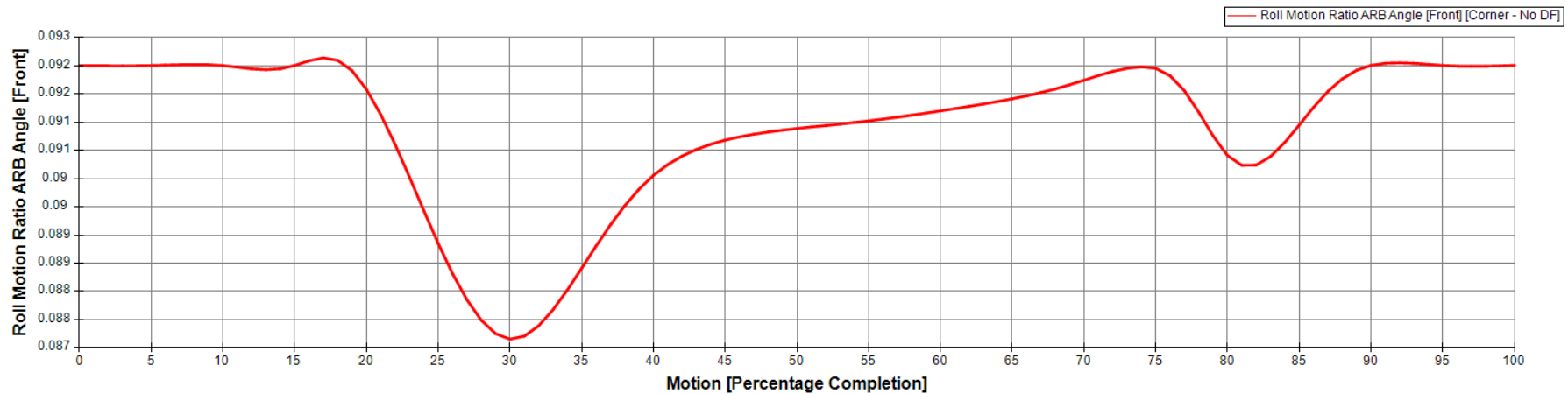
The front motion ratio variation in heave is large, the direction of change leads to a softer suspension as the chassis moves down which is questionable even more for a car with downforce.



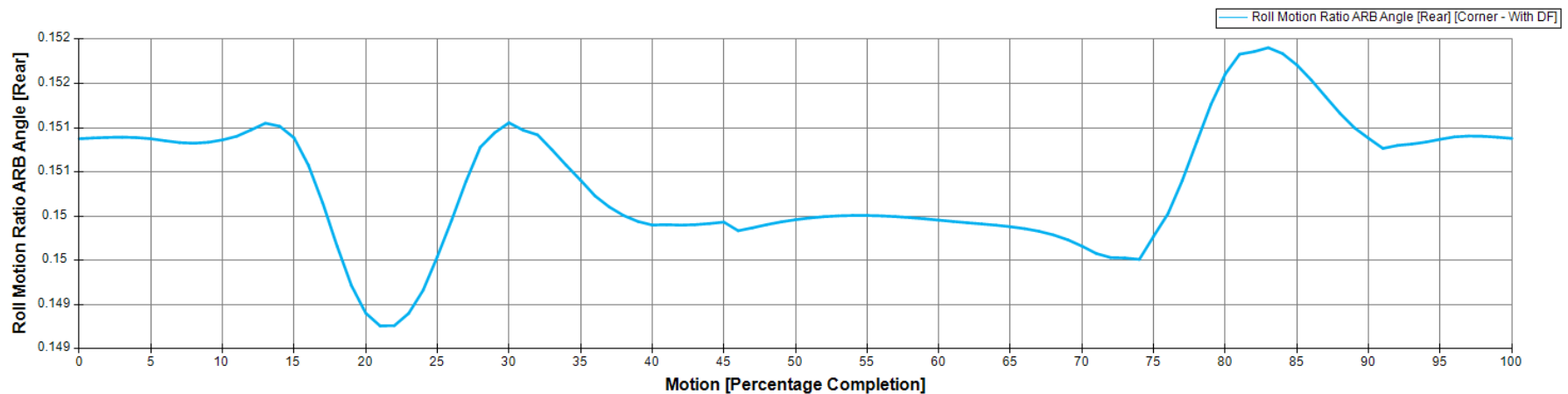
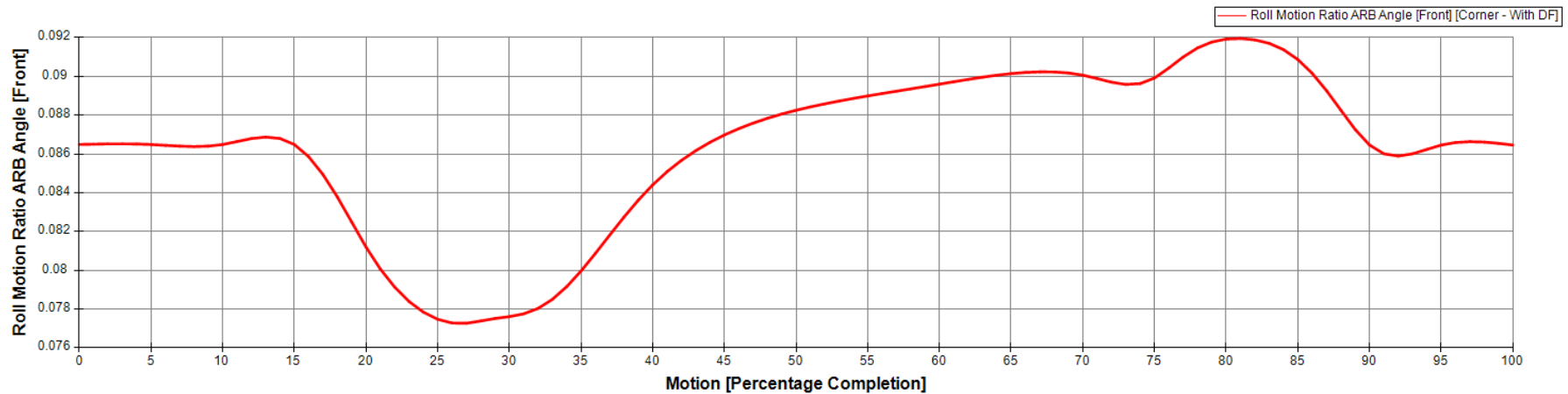
ARB Motion Ratio – Roll



ARB Motion Ratio – Corner No DF

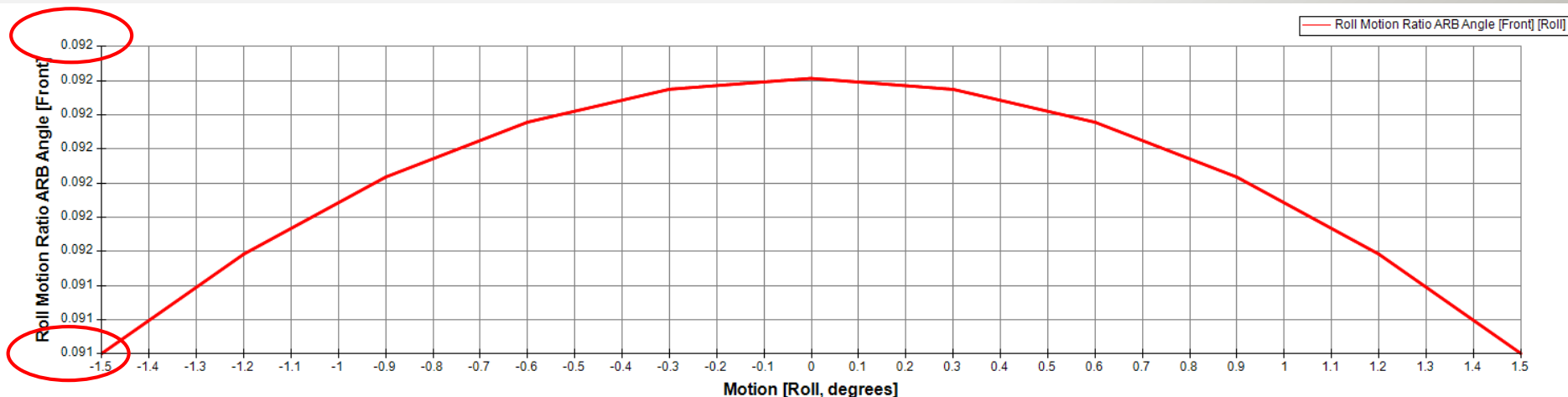


ARB Motion Ratio – Corner DF



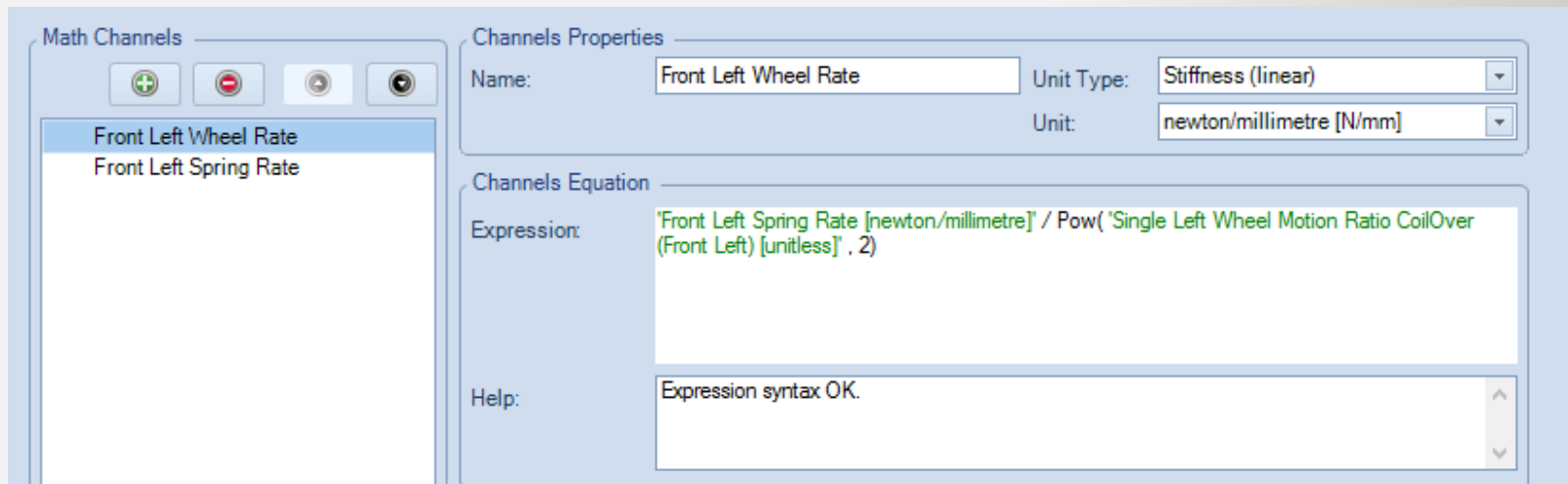
ARB Motion Ratio – Comments

- ARB motion ratio stays relatively constant for both front and rear axles (again compliance not taken into account)
- Rising rate could be useful
- Using different rate of motion ratio change front and rear can be a useful tool in tuning transient balance



Math Channels

- User defined math channels are available within OptimumKinematics. Any of the outputs available within the simulation are available to define a math channel.
- Math channels can be nested to make expressions more manageable and easier to follow



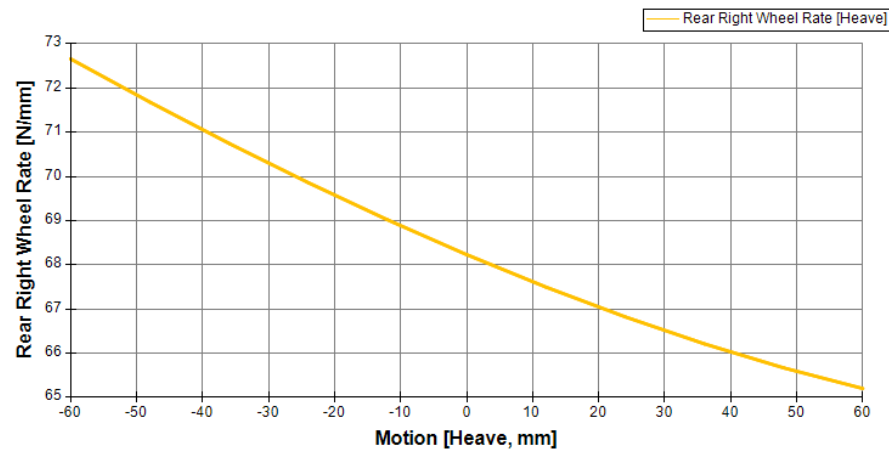
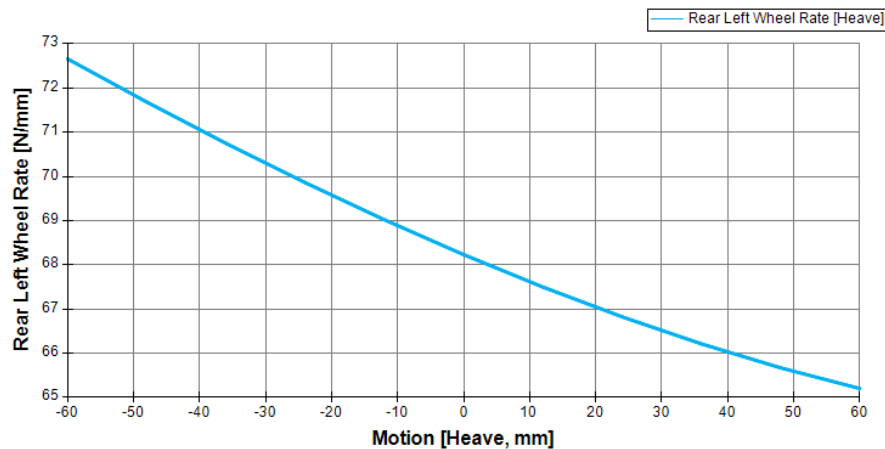
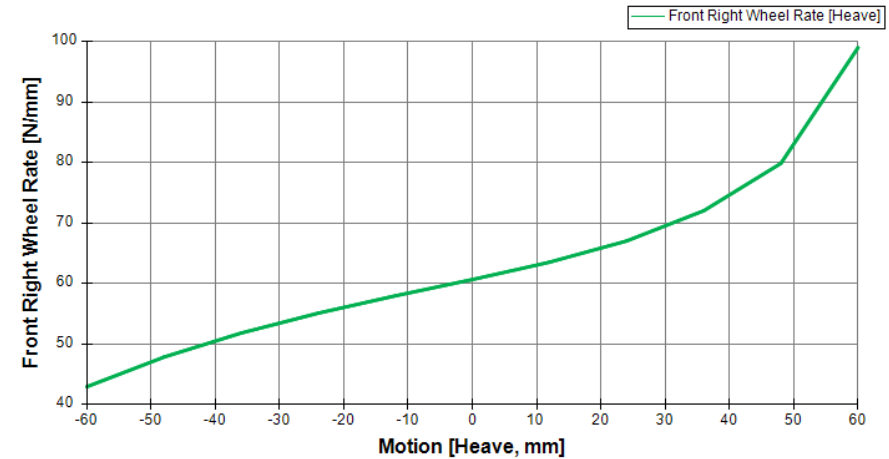
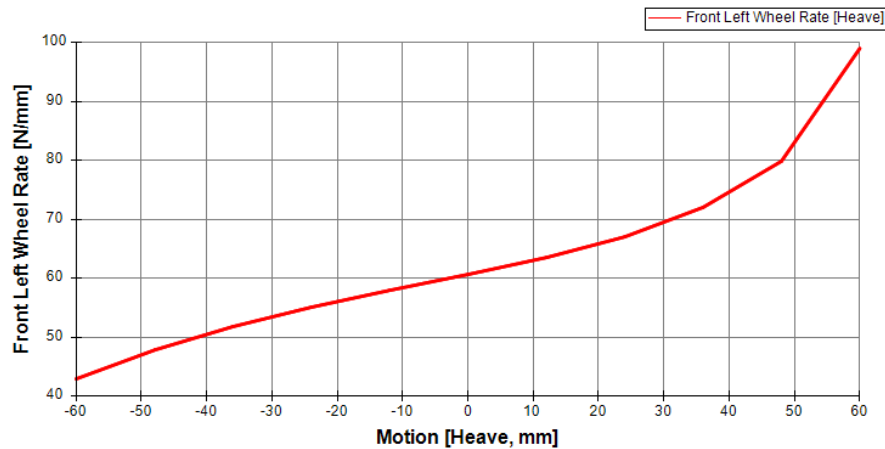
Math Channel Example- Wheel Rate

With the knowledge of the fitted spring rates of the suspension it is possible to compute the wheel rate and verify its variation along the motion using a simple math channel.

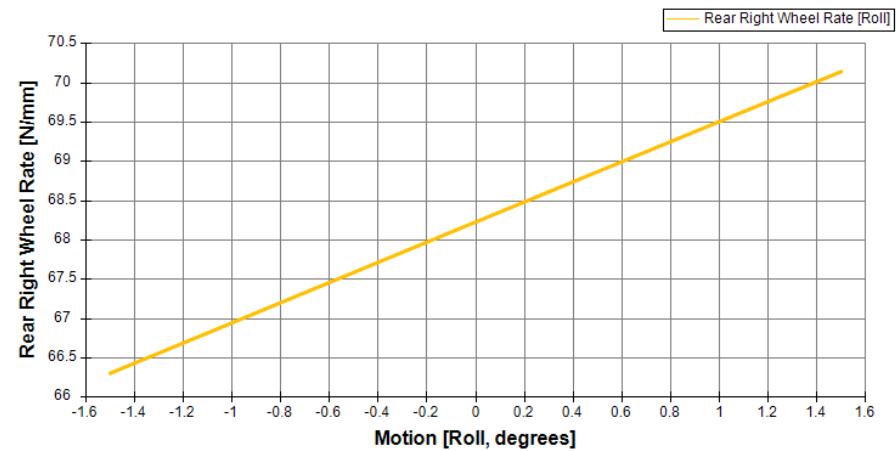
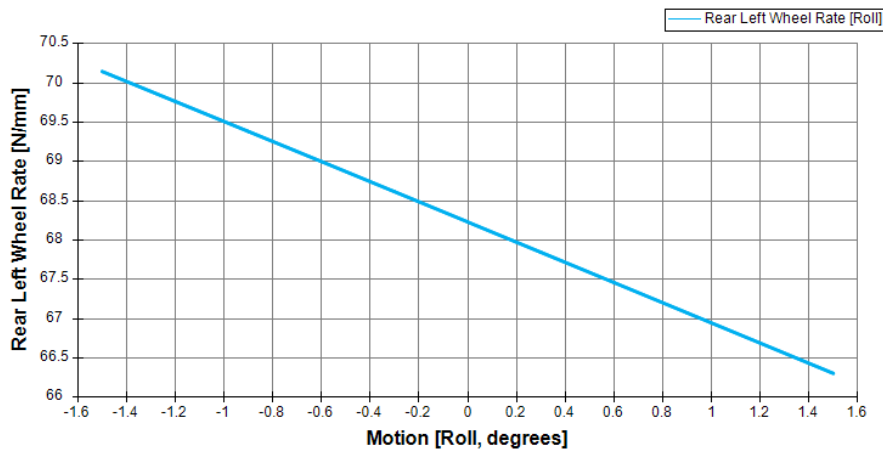
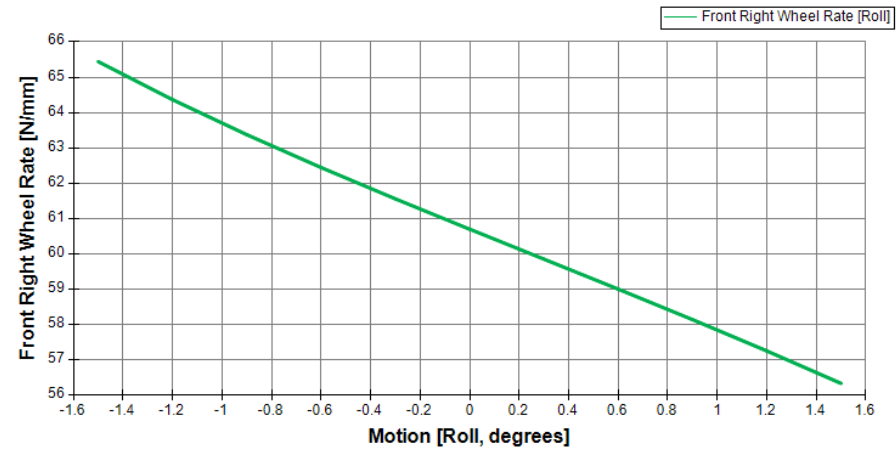
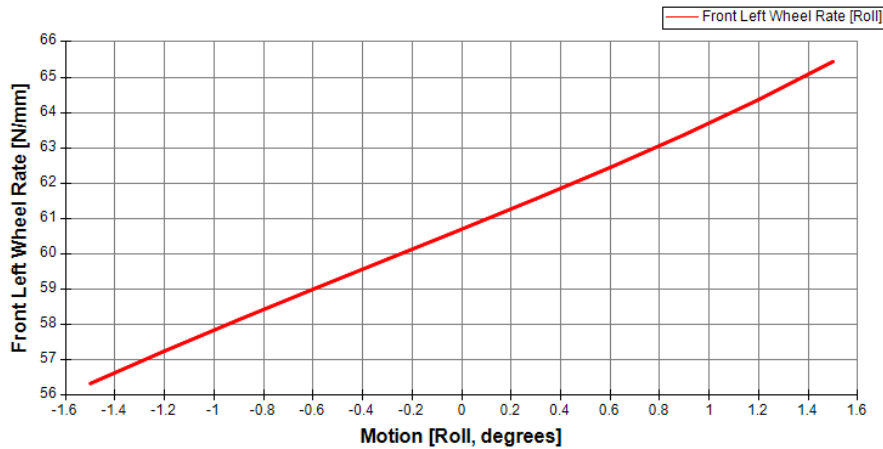
```
'Front Left Spring Rate [newton/millimetre]' / Pow( 'Single Left Wheel Motion Ratio CoilOver (Front Left) [unitless]' , 2)
```

Can define constants that can be used in as many math channels as required

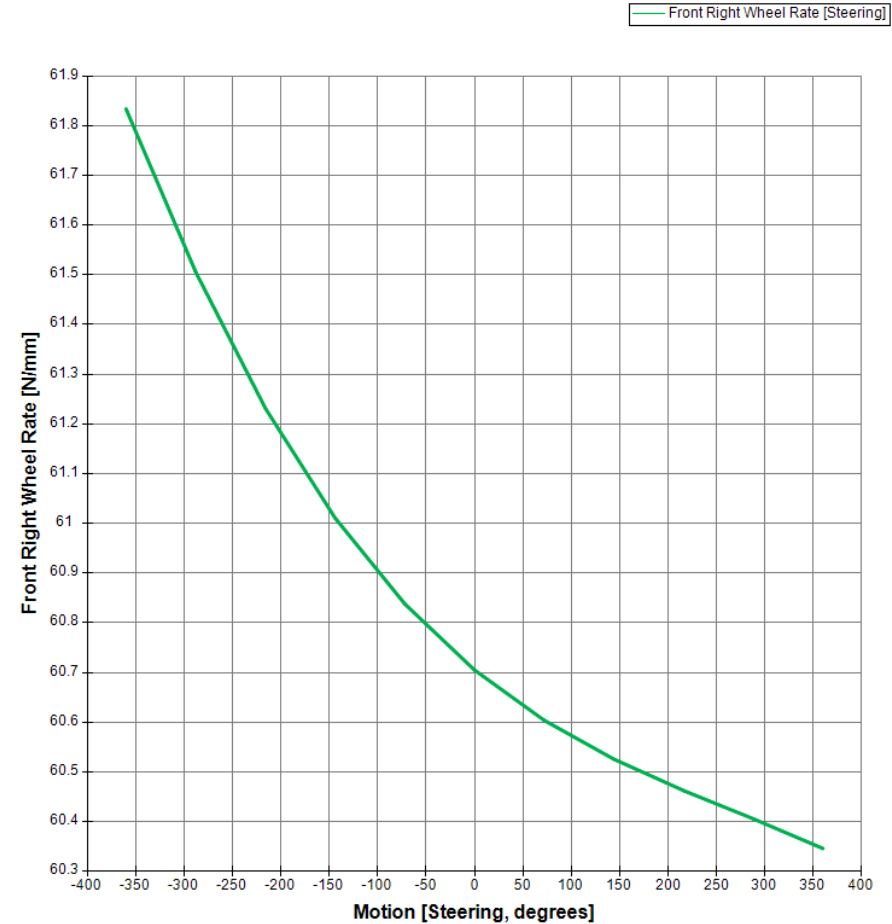
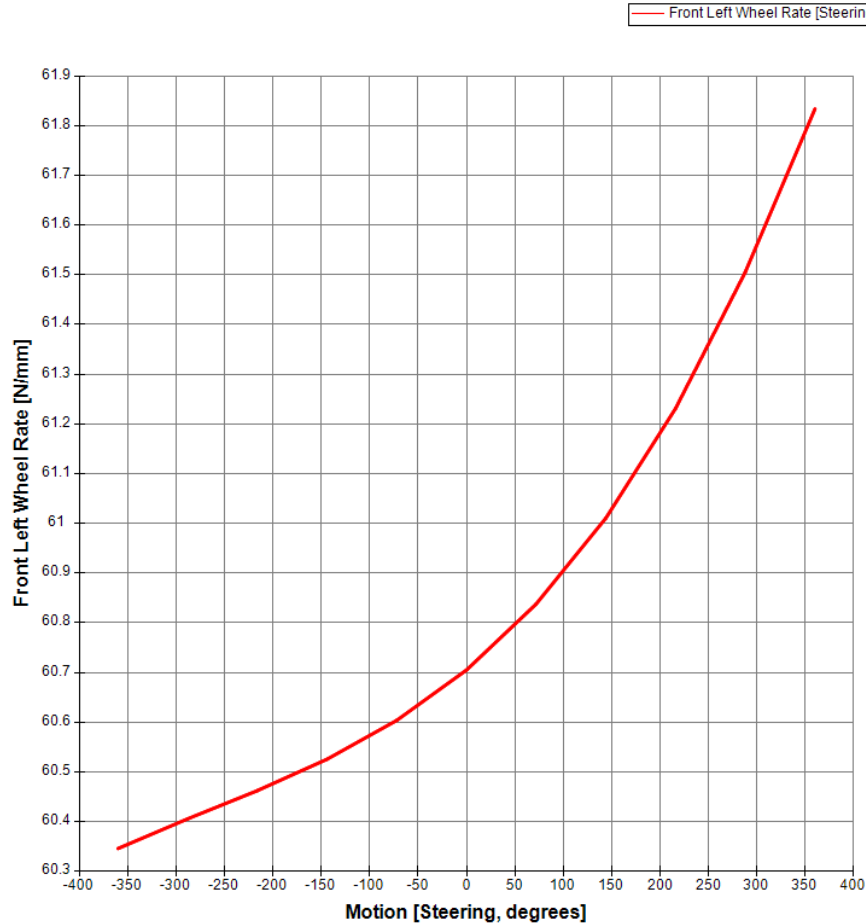
Spring Wheel Rate – Heave



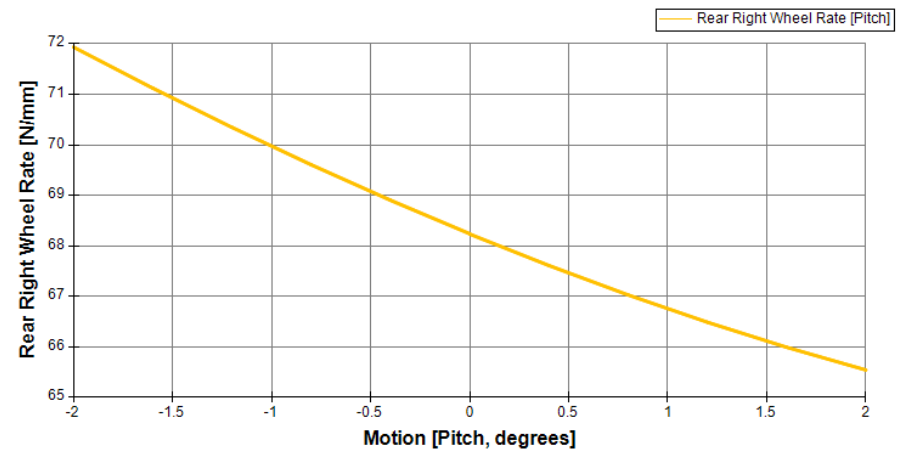
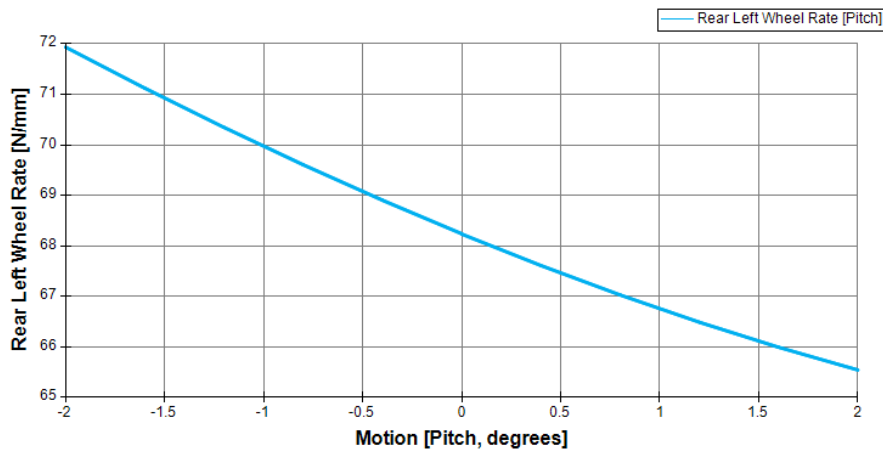
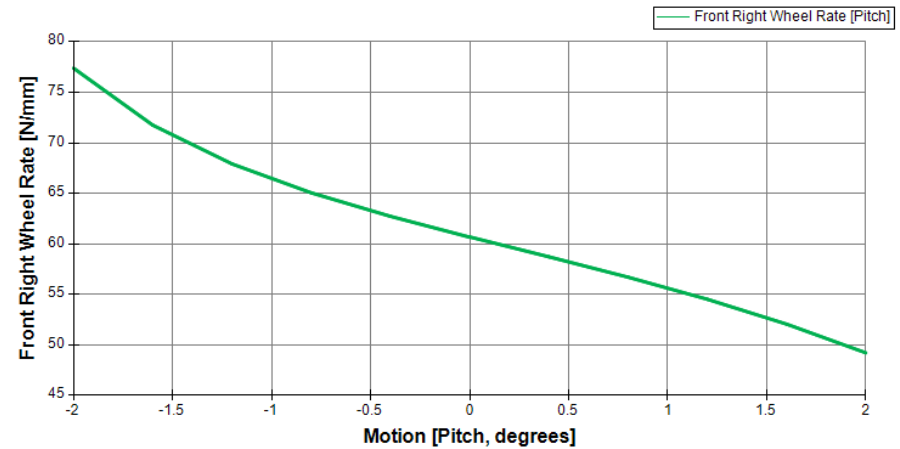
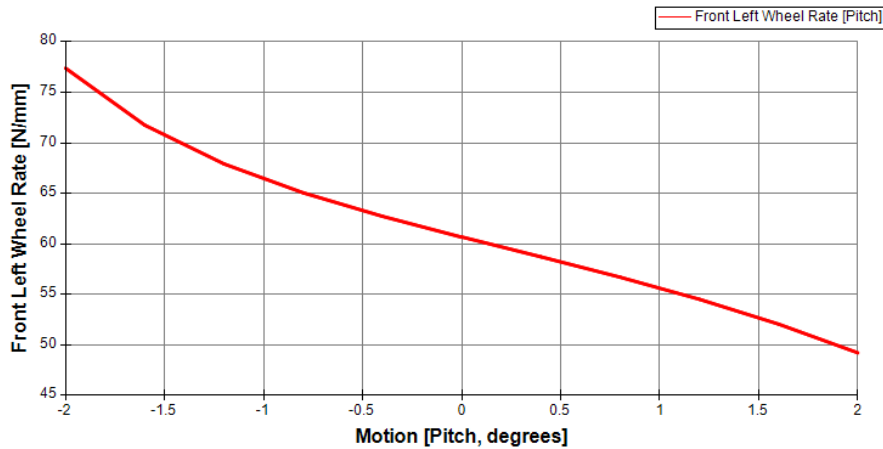
Spring Wheel Rate – Roll



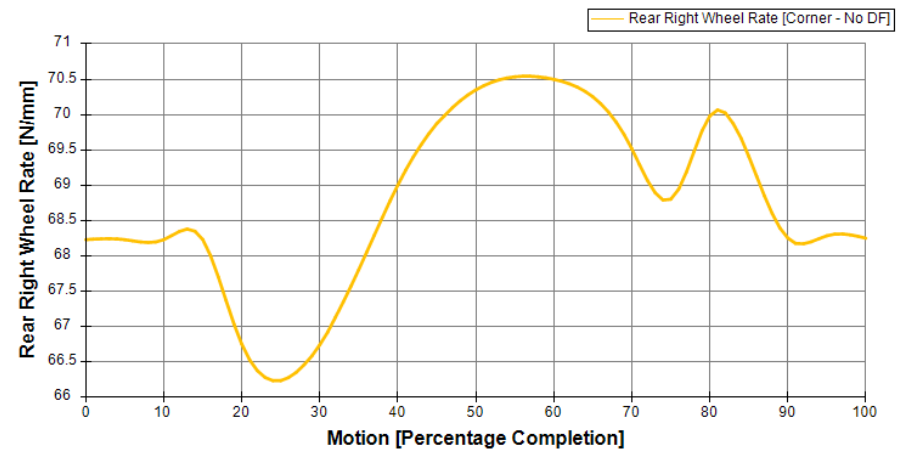
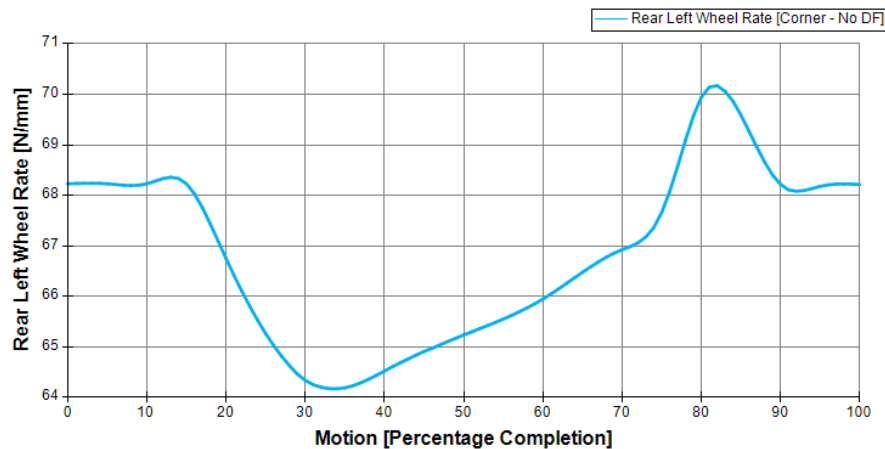
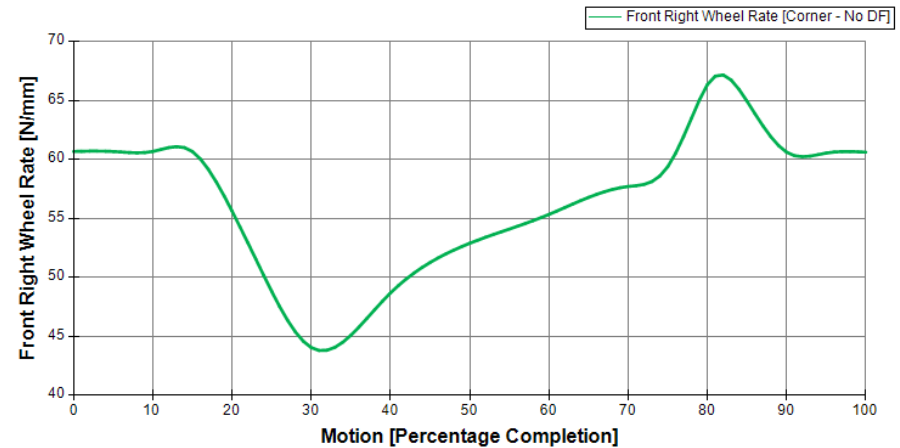
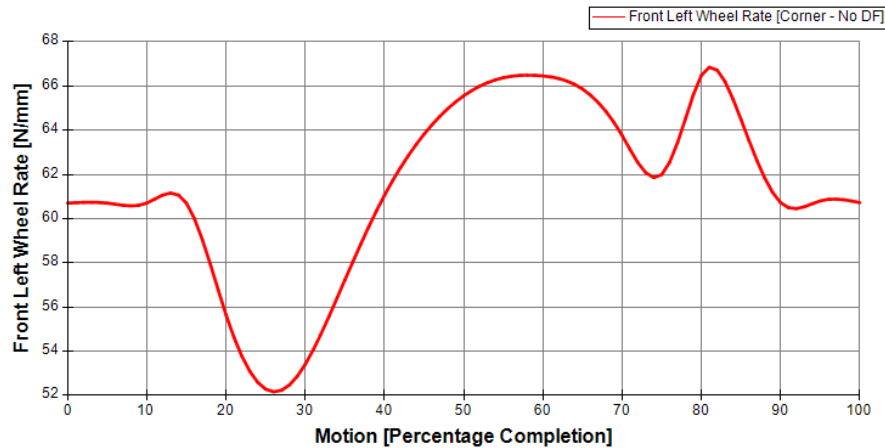
Spring Wheel Rate – Steering



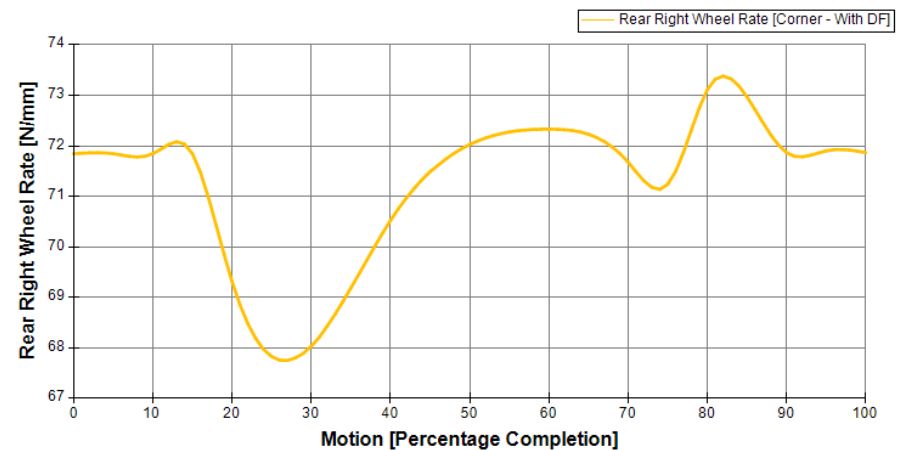
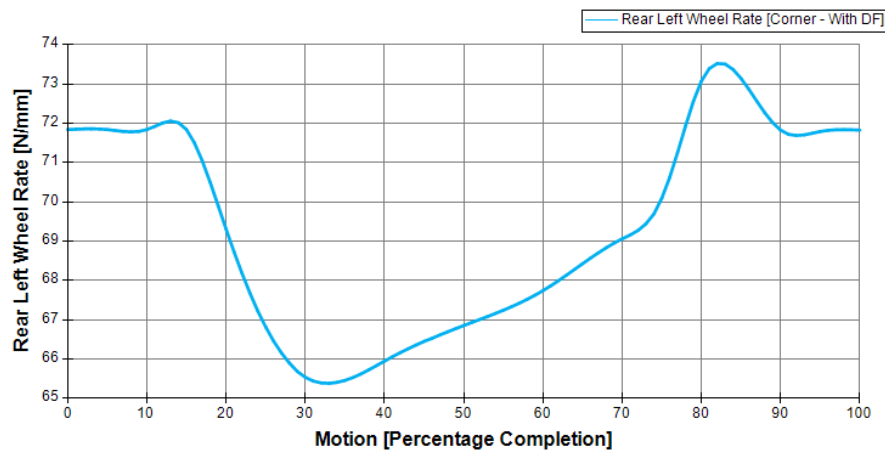
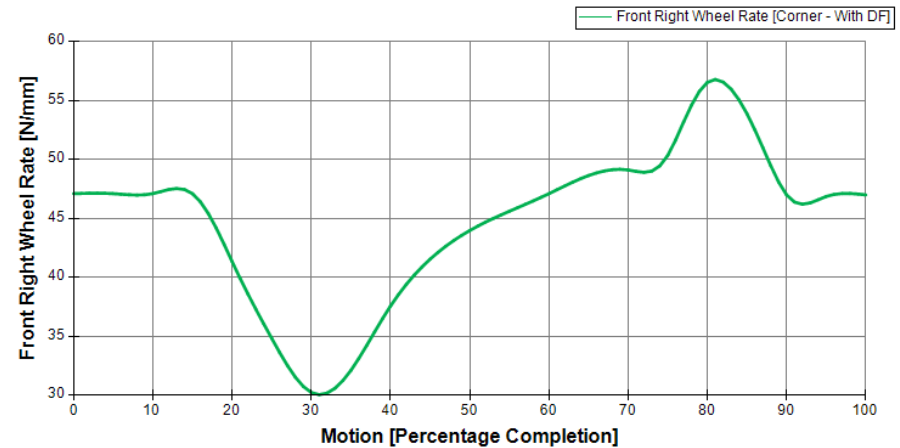
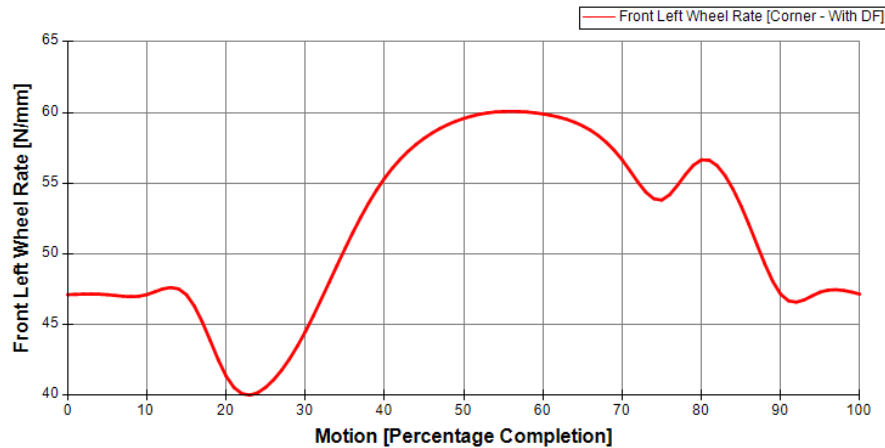
Spring Wheel Rate – Pitch



Spring Wheel Rate – Corner No DF

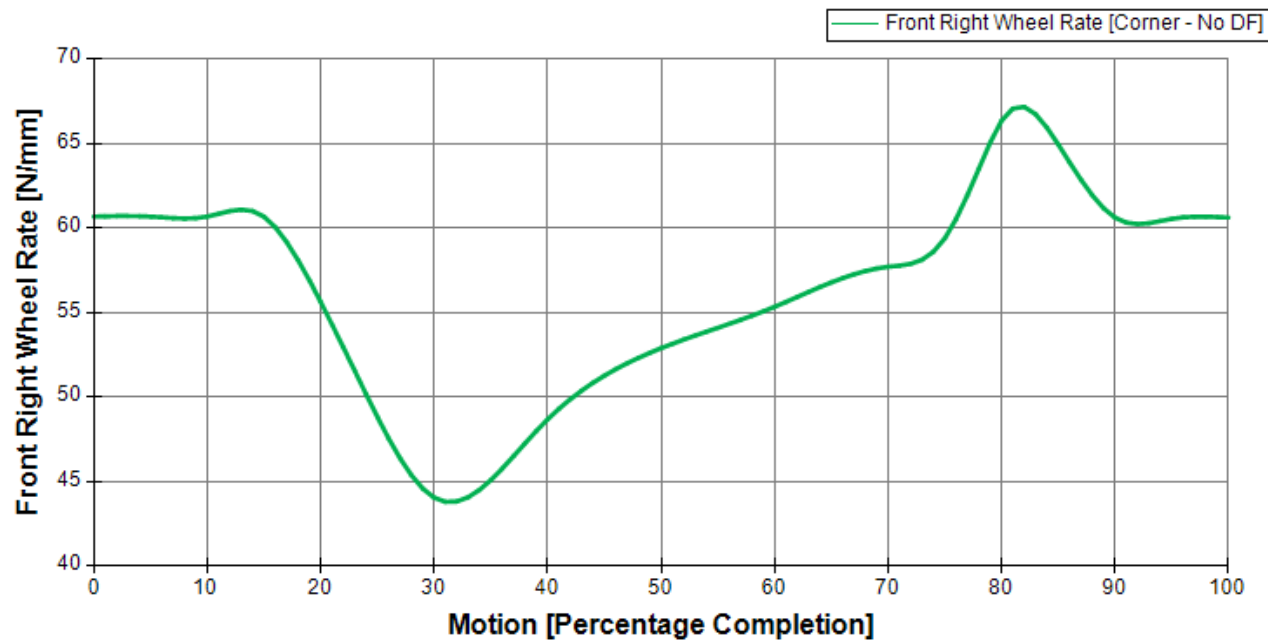


Spring Wheel Rate – Corner DF



Wheel Spring Rate – Comments

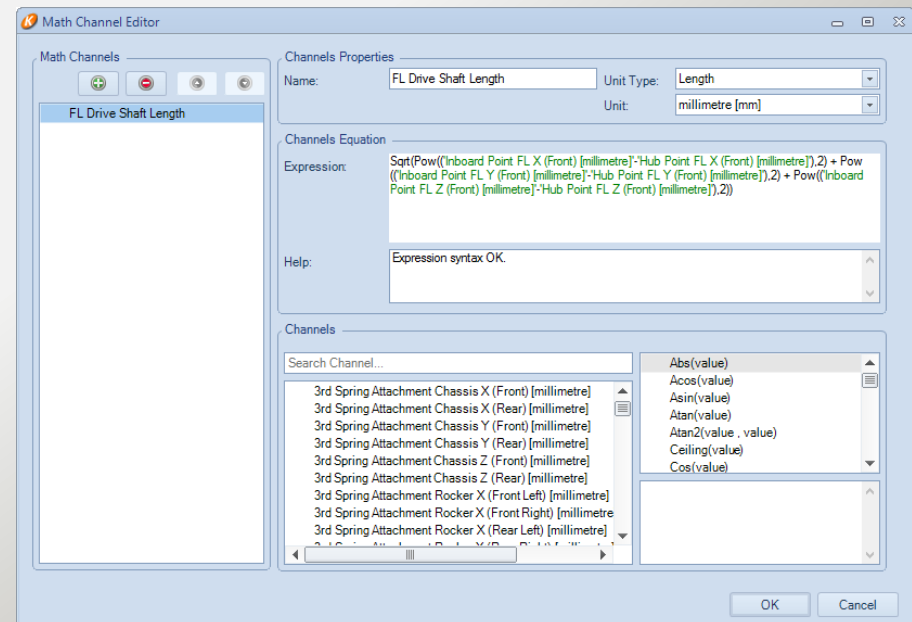
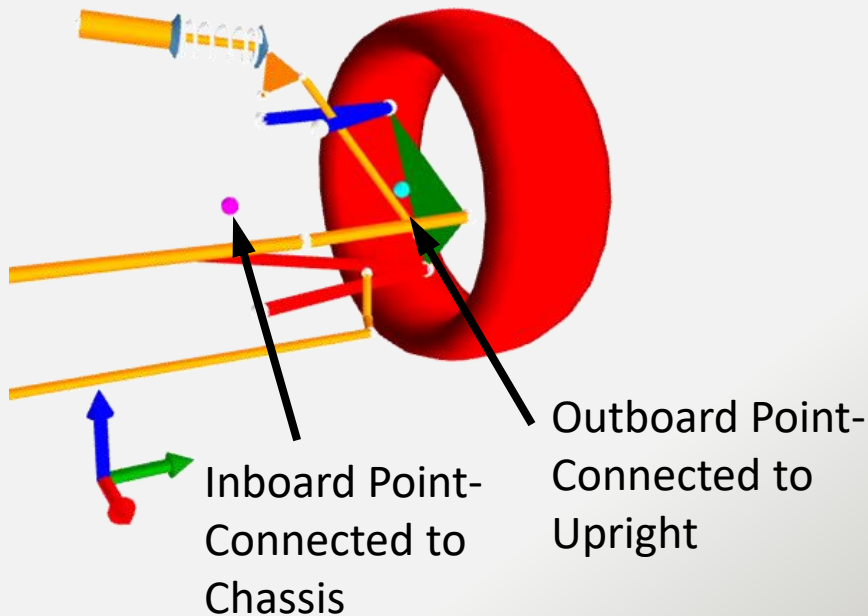
Due to the poor front motion ratio the wheel spring rate decreases as the vehicle pitches under brakes and turns into the corner. This is undesirable behavior which leads to a stiffer anti roll bar being required for a given roll magnitude.



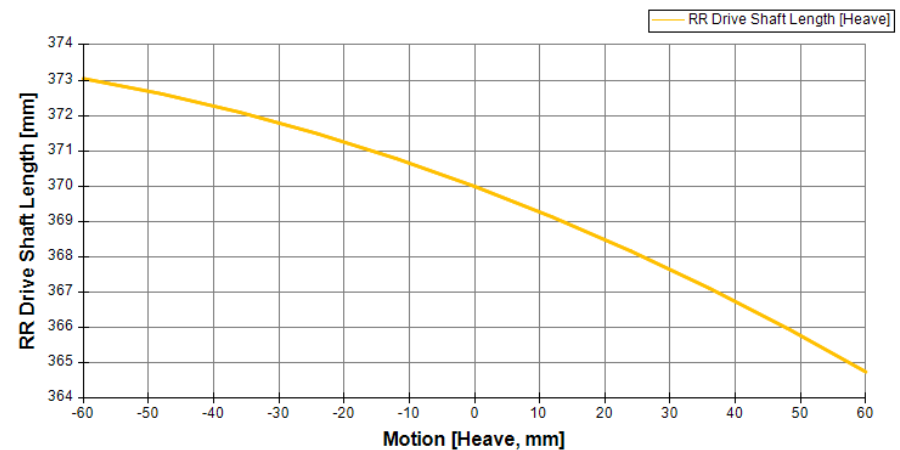
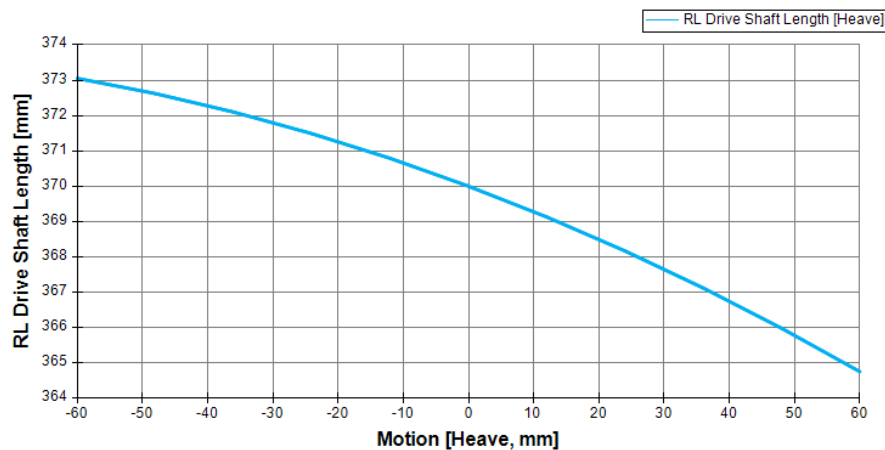
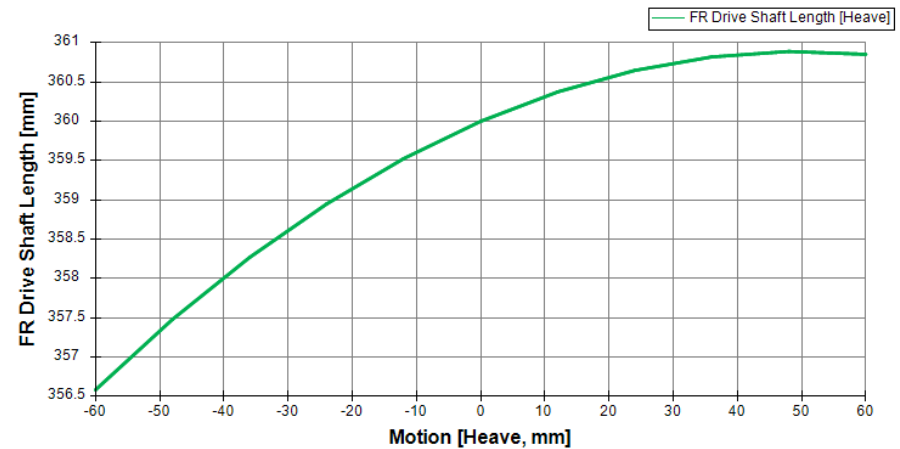
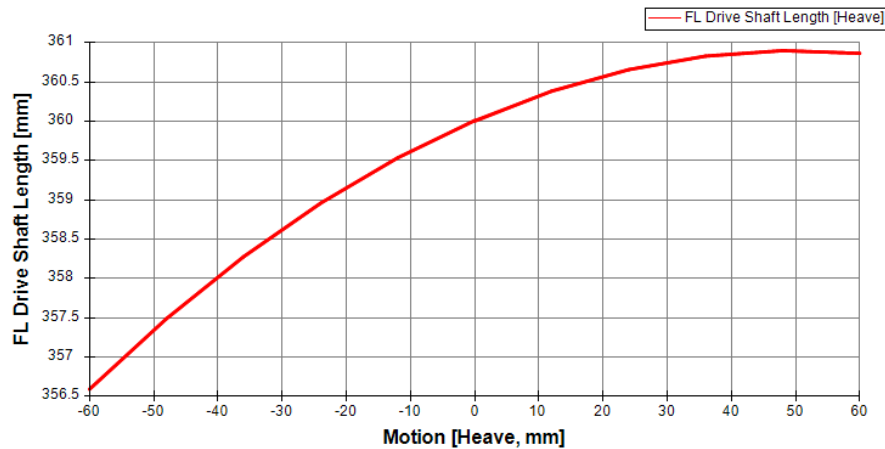
Using Math Channels and Reference Points Together- Drive Shaft Length

Combining reference points in the suspension and the creation of math channels, the varying length of a drive shaft can be modelled. Note reference points representing driveshaft chosen arbitrarily, only for example.

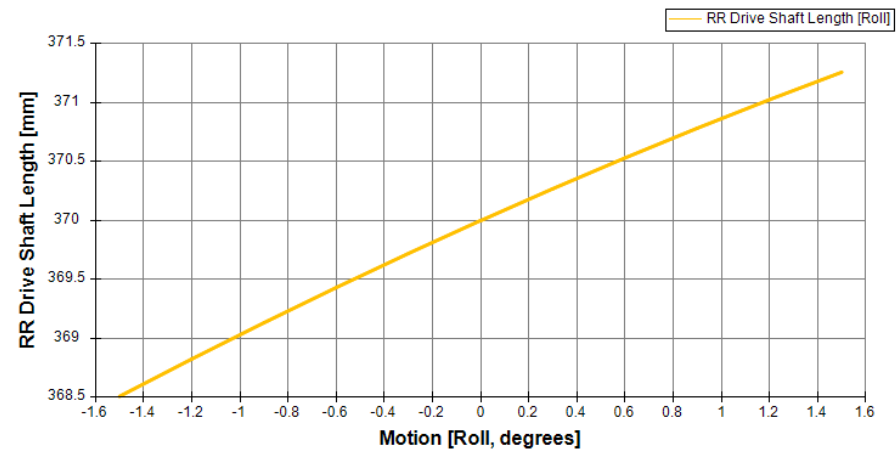
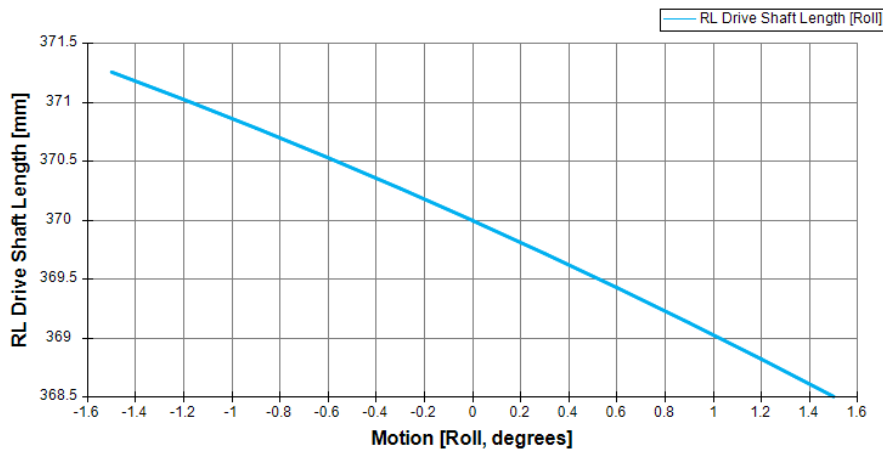
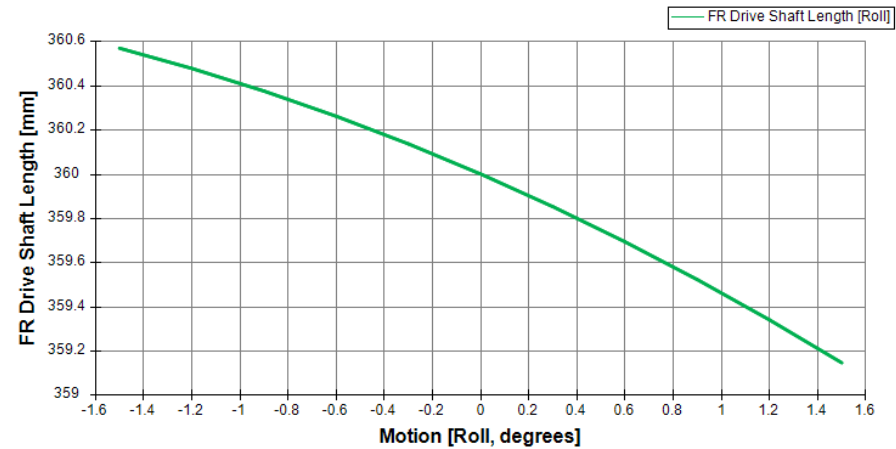
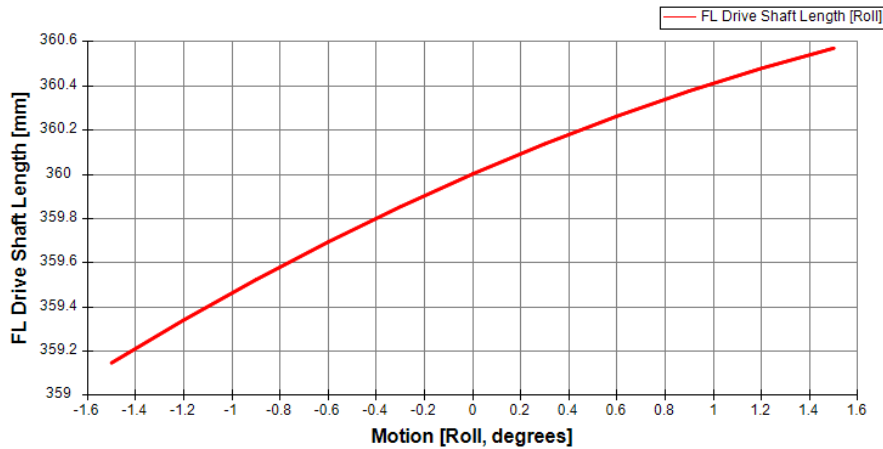
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(("Inboard Point FL Y (Front) [millimetre]"-Hub Point FL Y (Front) [millimetre]"),2) + Pow(("Inboard  
Point FL Z (Front) [millimetre]"-Hub Point FL Z (Front) [millimetre]"),2))
```



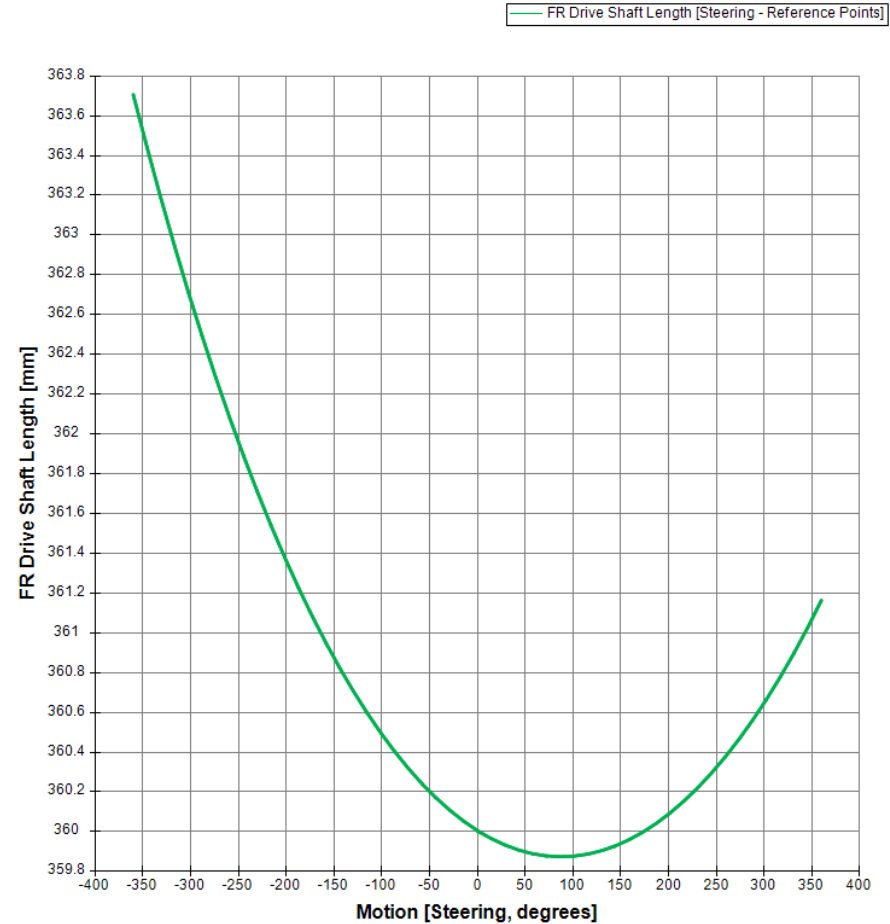
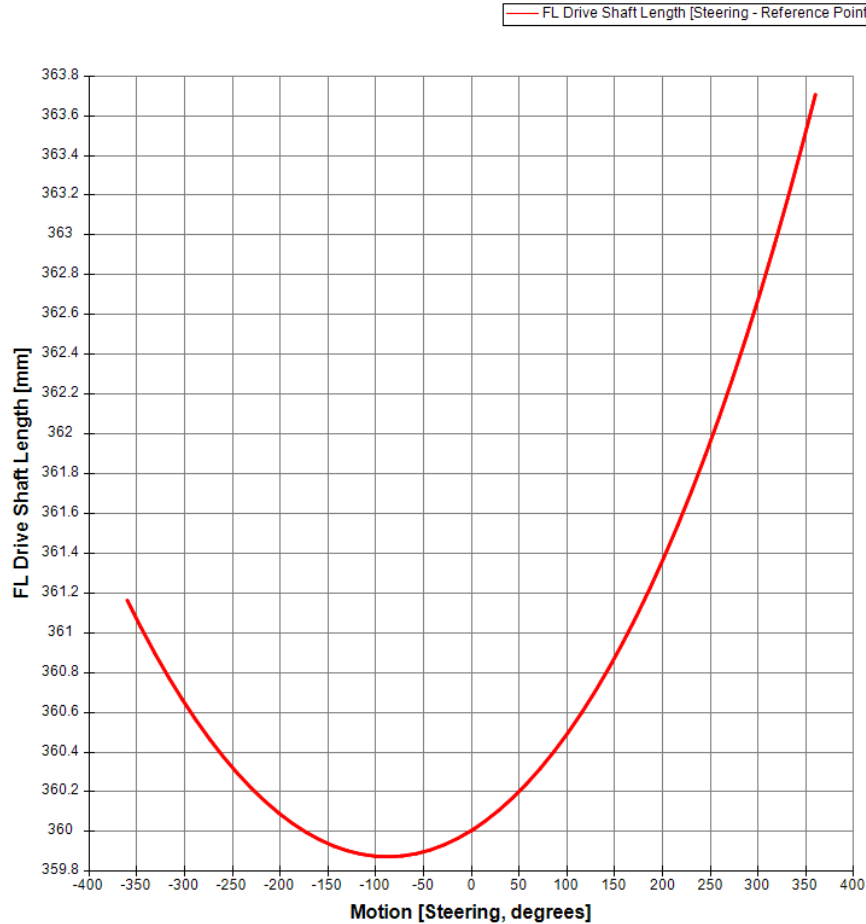
Drive Shaft Length – Heave



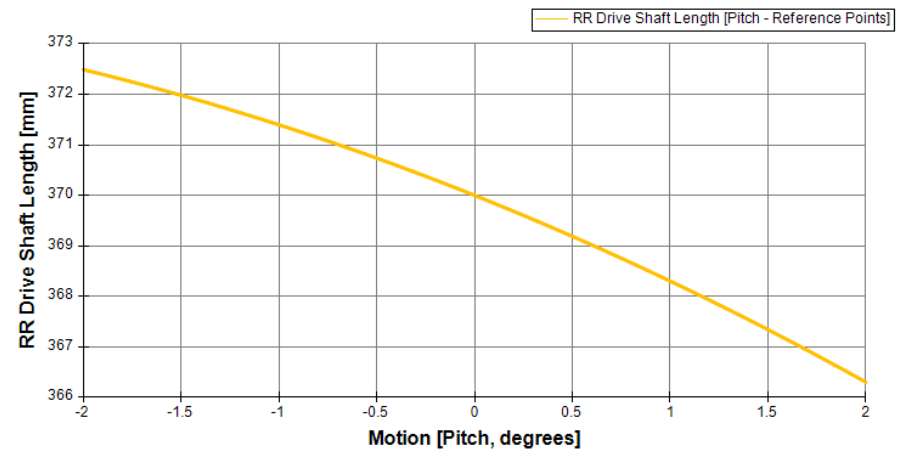
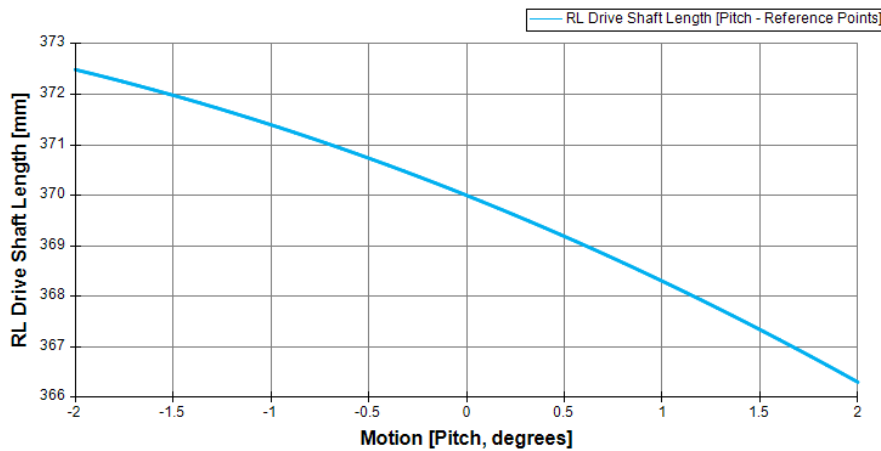
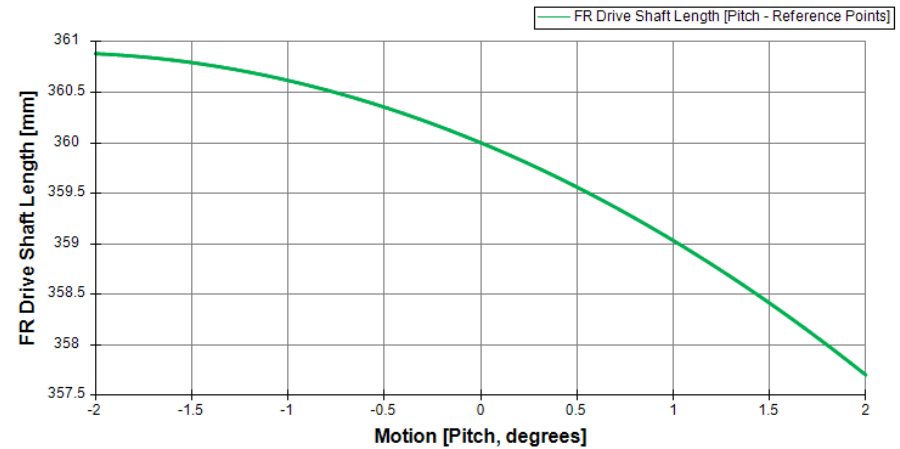
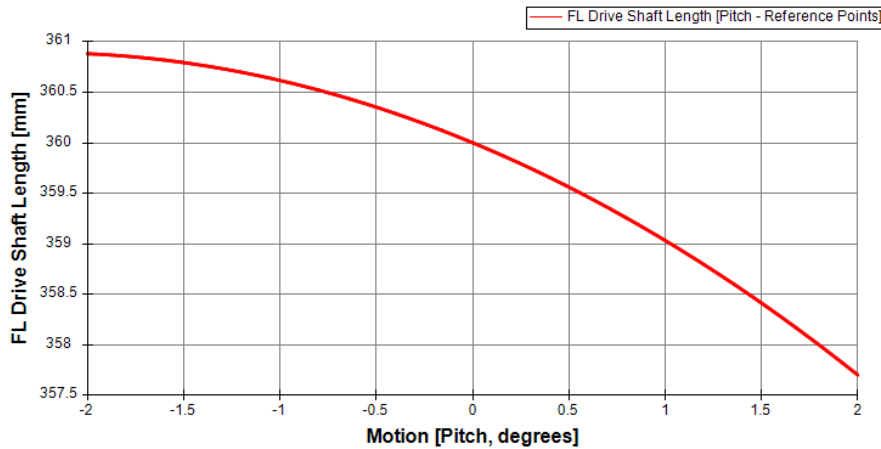
Drive Shaft Length – Roll



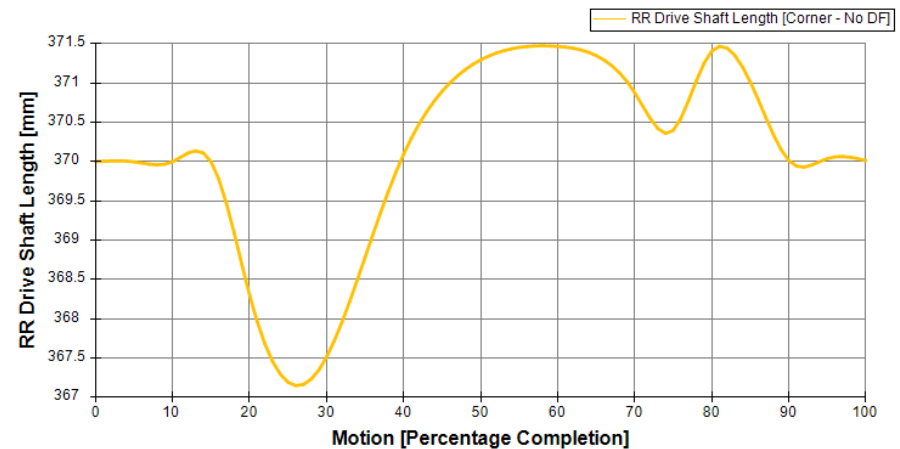
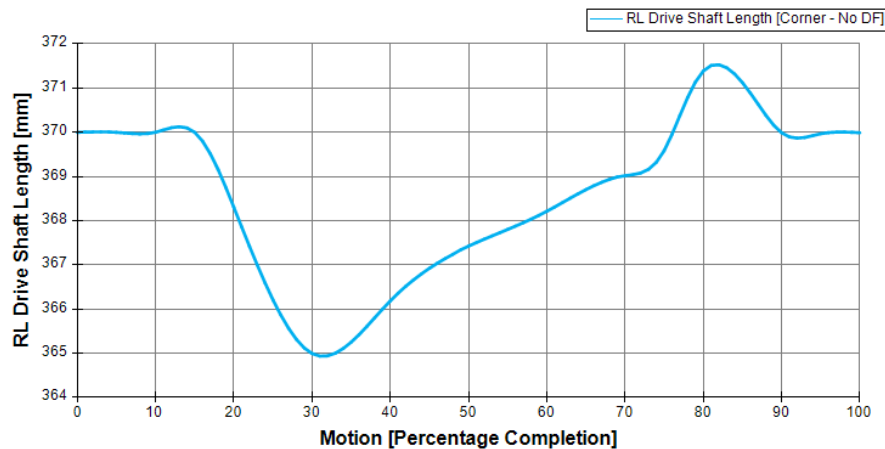
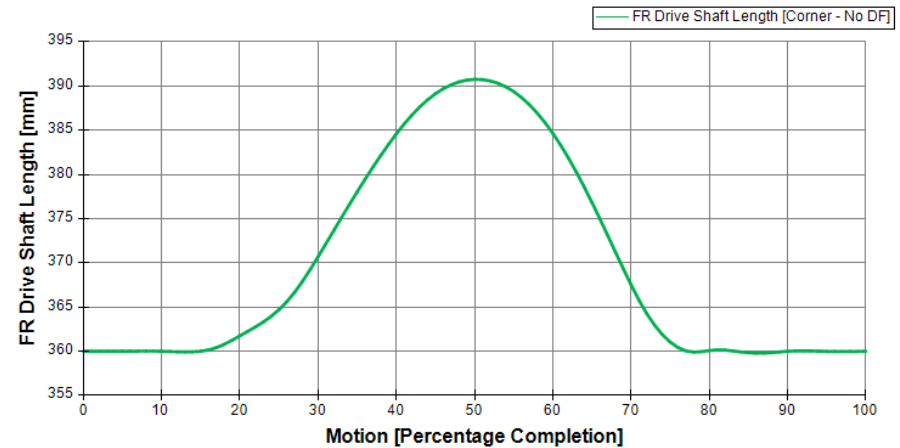
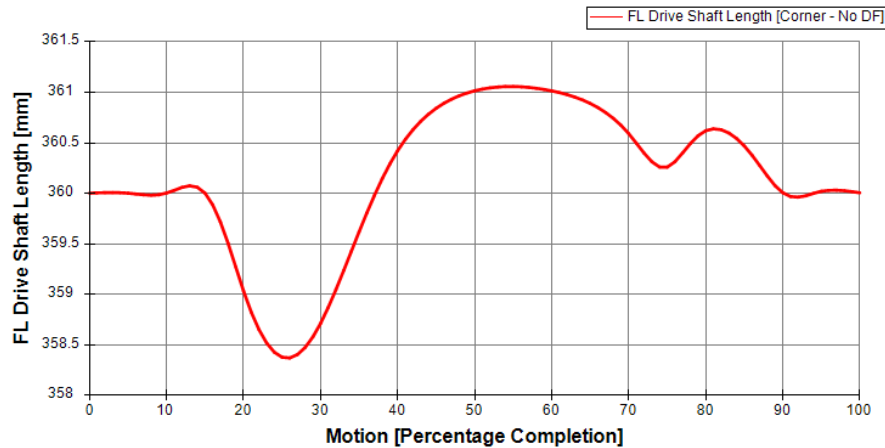
Drive Shaft Length – Steering



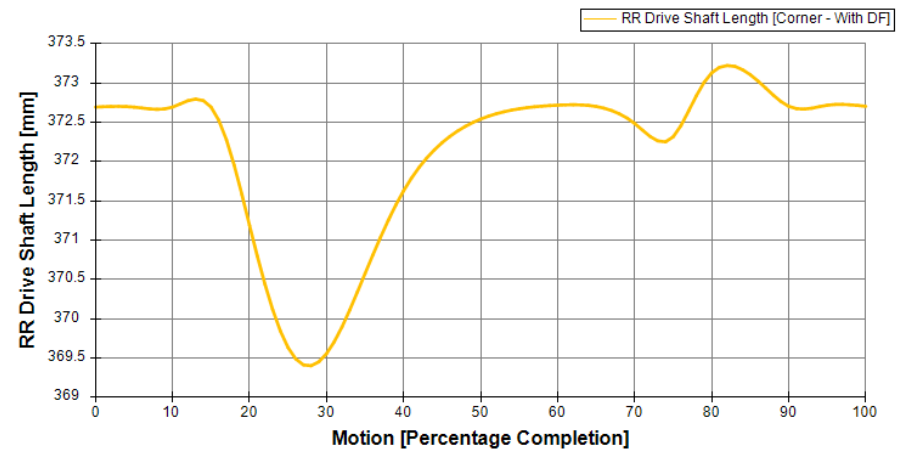
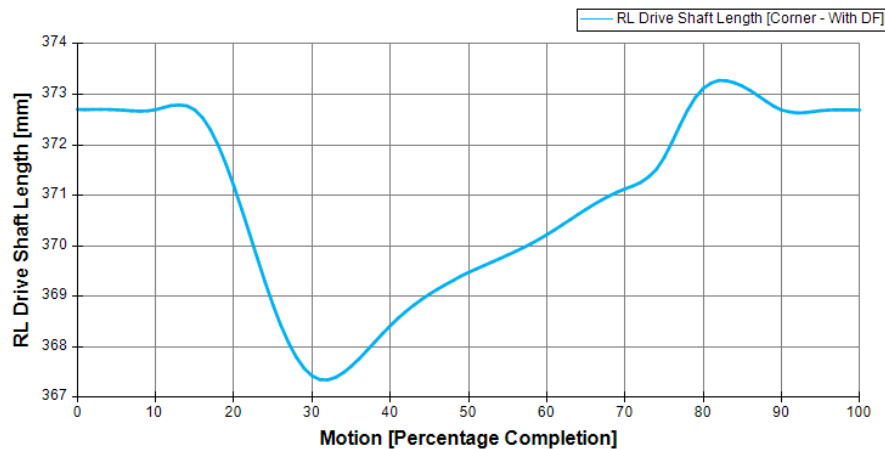
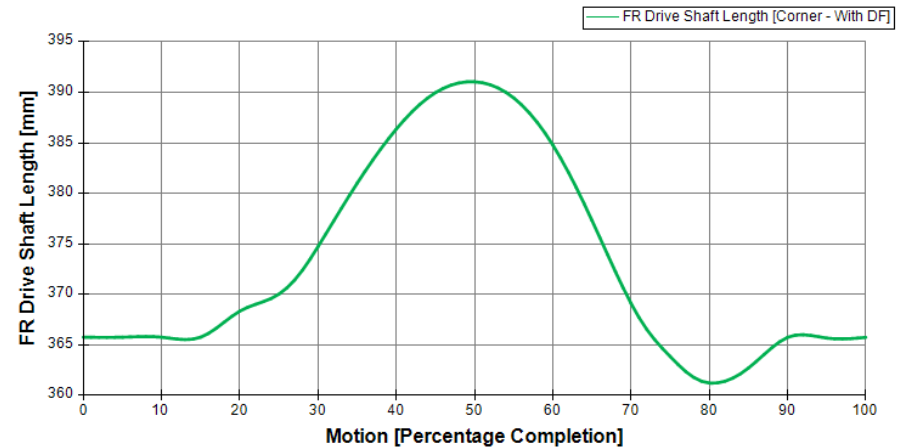
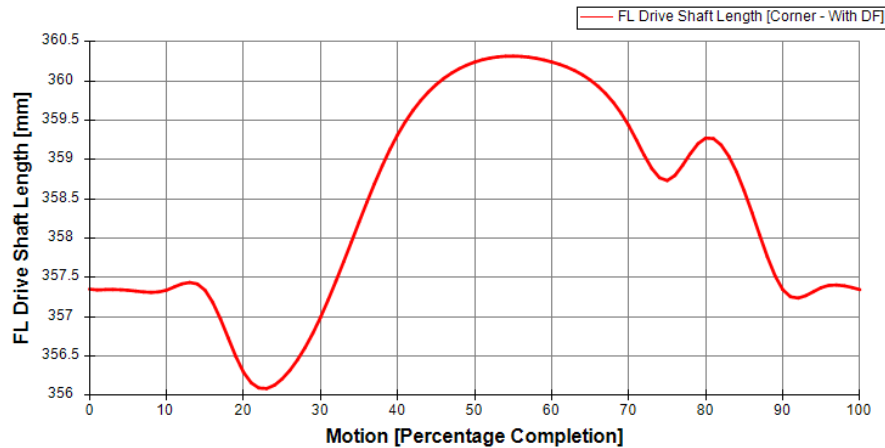
Drive Shaft Length - Pitch



Drive Shaft Length – Corner No DF

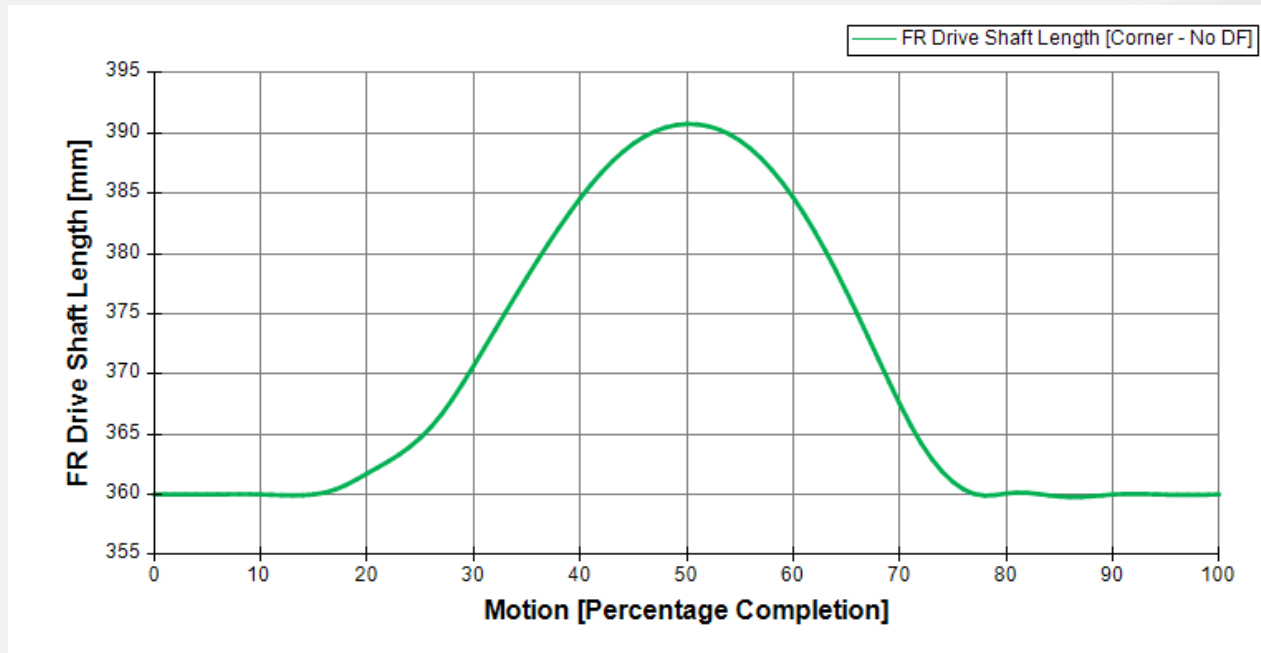


Drive Shaft Length – Corner DF



Driveshaft Length– Comments

- Significant change in driveshaft length on LF corner during cornering simulation- approximately 30mm



Using Math Channels and Reference Points Together- Drive Shaft Joint Angles

Combining reference points in the suspension and the creation of math channels, the angles of the drive shaft joints can be modelled. Note reference points representing driveshaft chosen arbitrarily, only for example.

In order to compute the absolute angle between two vectors, we take the dot product. We will need to find vectors representing the inboard joint, the driveshaft, and the outboard joint, in order to find all the angles in the driveline system.

Inboard Joint Vector – Called the “Chassis Vector”

'Inboard Point FL X (Front) [millimetre]'-'Inboard Point FR X (Front) [millimetre]'

Drive Shaft Vector

'Hub Point FL X (Front) [millimetre]'-'Inboard Point FL X (Front) [millimetre]'

Outboard Joint Vector – Called the “Wheel Vector”

'FL Wheel Point X (Front) [millimetre]'-'Hub Point FL X (Front) [millimetre]'

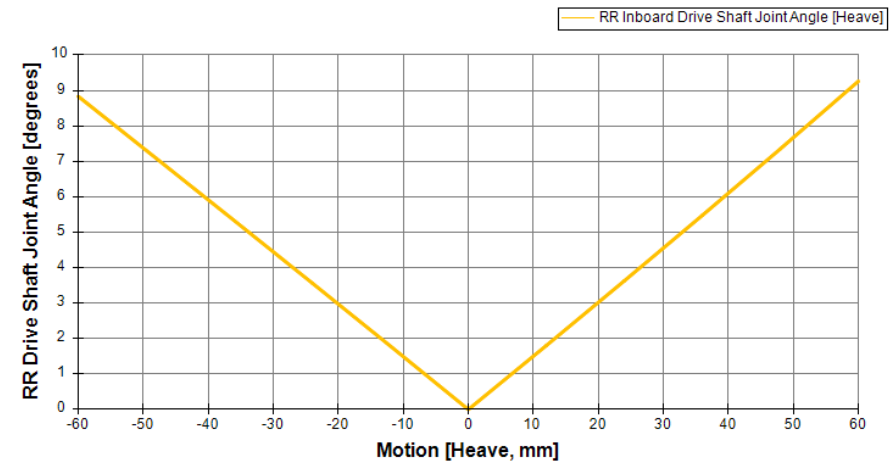
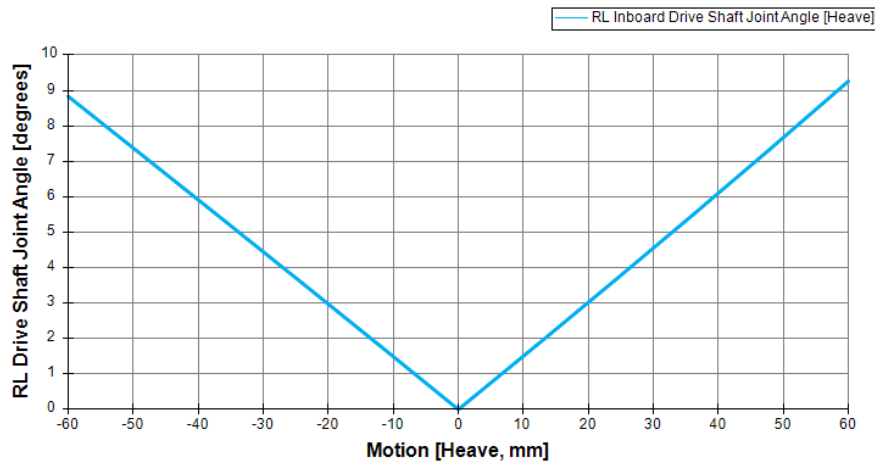
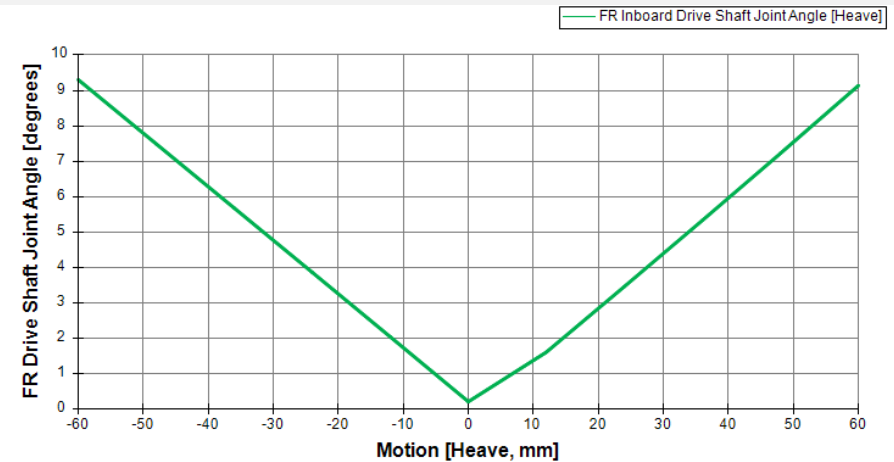
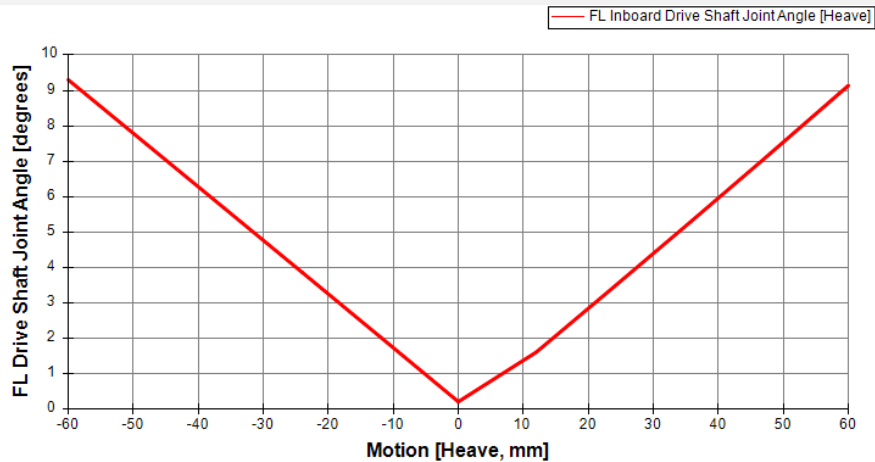
Inboard Joint Angle

$$\text{Acos}((\text{'FL Chassis Vector X [millimetre]'} * \text{'FL Drive Shaft Vector X [millimetre]'} + \text{'FL Chassis Vector Y [millimetre]'} * \text{'FL Drive Shaft Vector Y [millimetre]'} + \text{'FL Chassis Vector Z [millimetre]'} * \text{'FL Drive Shaft Vector Z [millimetre]'})) / (\text{'FL Chassis Vector R [millimetre]'} * \text{'FL Drive Shaft Vector R [millimetre]'})) * 180 / \text{PI [unitless]}$$

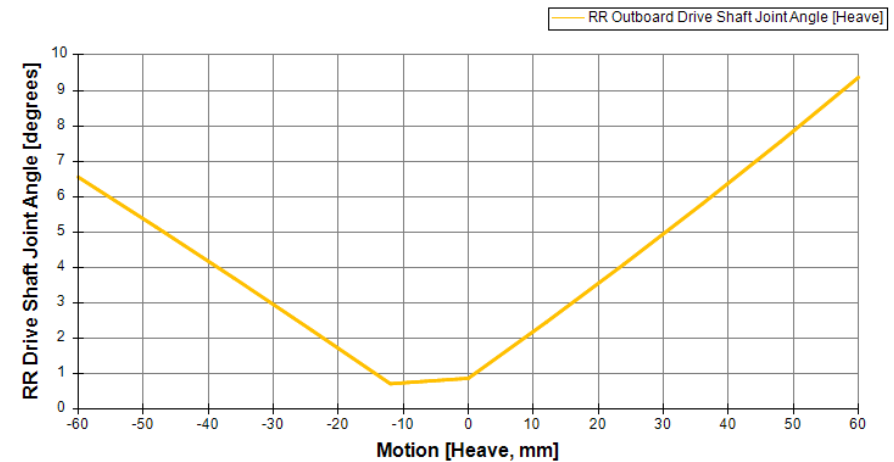
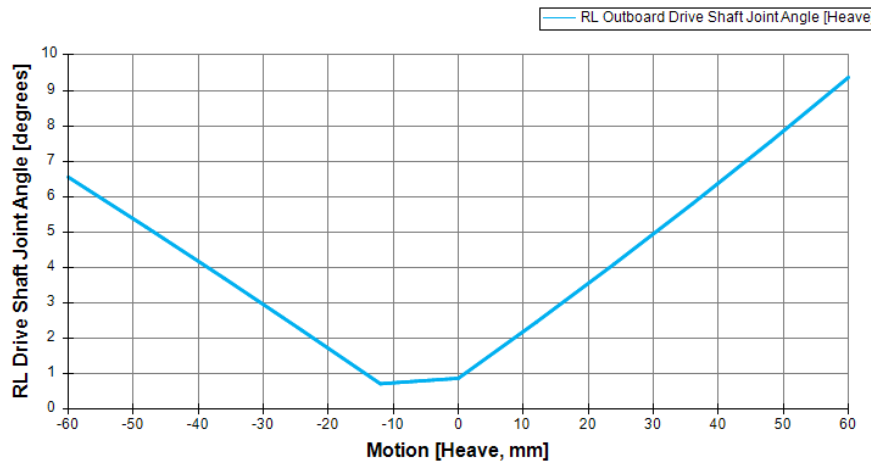
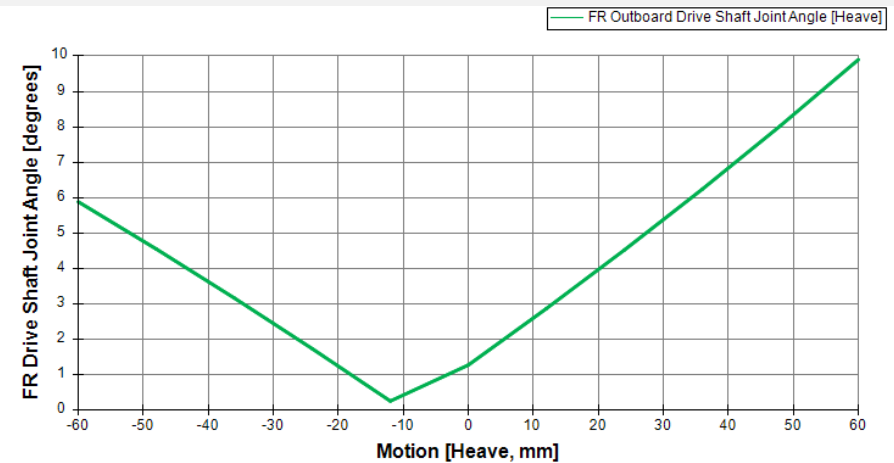
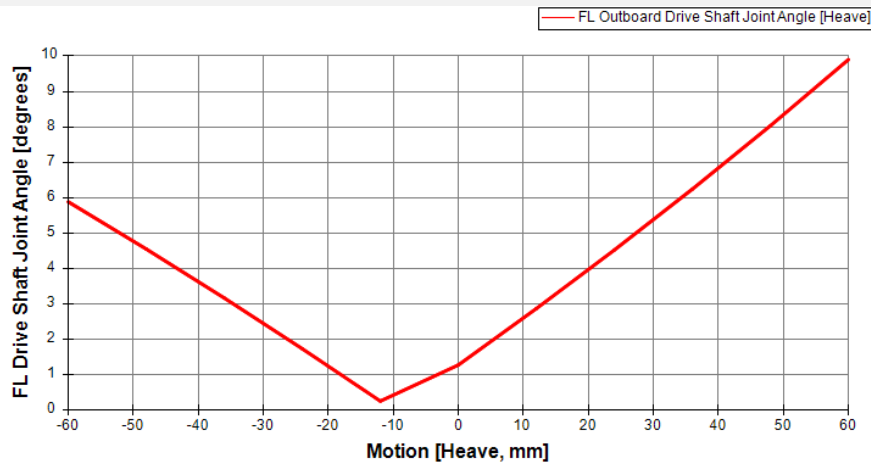
Outboard Joint Angle

$$\text{Acos}((\text{'FL Drive Shaft Vector X [millimetre]'} * \text{'FL Wheel Vector X [millimetre]'} + \text{'FL Drive Shaft Vector Y [millimetre]'} * \text{'FL Wheel Vector Y [millimetre]'} + \text{'FL Drive Shaft Vector Z [millimetre]'} * \text{'FL Wheel Vector Z [millimetre]'})) / (\text{'FL Drive Shaft Vector R [millimetre]'} * \text{'FL Wheel Vector R [millimetre]'})) * 180 / \text{PI [unitless]}$$

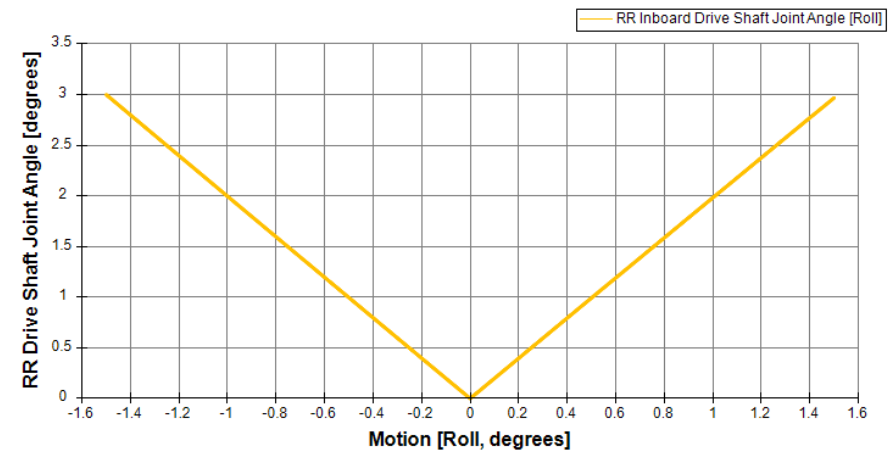
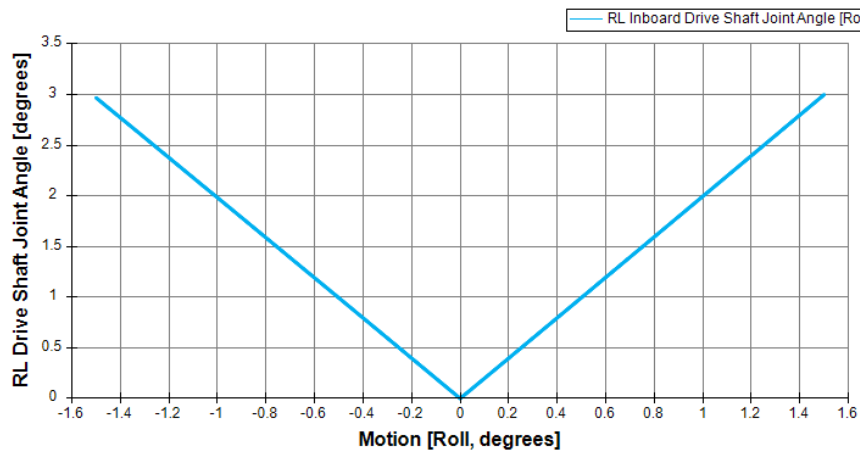
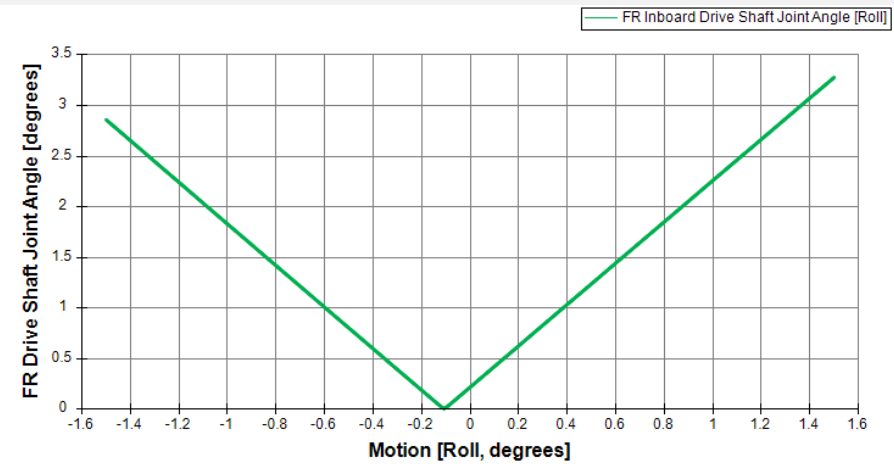
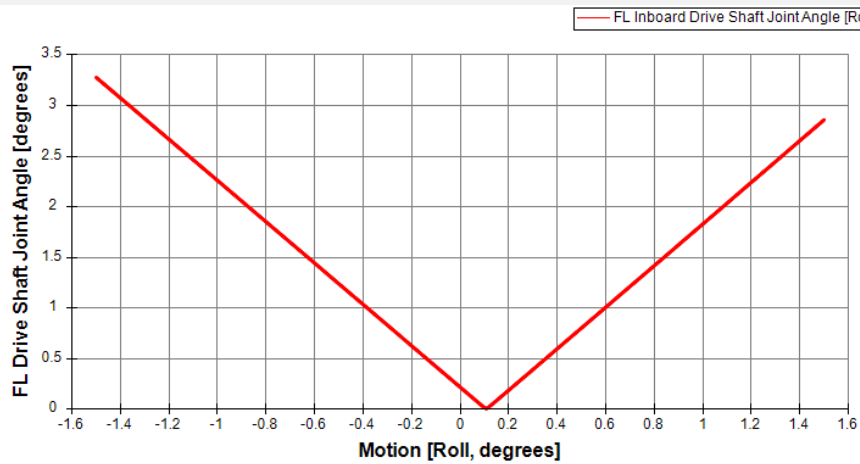
Inboard Drive Shaft Joint Angle – Heave



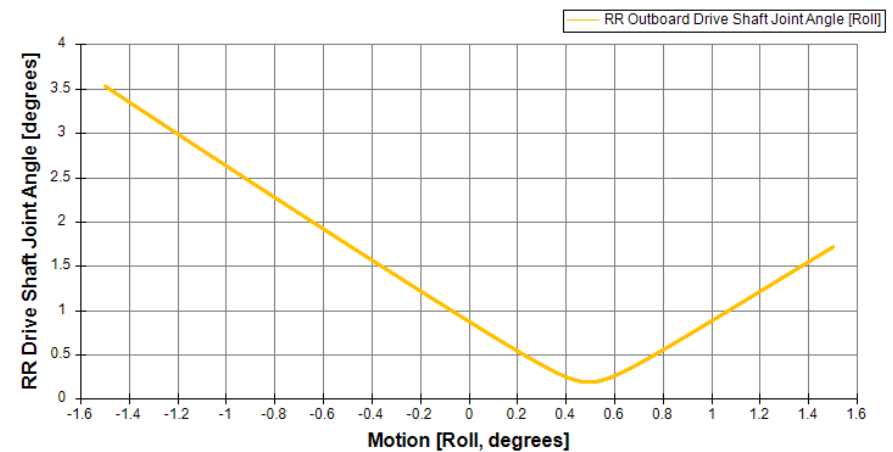
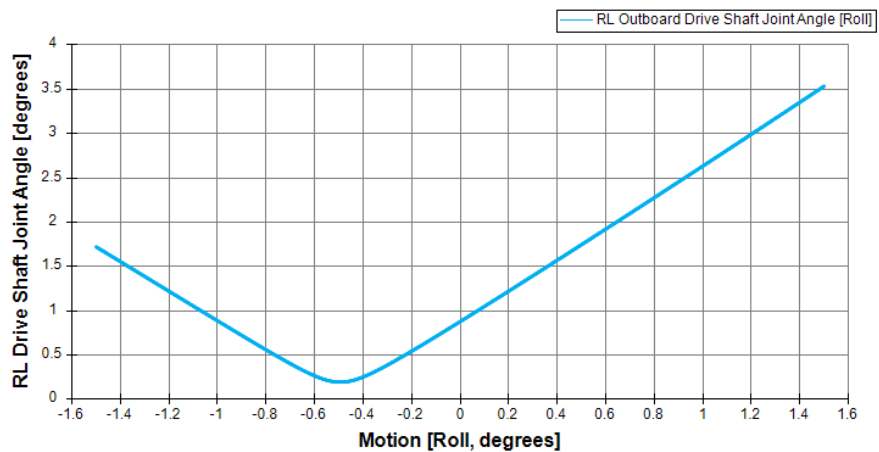
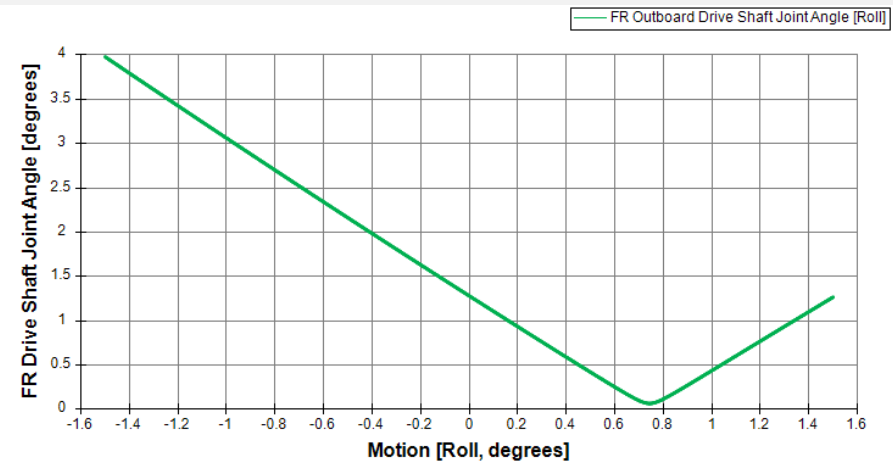
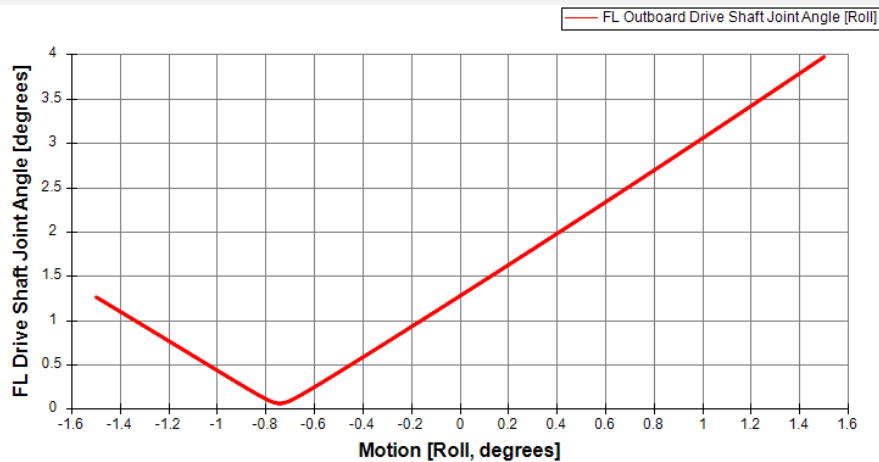
Outboard Drive Shaft Joint Angle – Heave



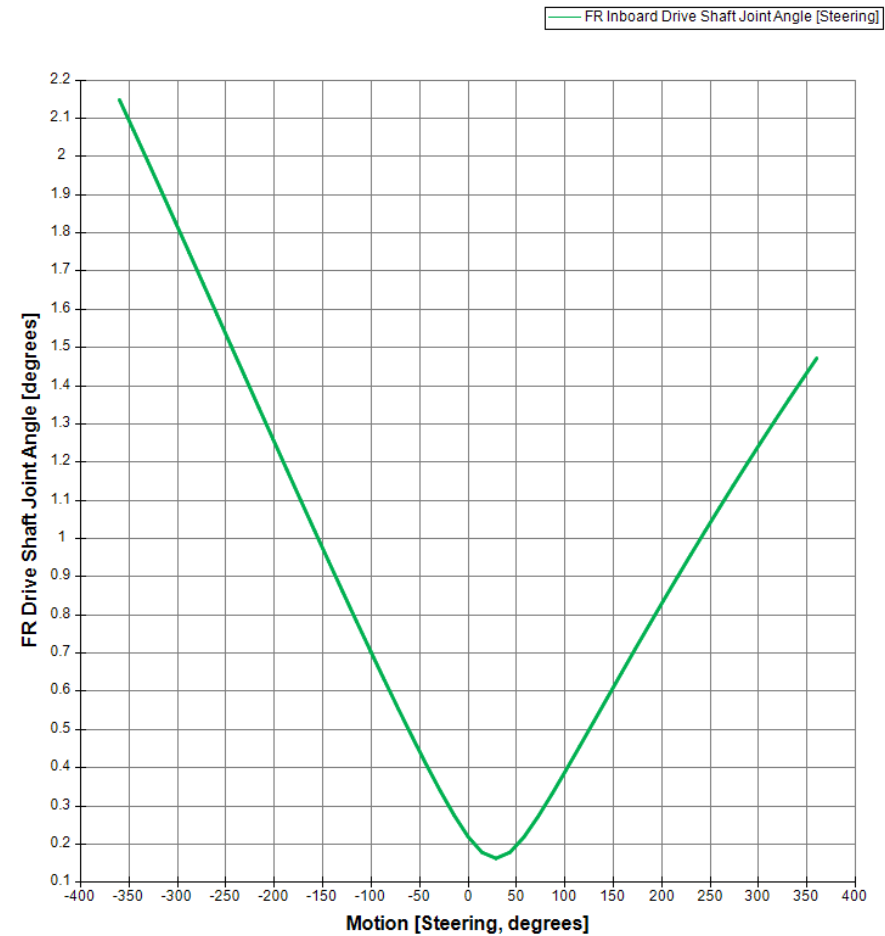
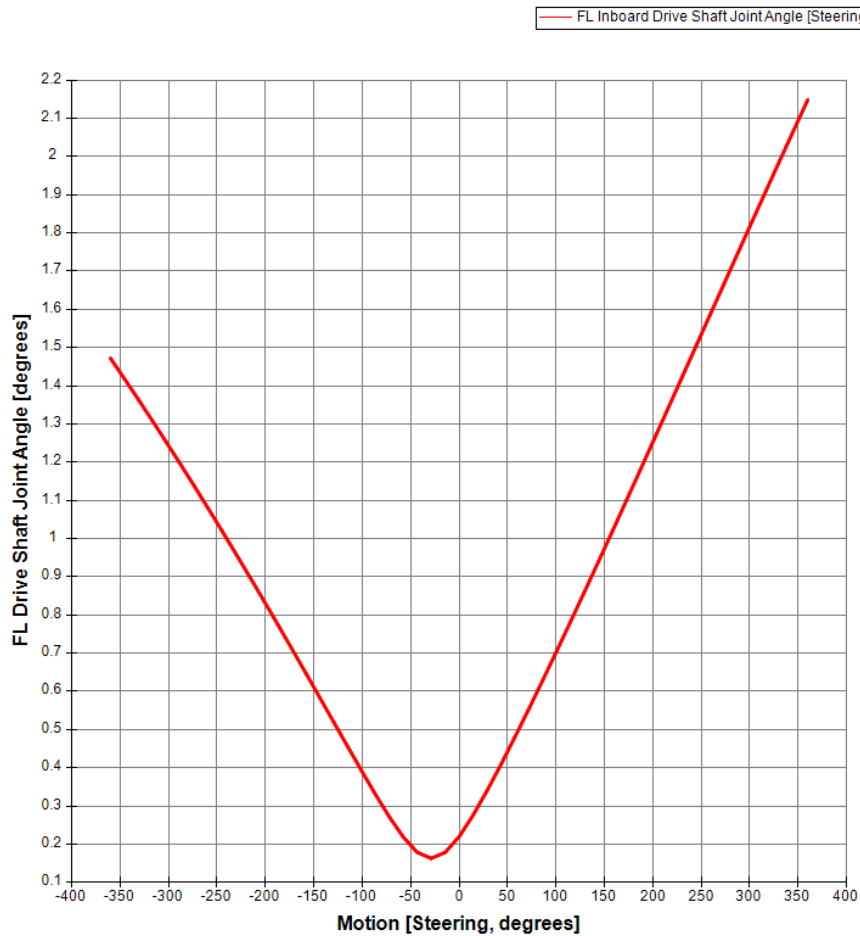
Inboard Drive Shaft Joint Angle – Roll



Outboard Drive Shaft Joint Angle – Roll

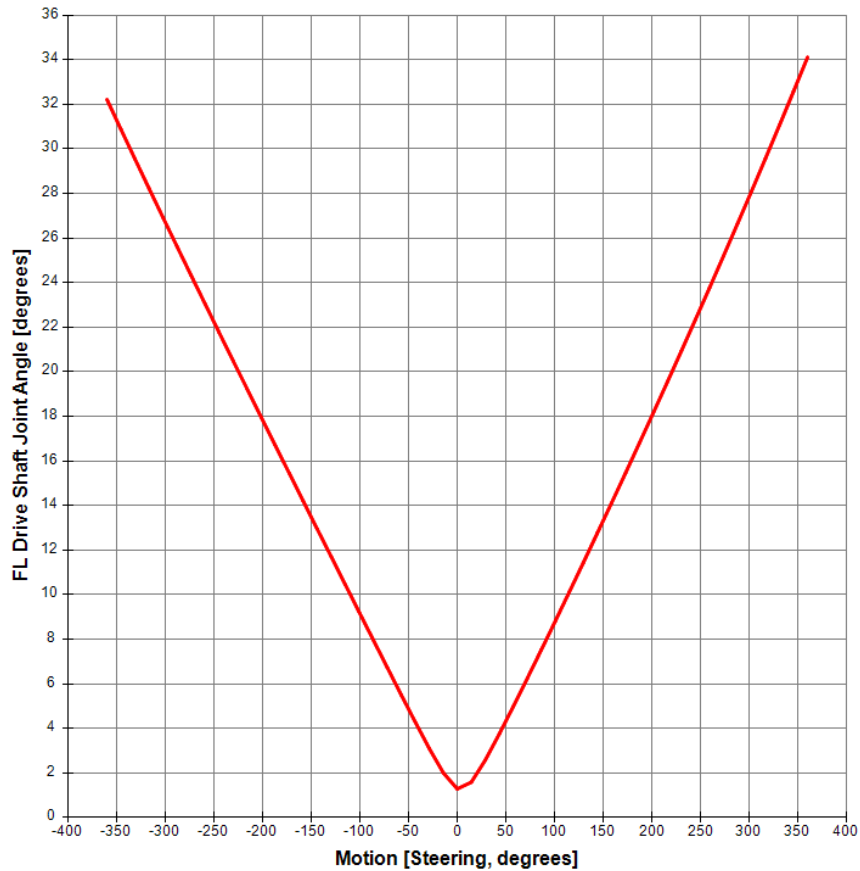


Inboard Drive Shaft Joint Angle – Steering

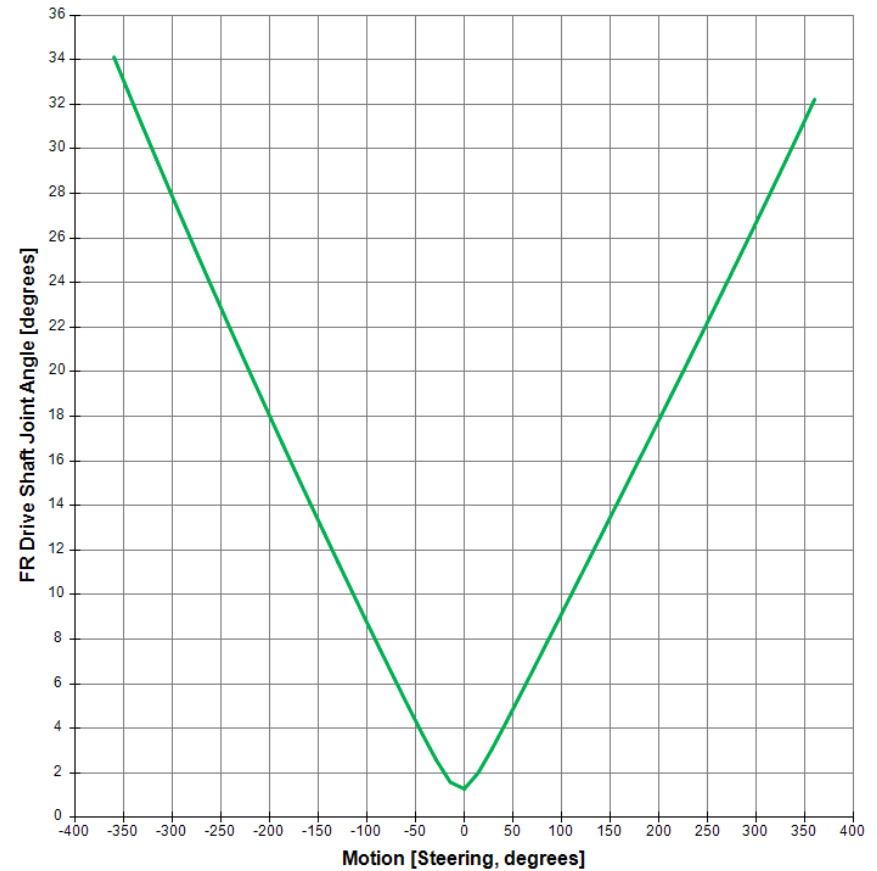


Outboard Drive Shaft Joint Angle – Steering

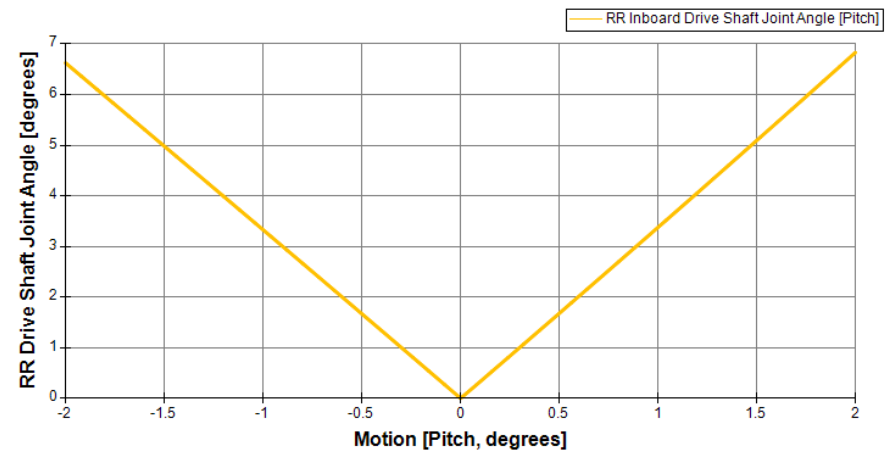
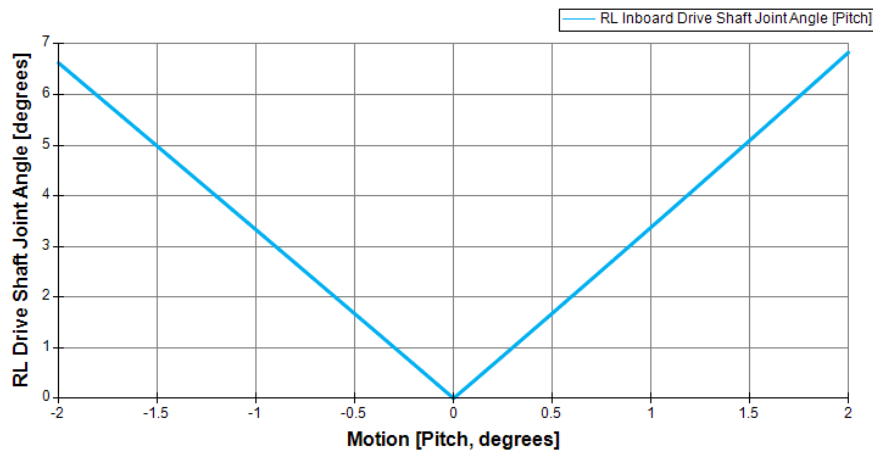
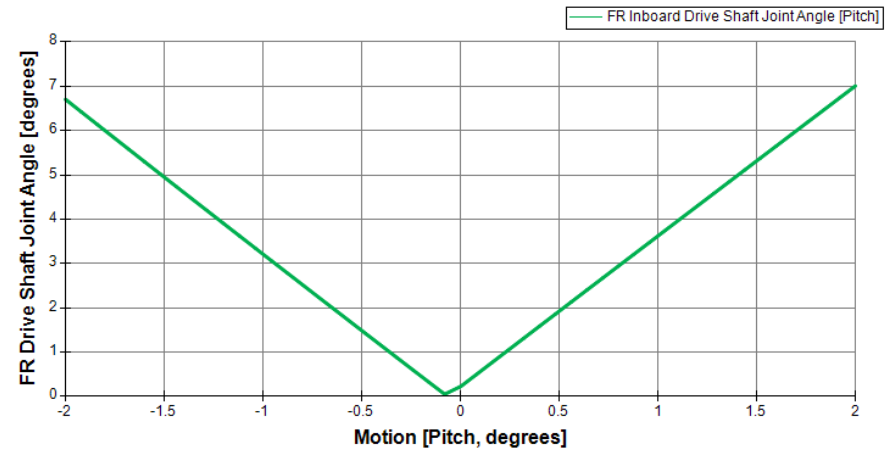
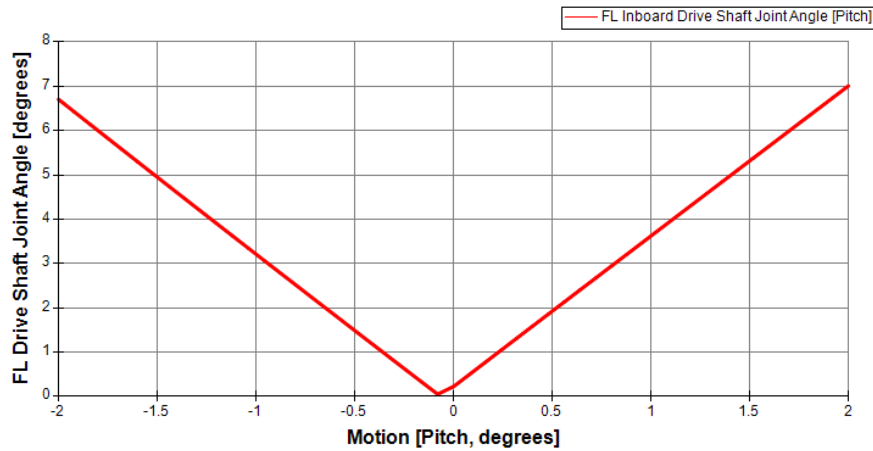
FL Outboard Drive Shaft Joint Angle [Steering]



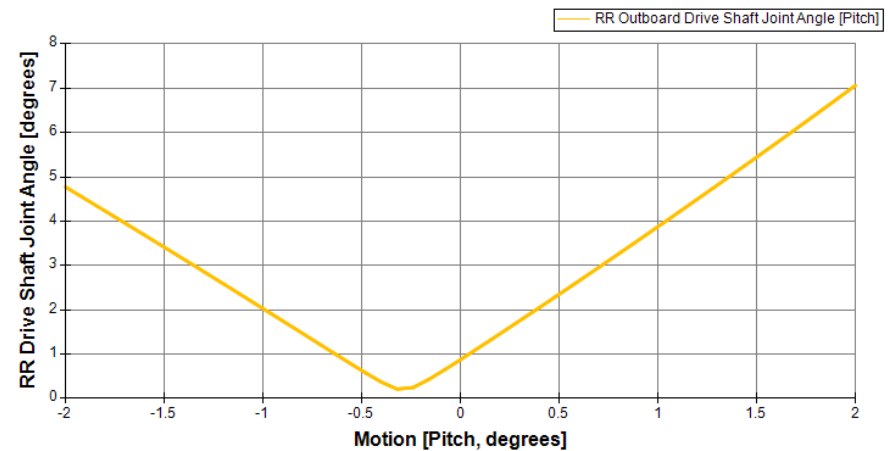
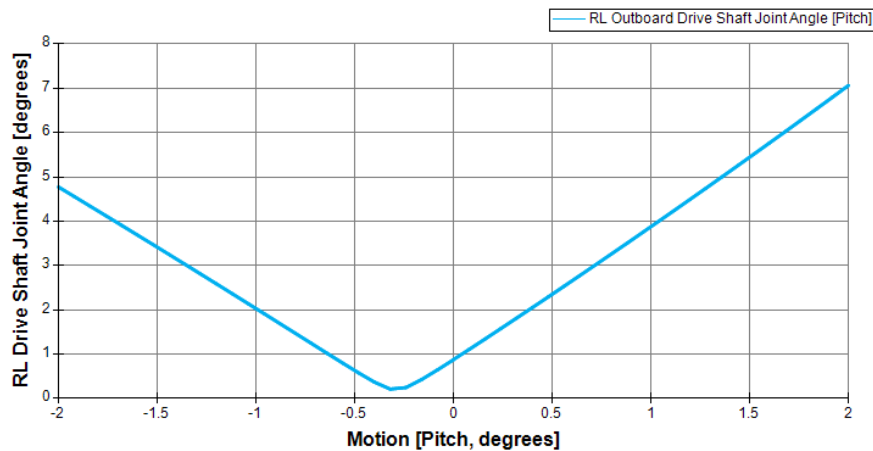
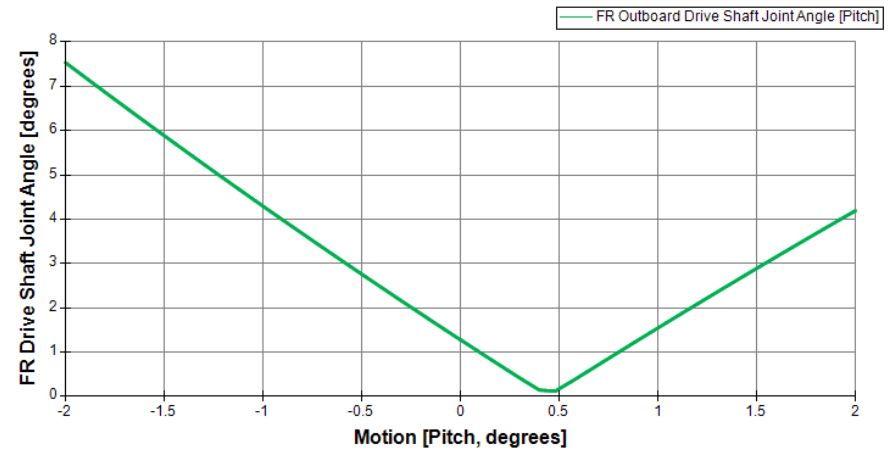
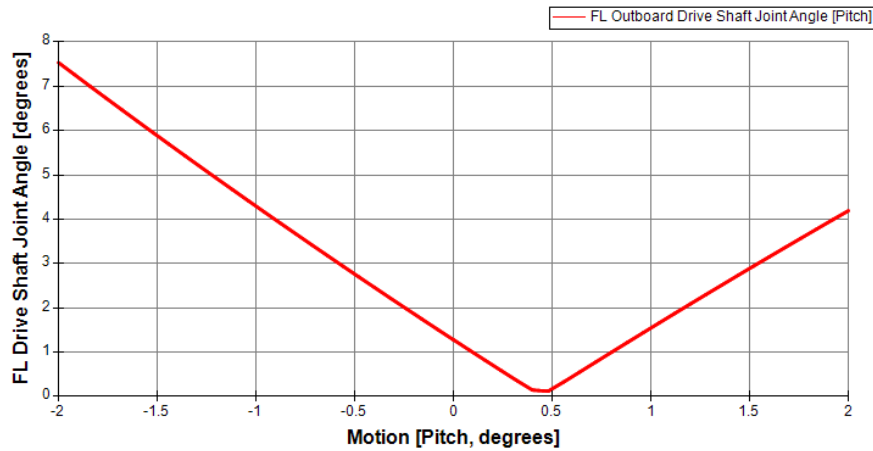
FR Outboard Drive Shaft Joint Angle [Steering]



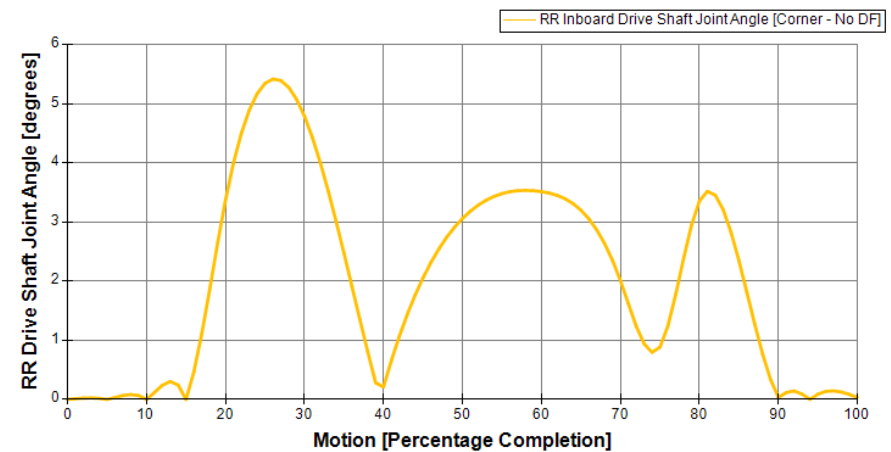
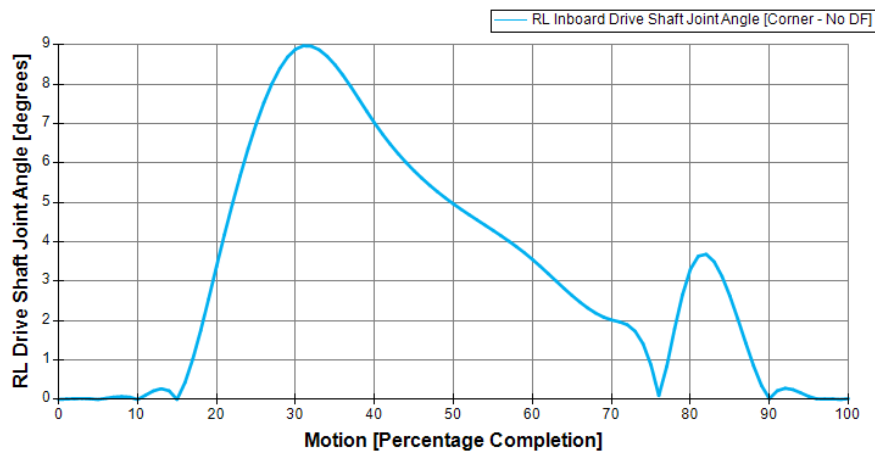
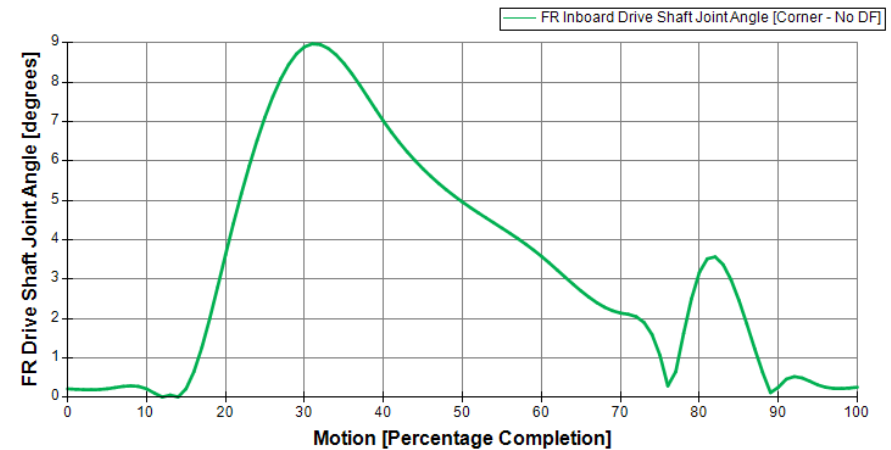
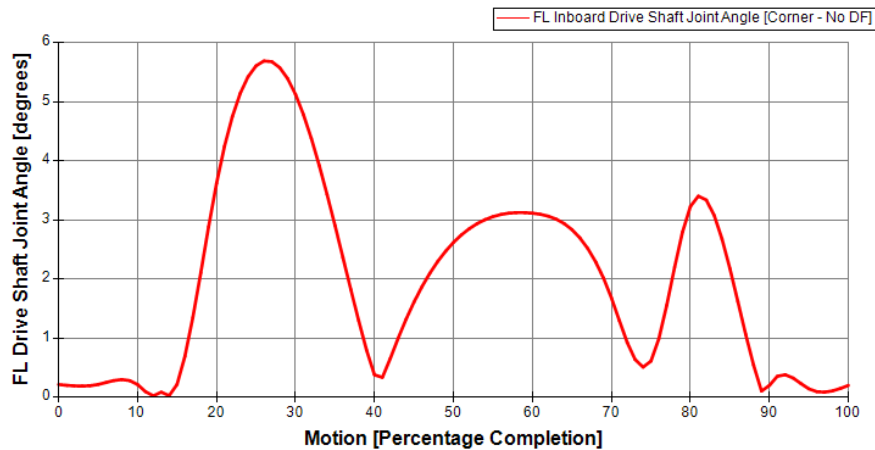
Inboard Drive Shaft Joint Angle - Pitch



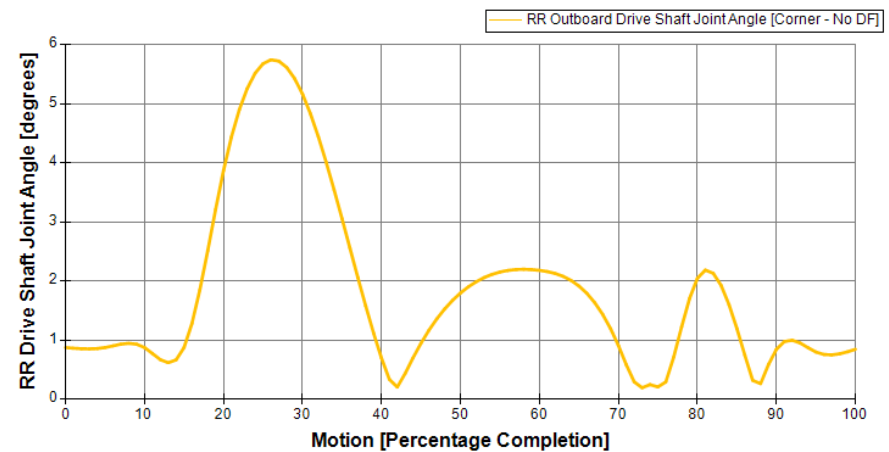
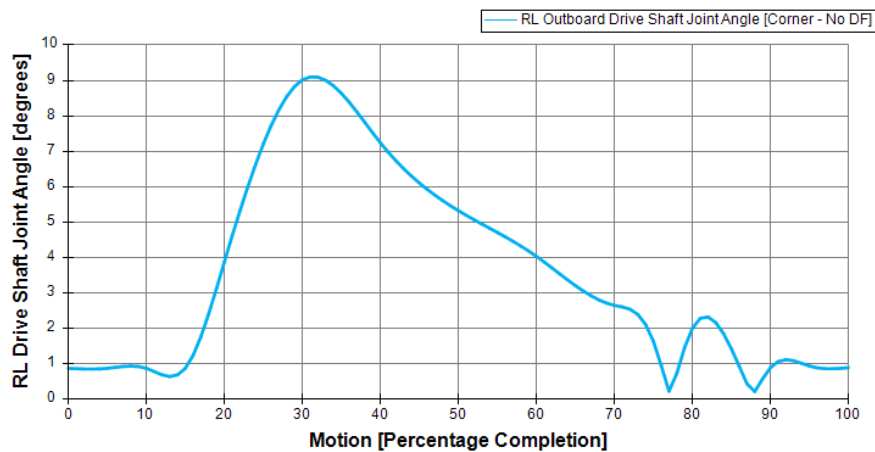
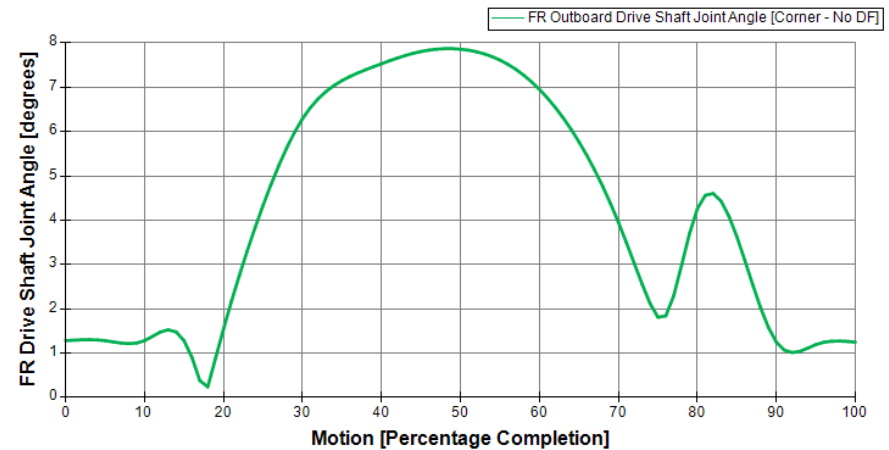
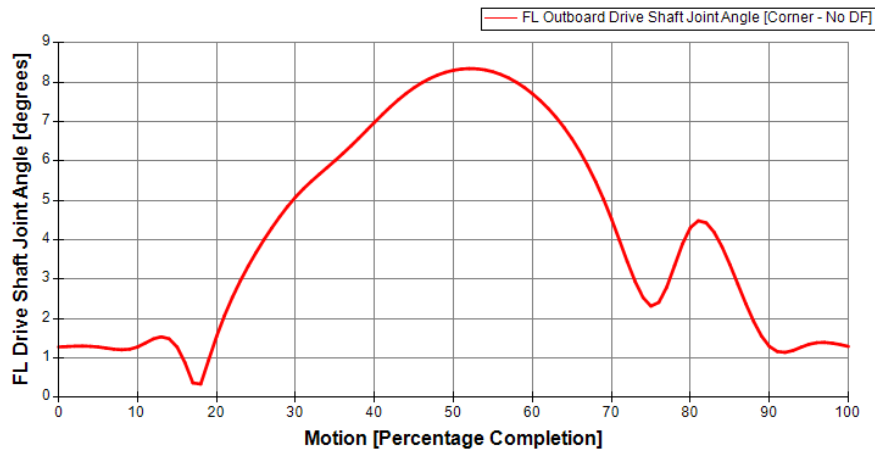
Outboard Drive Shaft Joint Angle - Pitch



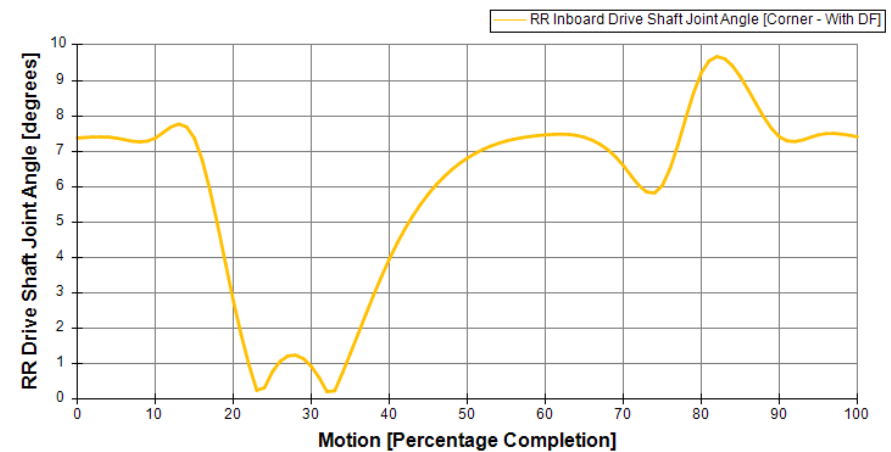
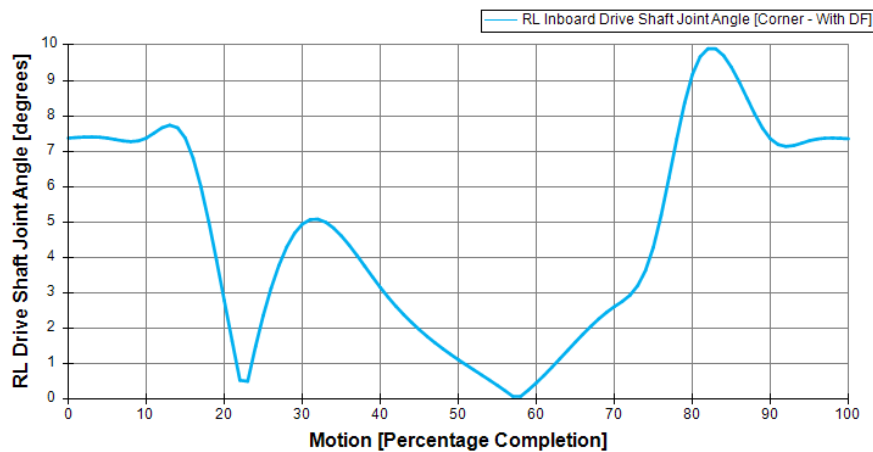
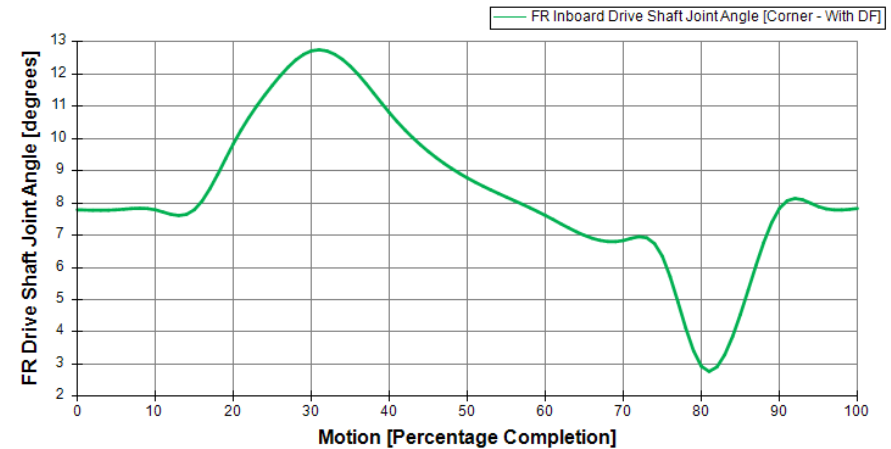
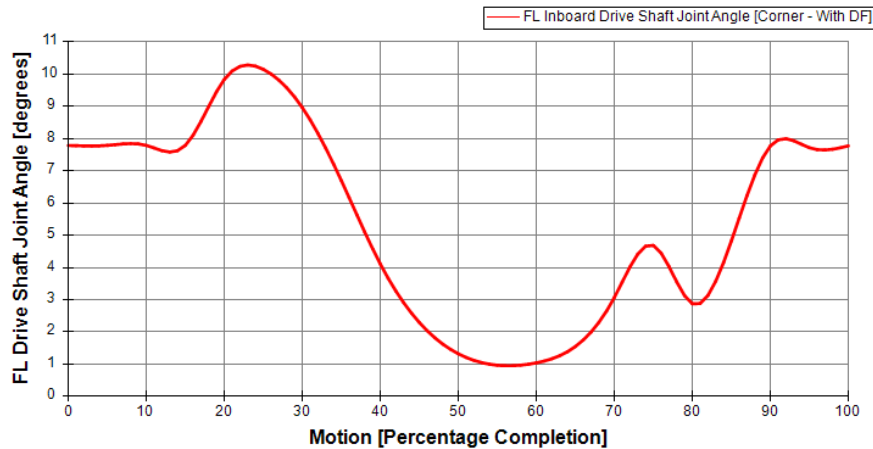
Inboard Drive Shaft Joint Angle – Corner No DF



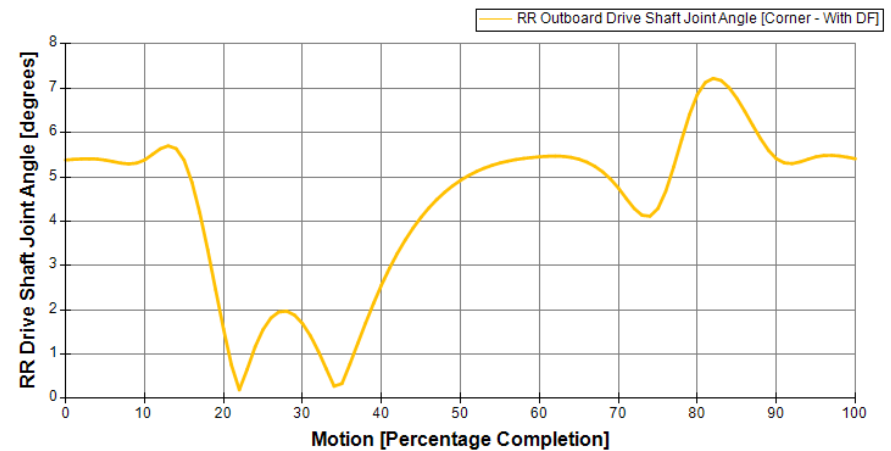
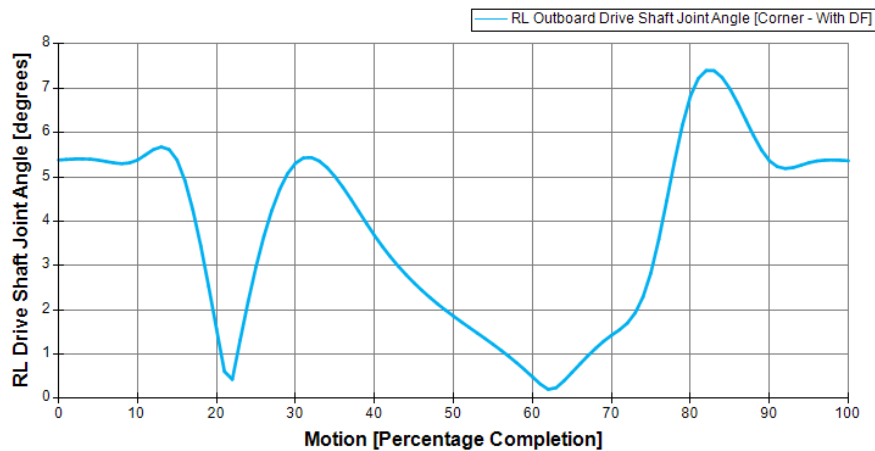
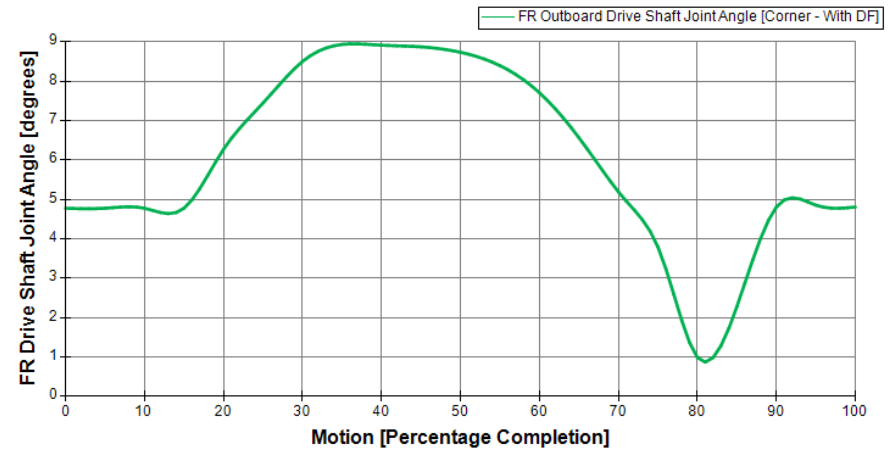
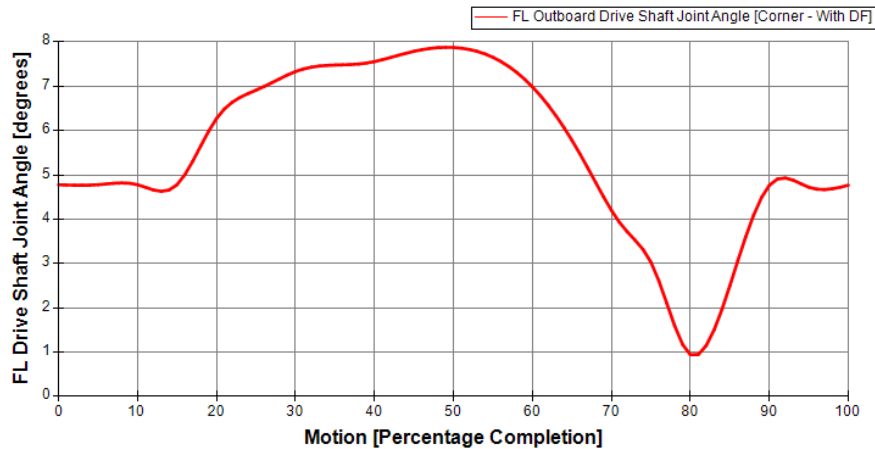
Outboard Drive Shaft Joint Angle – Corner No DF



Inboard Drive Shaft Joint Angle – Corner DF

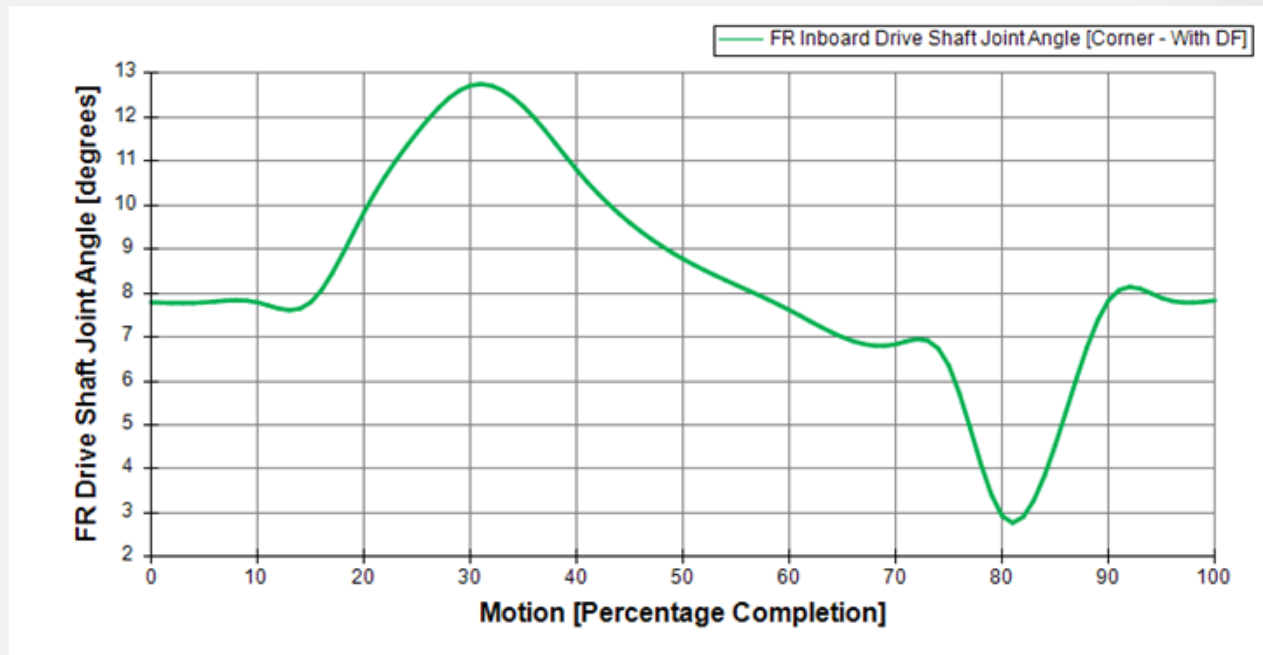


Outboard Drive Shaft Joint Angle – Corner DF



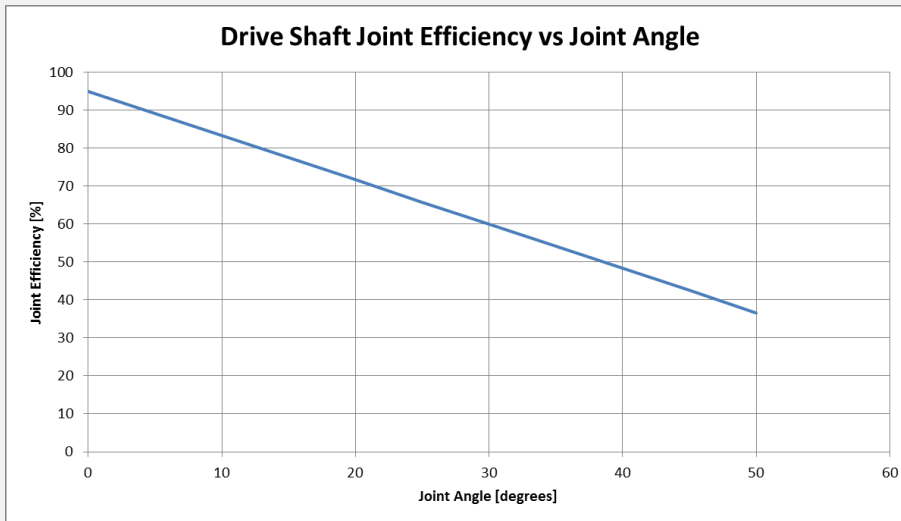
Driveshaft Joint Angles – Comments

- FR Inboard joint angle approaches 13° during the cornering with downforce simulation



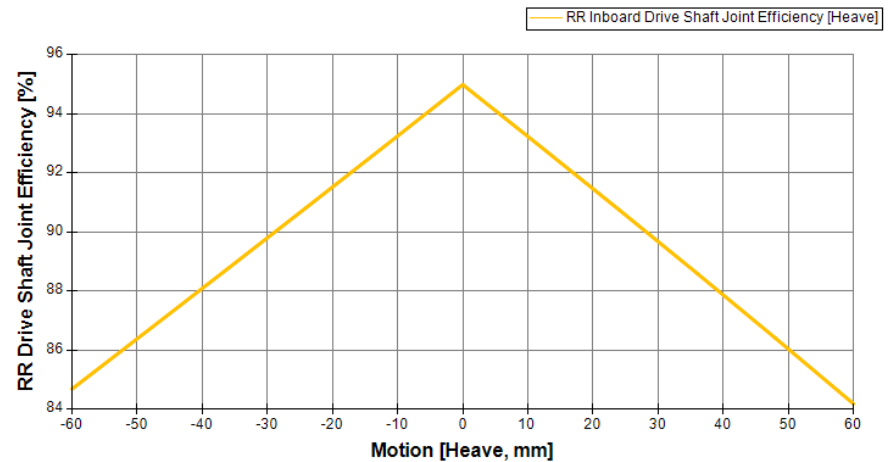
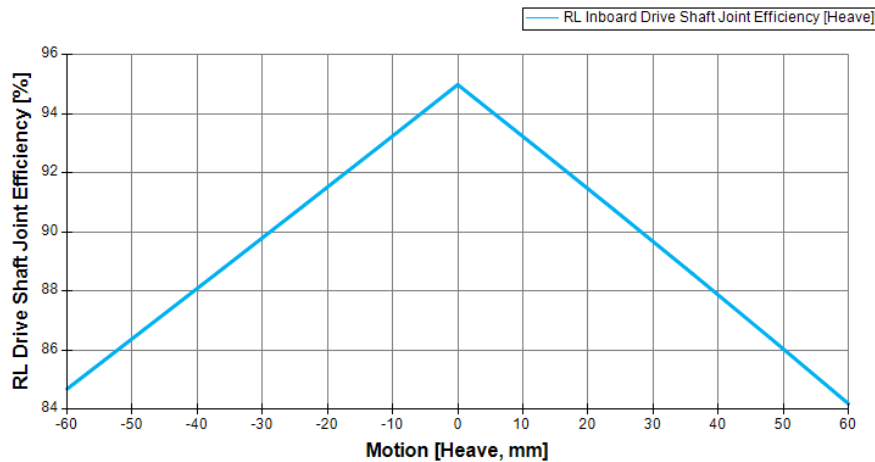
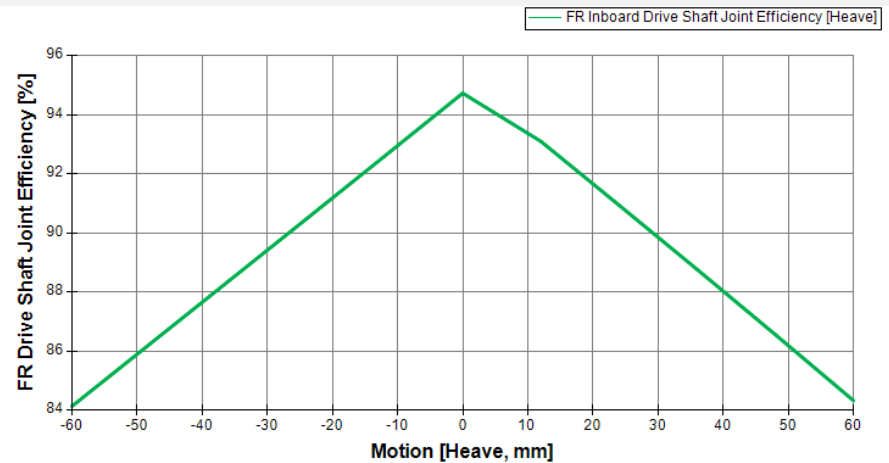
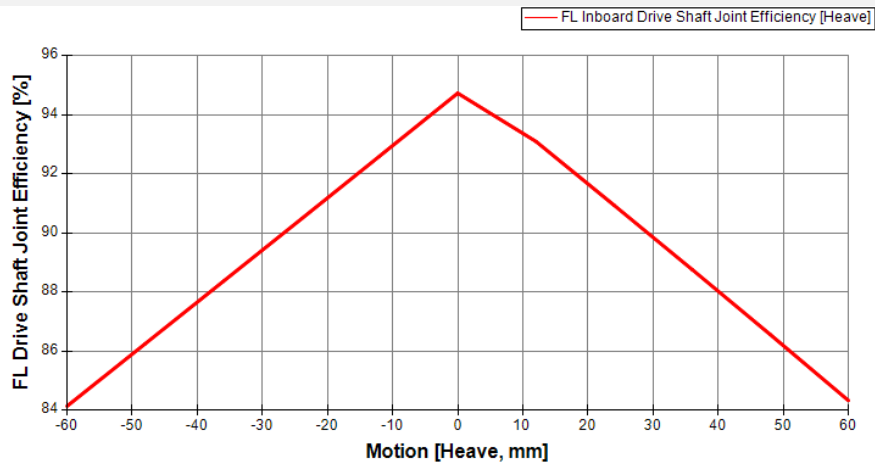
Using Math Channels and Reference Points Together- Drive Shaft Joint Efficiencies

Assuming the drive shaft joints have a certain efficiency curve, we can use the inboard and outboard drive shaft joint angles to calculate the efficiencies of each of the inboard and outboard joints, as well as the efficiency of the system considering both joints simultaneously. Note for the sake of simplicity, we will assume that all driveshaft joints have the same linear efficiency curve, shown below.

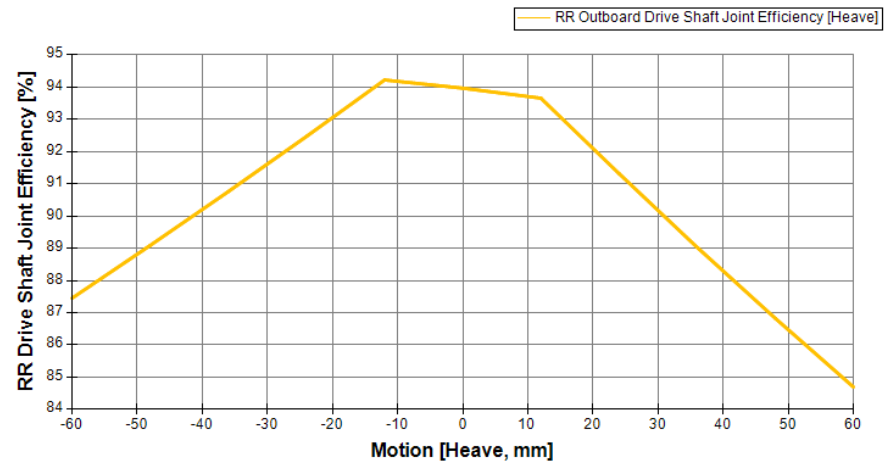
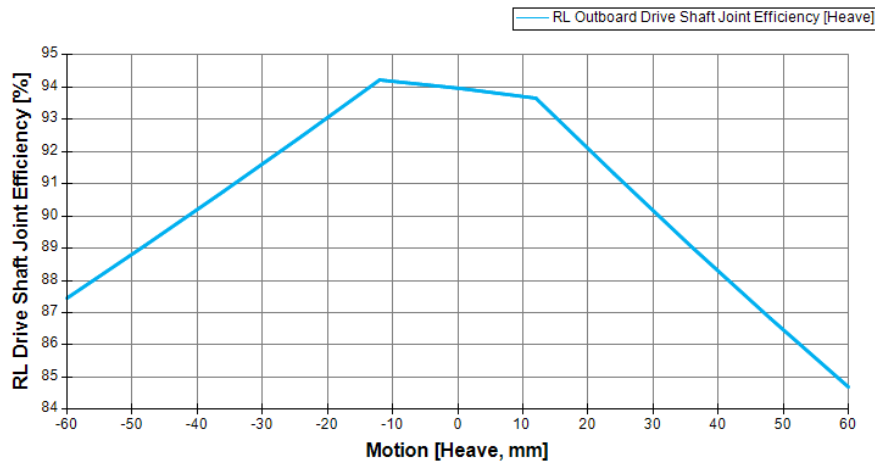
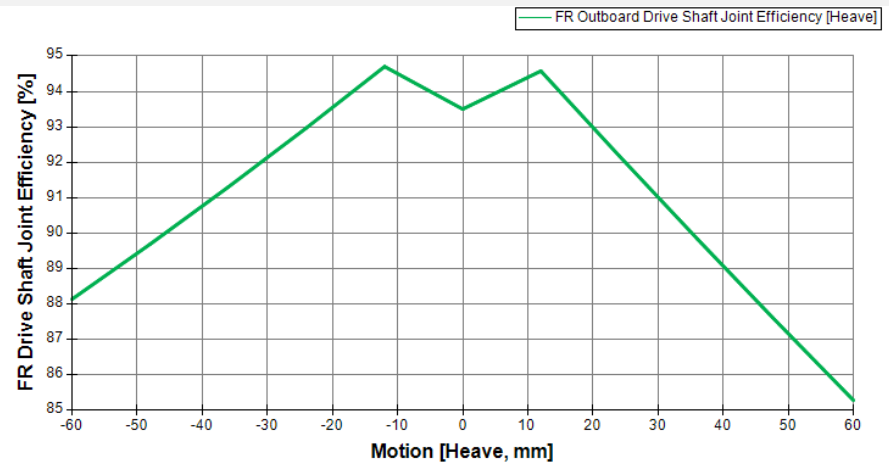
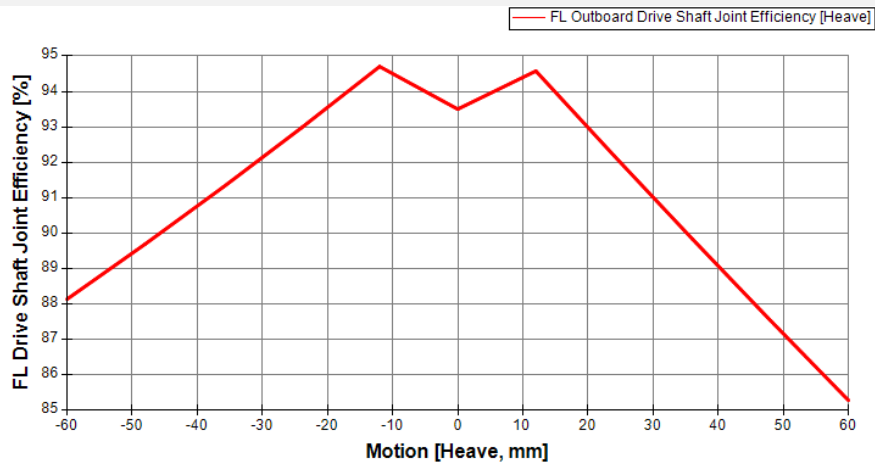


'Front Inboard U Joint Efficiency Coefficient [unitless]*abs('FL Inboard Drive Shaft Joint Angle [degree]')+Front Inboard U Joint Efficiency Intercept [percent]'

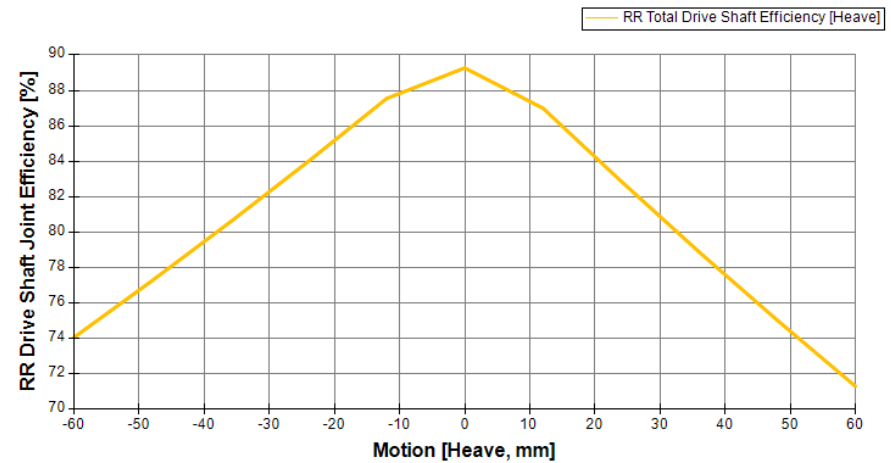
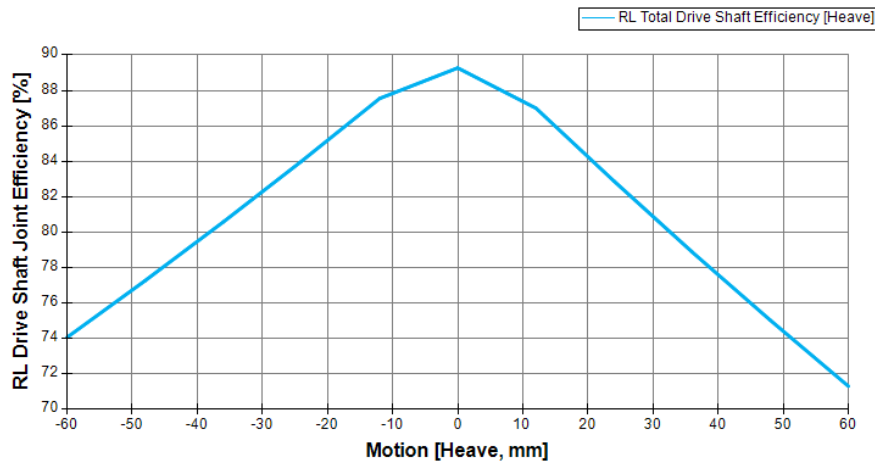
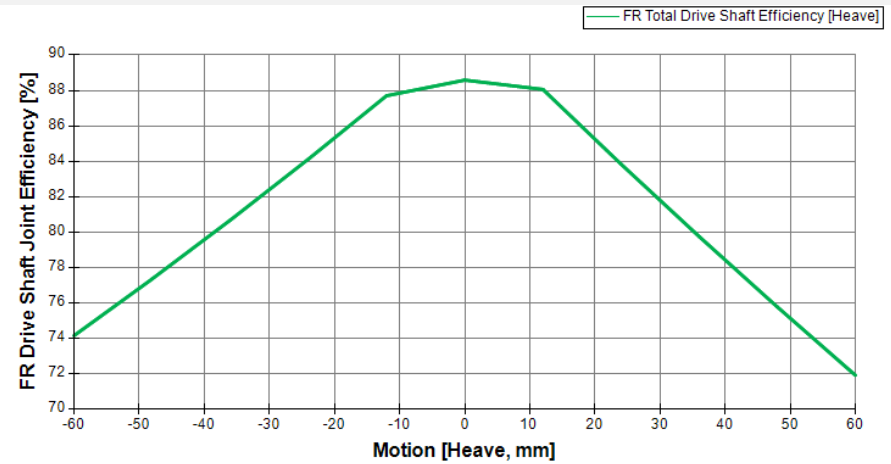
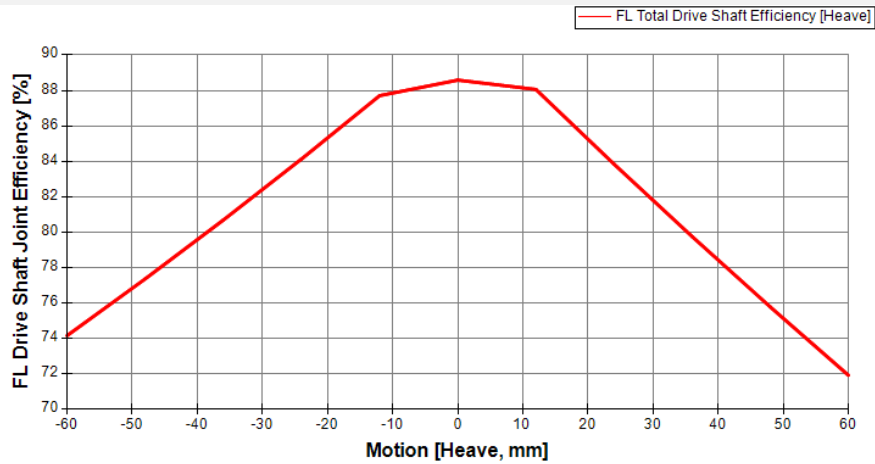
Inboard Drive Shaft Joint Efficiency – Heave



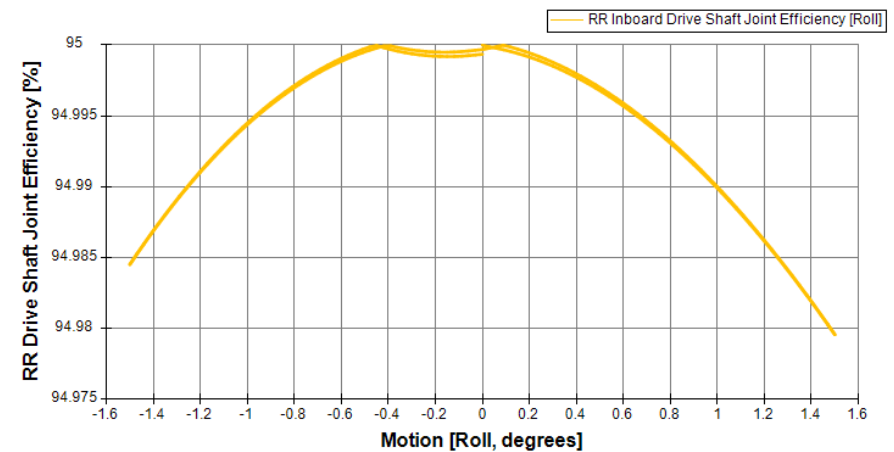
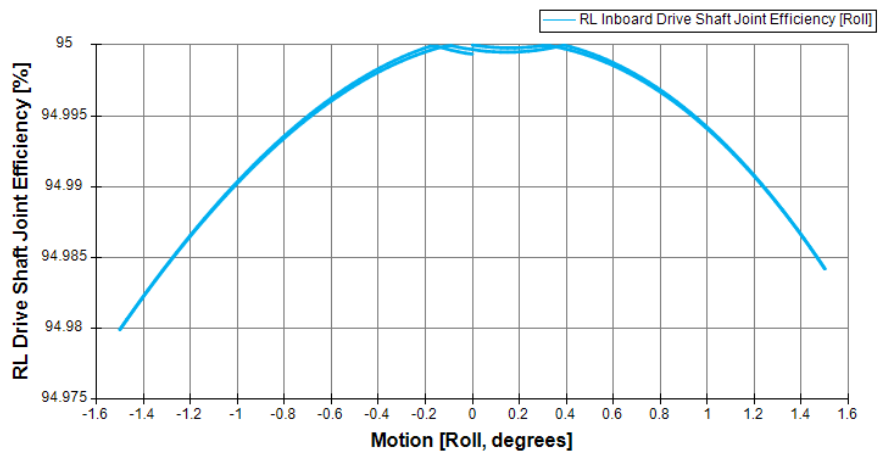
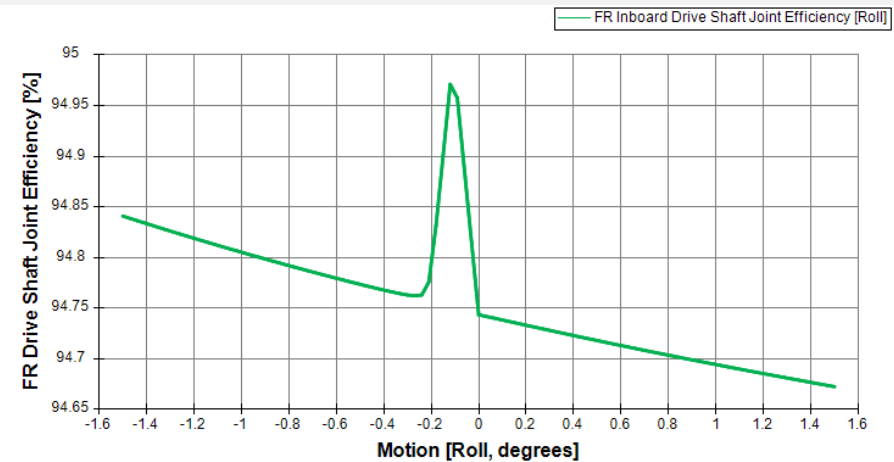
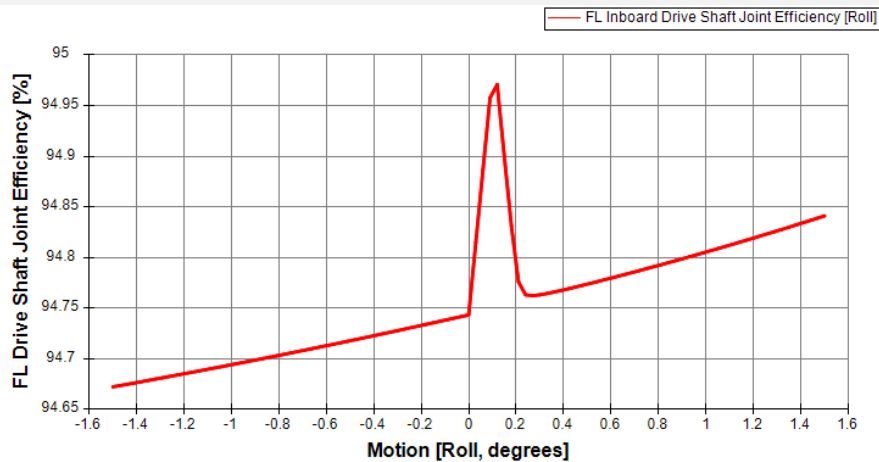
Outboard Drive Shaft Joint Efficiency – Heave



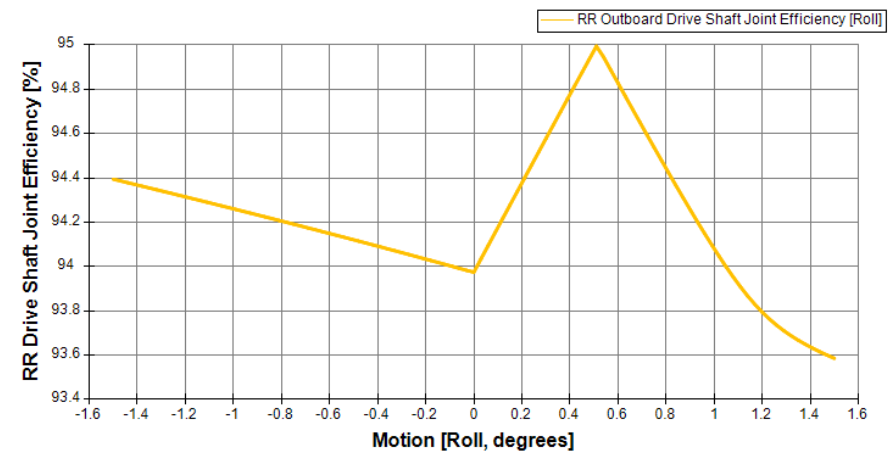
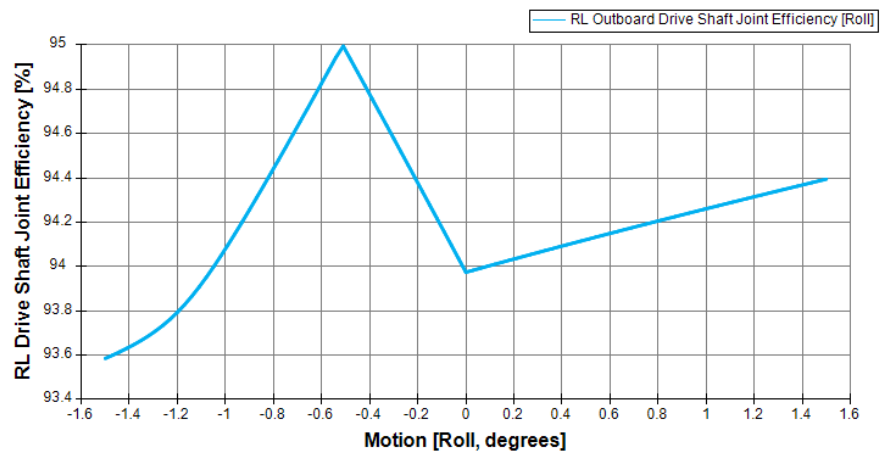
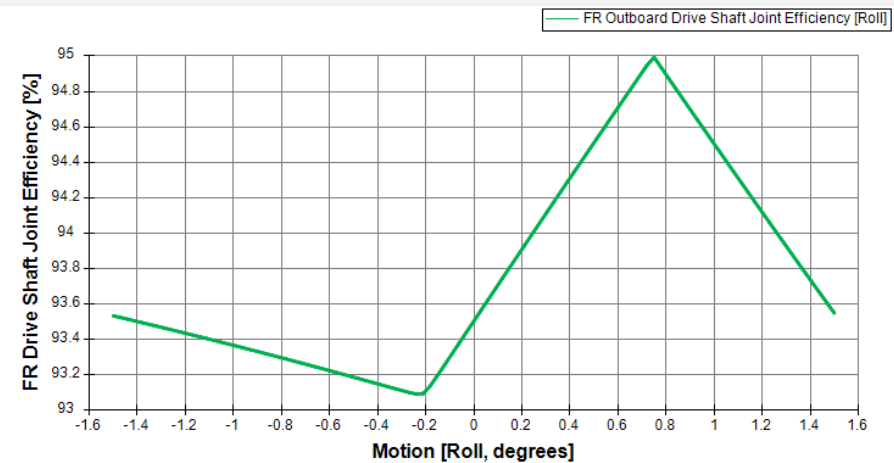
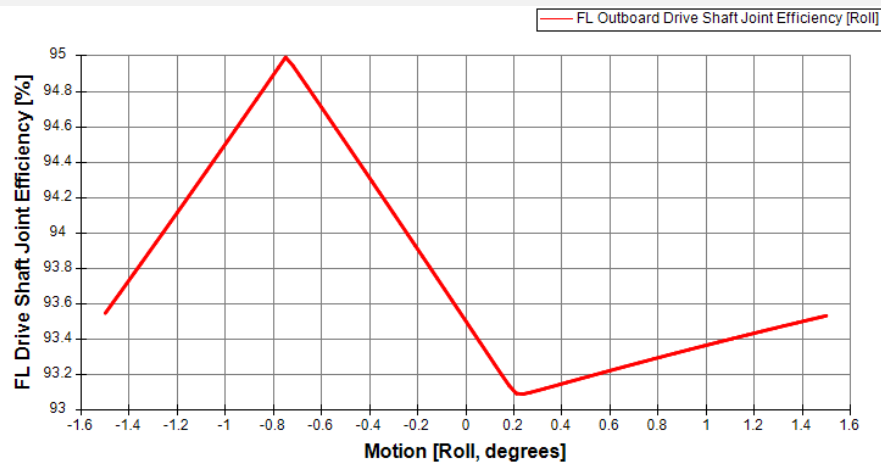
Total Drive Shaft Joint Efficiency – Heave



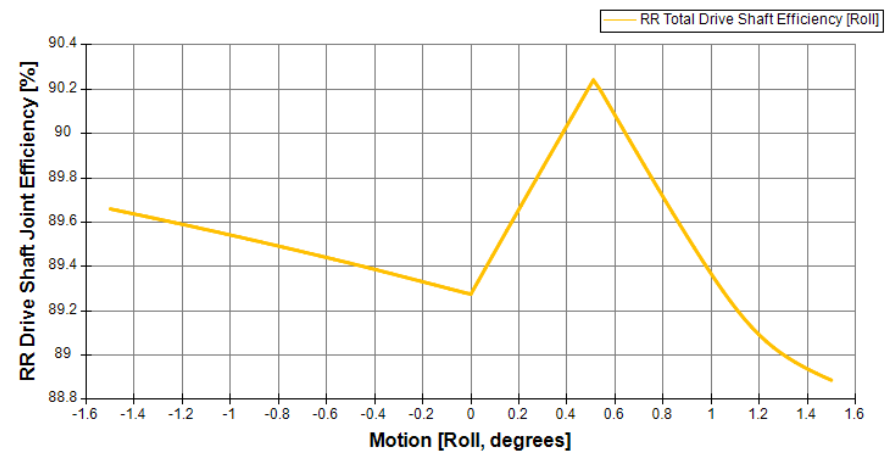
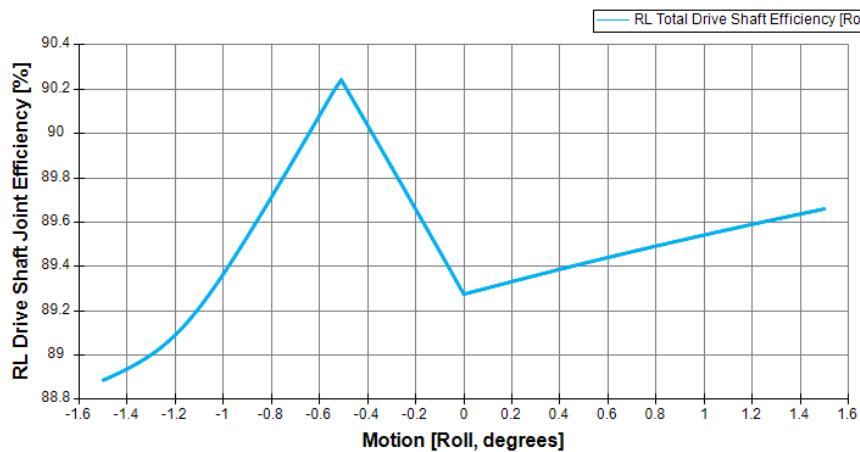
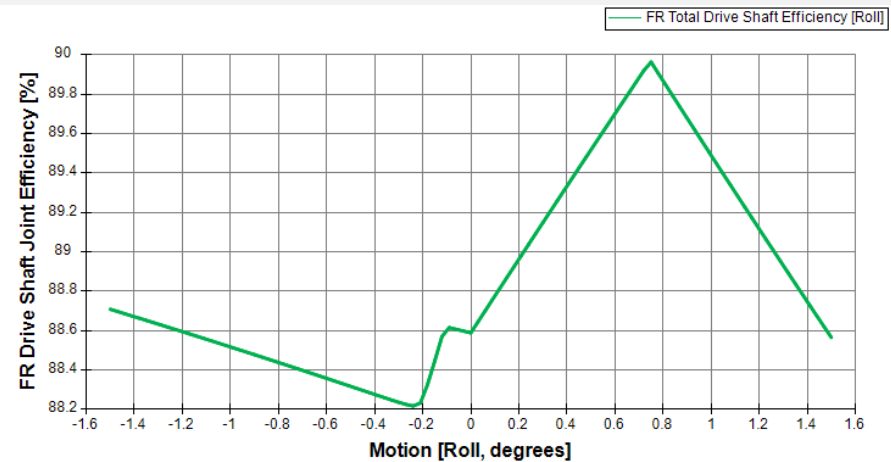
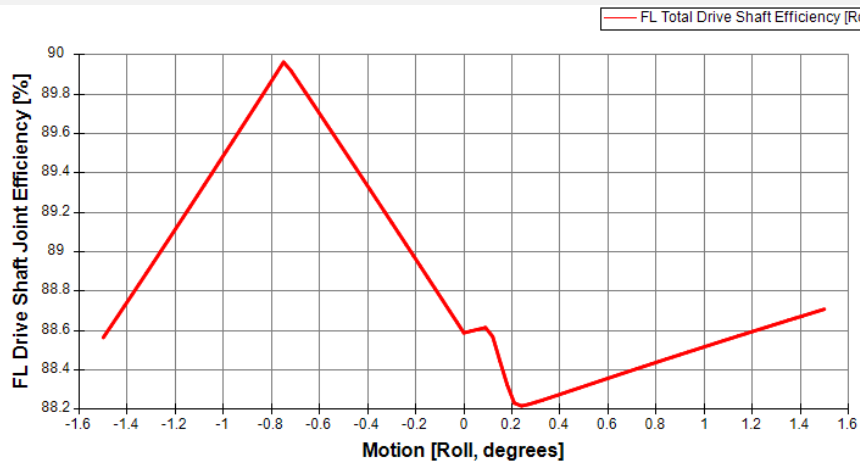
Inboard Drive Shaft Joint Efficiency – Roll



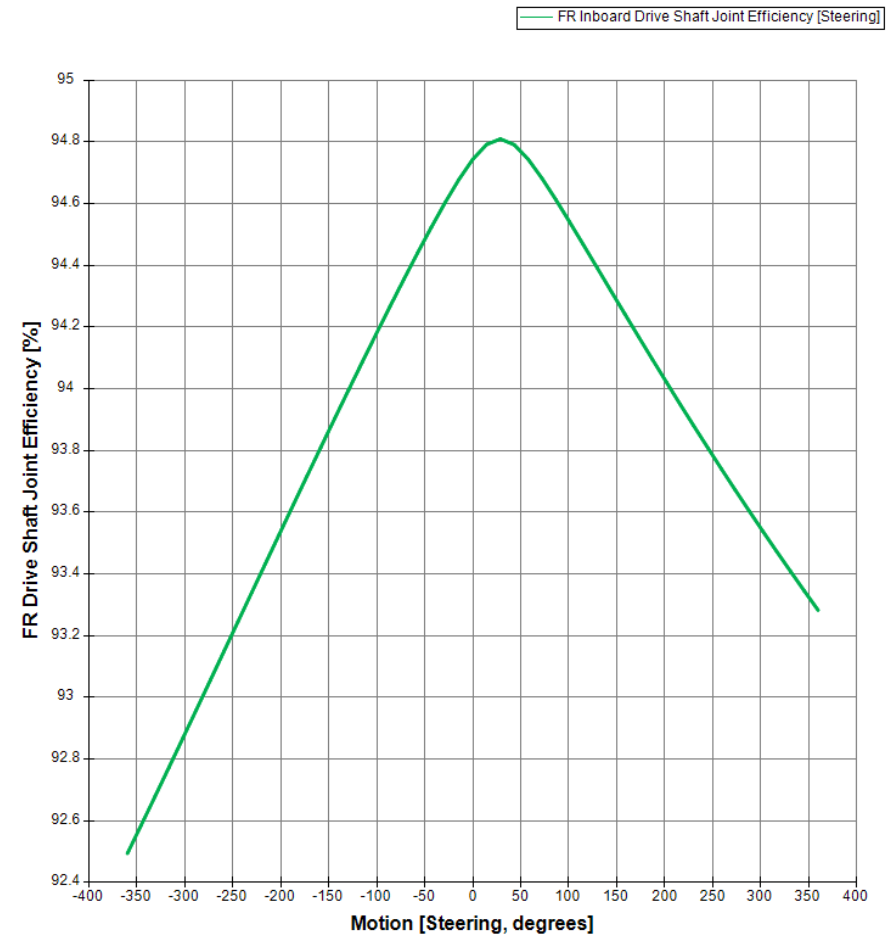
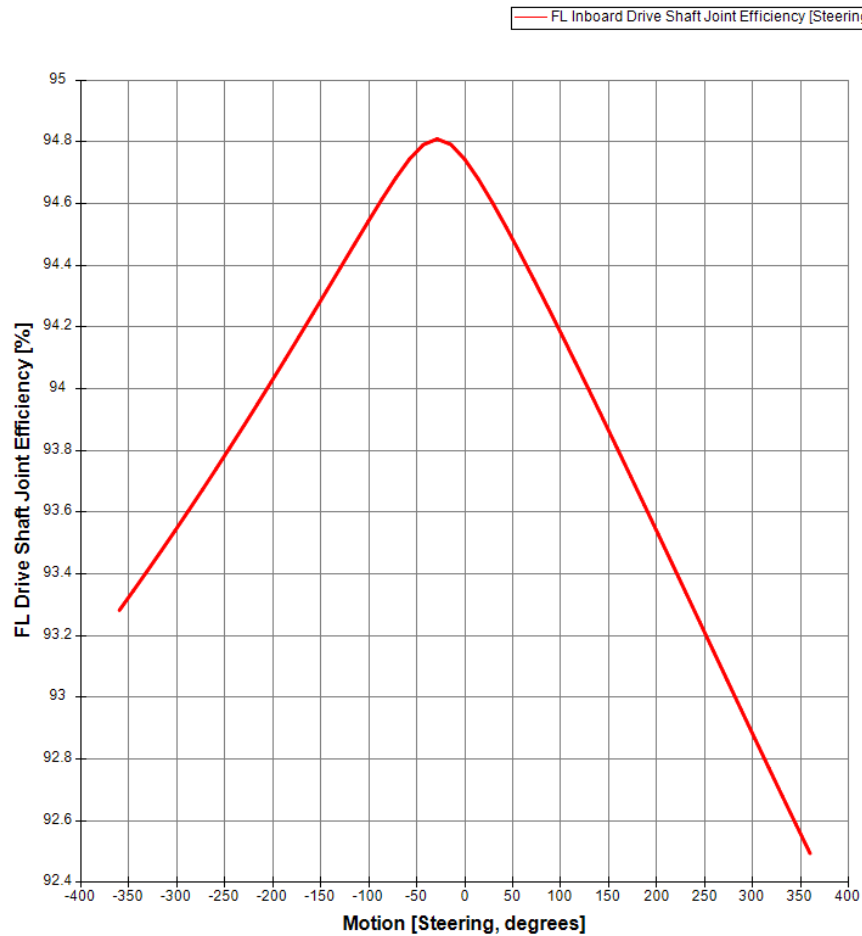
Outboard Drive Shaft Joint Efficiency – Roll



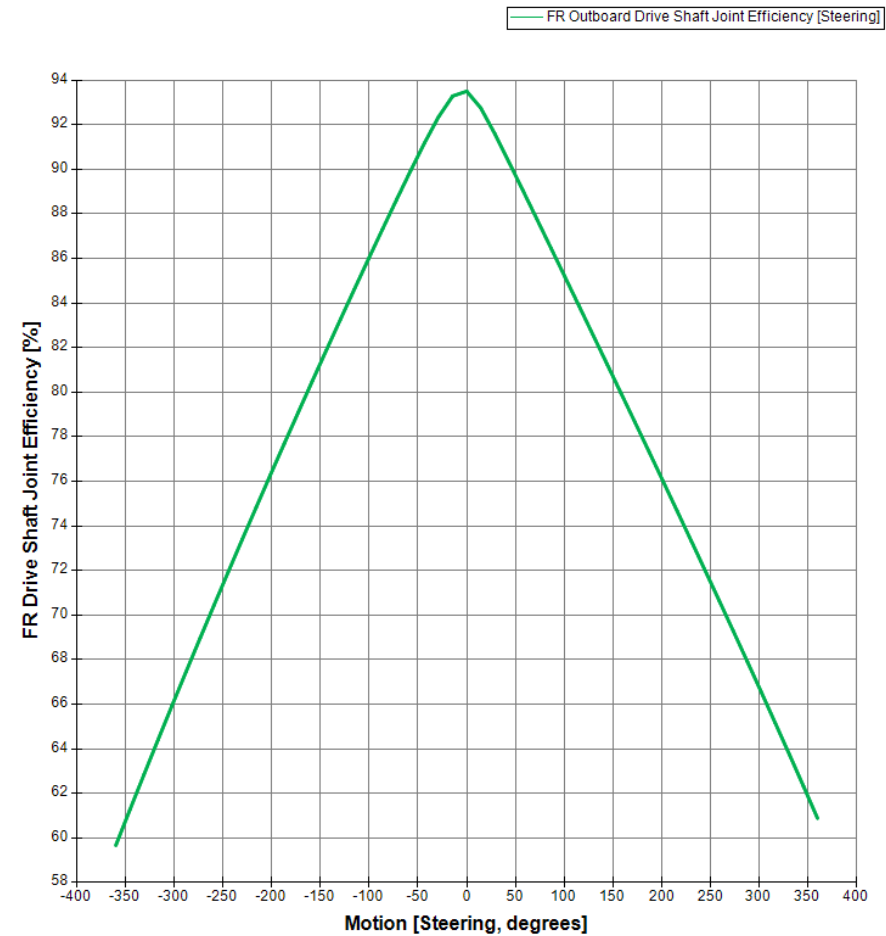
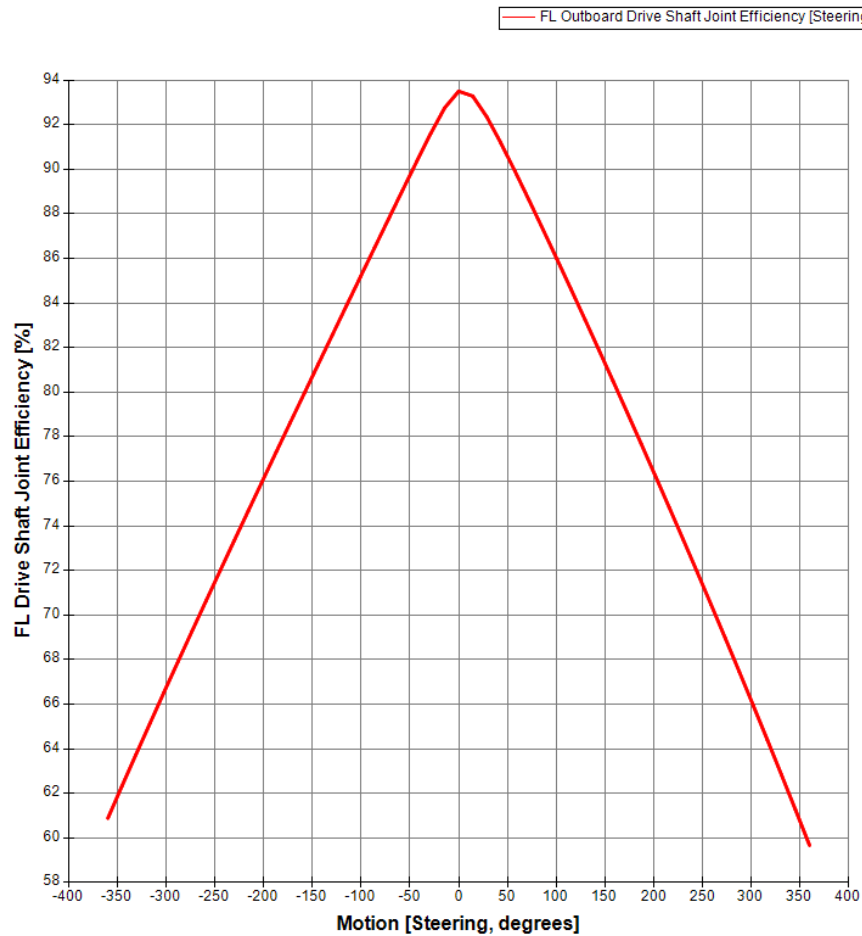
Total Drive Shaft Joint Efficiency – Roll



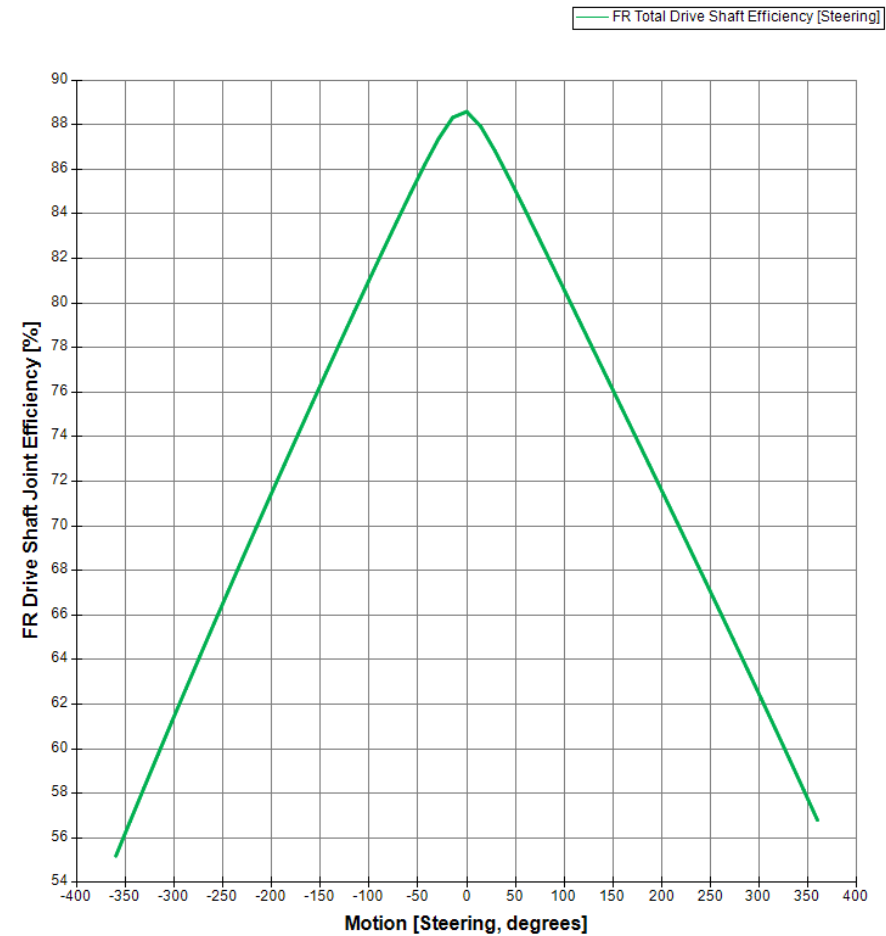
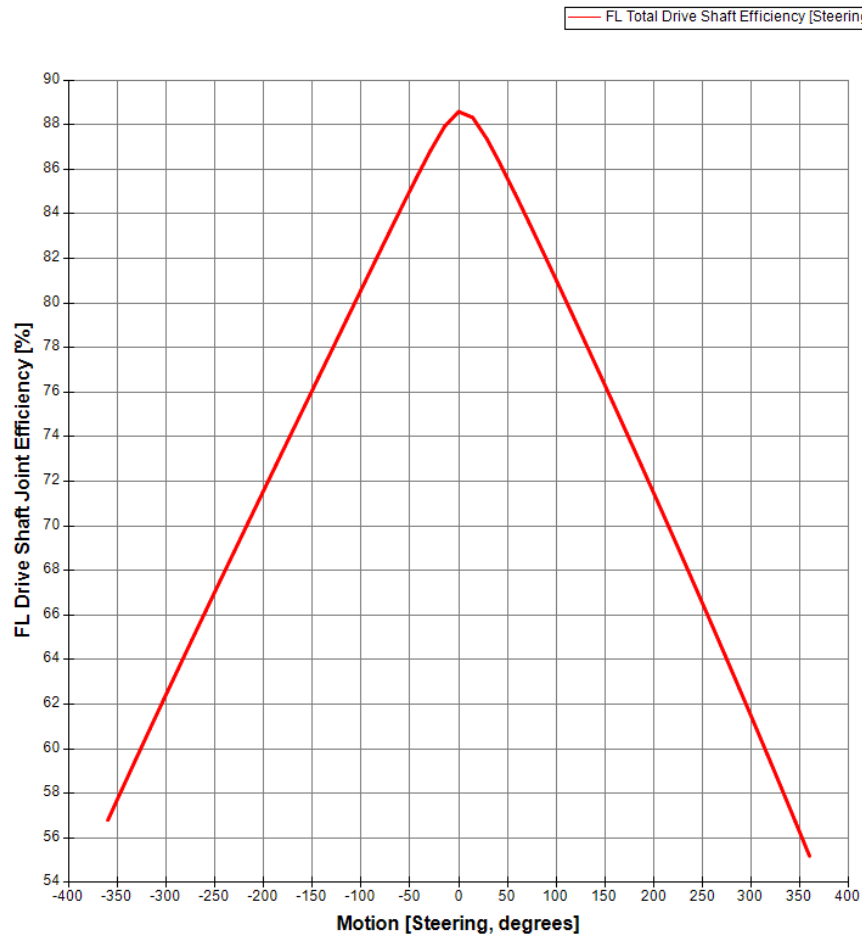
Inboard Drive Shaft Joint Efficiency – Steering



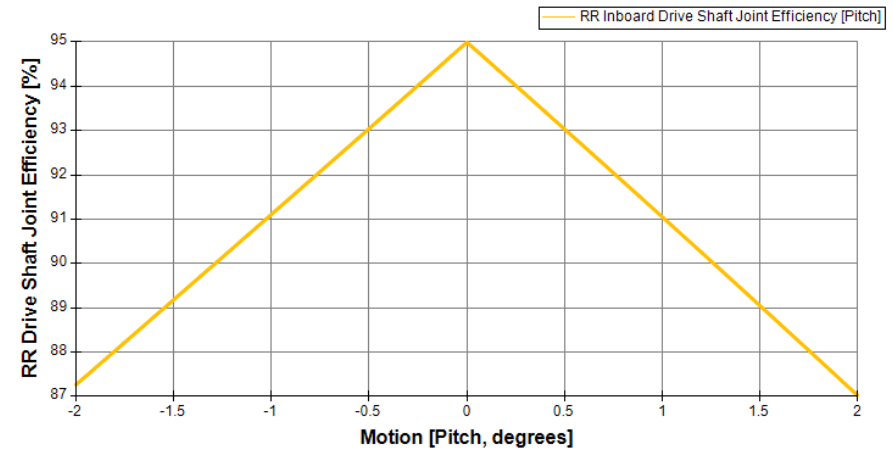
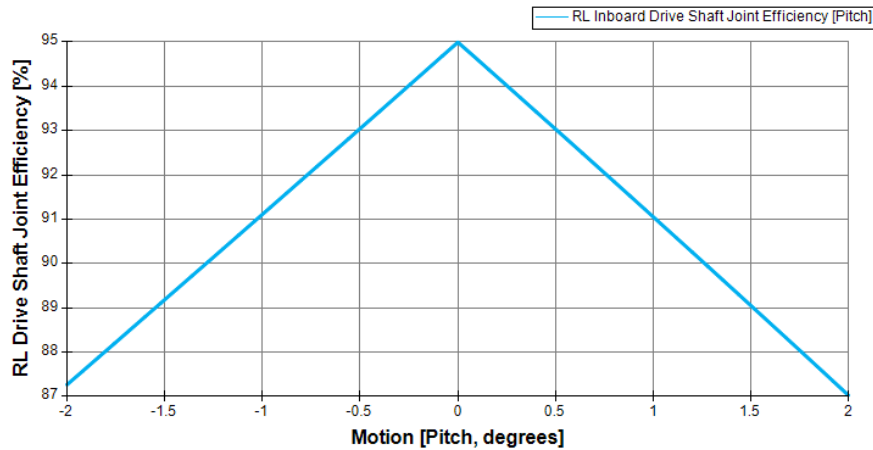
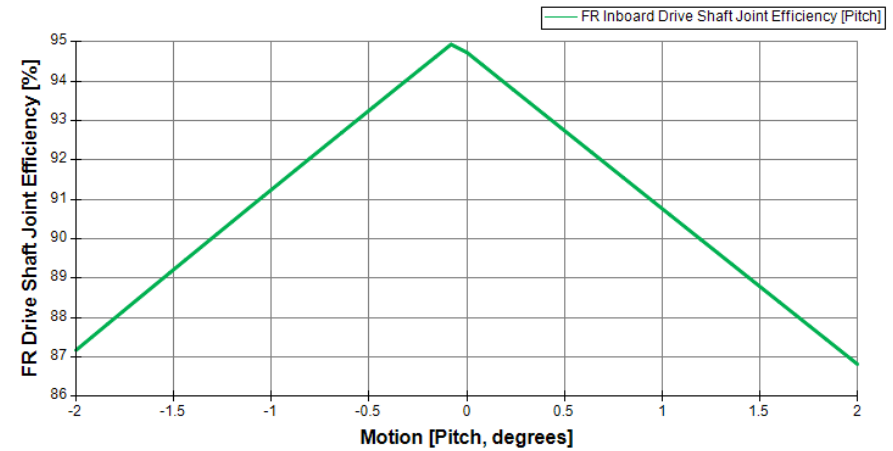
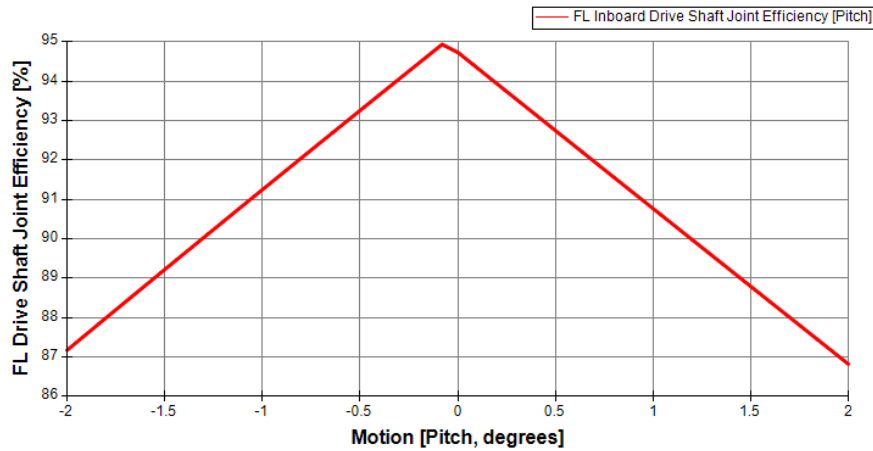
Outboard Drive Shaft Joint Efficiency – Steering



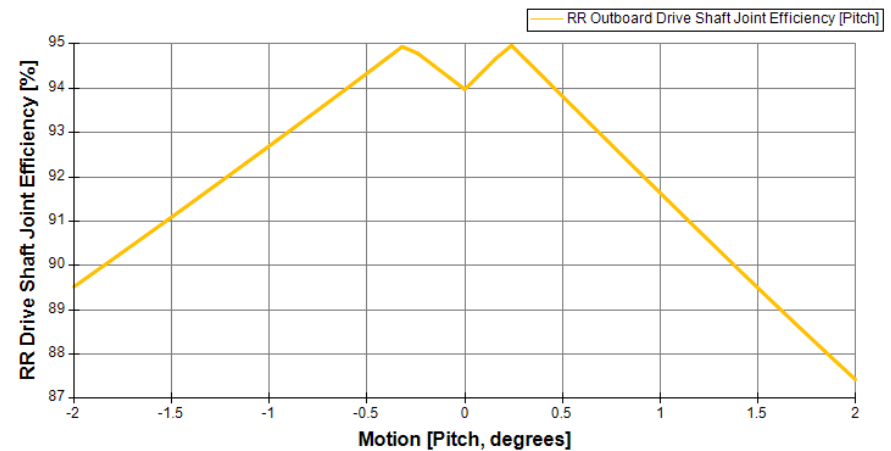
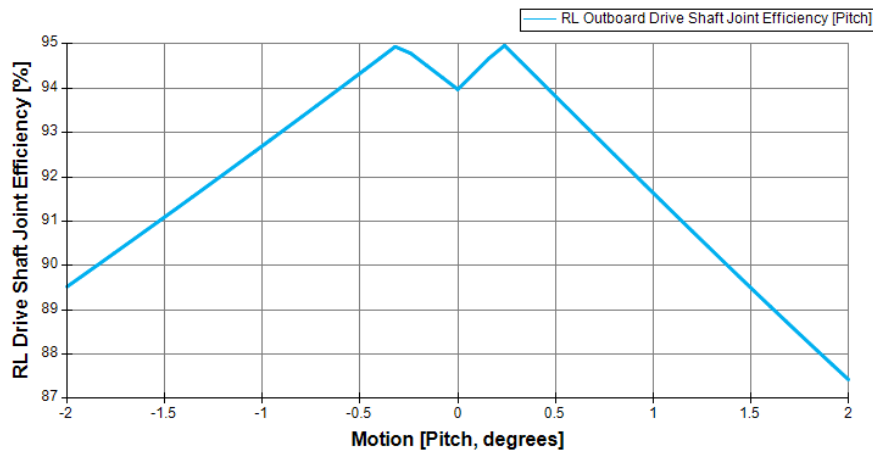
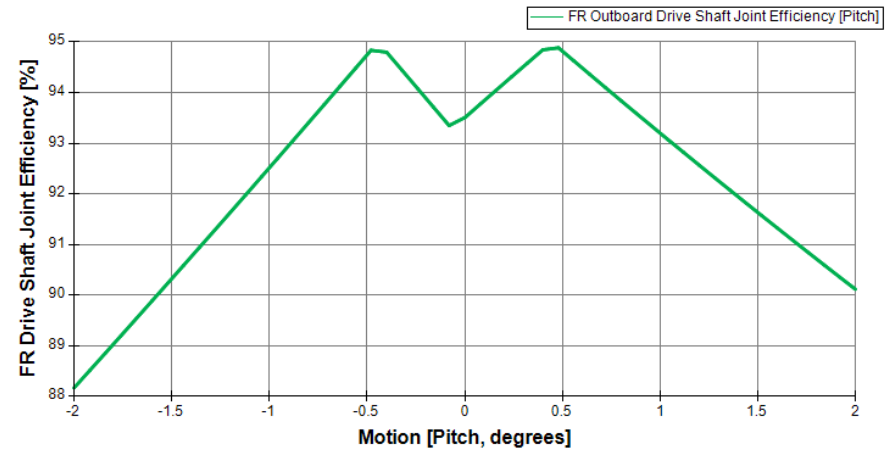
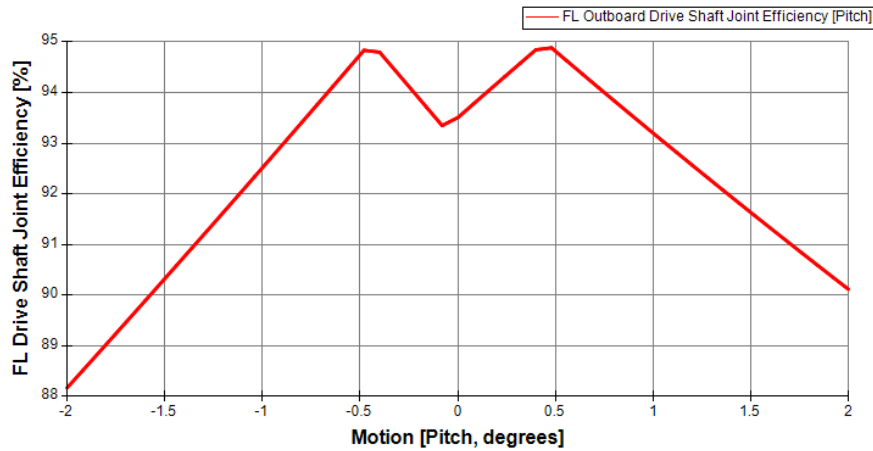
Total Drive Shaft Joint Efficiency – Steering



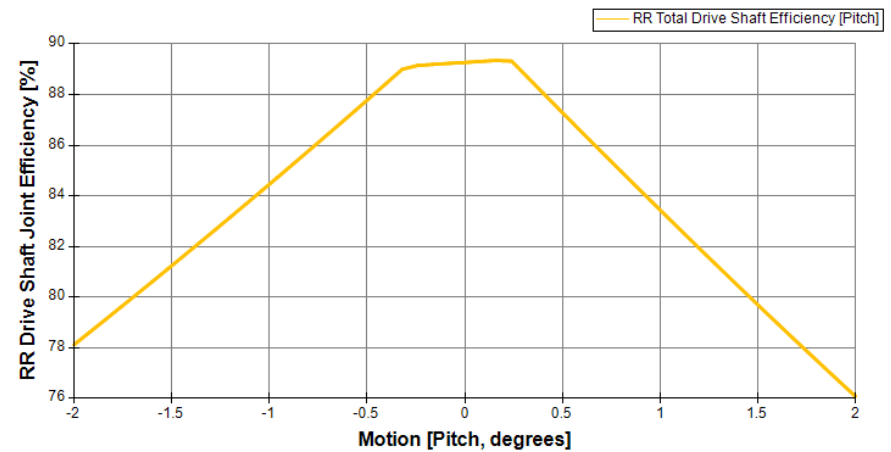
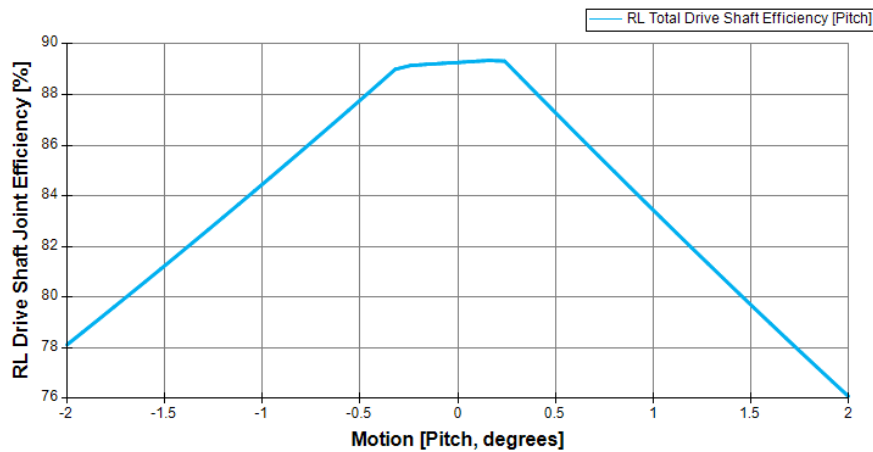
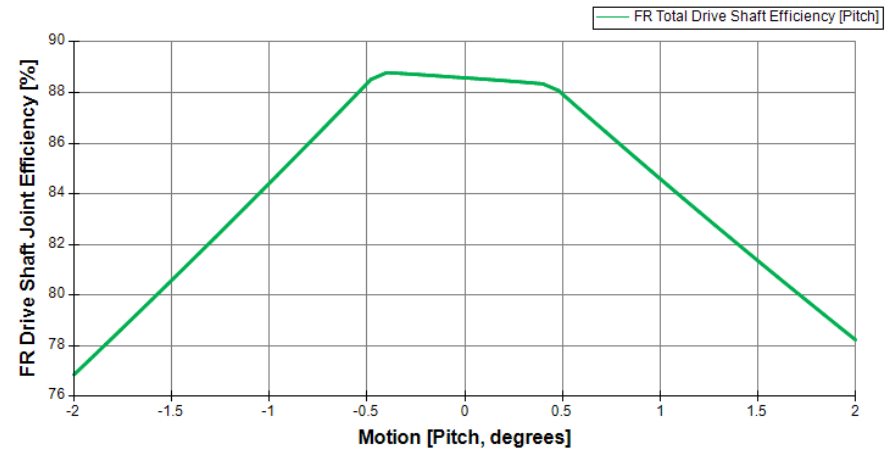
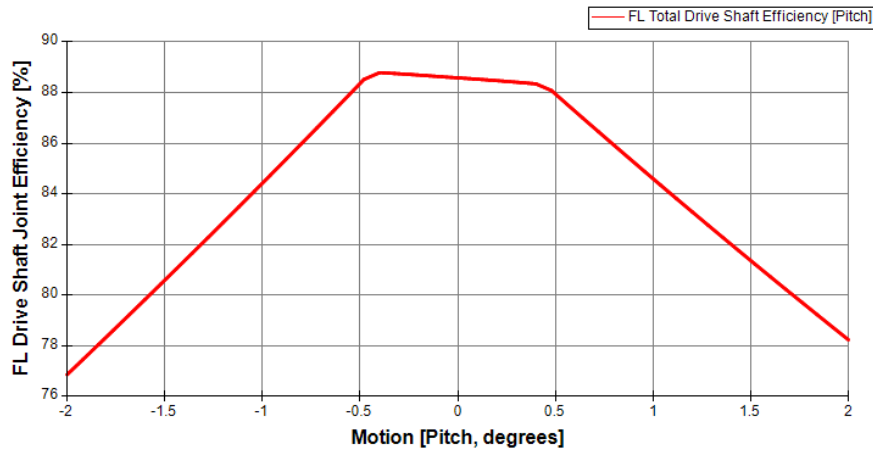
Inboard Drive Shaft Joint Efficiency - Pitch



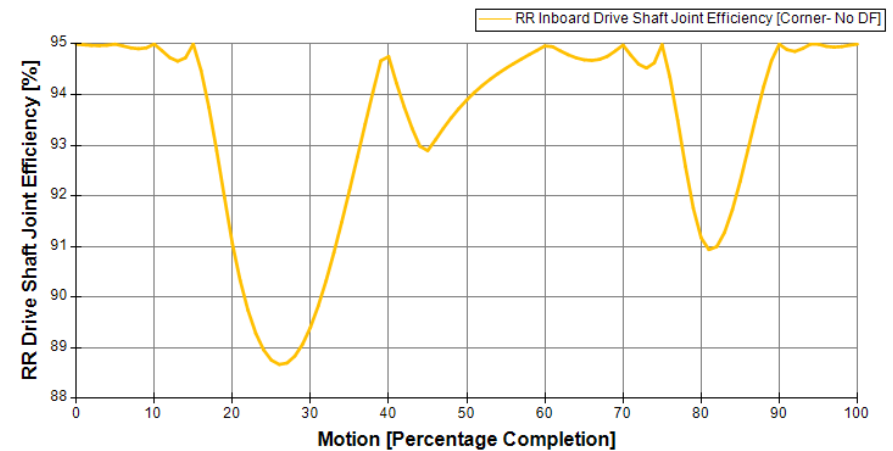
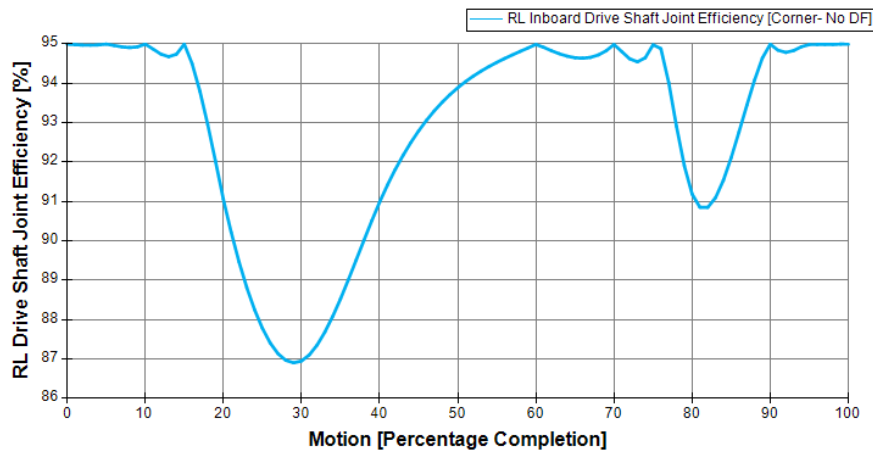
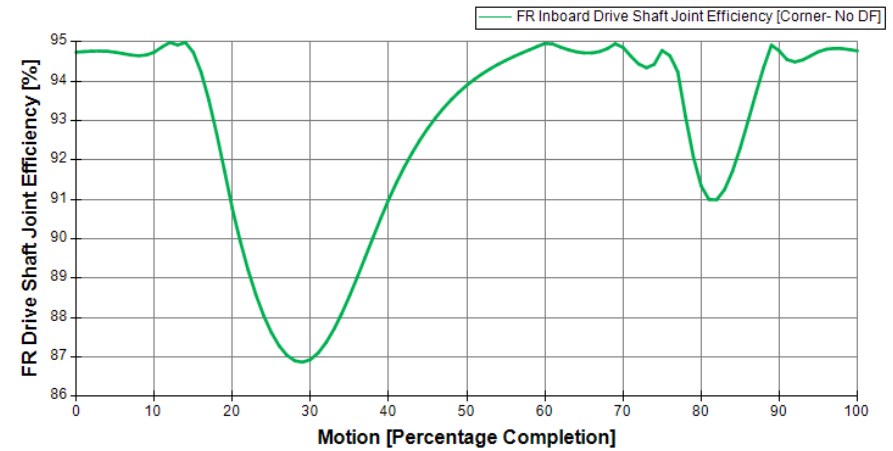
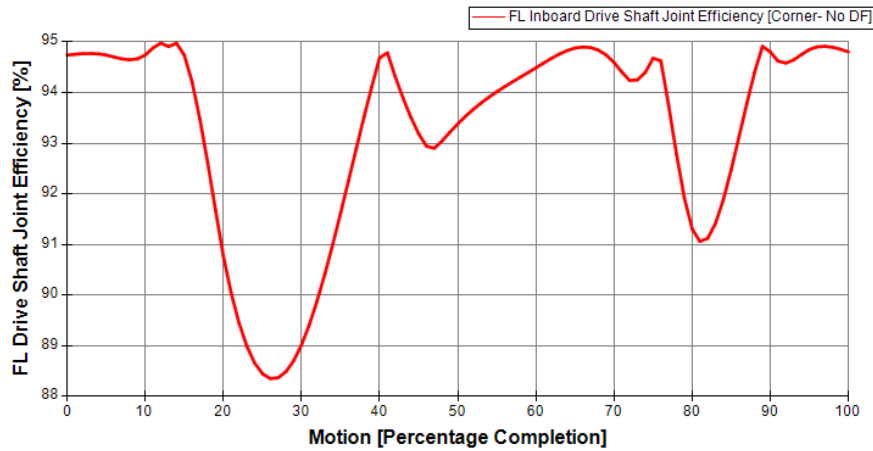
Outboard Drive Shaft Joint Efficiency - Pitch



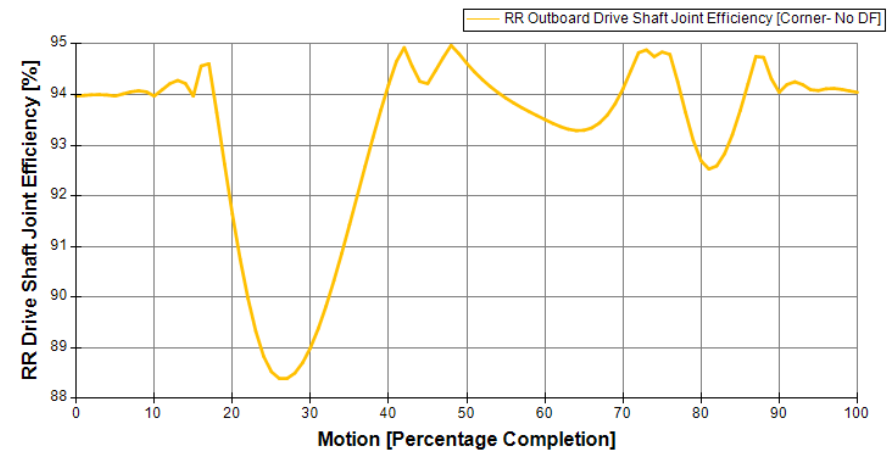
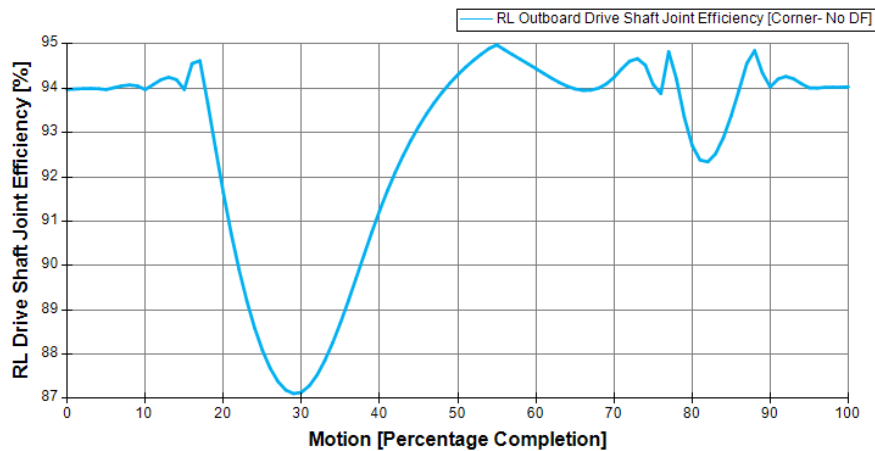
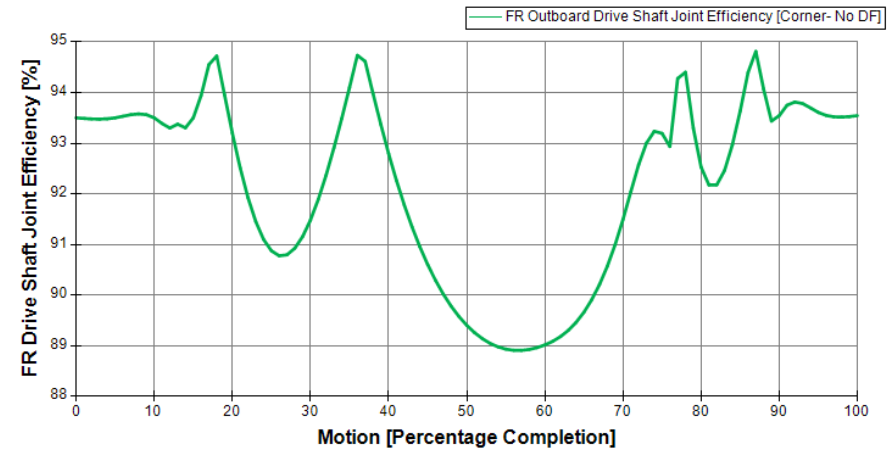
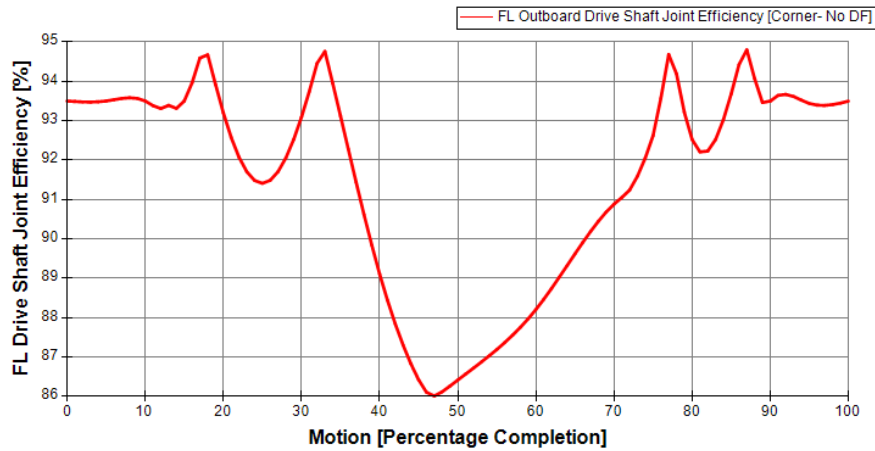
Total Drive Shaft Joint Efficiency - Pitch



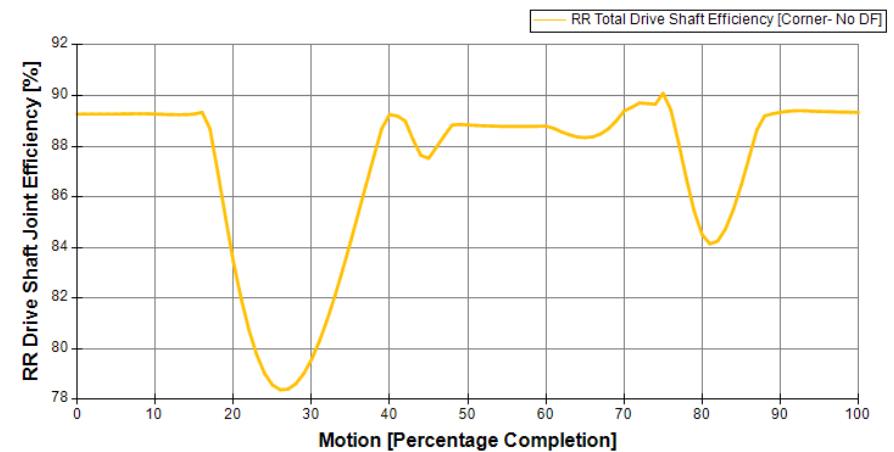
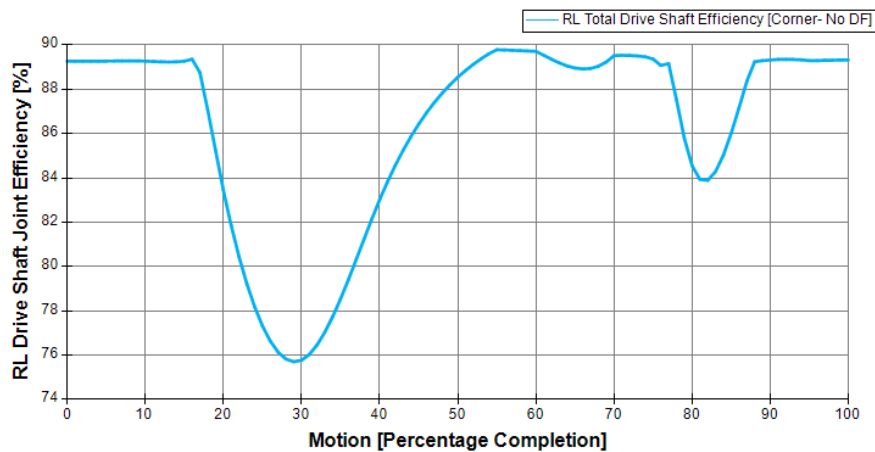
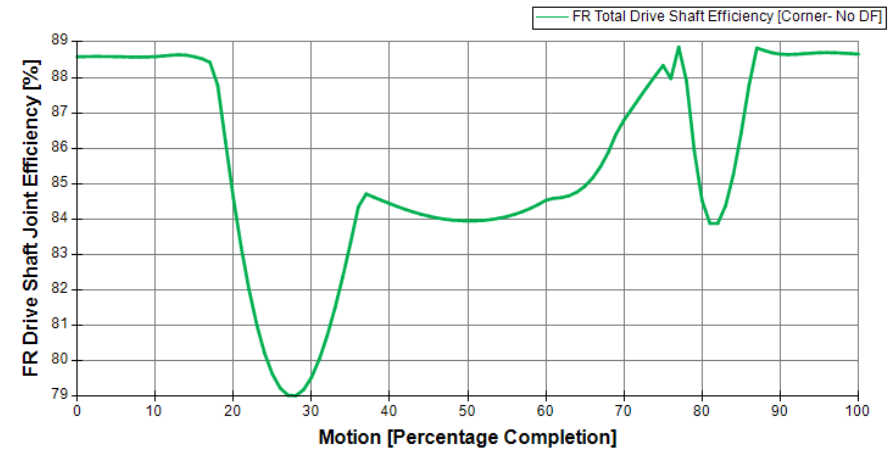
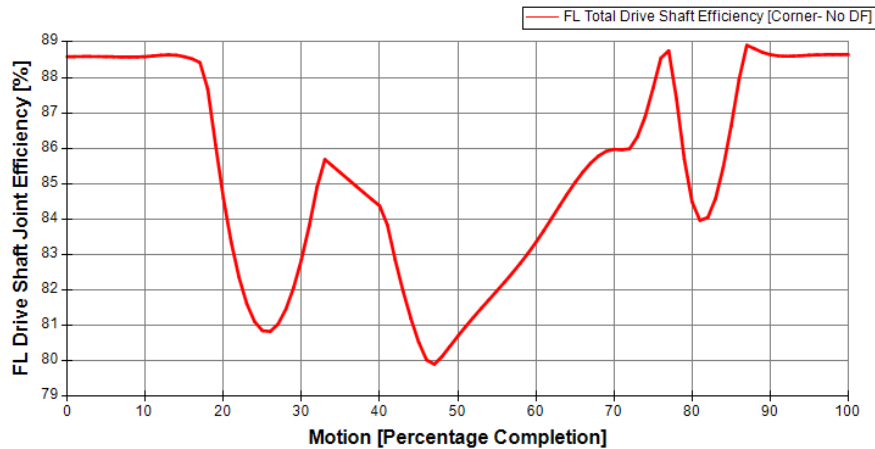
Inboard Drive Shaft Joint Efficiency – Corner No DF



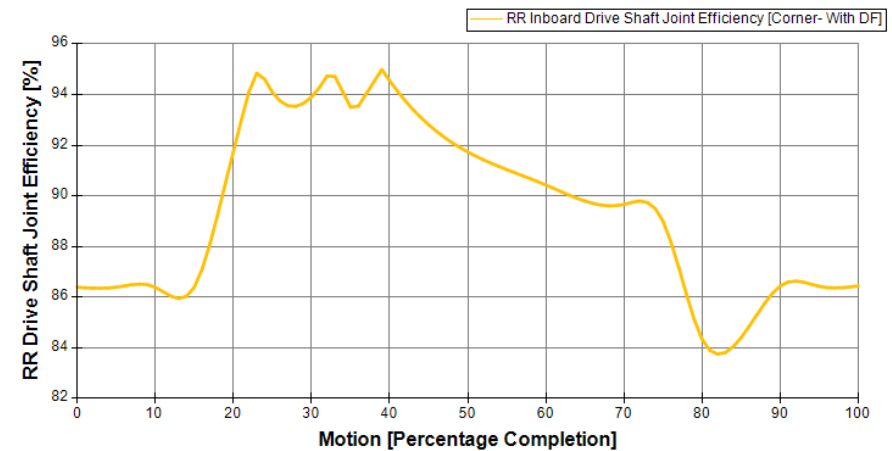
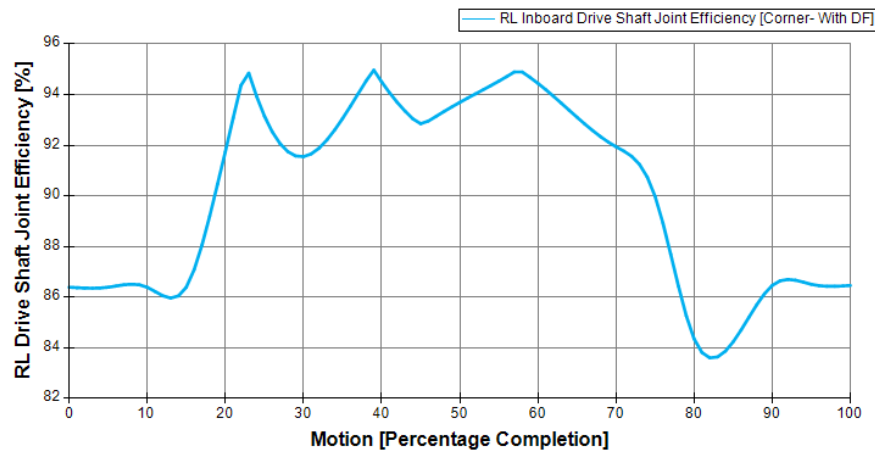
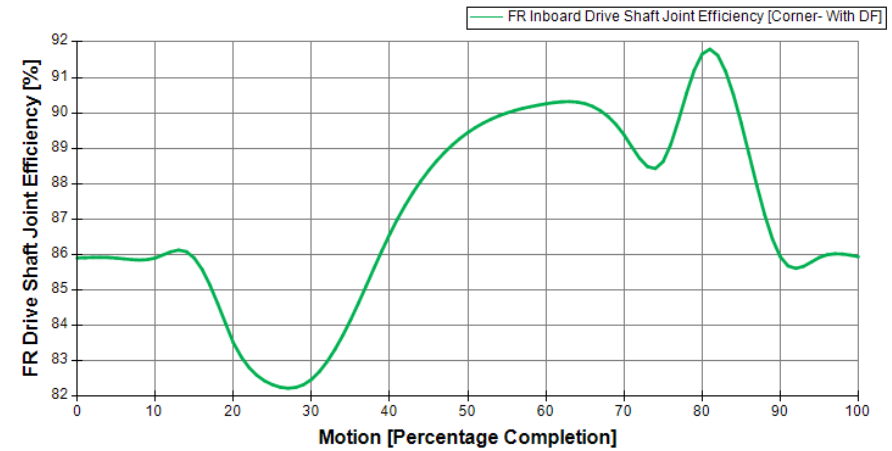
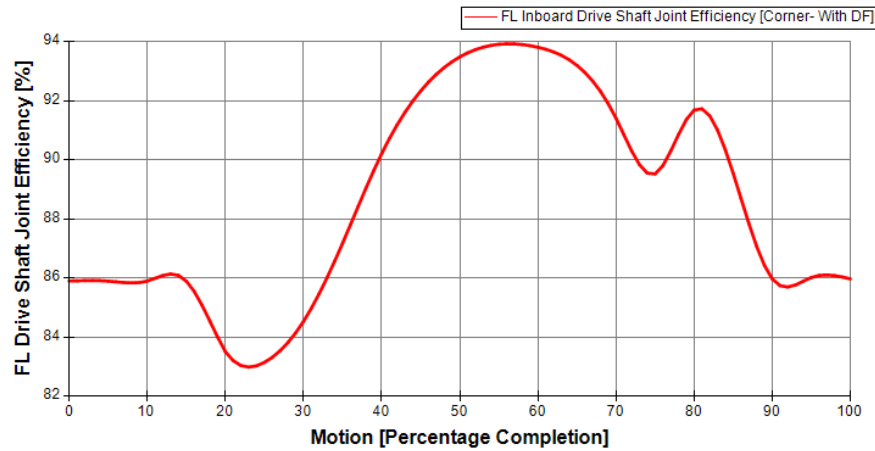
Outboard Drive Shaft Joint Efficiency – Corner No DF



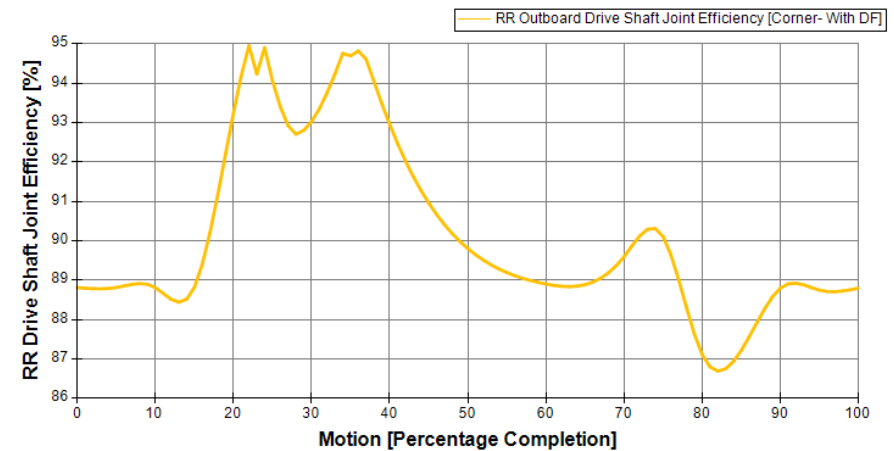
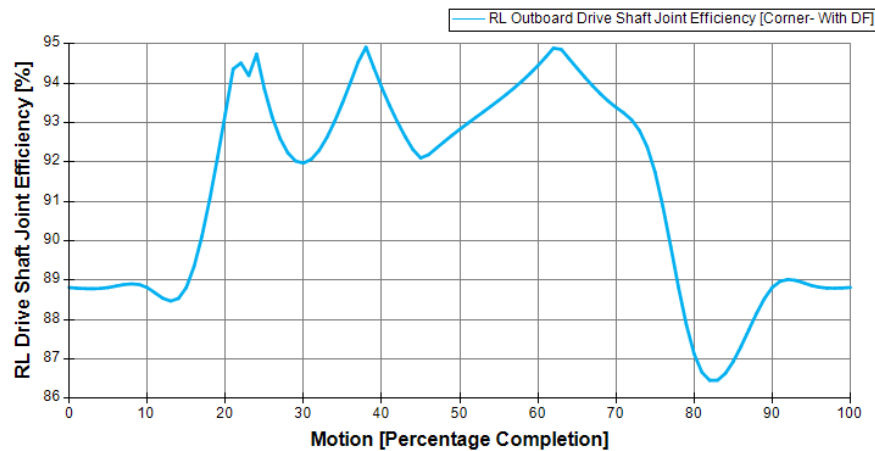
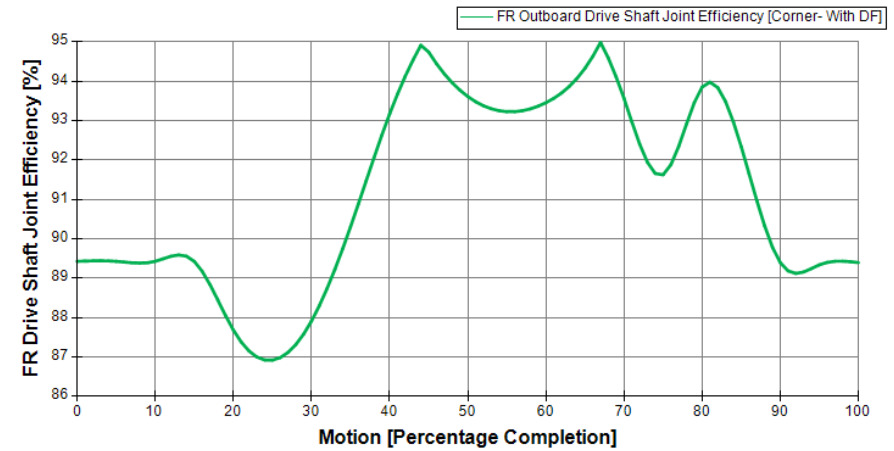
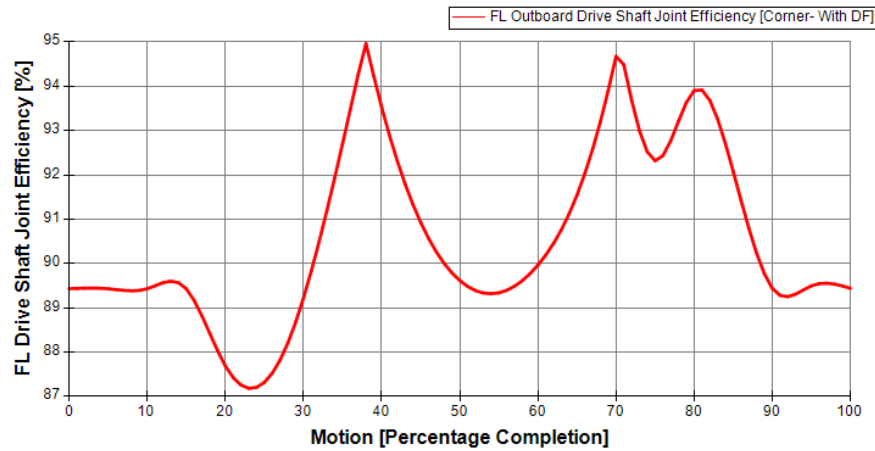
Total Drive Shaft Joint Efficiency – Corner No DF



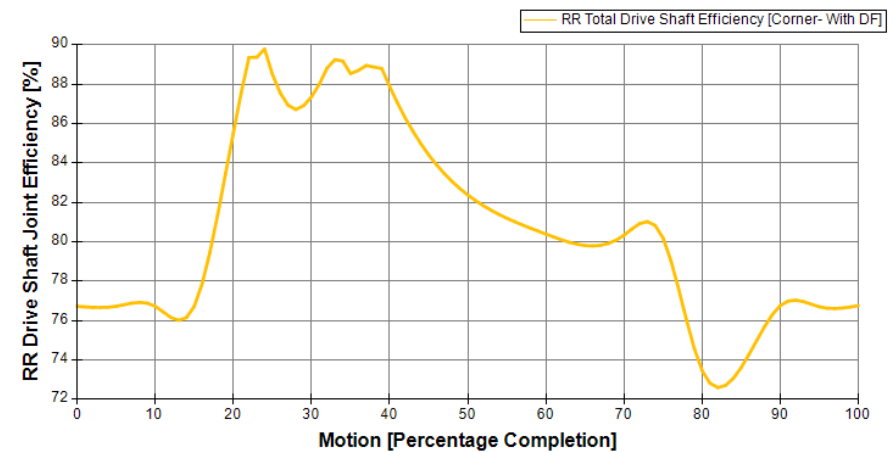
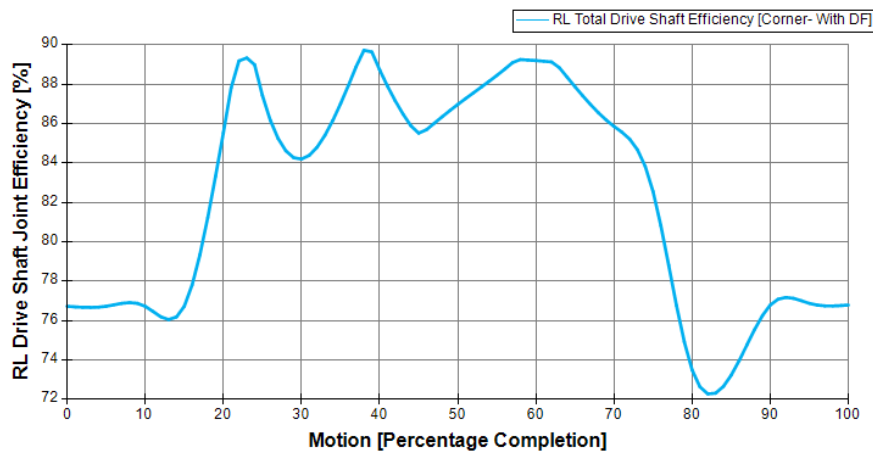
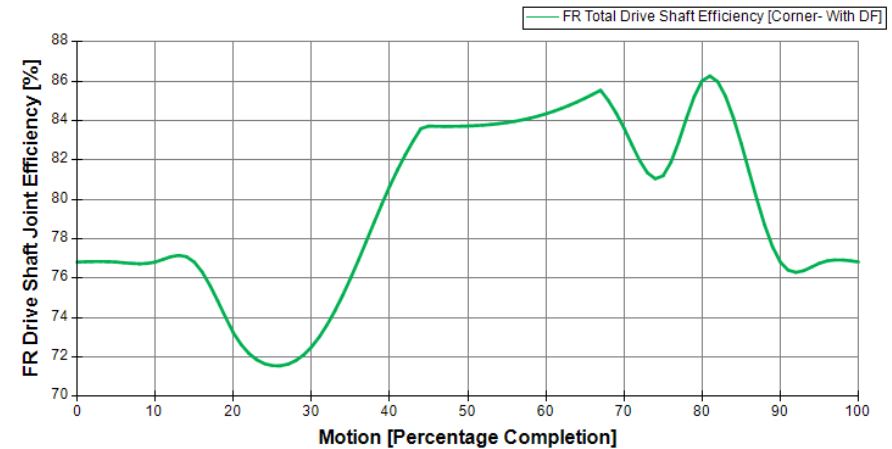
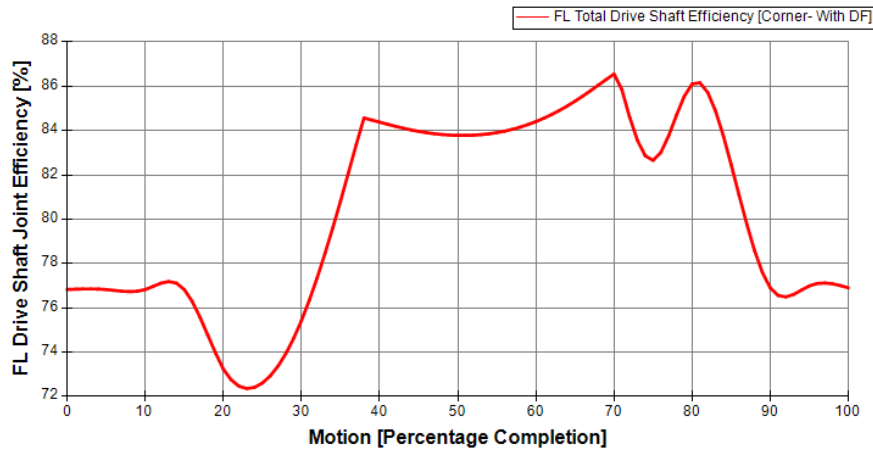
Inboard Drive Shaft Joint Efficiency – Corner DF



Outboard Drive Shaft Joint Efficiency – Corner DF

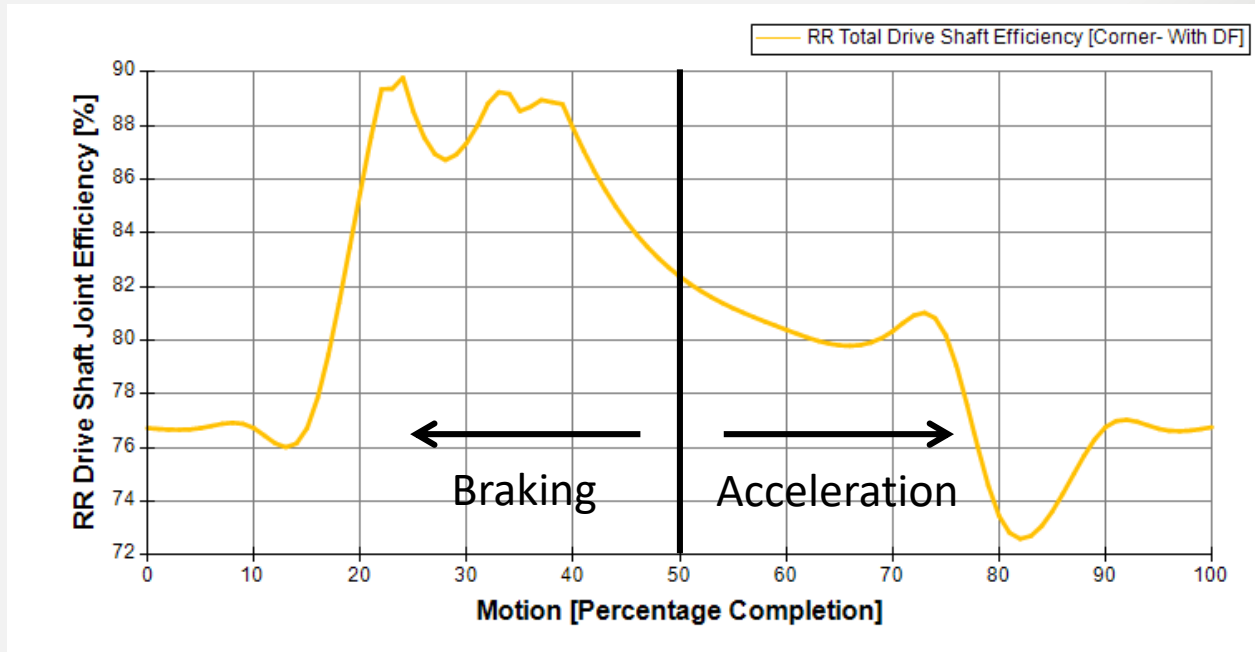


Total Drive Shaft Joint Efficiency – Corner DF



Driveshaft Joint Efficiencies – Comments

- RR Joint Efficiencies are high before the apex, low after. Joint efficiency should be as high as possible under acceleration



Magic Number

$$1^{\text{st}} \text{ Magic Number} = \frac{\text{Front roll stiffness}}{\text{Front roll stiffness} + \text{Rear roll stiffness}} \times 100$$

The creation of math channels allows us to go even further and calculate the variation in the Magic Number by calculating the Anti-Roll Stiffness from springs and anti-roll bars with varying motion ratios.

Front Roll Stiffness Calculation

'AR Stiffness ARB Front [newton metre/degree]' + 'AR Stiffness Spring Front [newton metre/degree]'

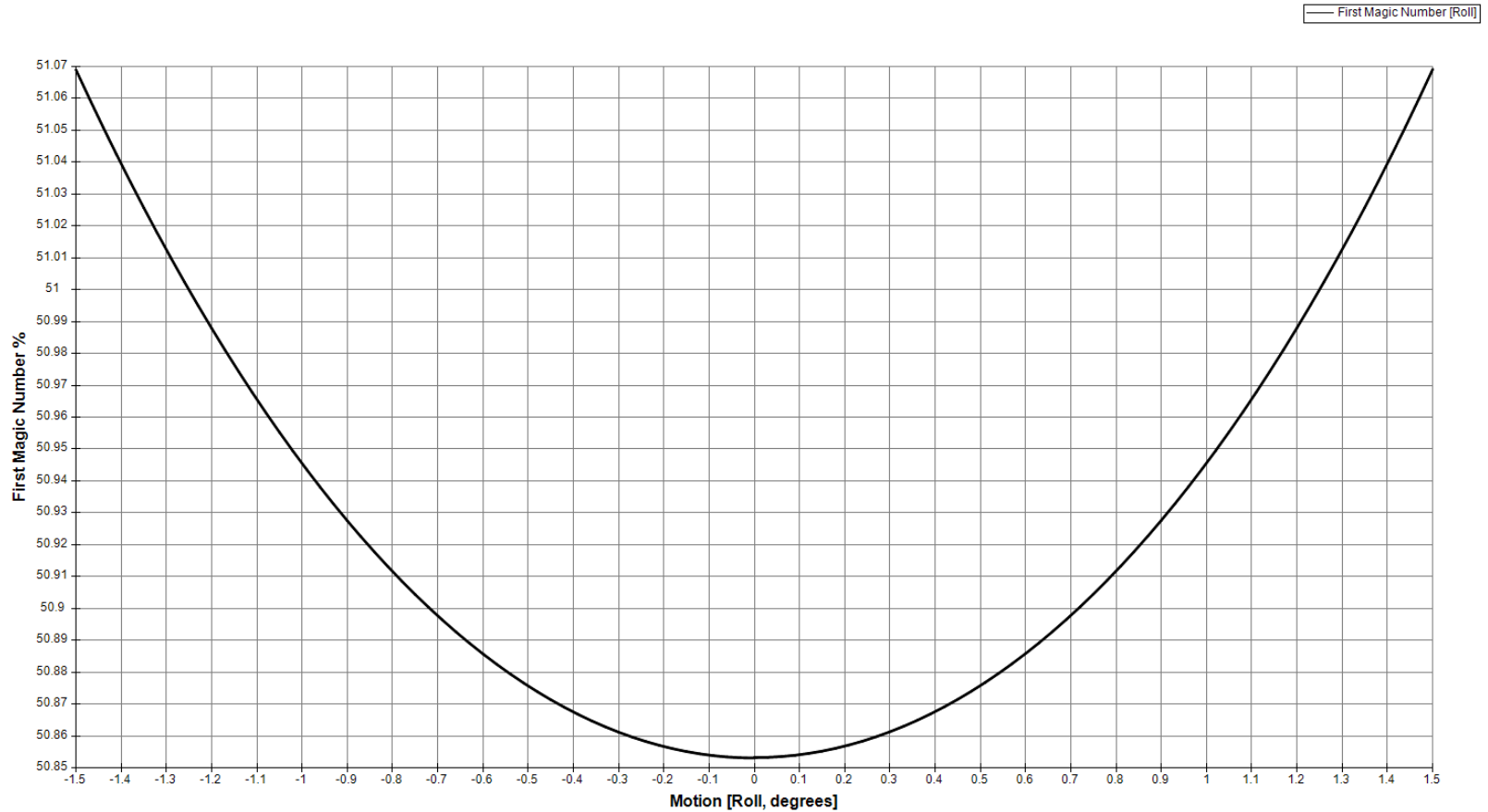
Rear Roll Stiffness Calculation

'AR Stiffness ARB Rear [newton metre/degree]' + 'AR Stiffness Spring Rear [newton metre/degree]'

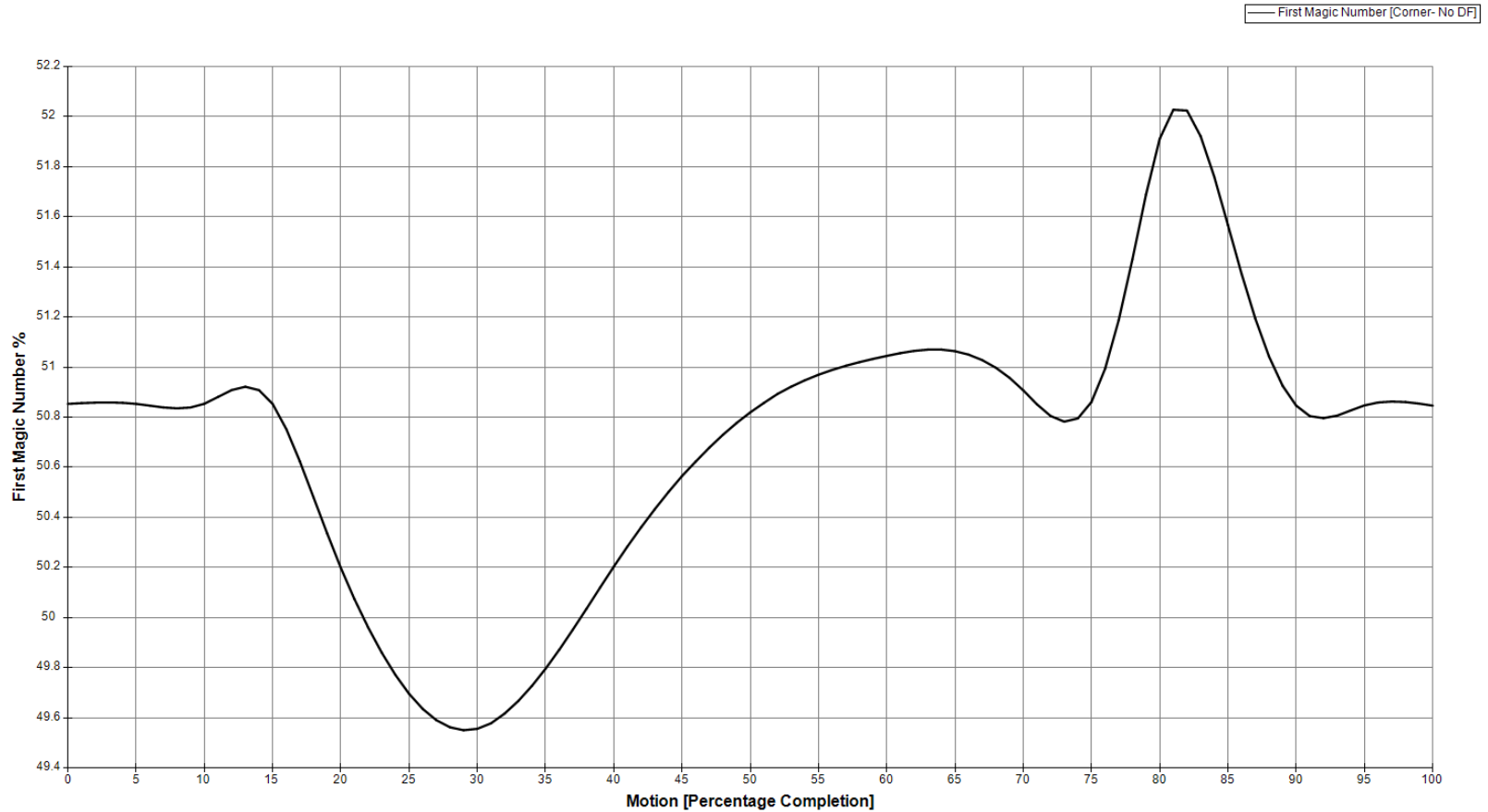
Ratio of Front Roll Stiffness to Rear Stiffness- 1st Magic Number

('Total Front Roll Stiffness [newton metre/degree]' / ('Total Front Roll Stiffness [newton metre/degree]' + 'Total Rear Roll Stiffness [newton metre/degree]')) * 100

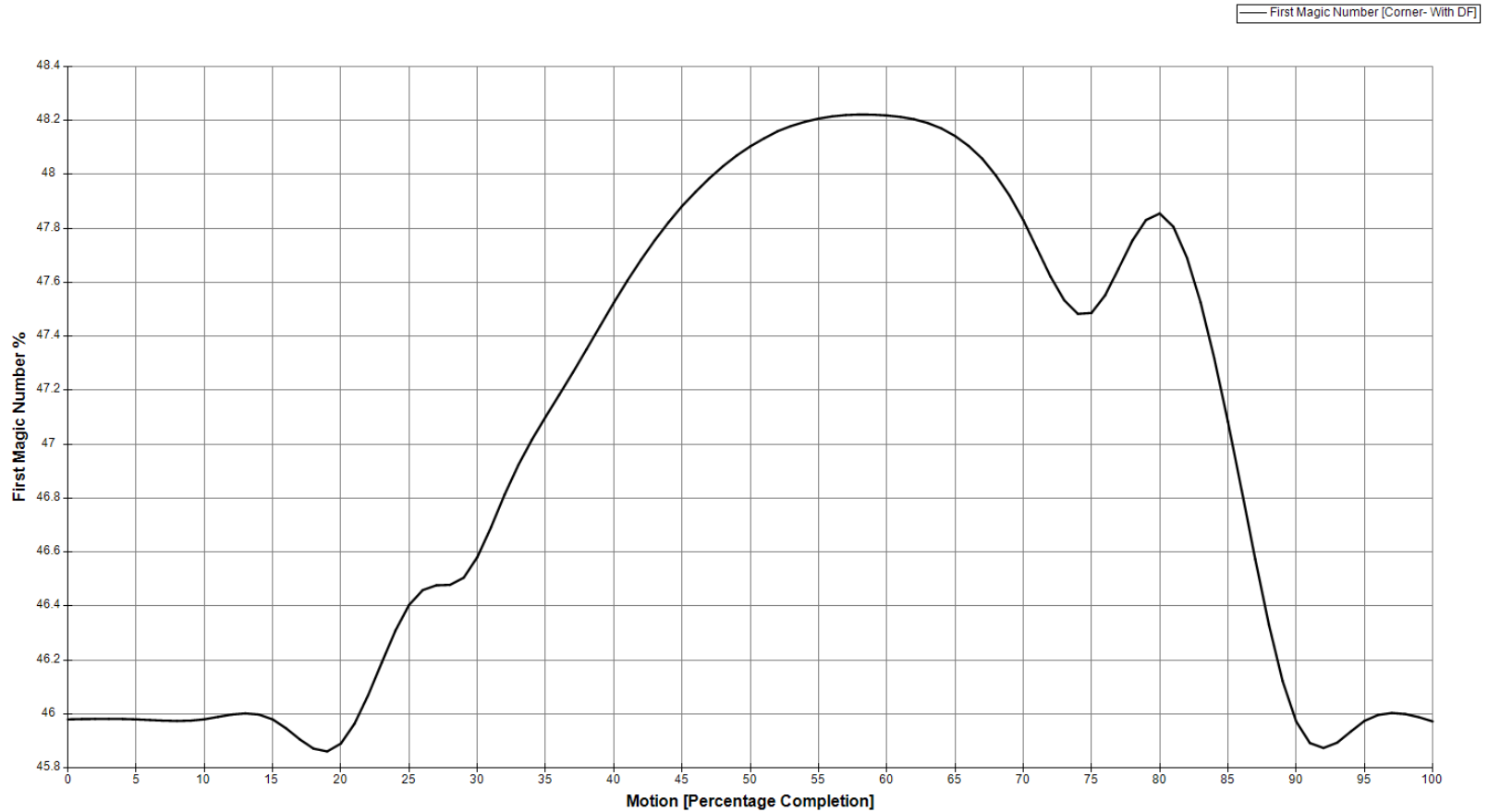
1st Magic Number – Roll



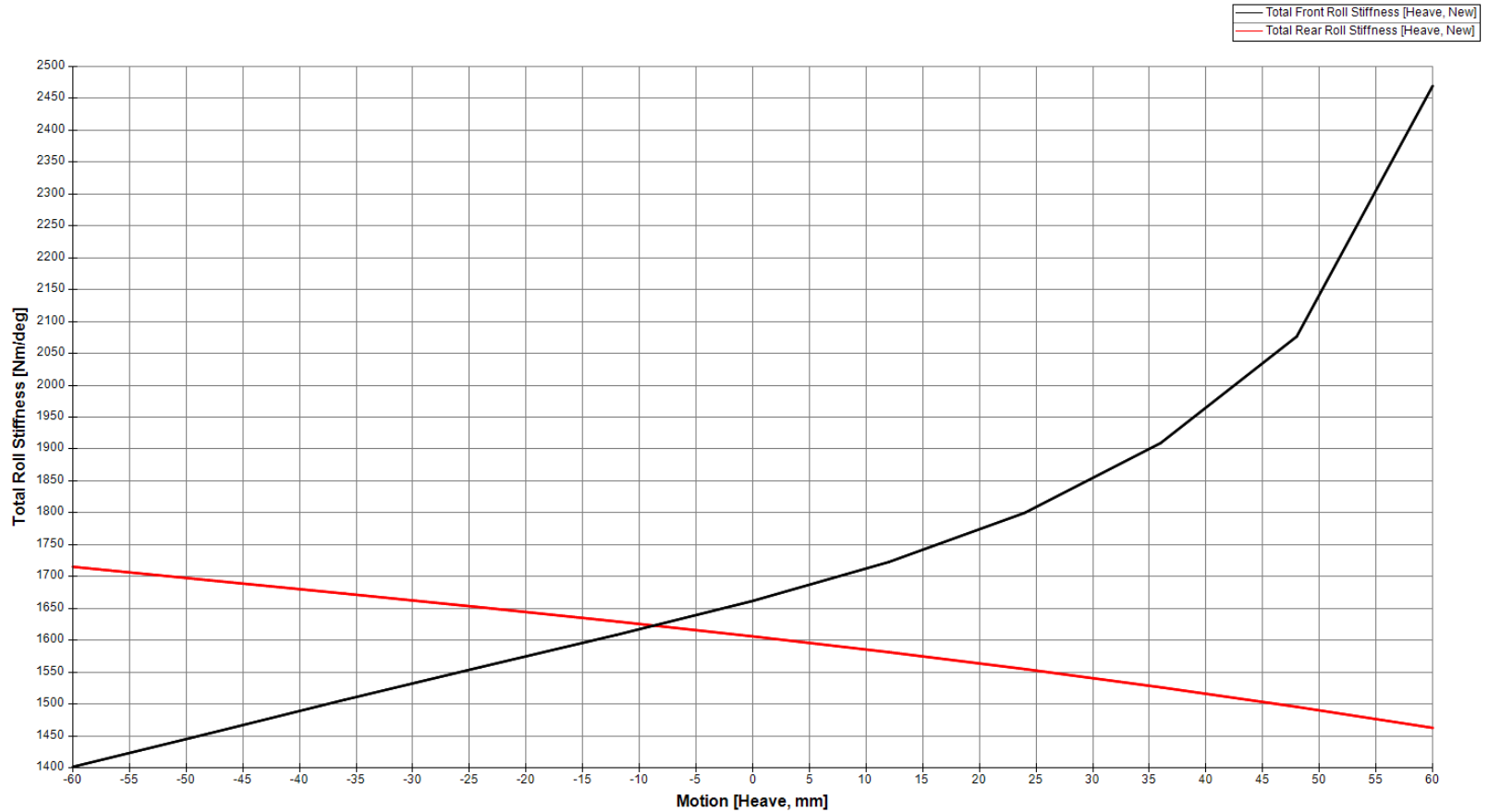
1st Magic Number – Corner No DF



1st Magic Number – Corner DF

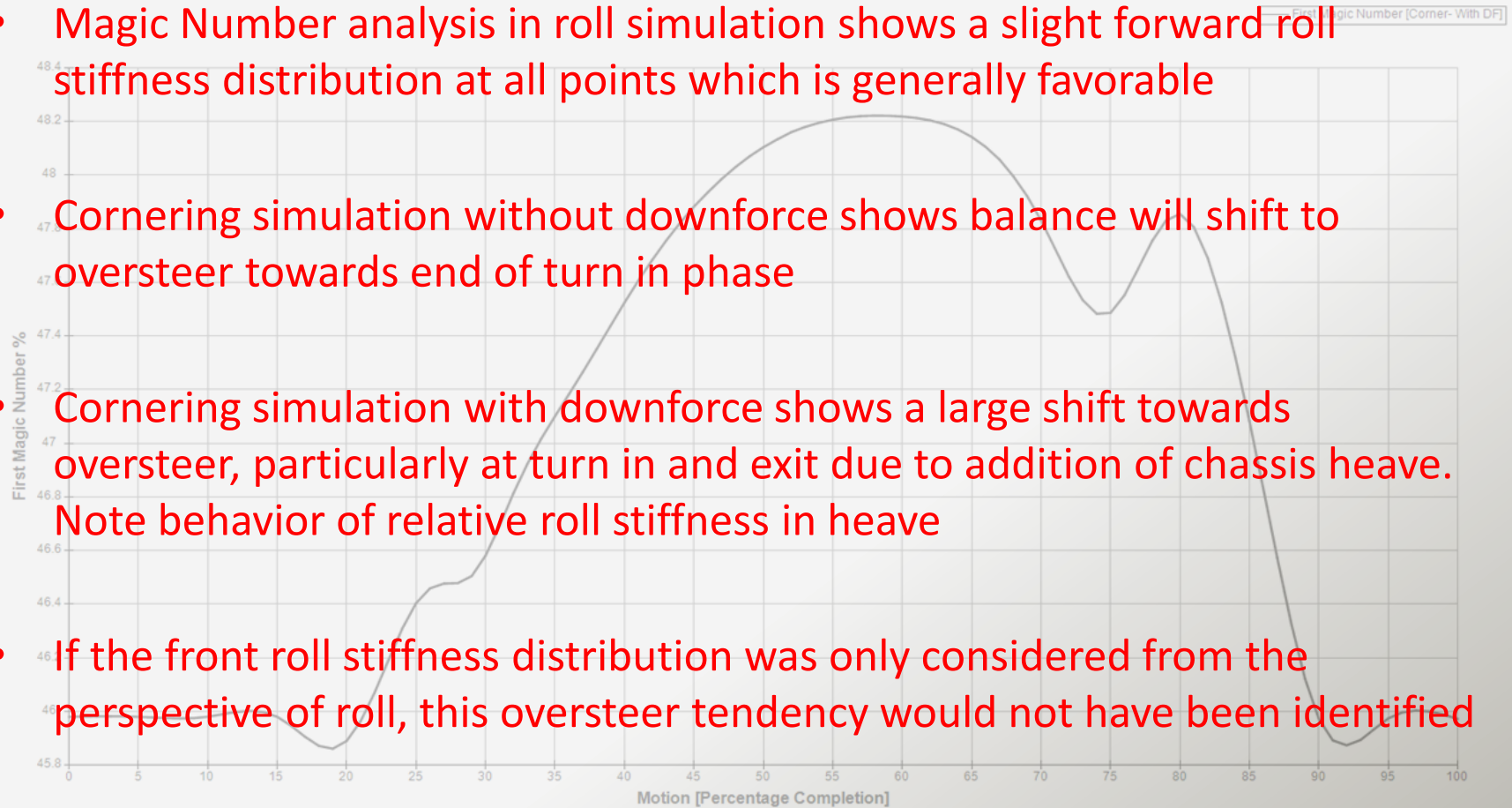


Roll Stiffness Distribution– Heave

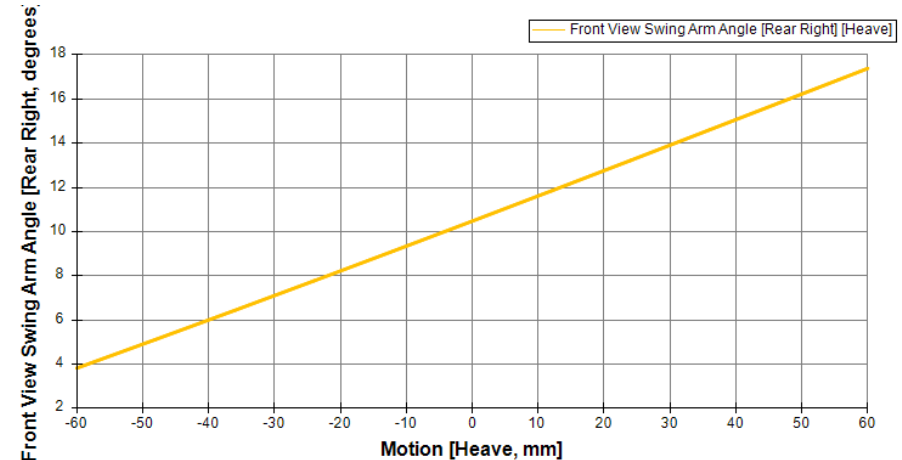
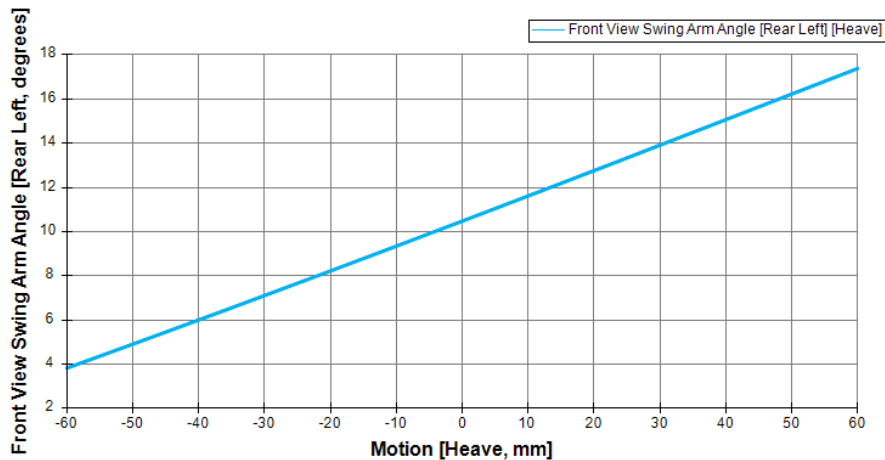
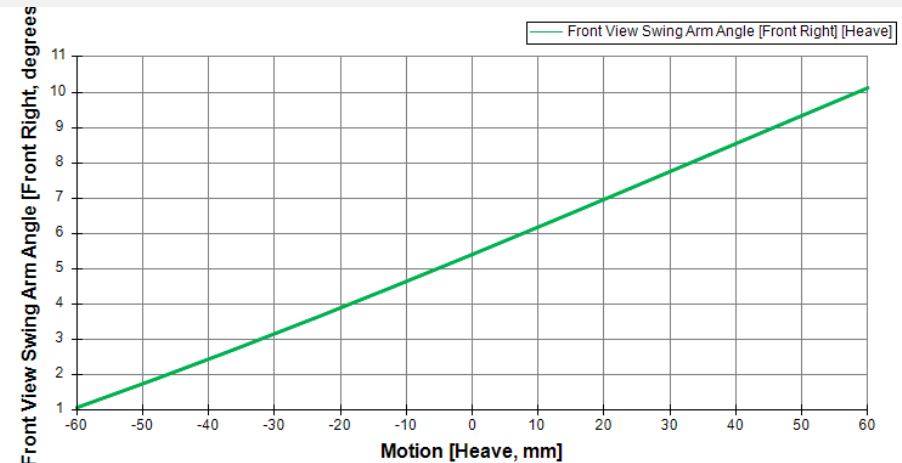
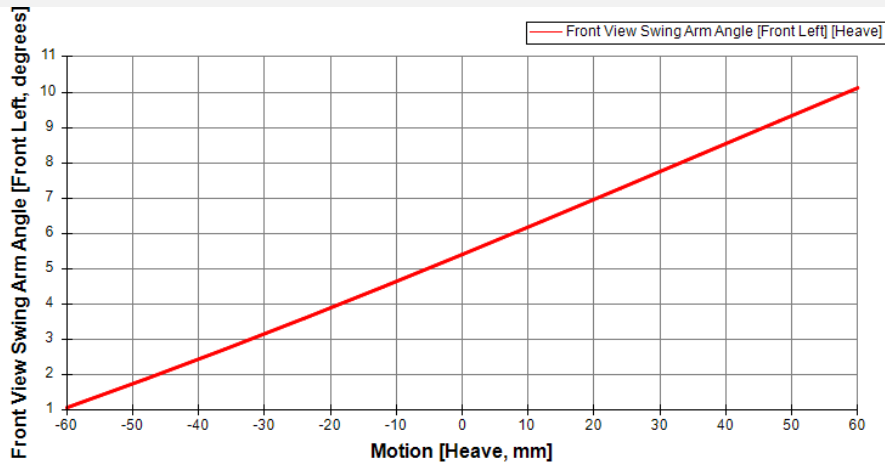


1st Magic Number

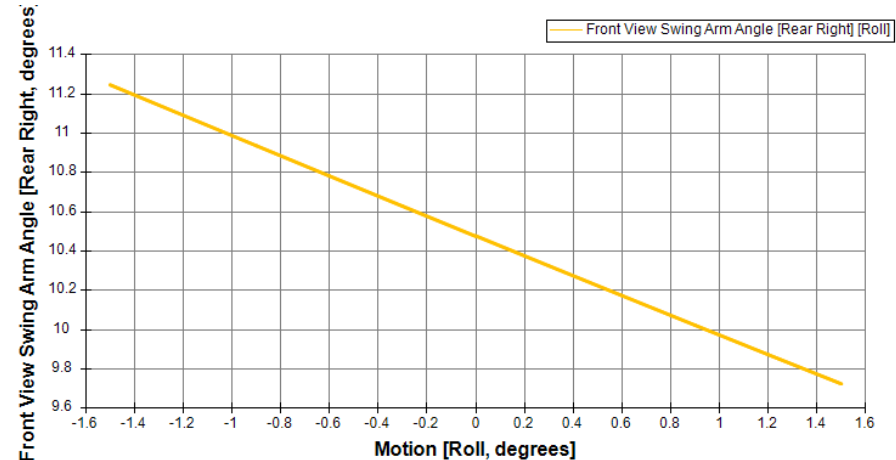
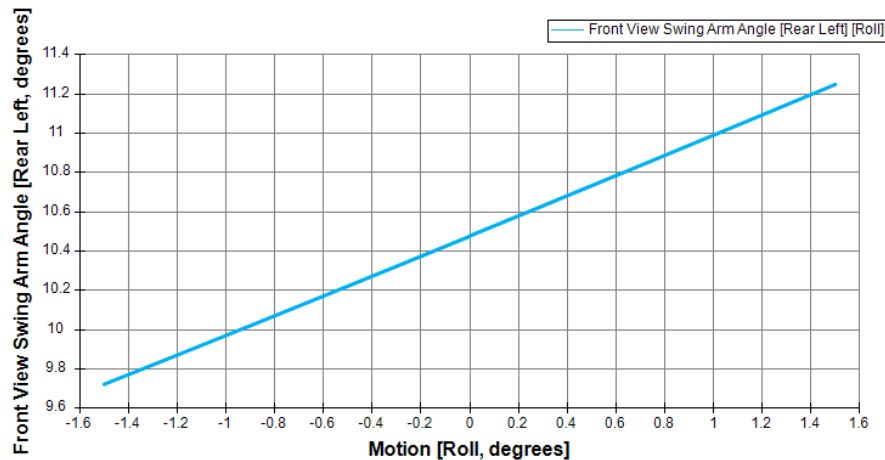
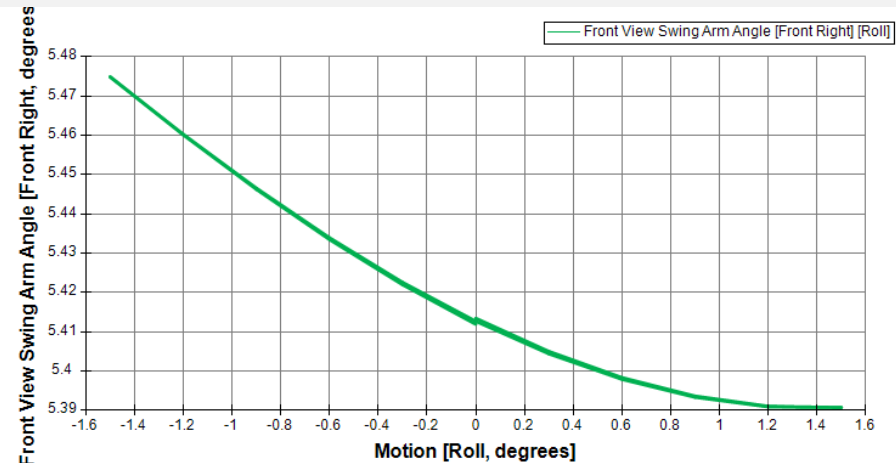
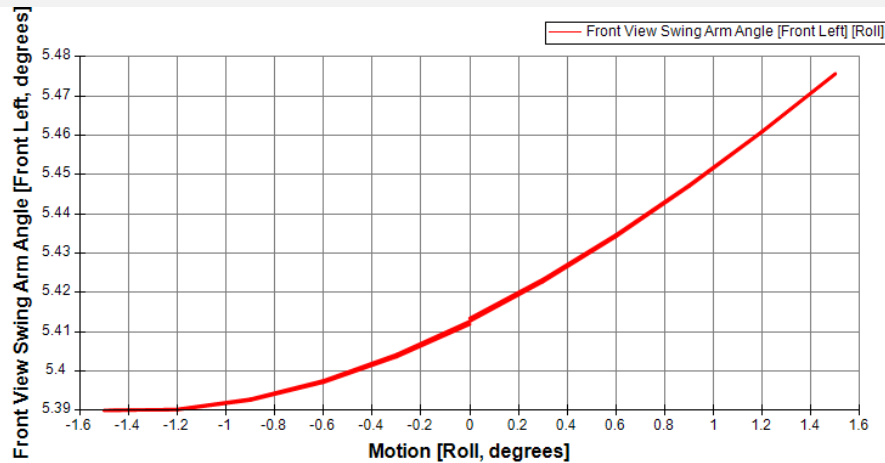
- Magic Number analysis in roll simulation shows a slight forward roll stiffness distribution at all points which is generally favorable
- Cornering simulation without downforce shows balance will shift to oversteer towards end of turn in phase
- Cornering simulation with downforce shows a large shift towards oversteer, particularly at turn in and exit due to addition of chassis heave. Note behavior of relative roll stiffness in heave
- If the front roll stiffness distribution was only considered from the perspective of roll, this oversteer tendency would not have been identified



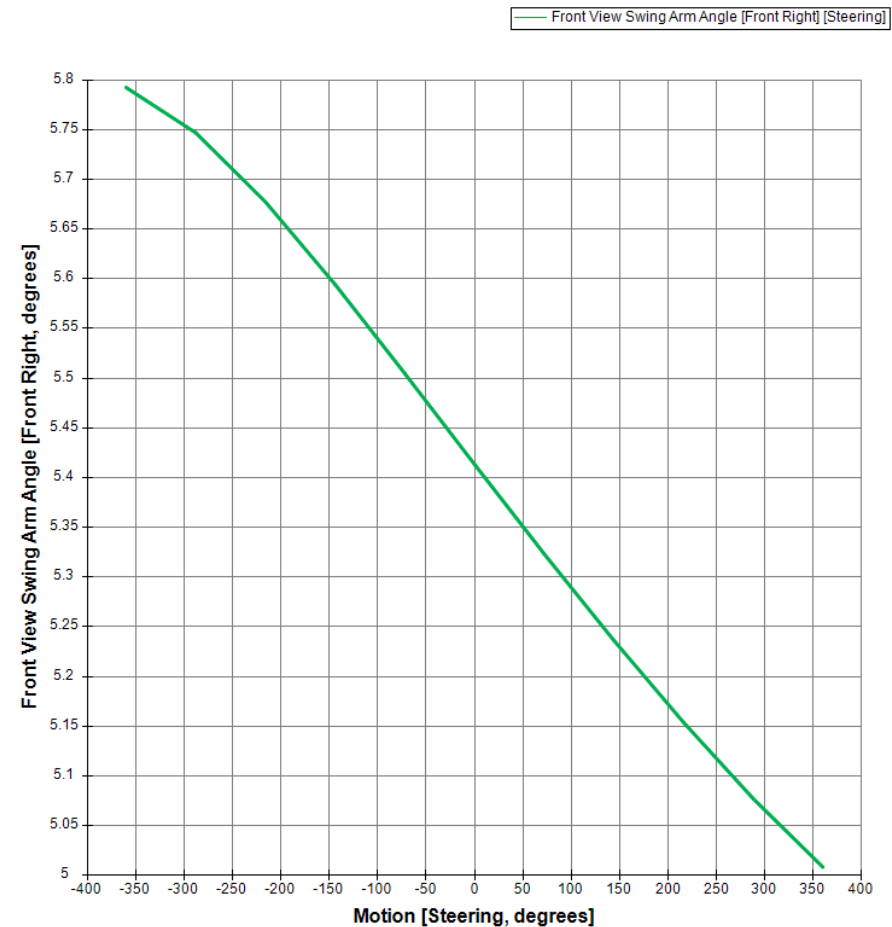
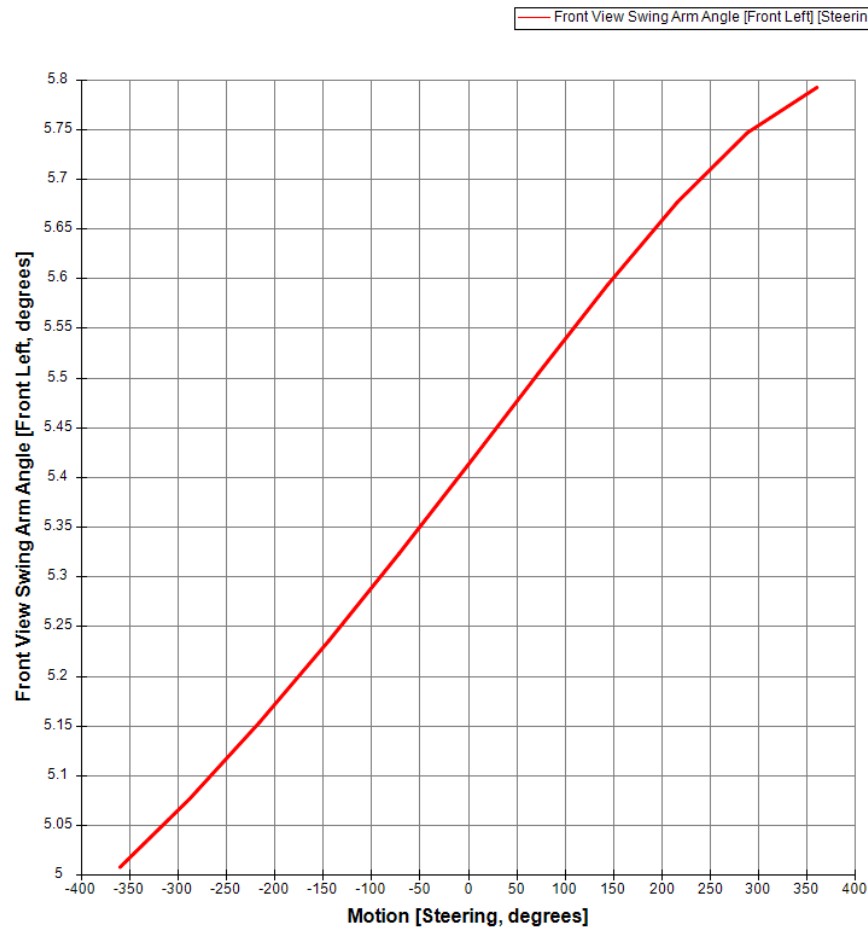
Front View IC angles – Heave



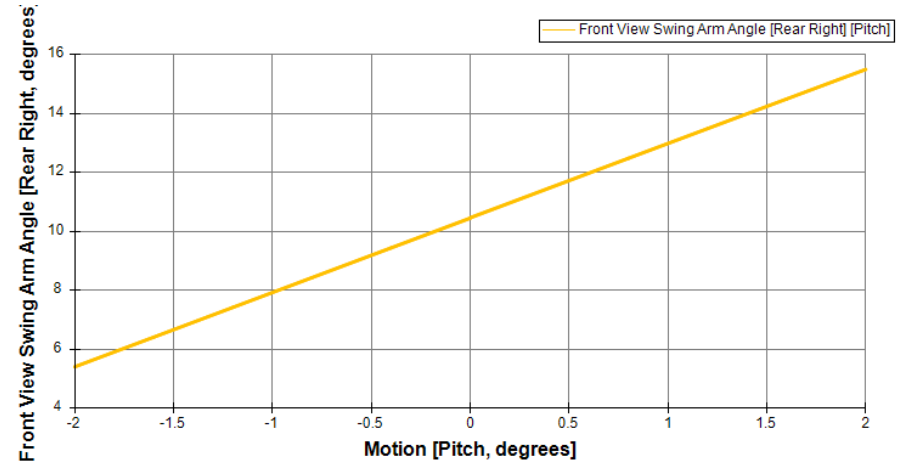
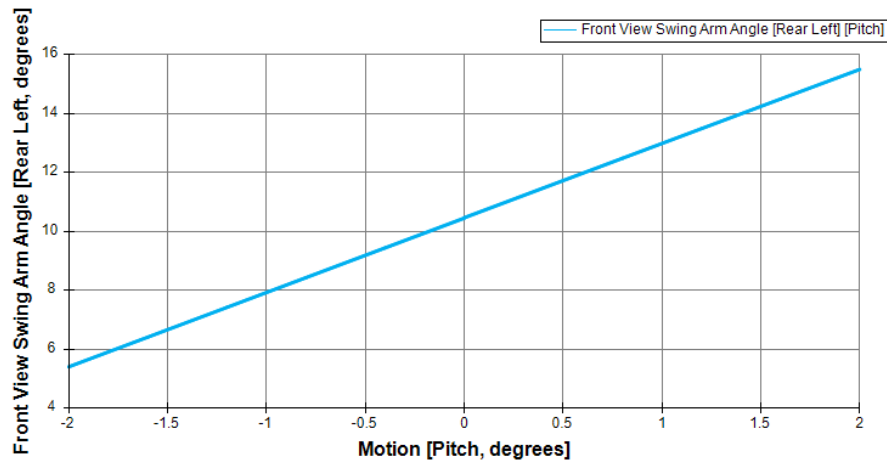
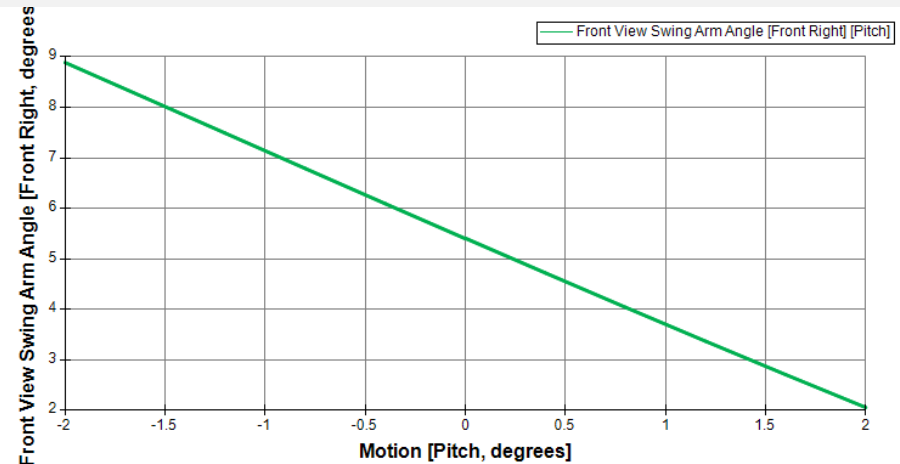
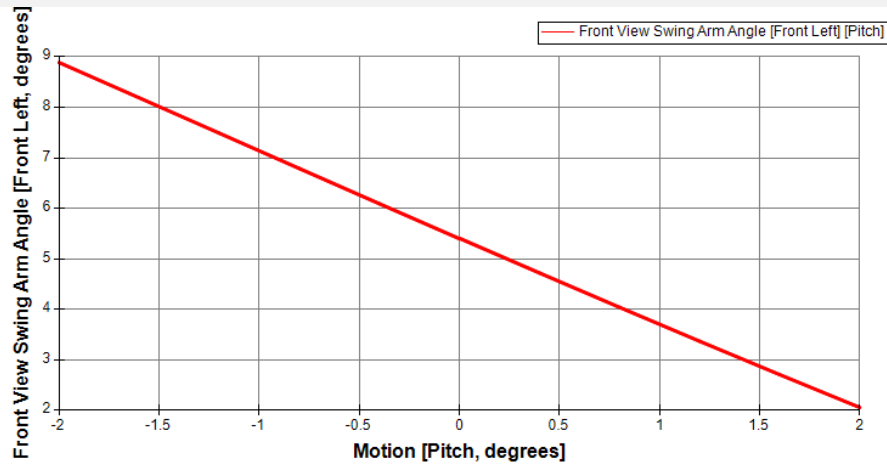
Front View IC angles – Roll



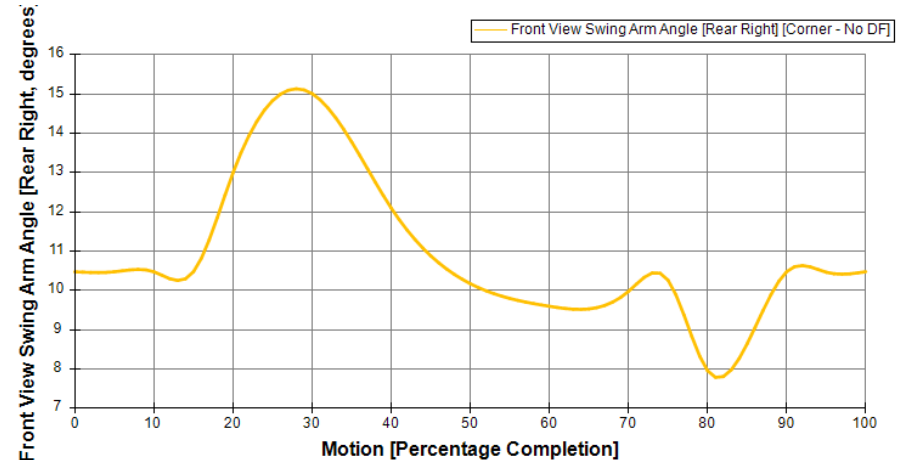
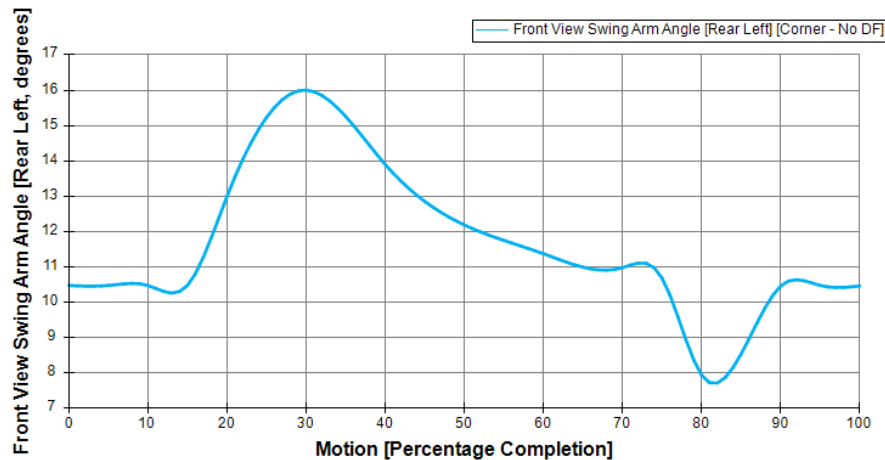
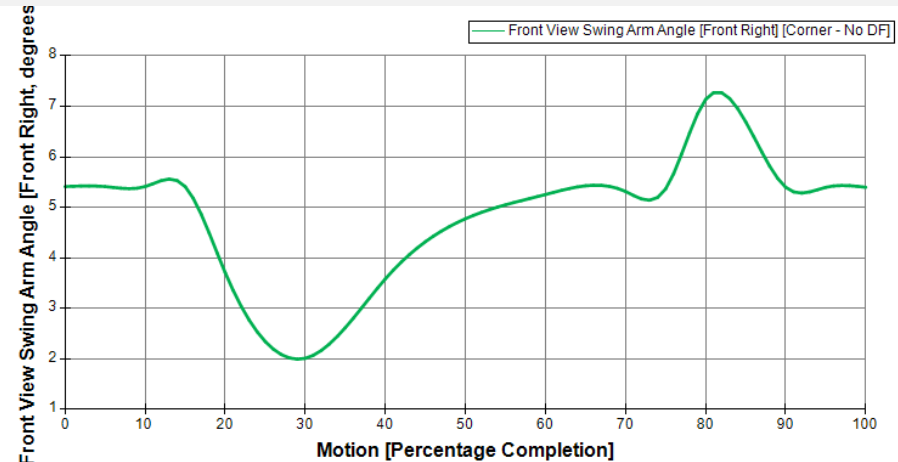
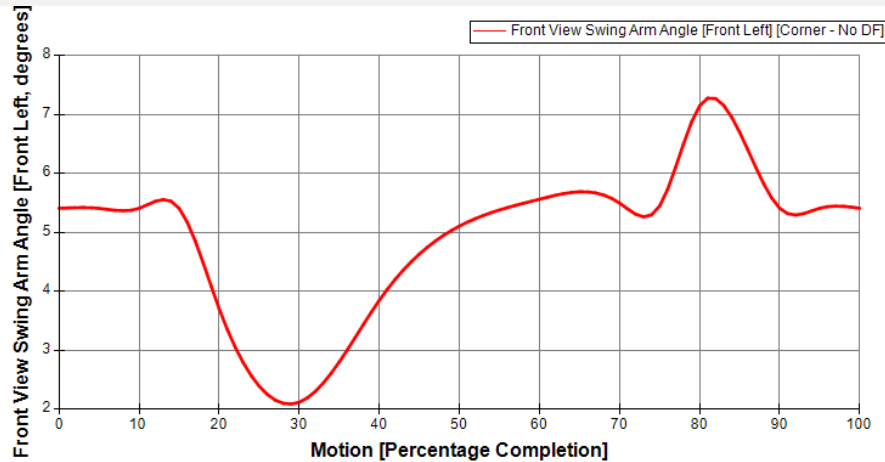
Front View IC angles – Steering



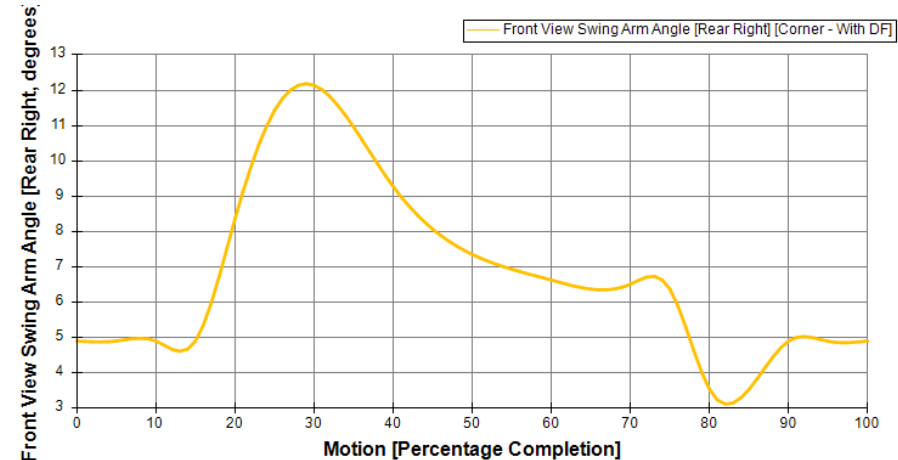
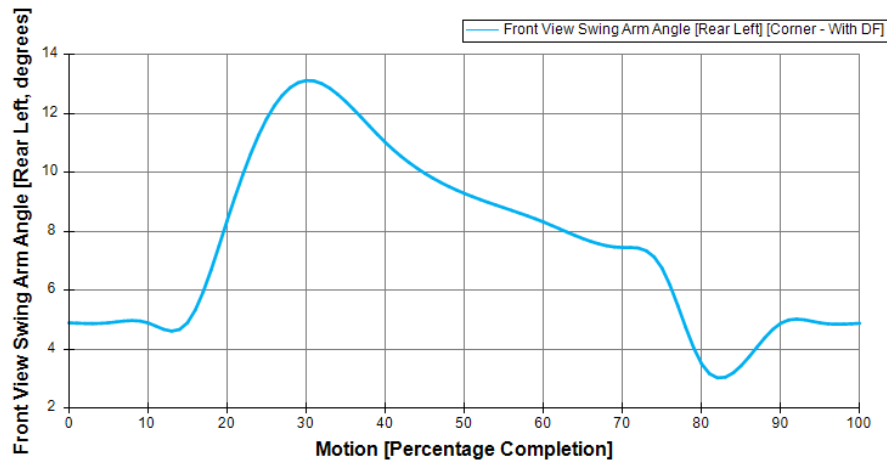
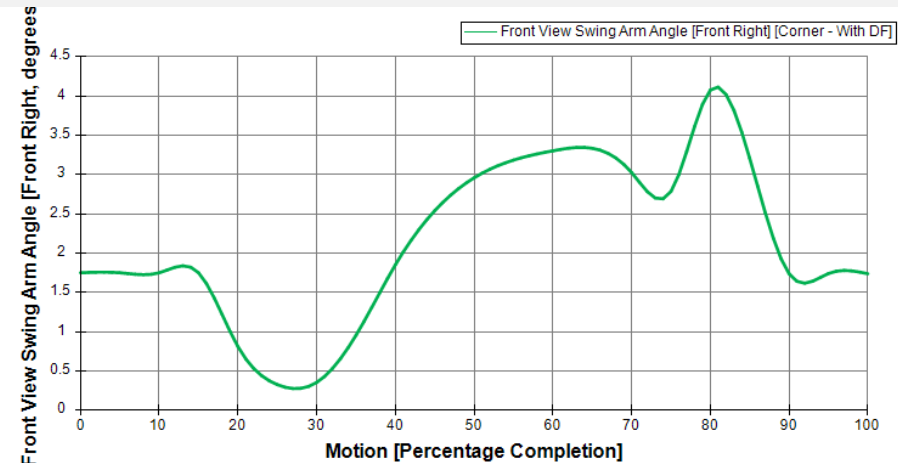
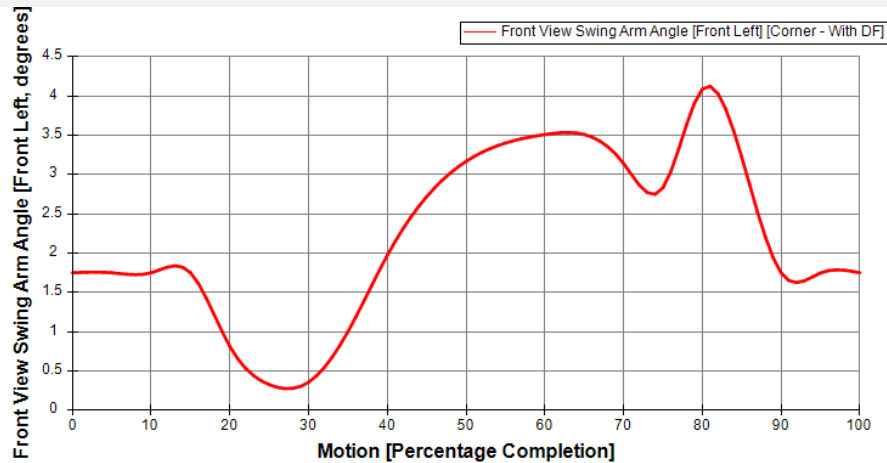
Front View IC angles – Pitch



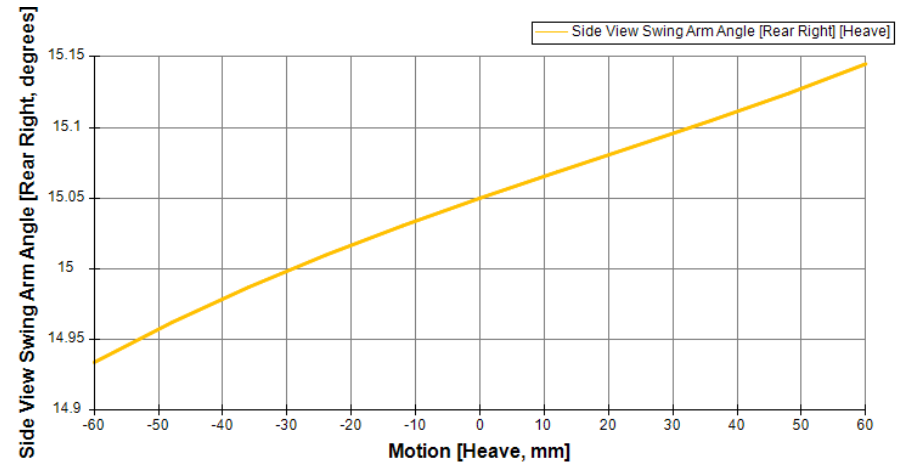
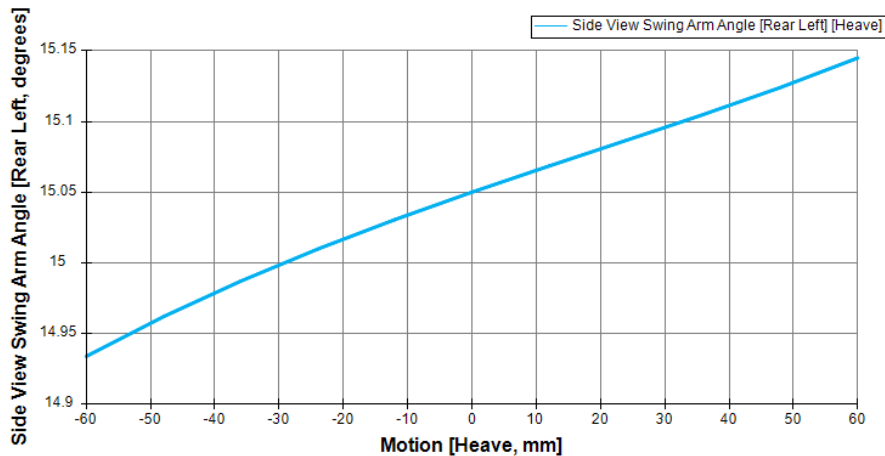
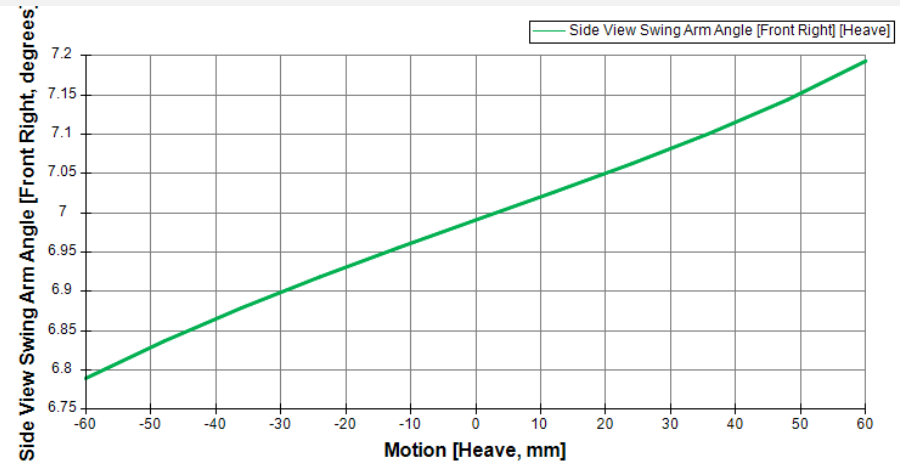
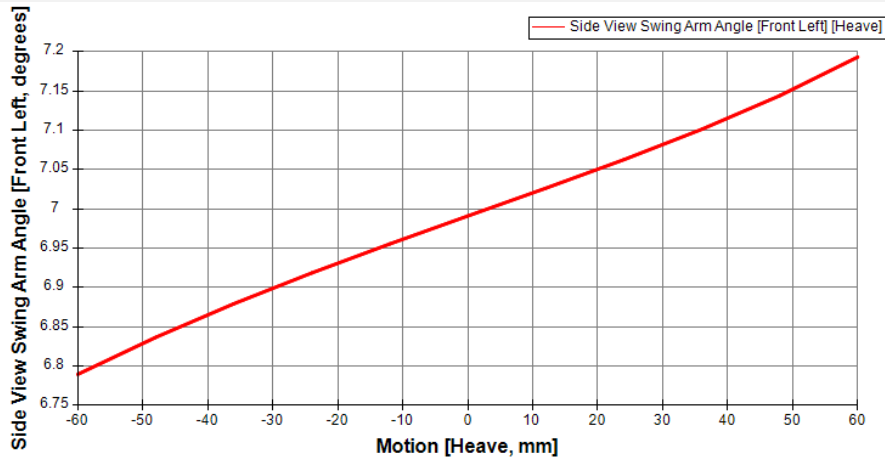
Front View IC angles – Corner No DF



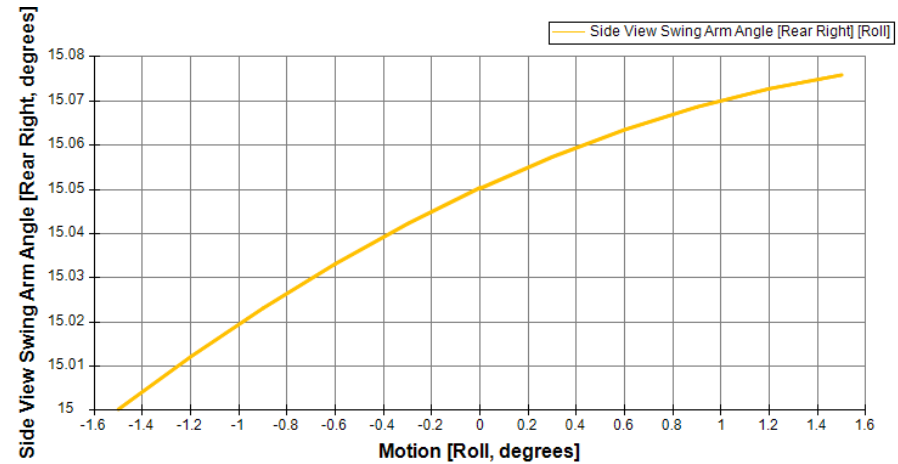
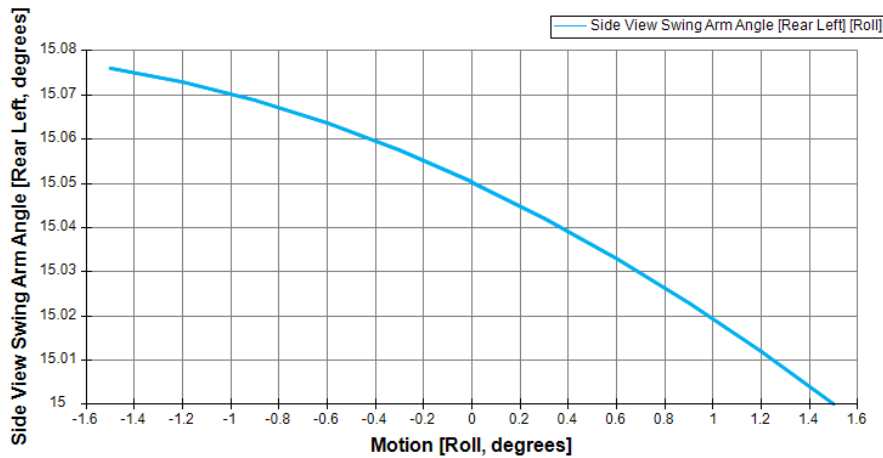
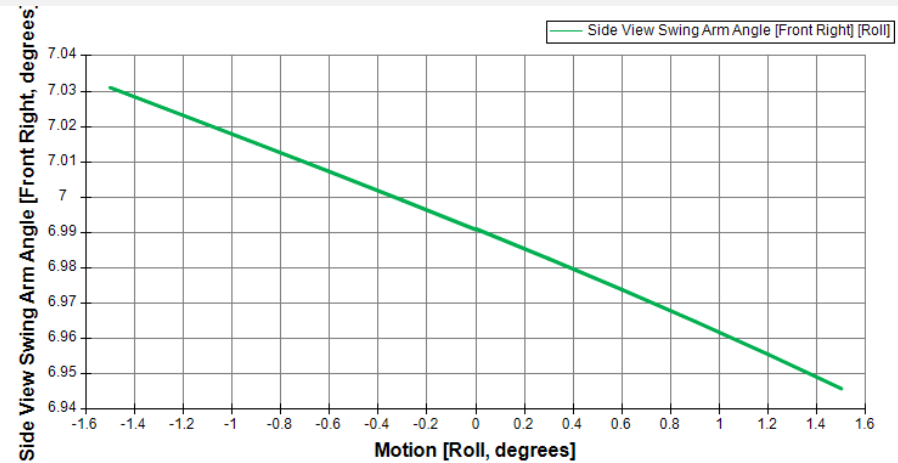
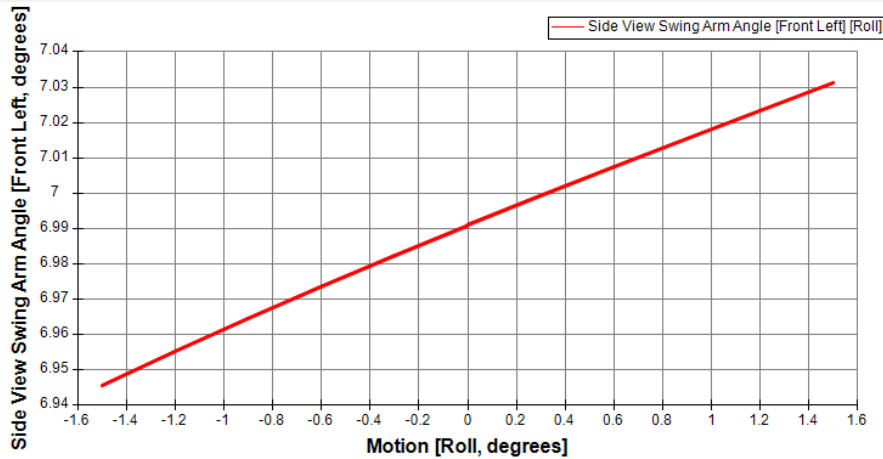
Front View IC angles – Corner DF



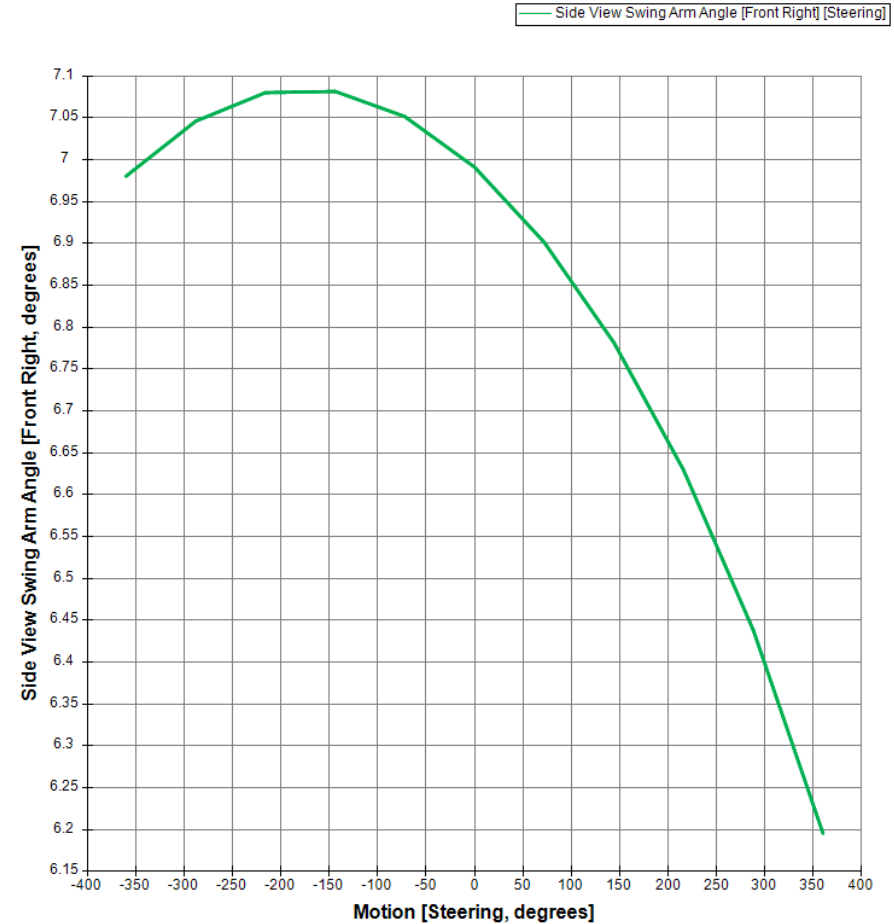
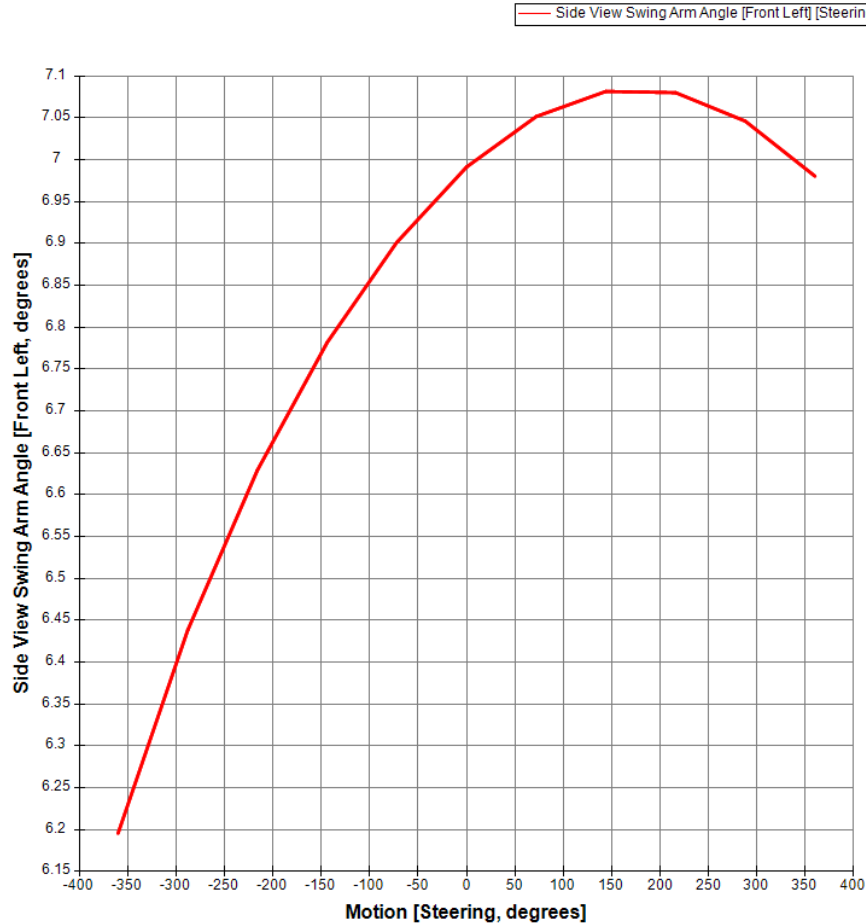
Side View IC angles – Heave



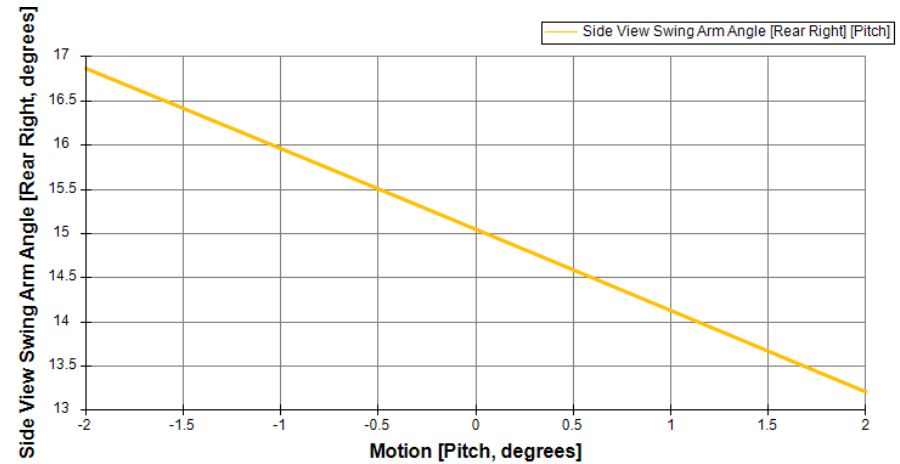
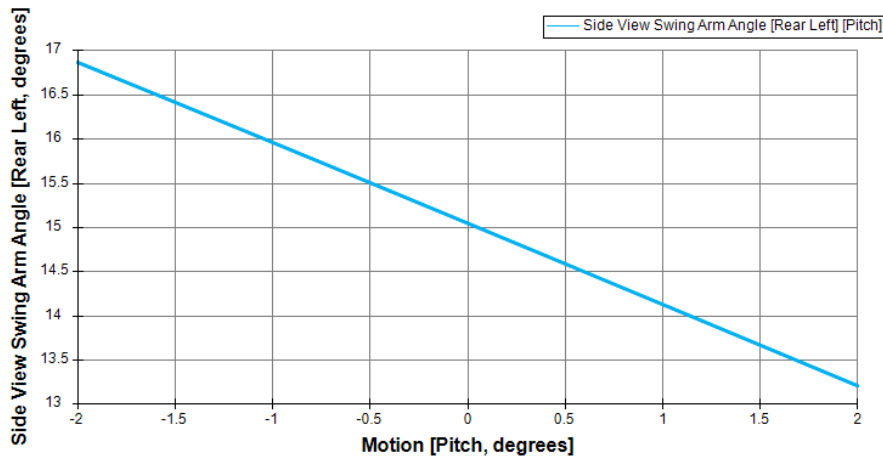
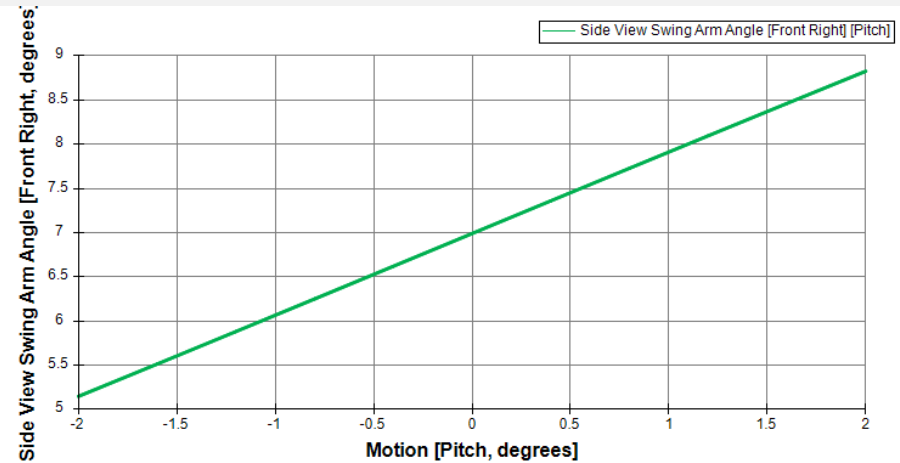
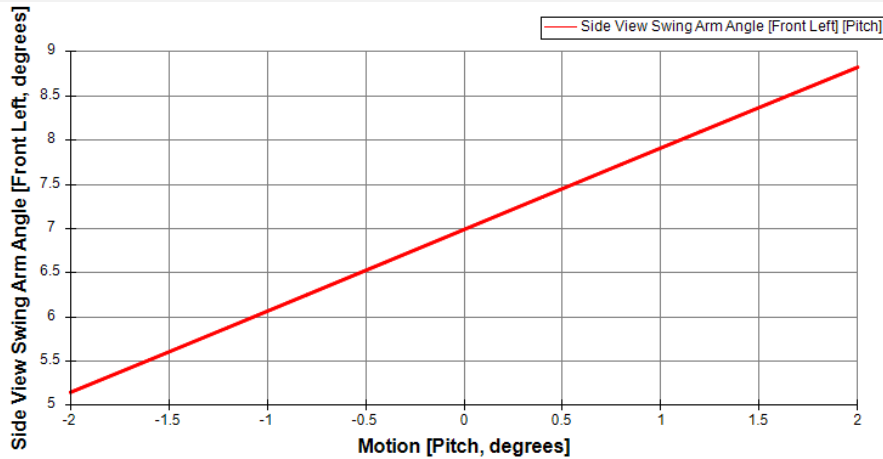
Side View IC angles – Roll



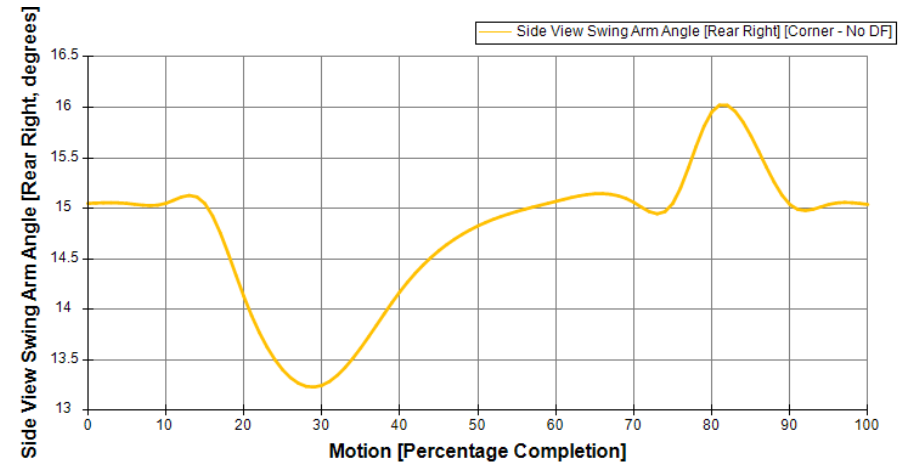
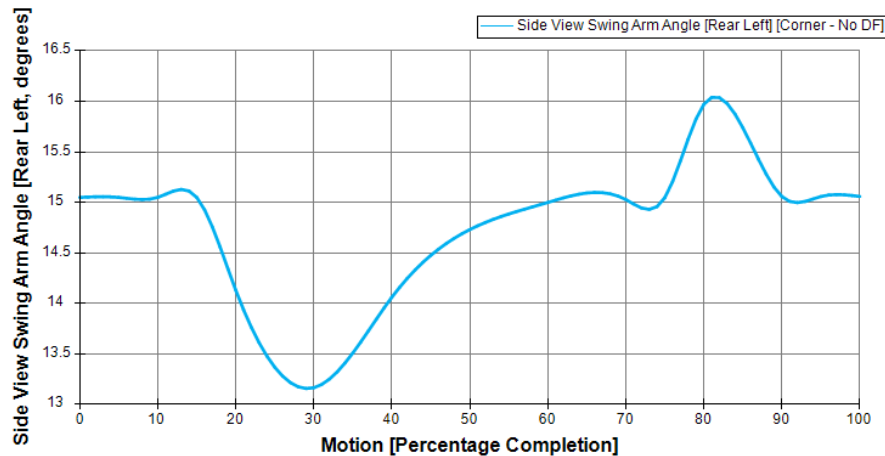
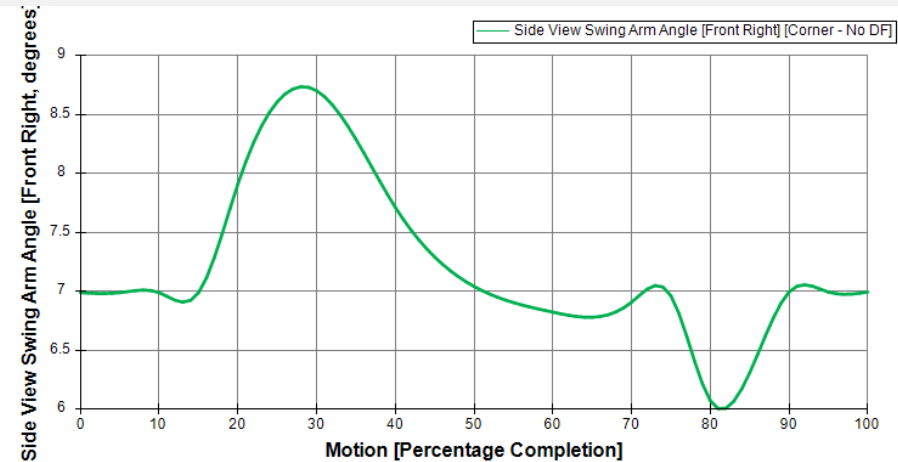
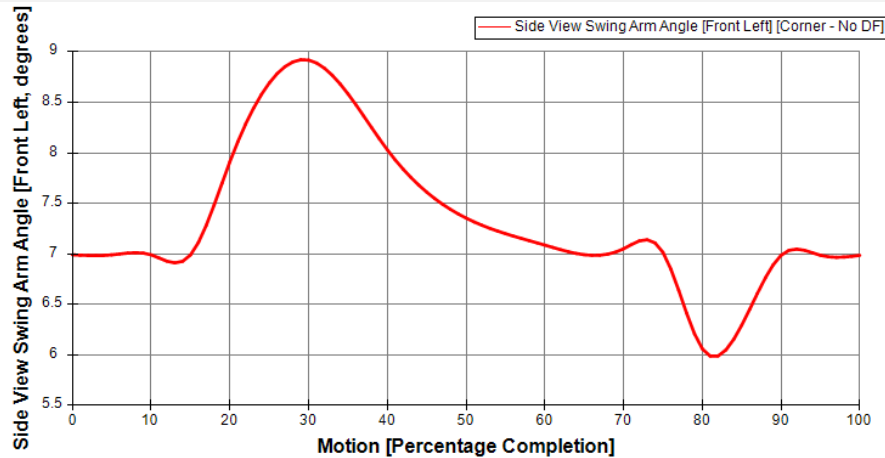
Side View IC angles – Steering



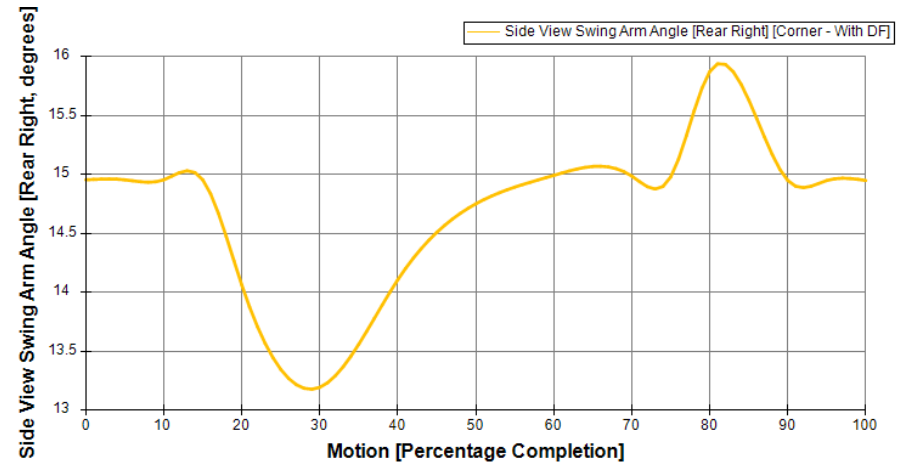
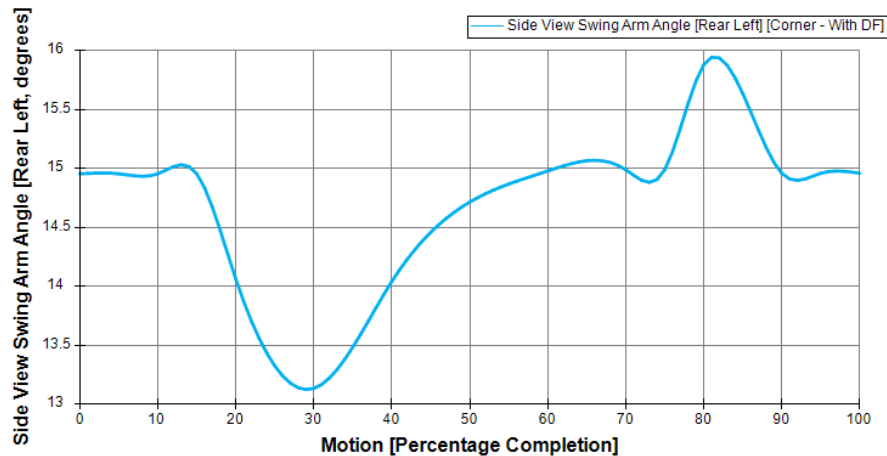
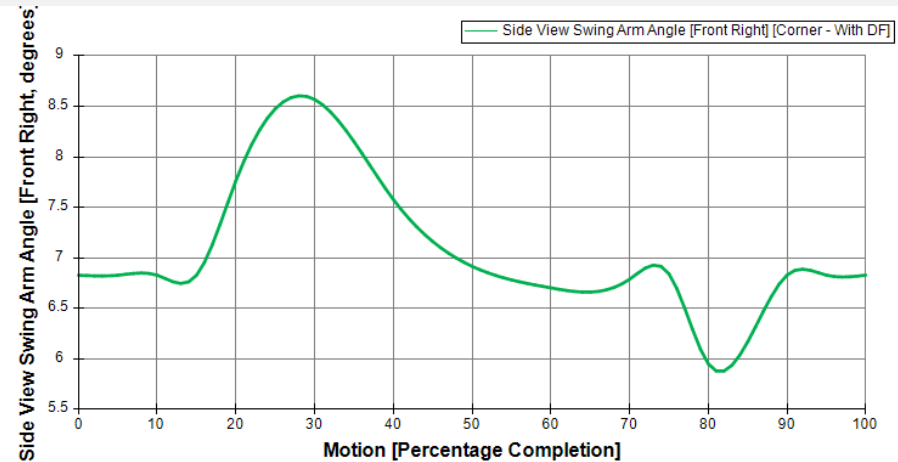
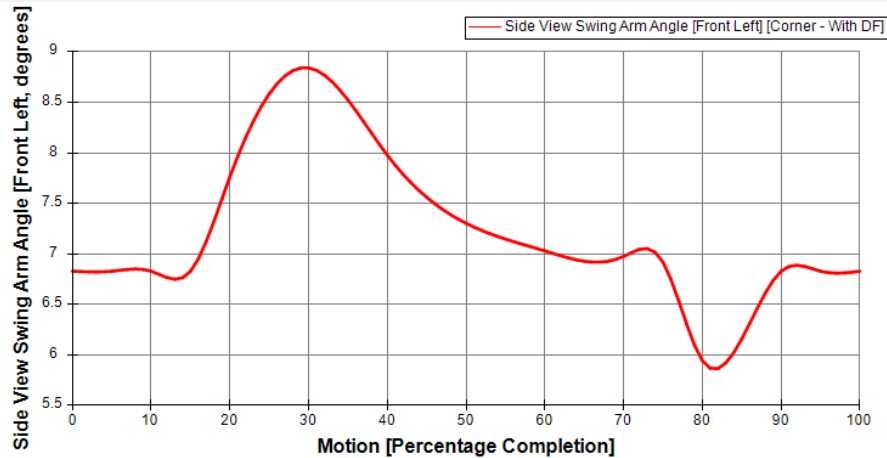
Side View IC angles – Pitch



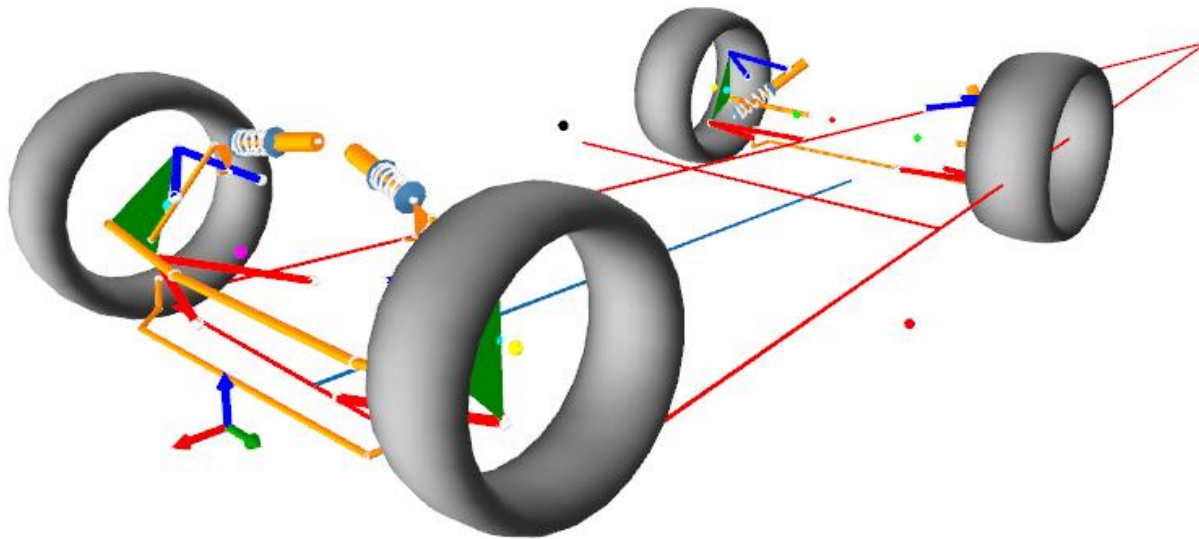
Side View IC angles – Corner No DF



Side View IC angles – Corner DF

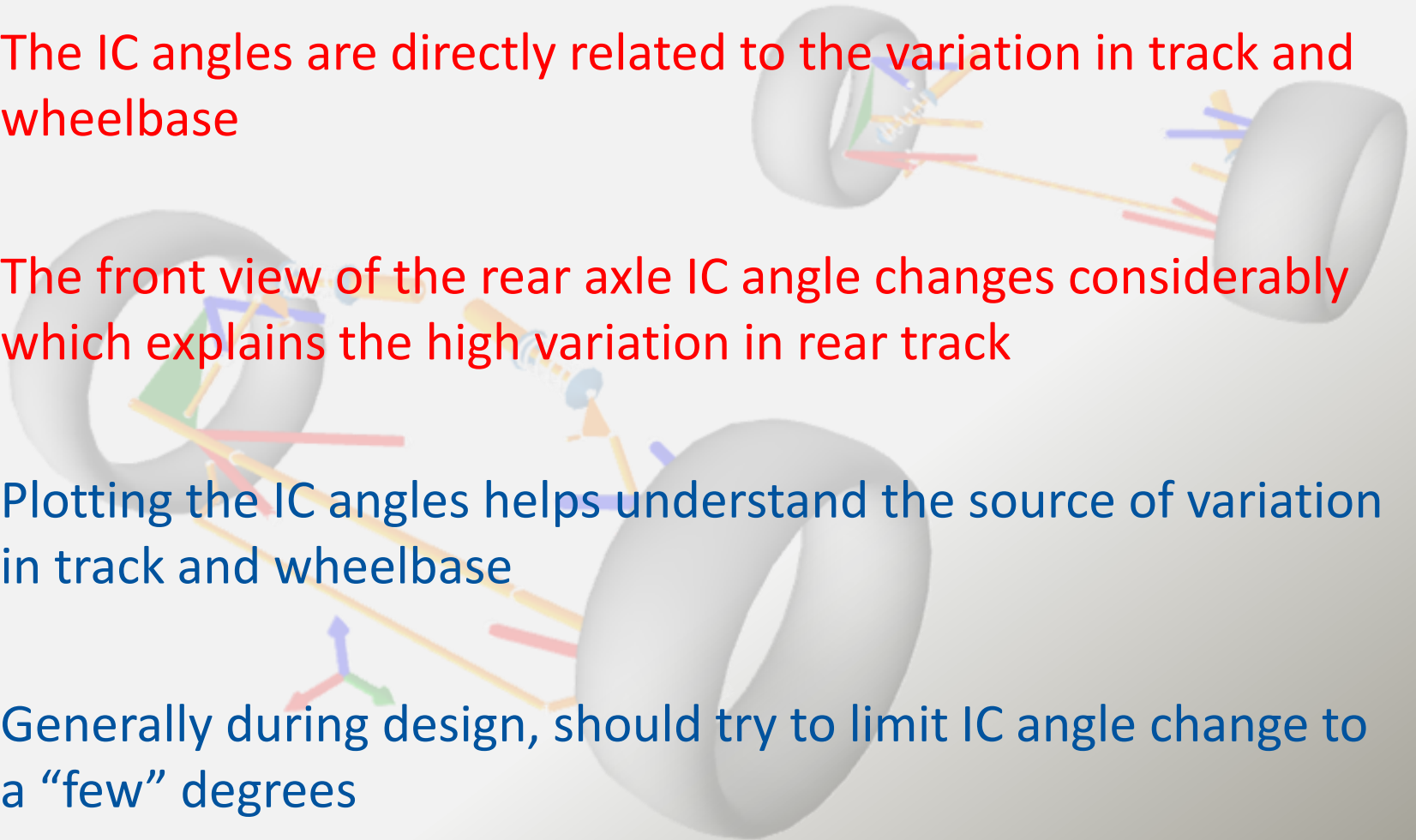


IC angles – Corner DF

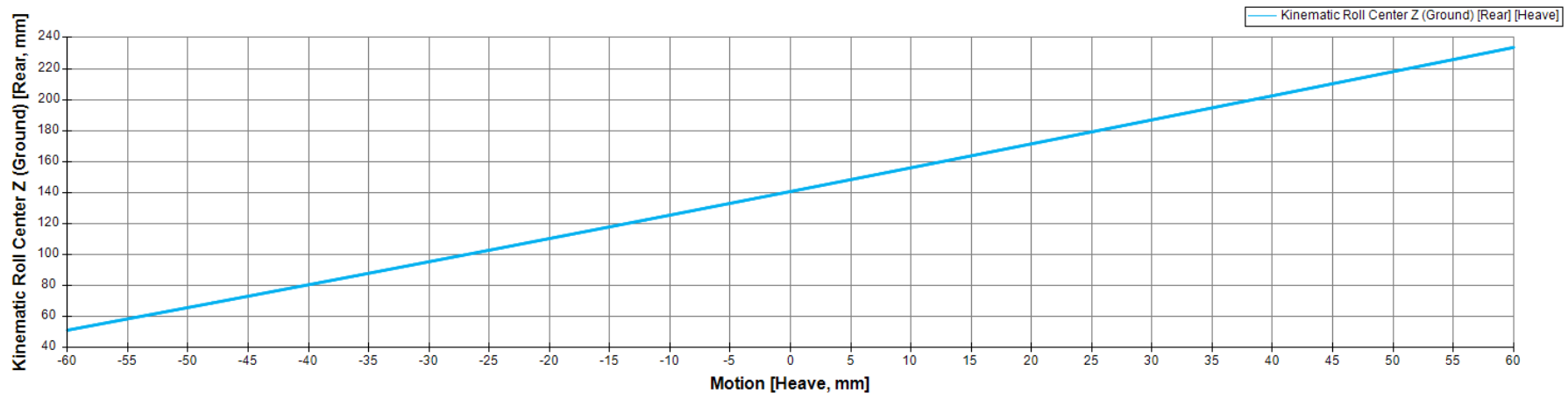
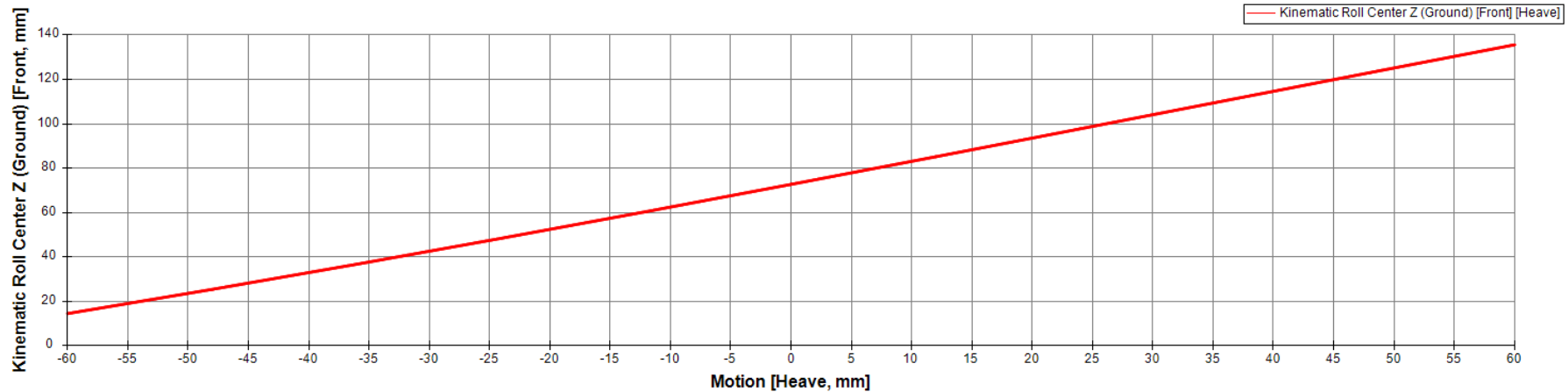
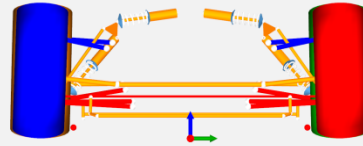


IC angles – Comments

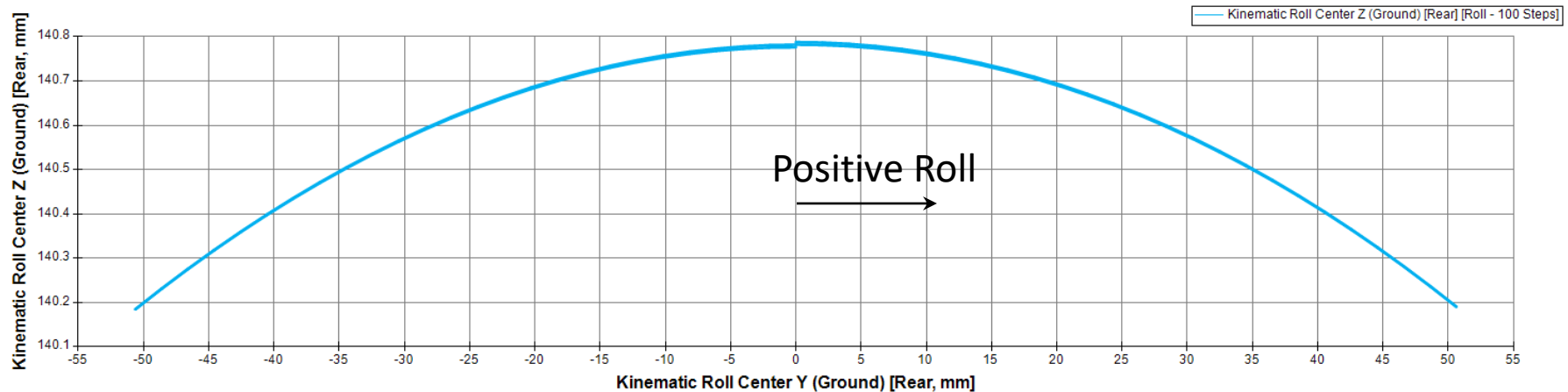
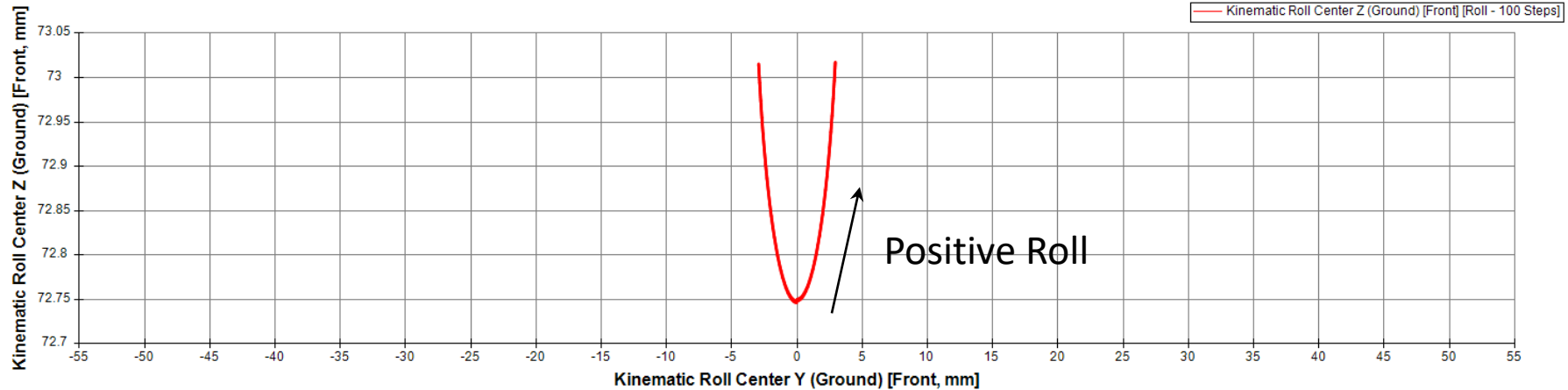
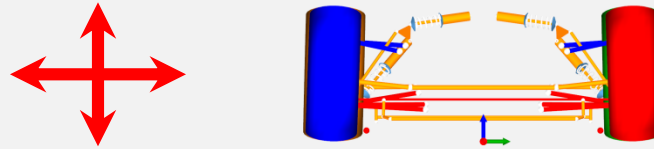
- The IC angles are directly related to the variation in track and wheelbase
- The front view of the rear axle IC angle changes considerably which explains the high variation in rear track
- Plotting the IC angles helps understand the source of variation in track and wheelbase
- Generally during design, should try to limit IC angle change to a “few” degrees



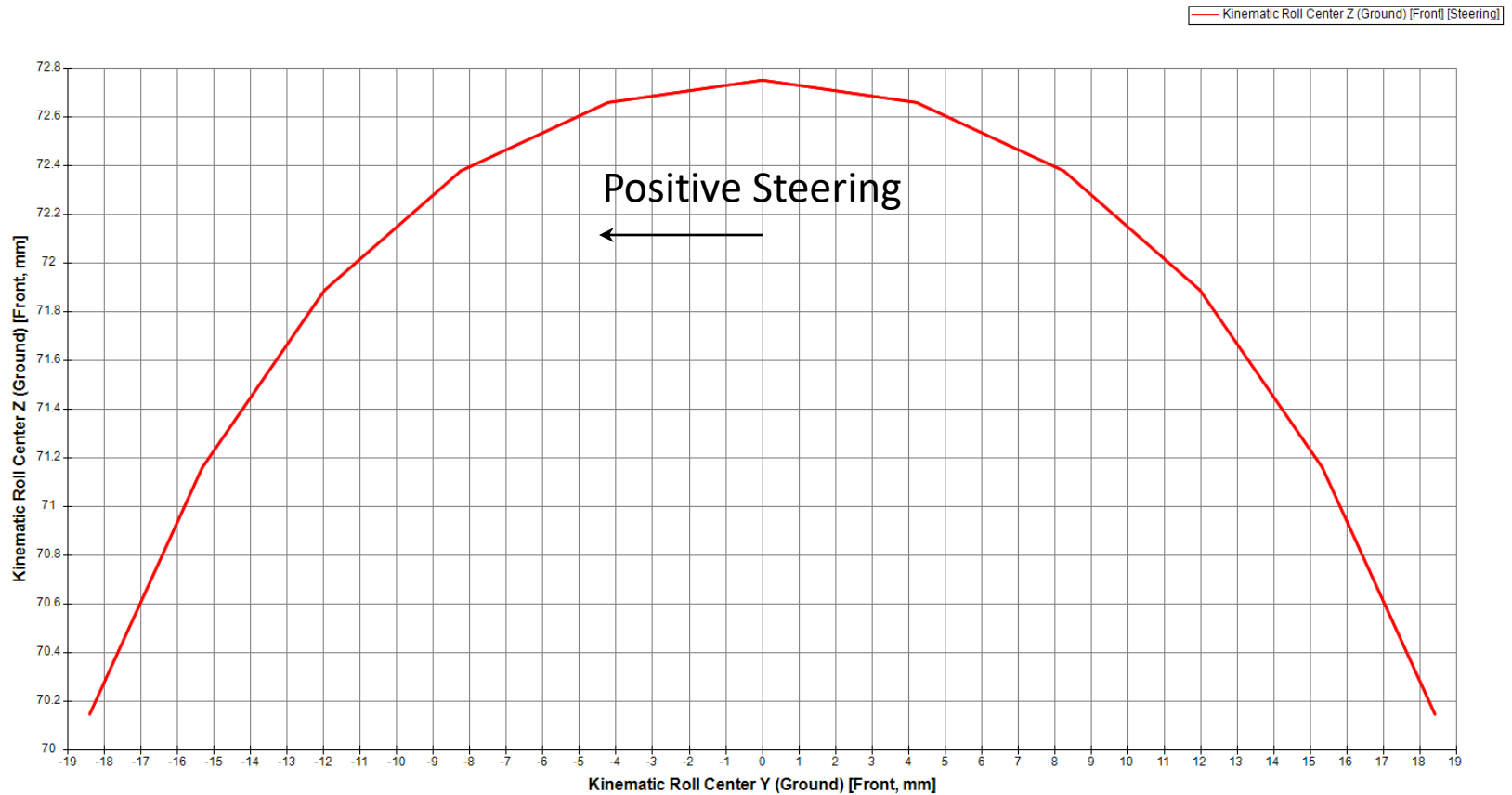
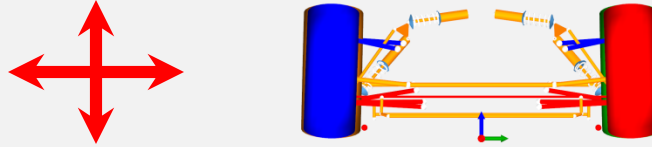
Vertical Roll Center Migration – Heave



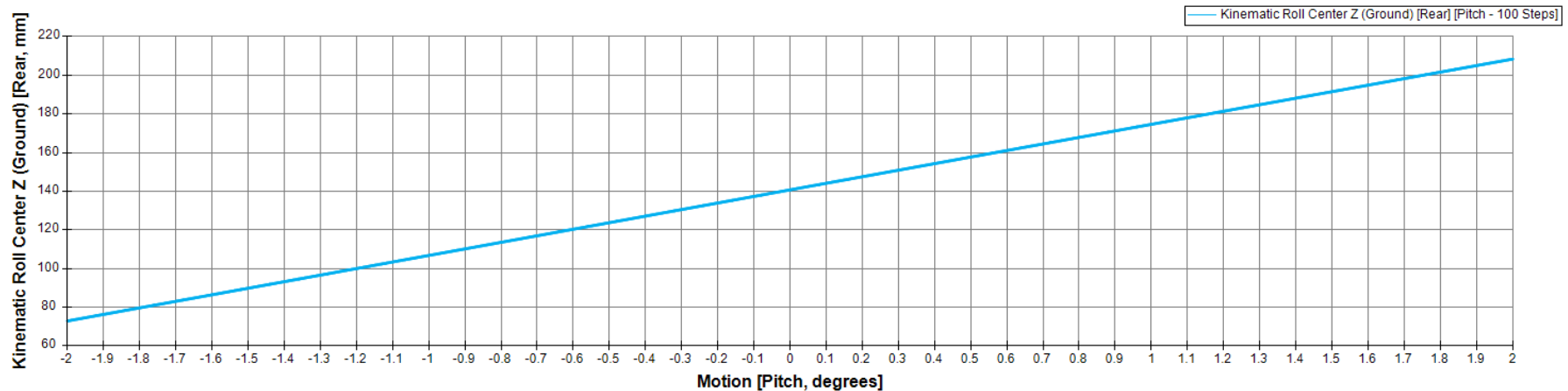
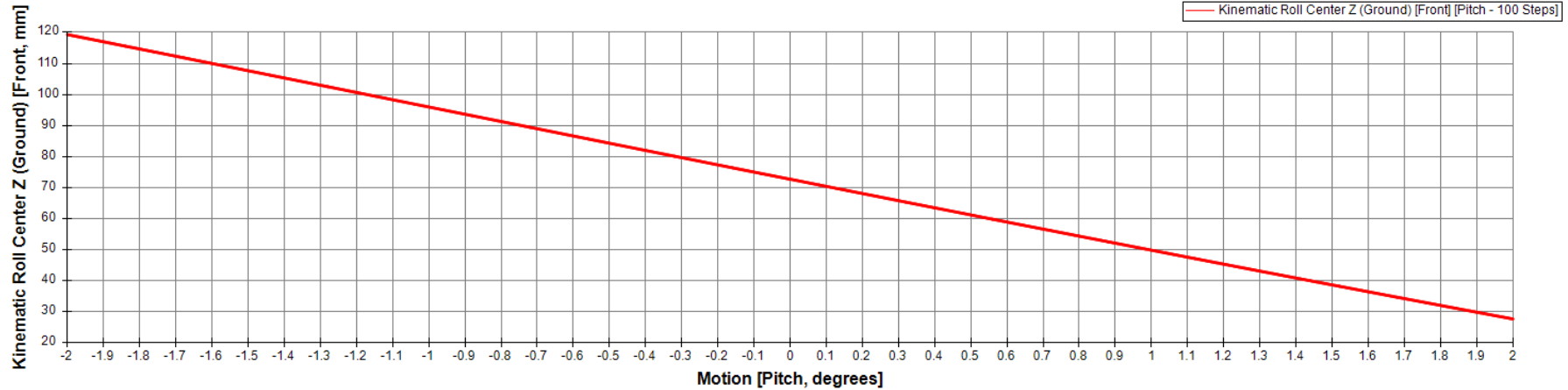
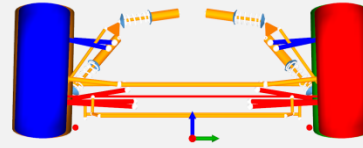
Y-Z Plane Roll Center Migration – Roll



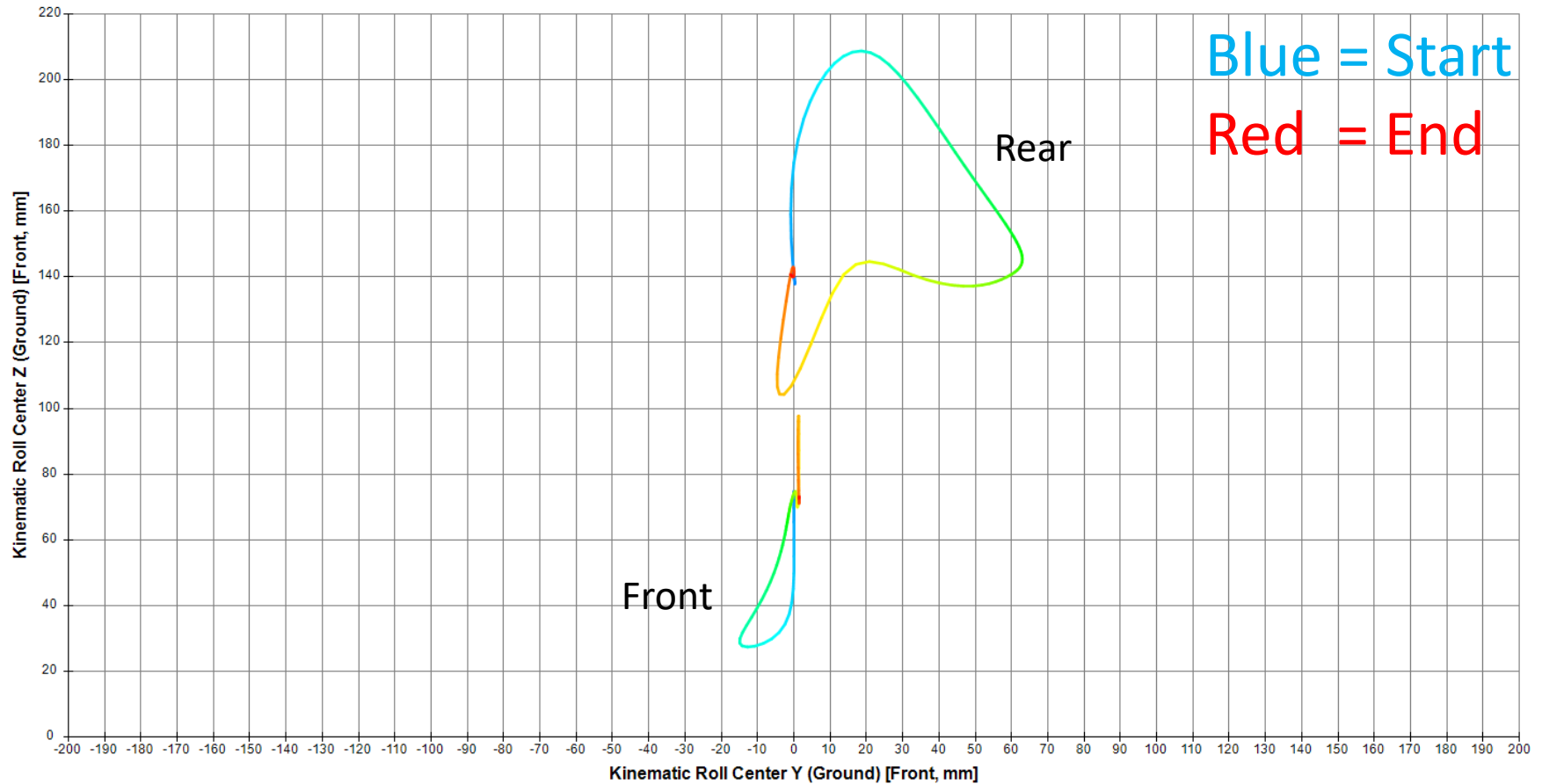
Y-Z Plane Roll Center Migration – Steering



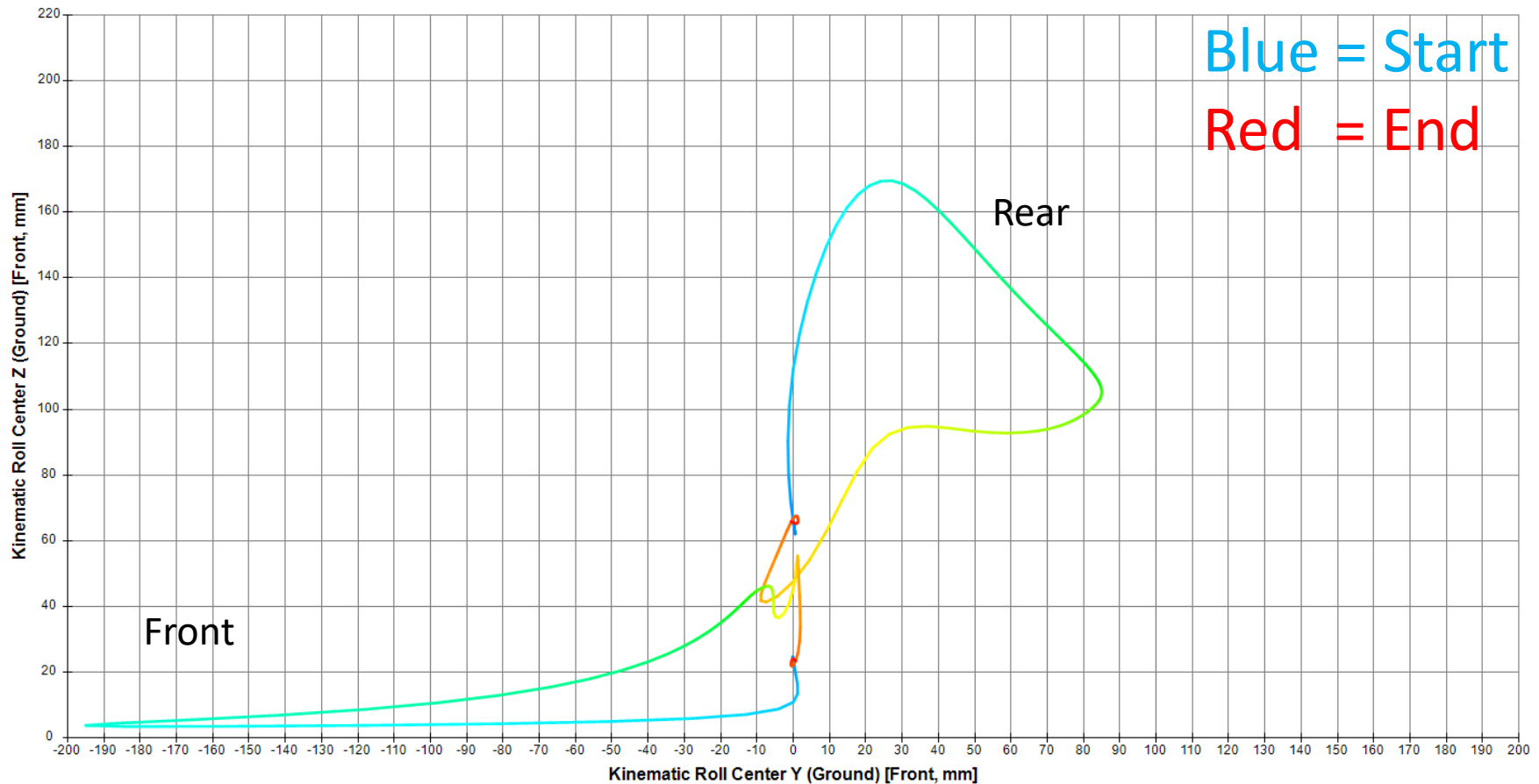
Vertical Roll Center Migration – Pitch



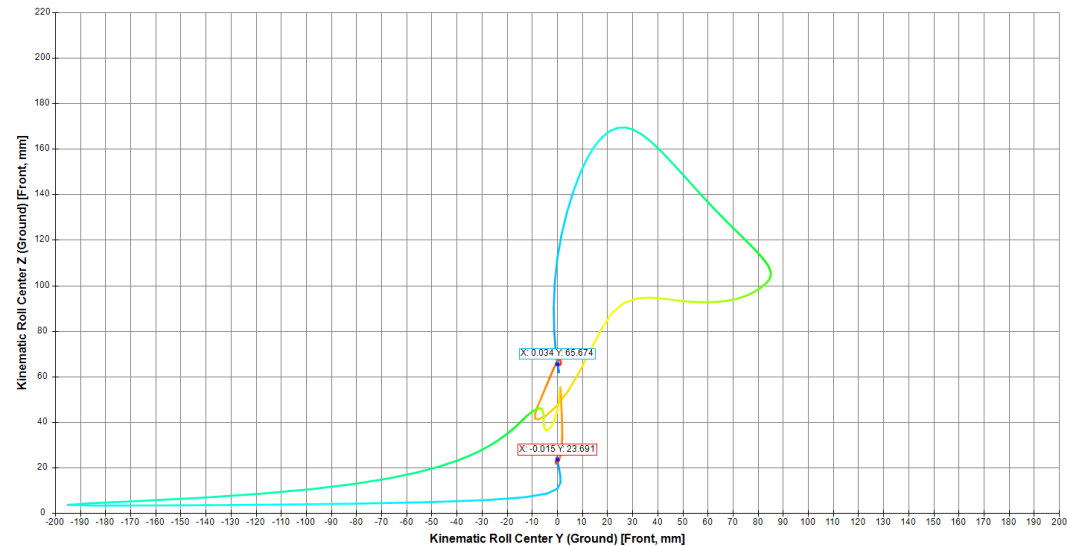
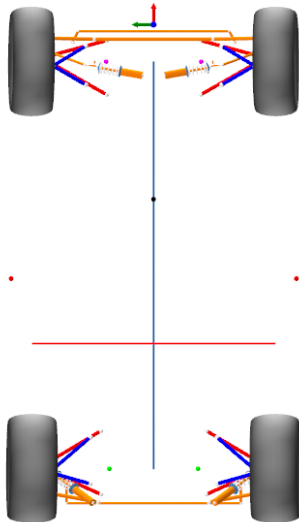
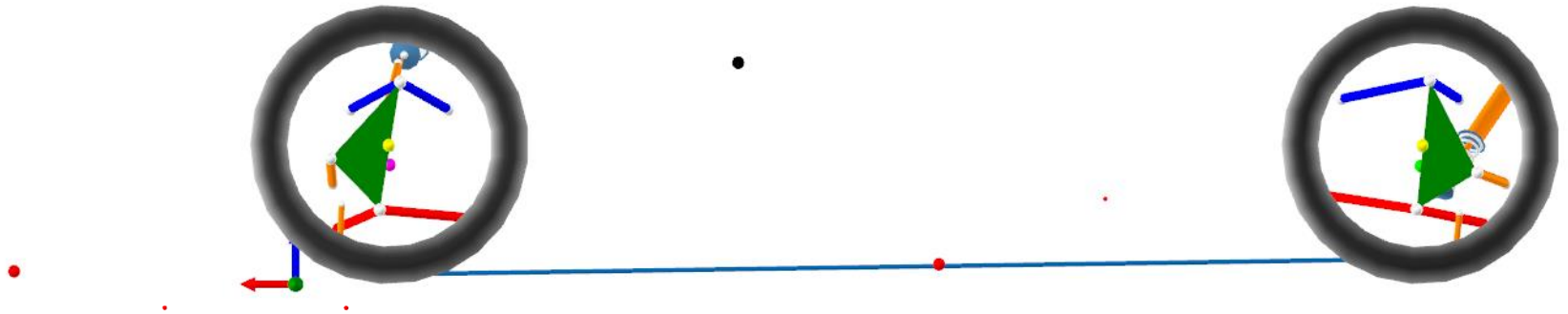
Roll Center Migration – Corner No DF



Roll Center Migration – Corner DF

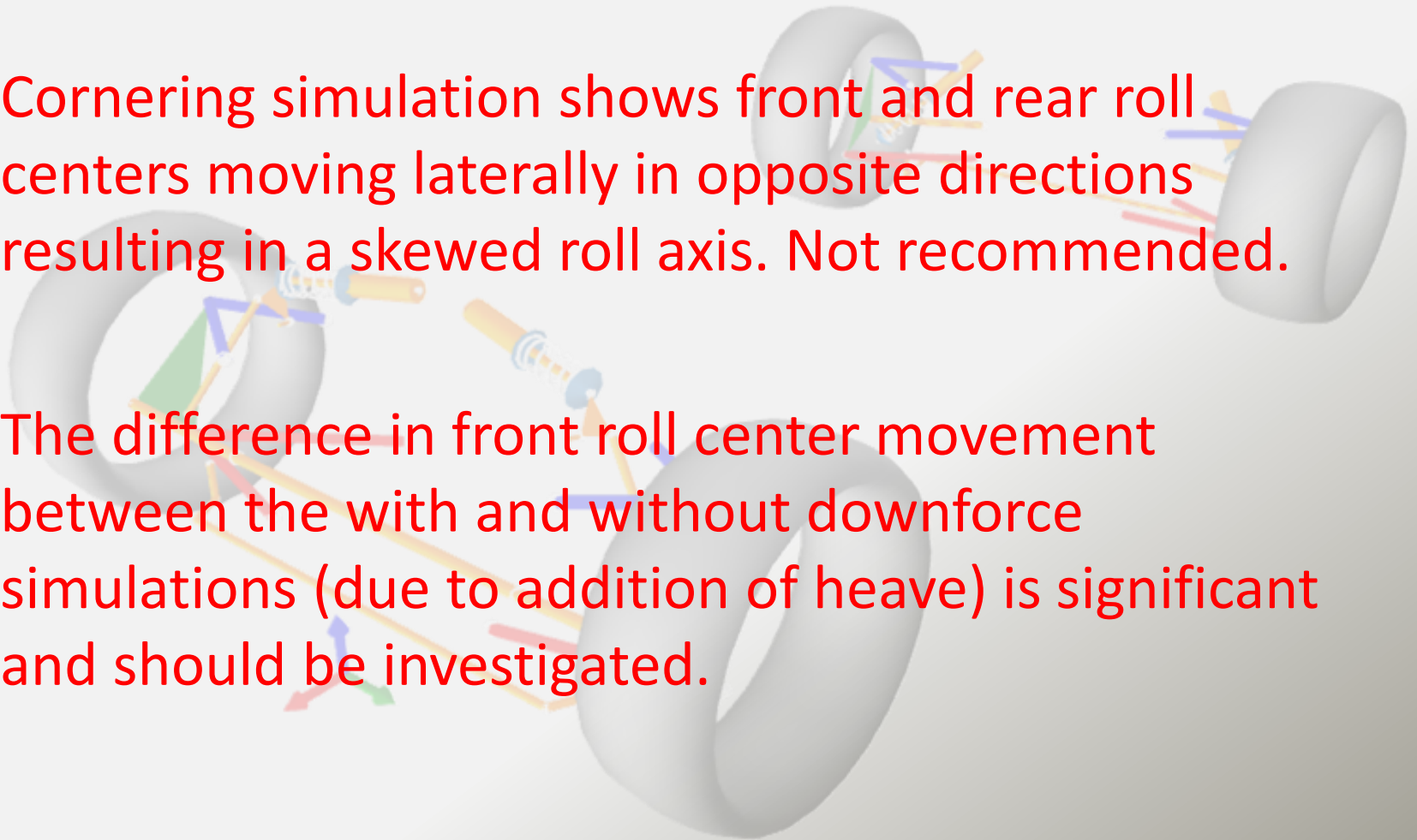


Roll Center Migration – Corner DF

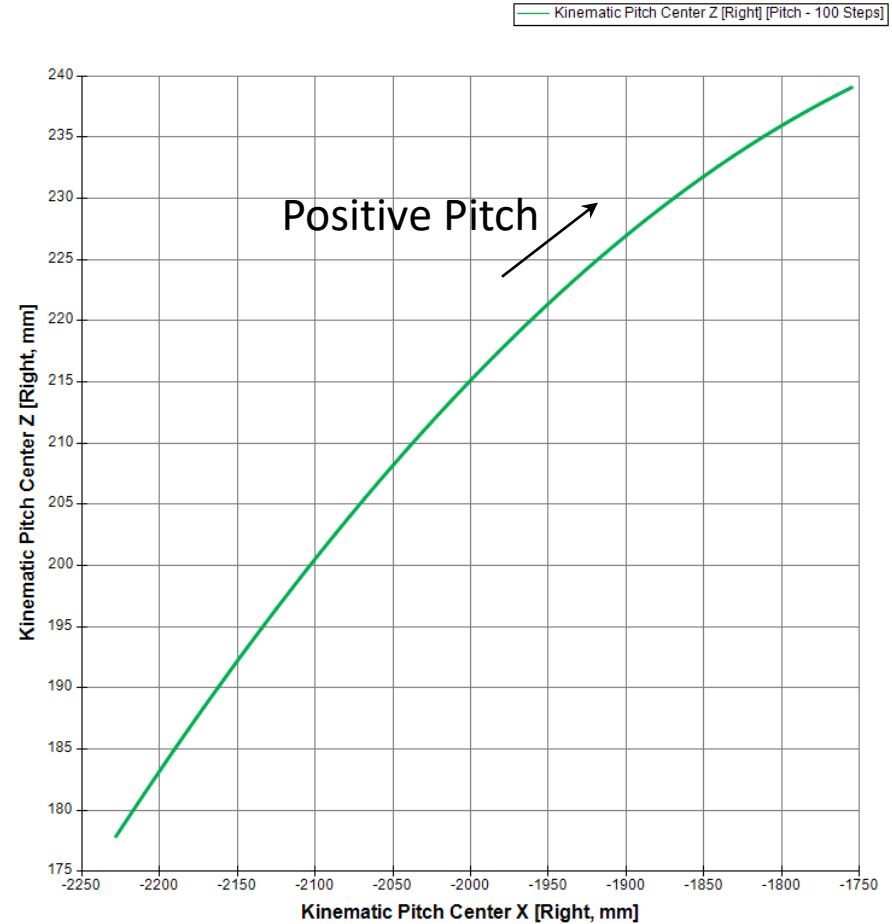
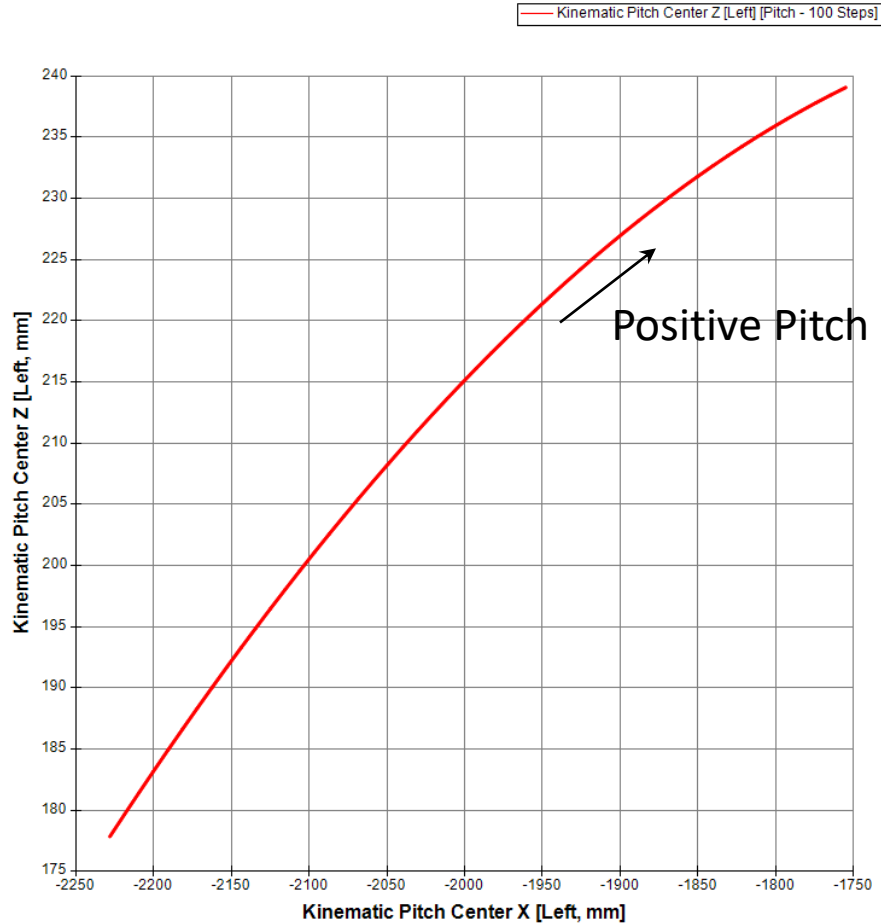


Roll Center Migration – Comments

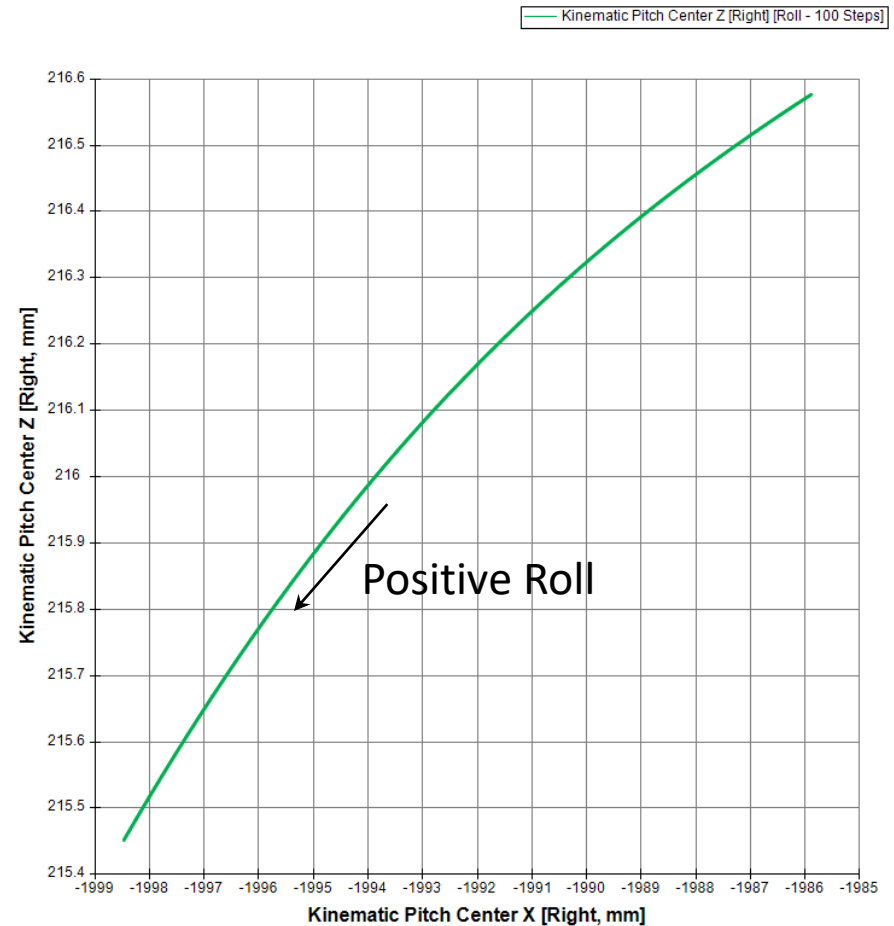
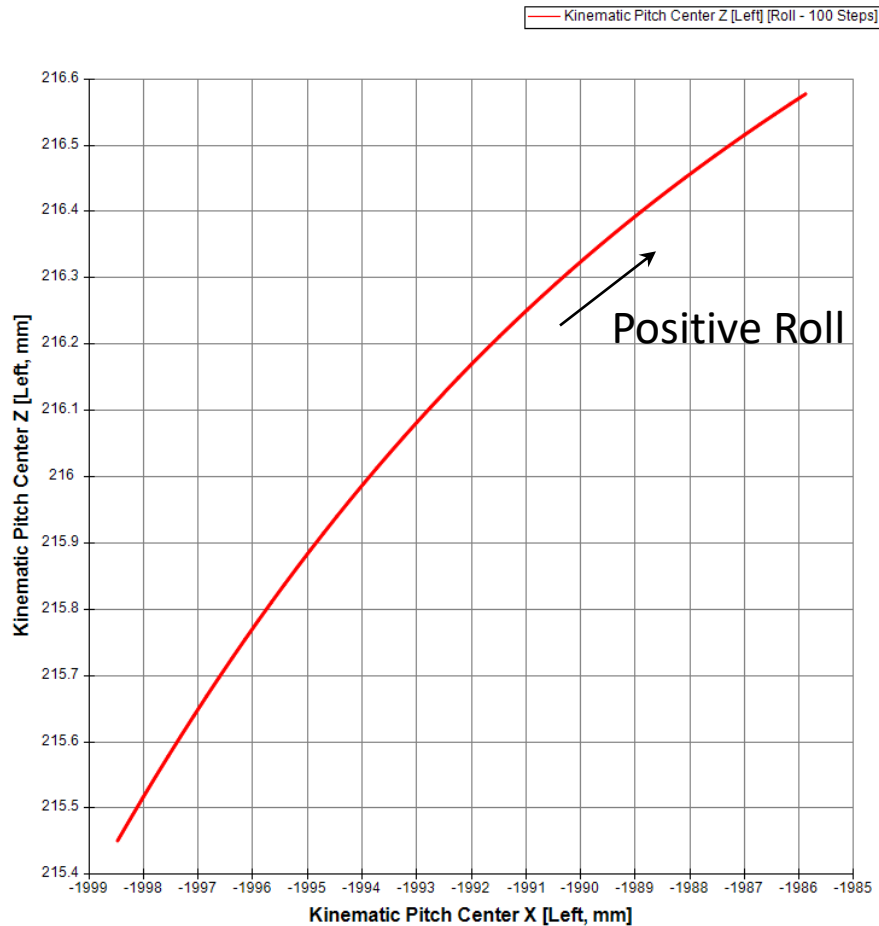
- Cornering simulation shows front and rear roll centers moving laterally in opposite directions resulting in a skewed roll axis. Not recommended.
- The difference in front roll center movement between the with and without downforce simulations (due to addition of heave) is significant and should be investigated.



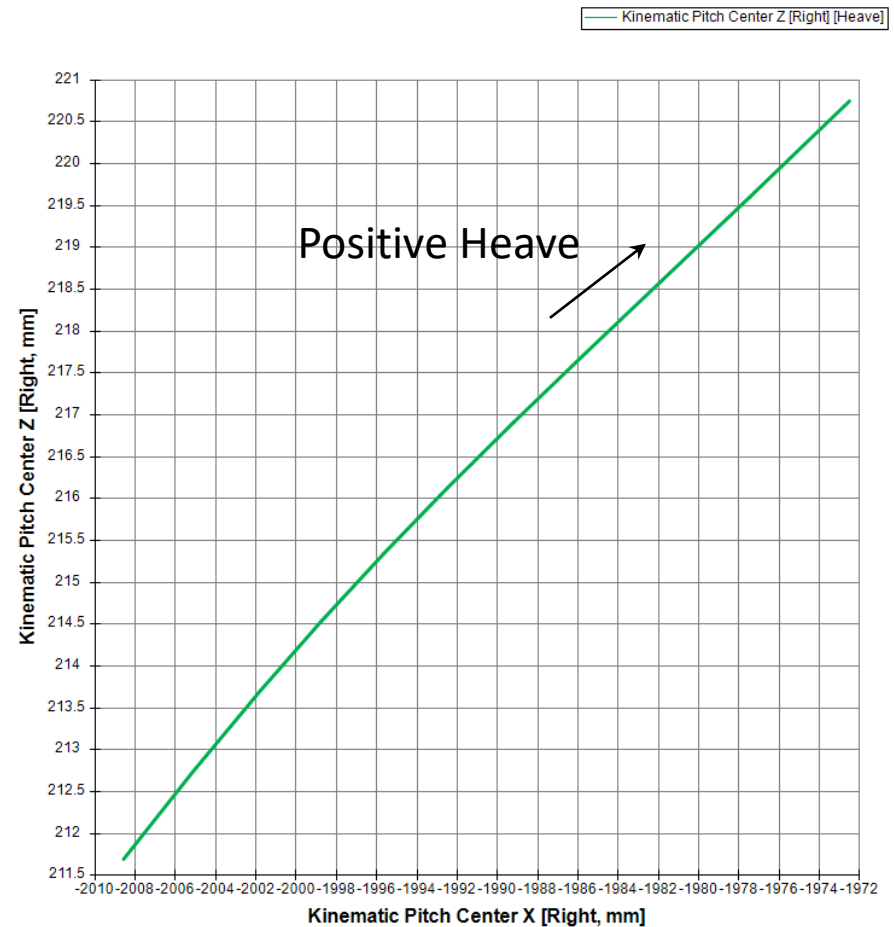
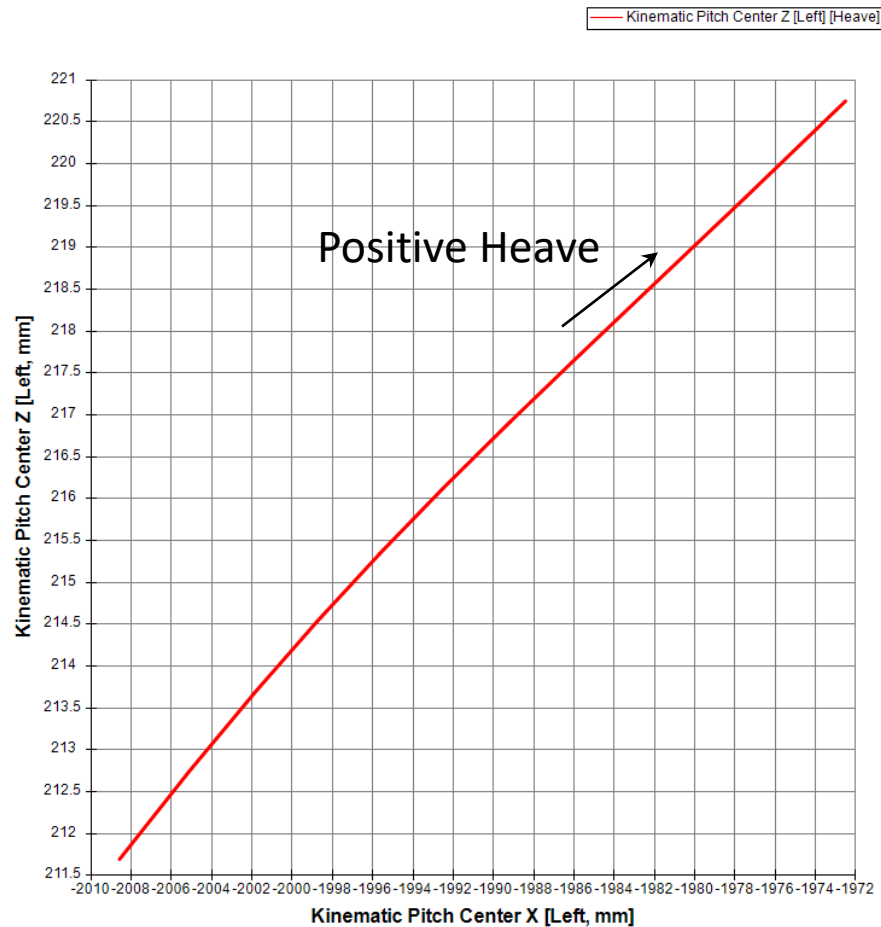
Pitch Center Migration – Pitch



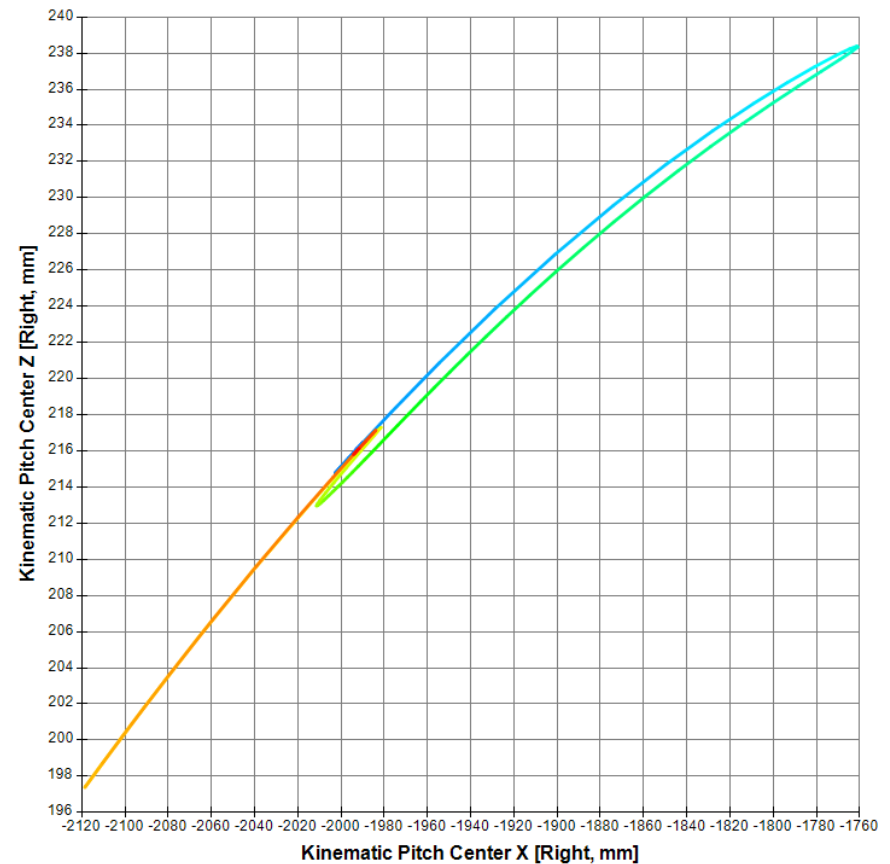
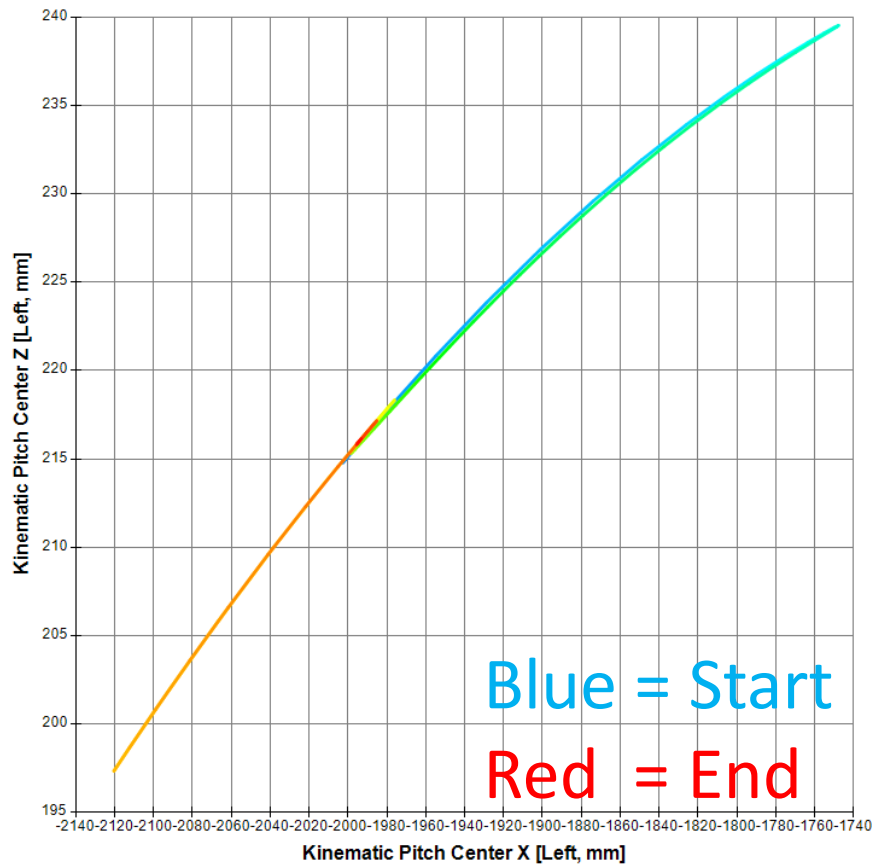
Pitch Center Migration – Roll



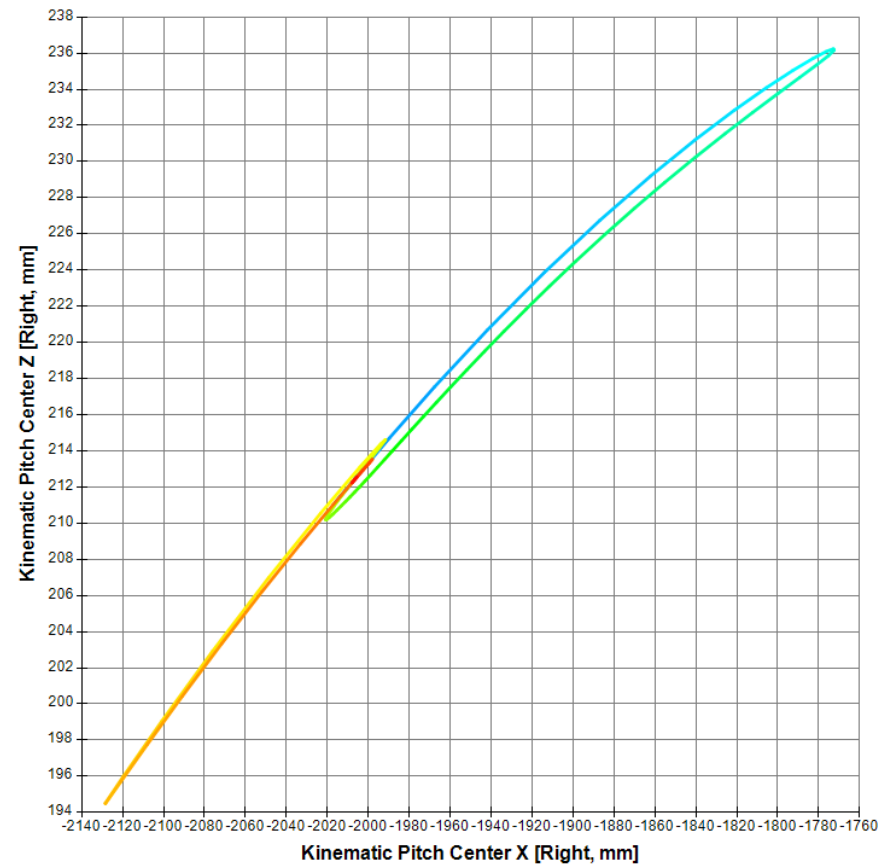
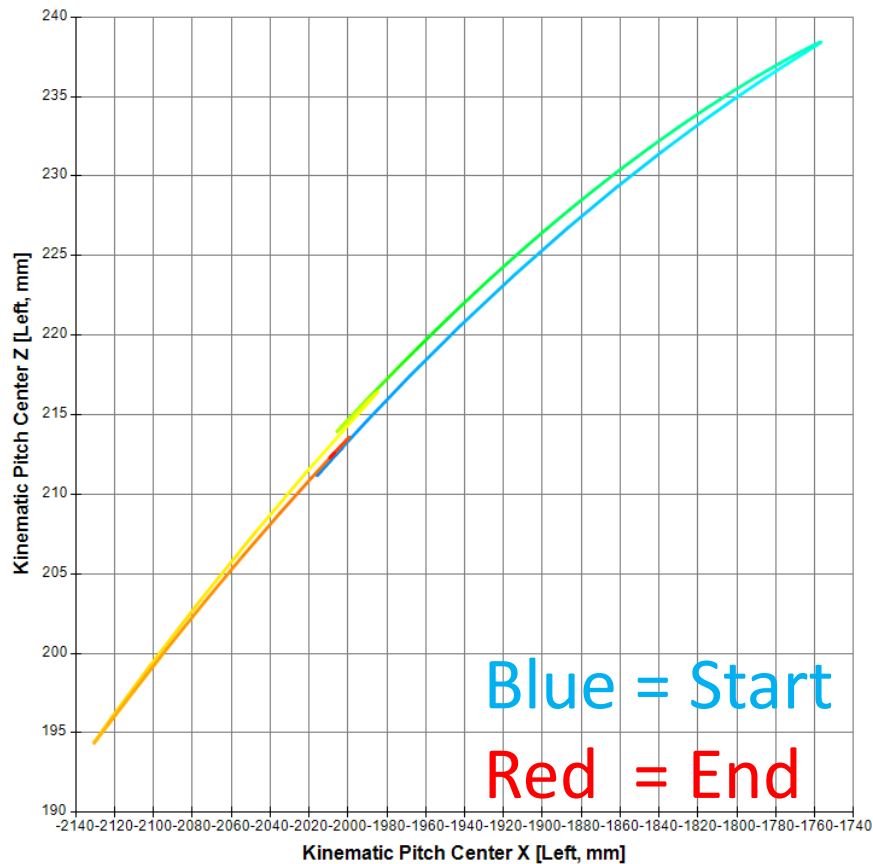
Pitch Center Migration – Heave



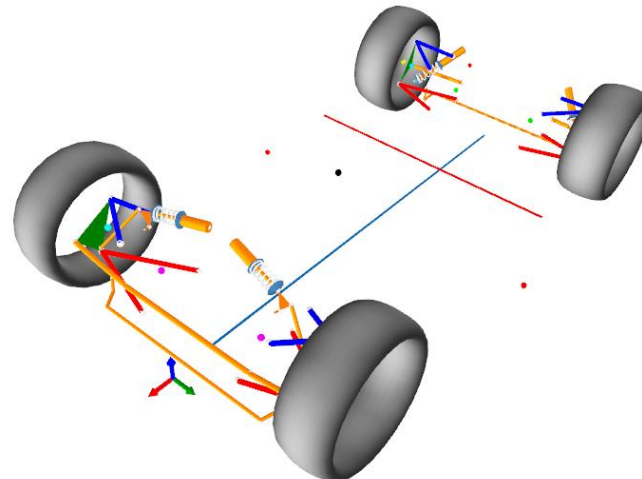
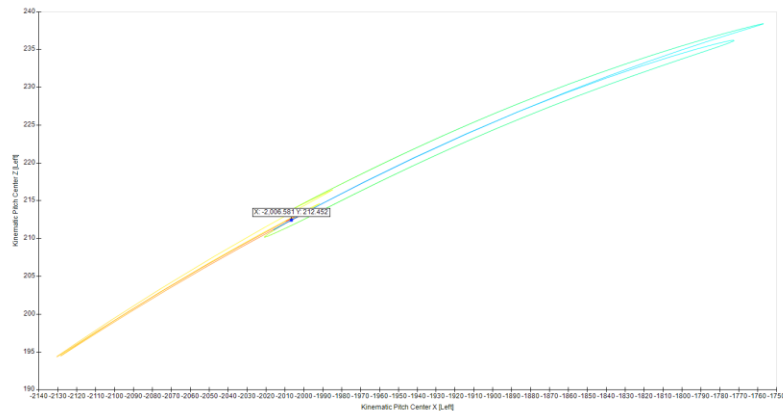
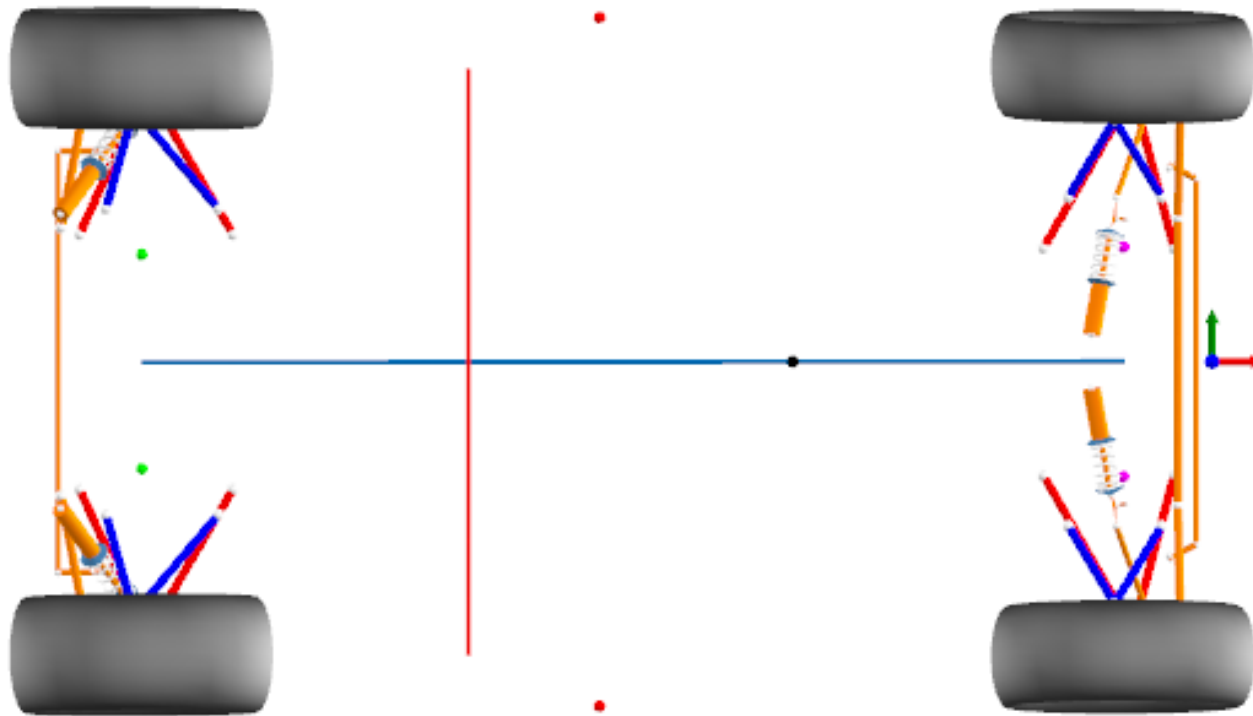
Pitch Center Migration – Corner No DF



Pitch Center Migration – Corner DF



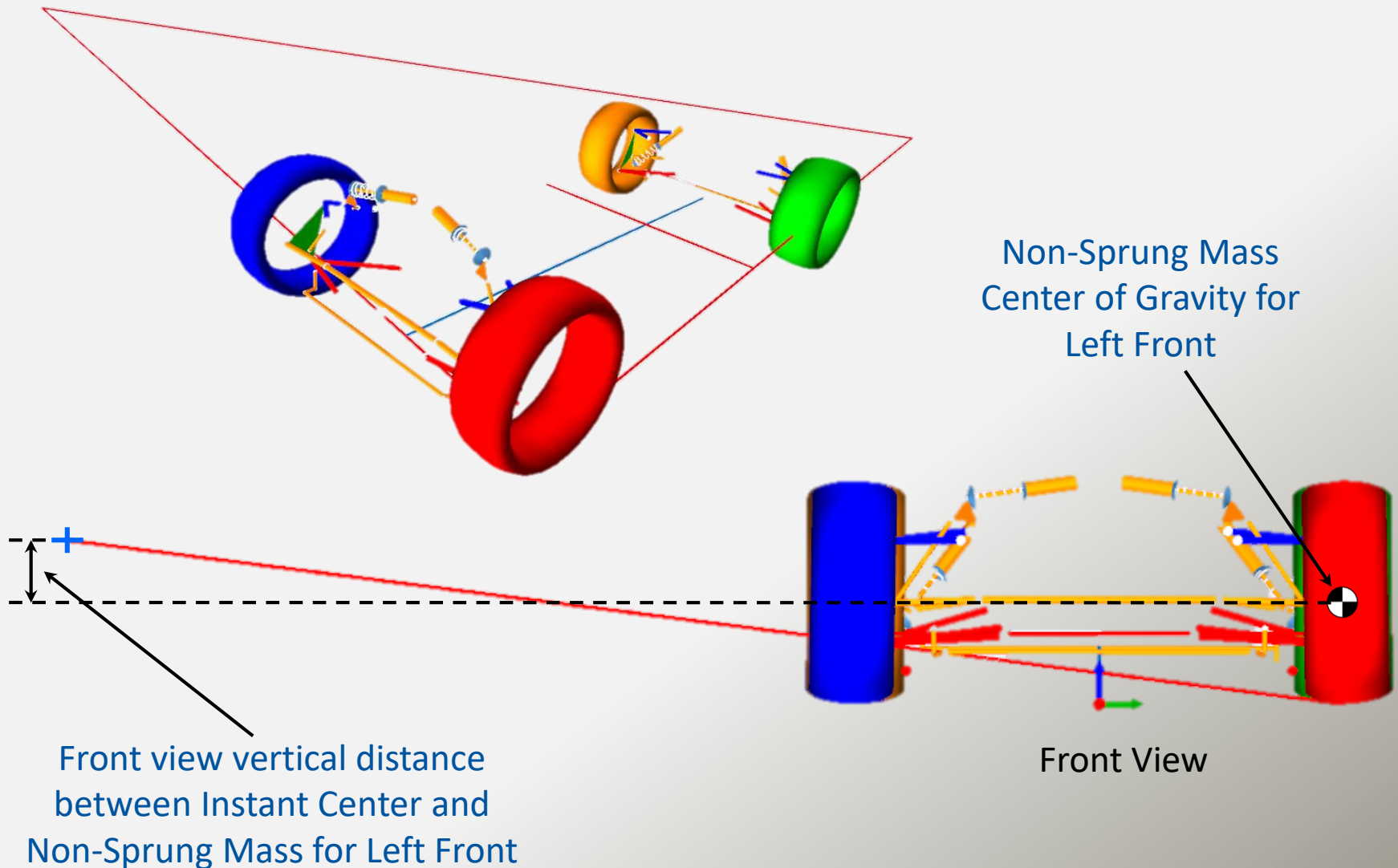
Pitch Center Migration – Corner DF



Pitch Center Migration – Comments

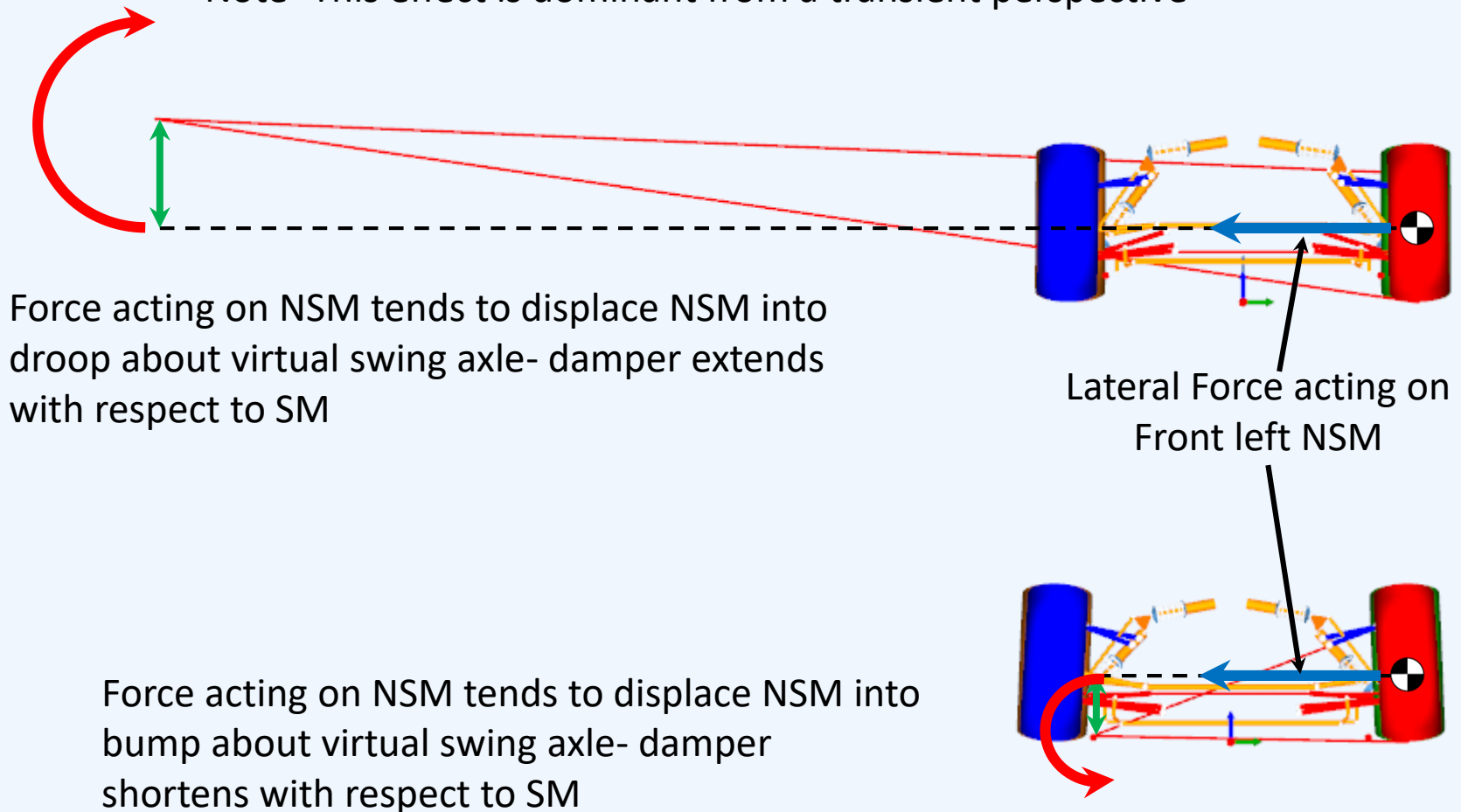
- Cornering simulation shows left and right pitch centers moving longitudinal in opposite directions resulting in a skewed pitch axis
- Pitch axis skew pronounced in cornering simulation without downforce- no heave

Front View IC to NSM CG Distance

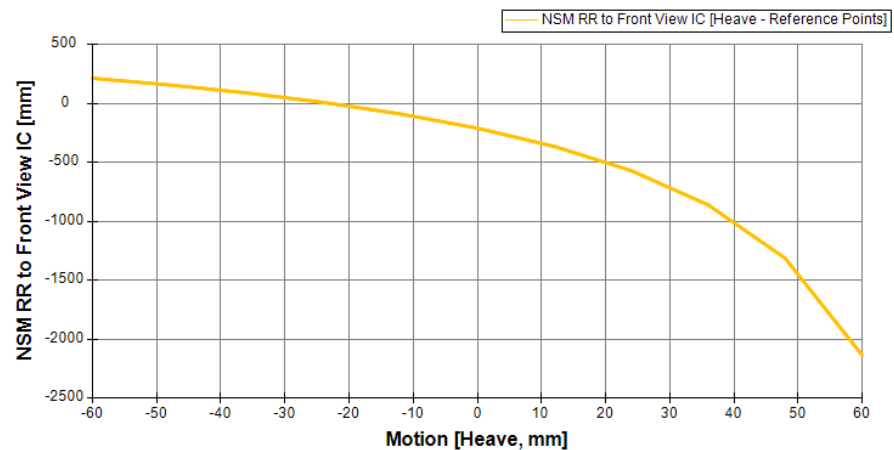
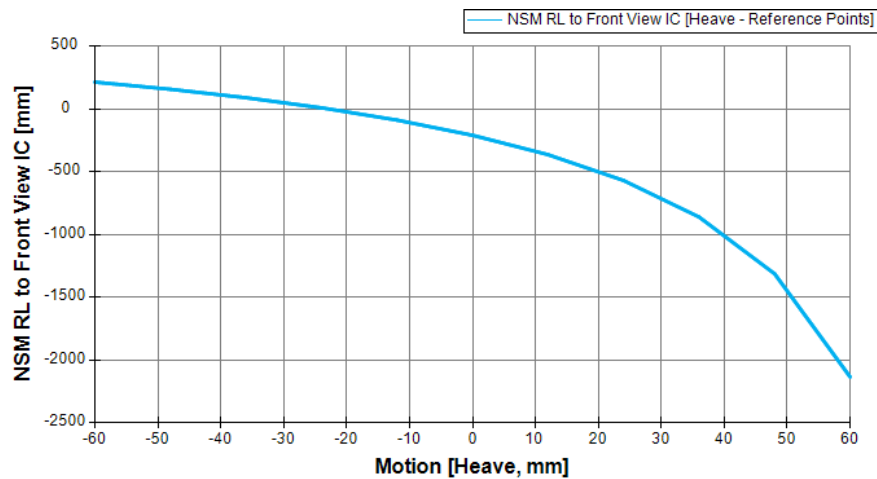
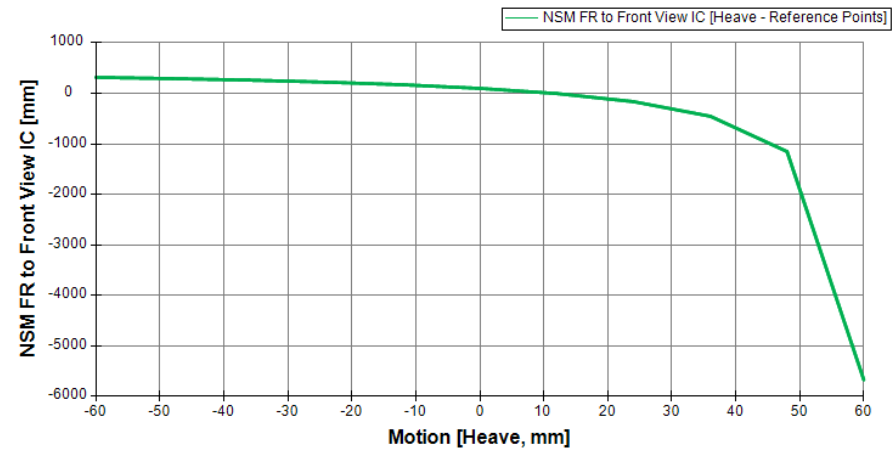
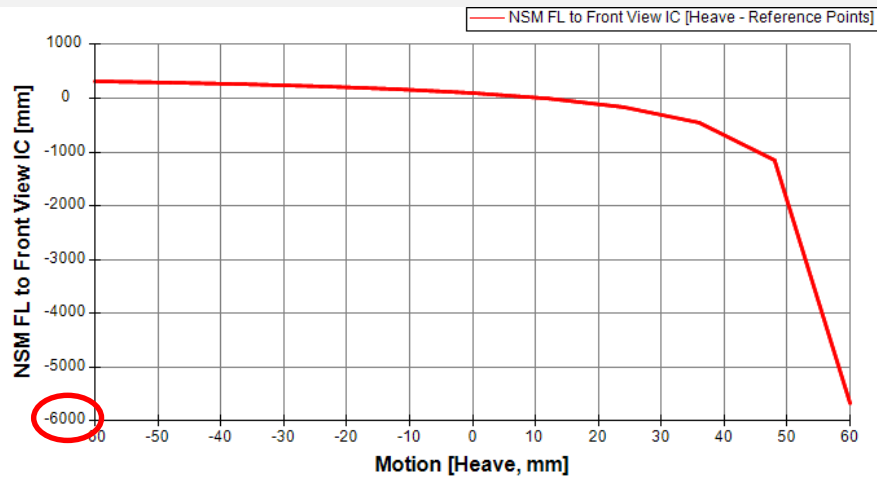


Front View IC to NSM CG Distance

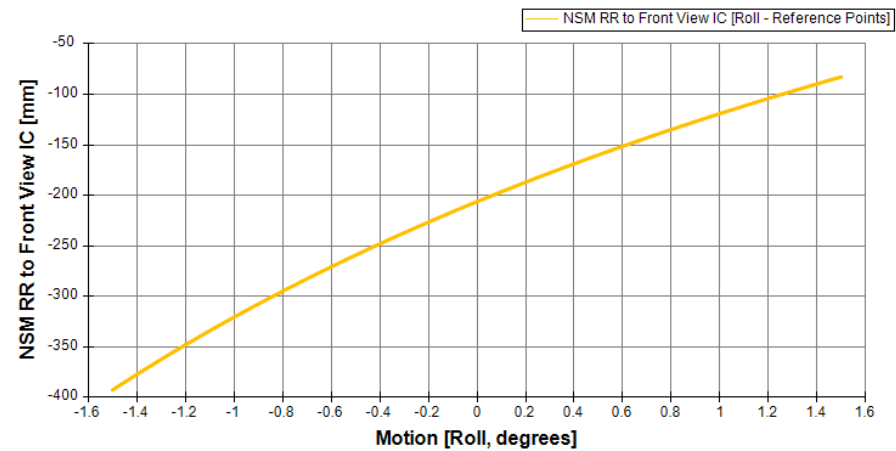
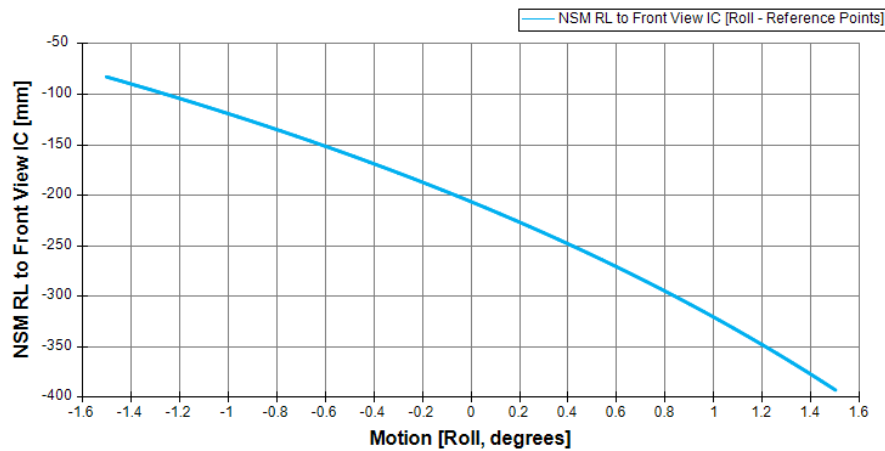
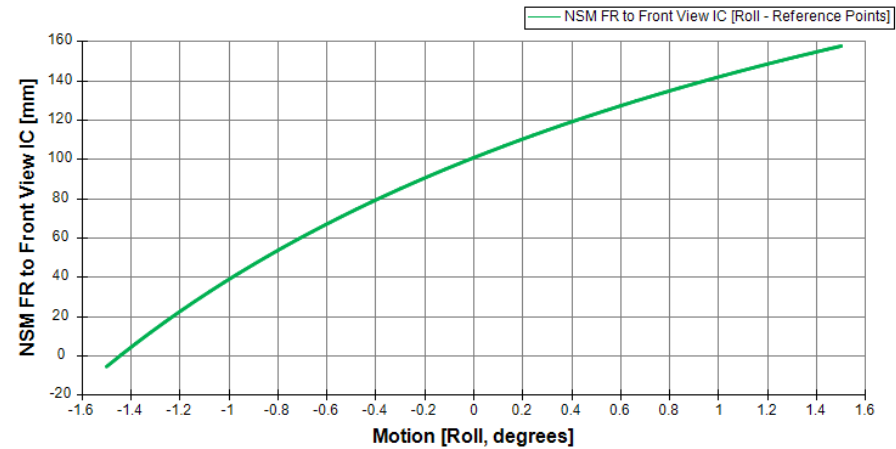
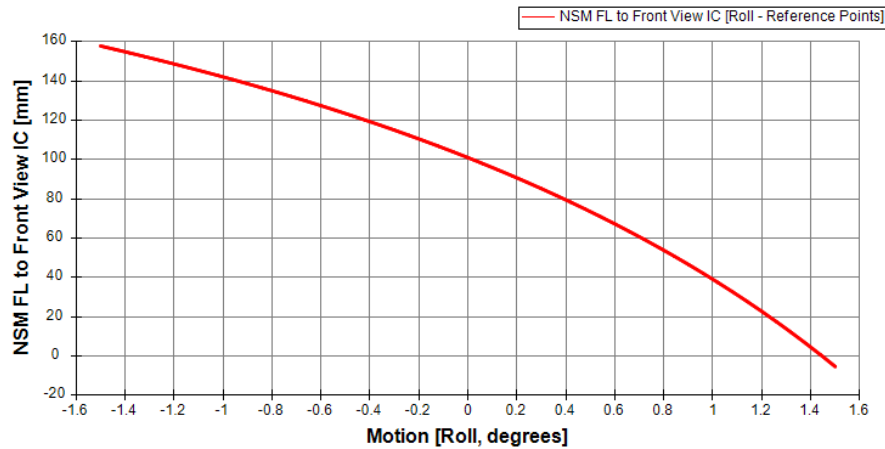
Note- This effect is dominant from a transient perspective



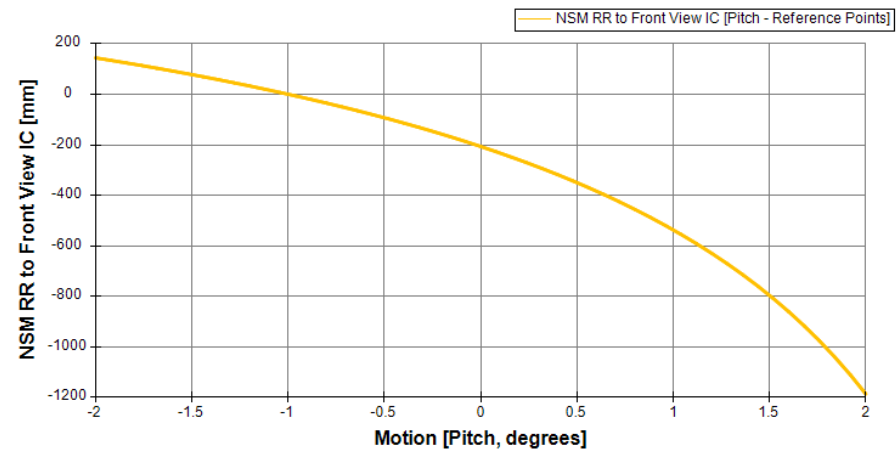
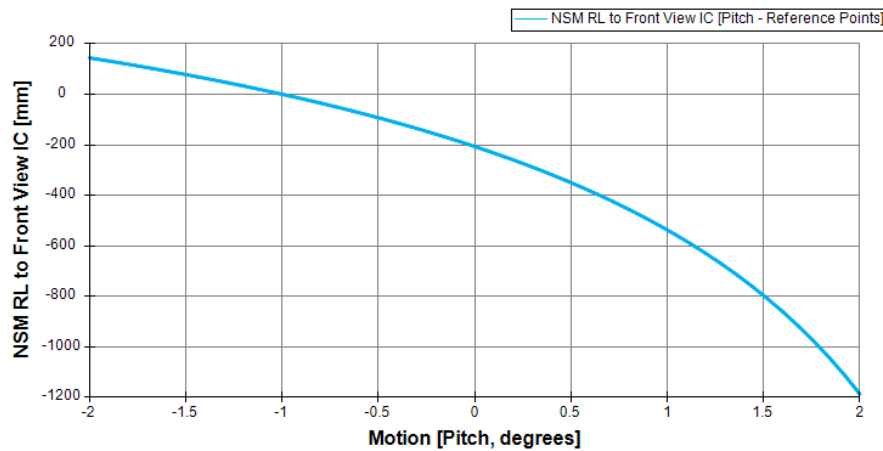
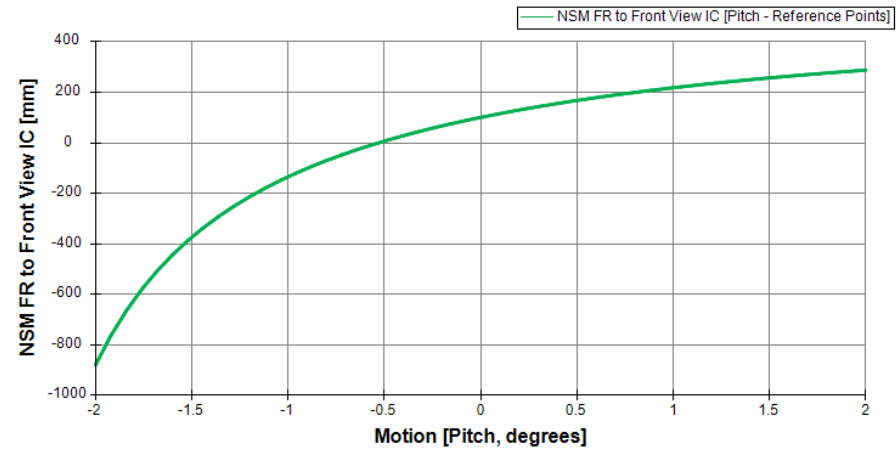
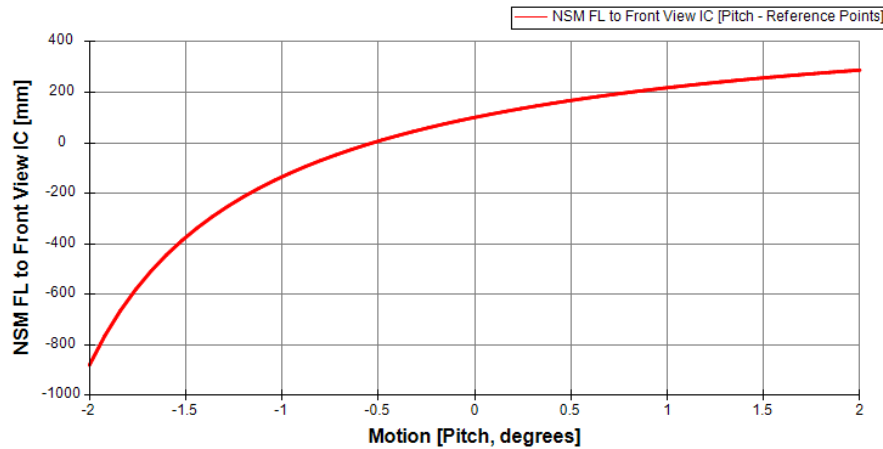
Front View IC to NSM CG Distance- Heave



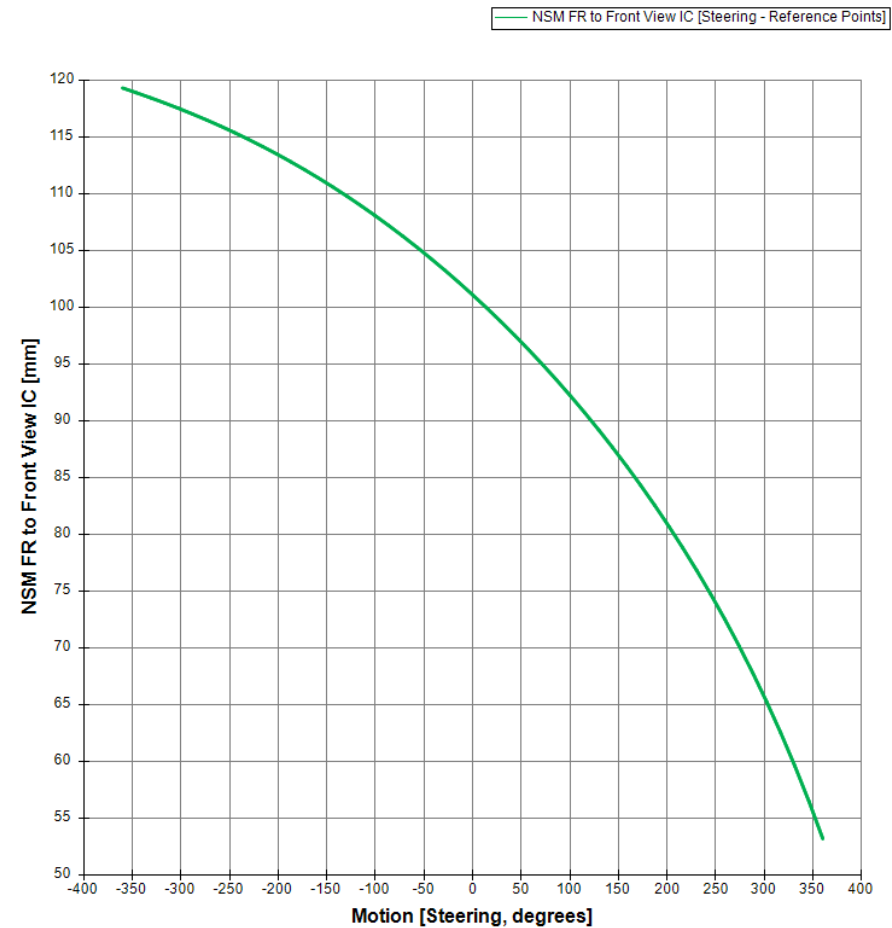
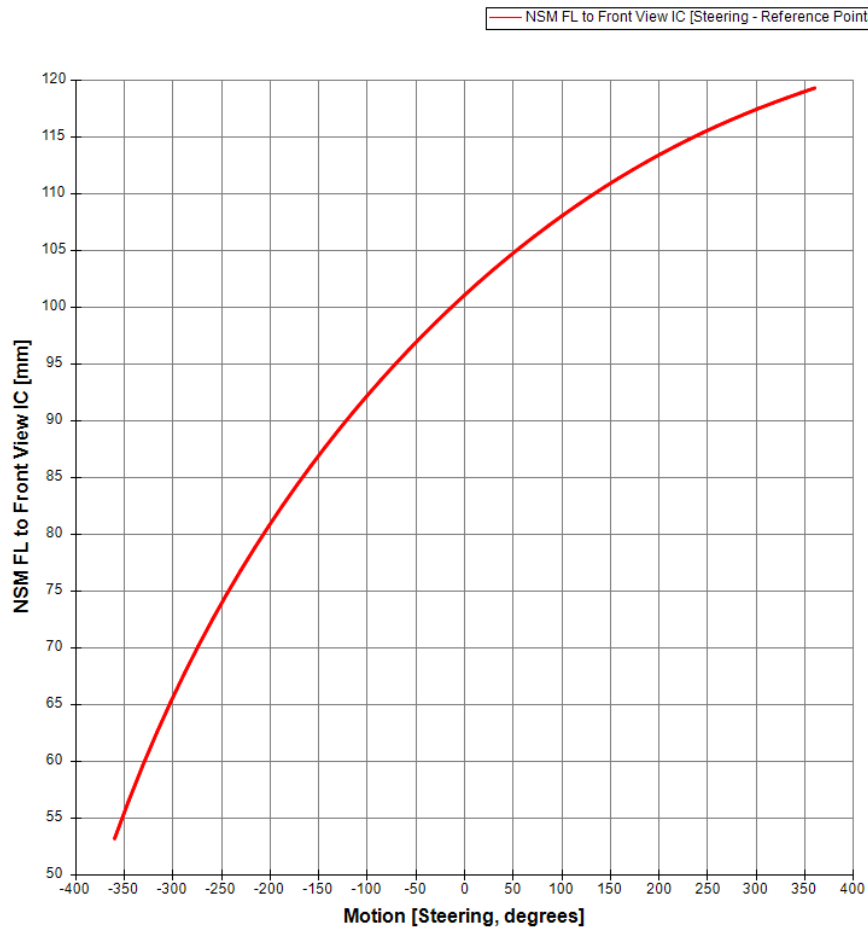
Front View IC to NSM CG Distance- Roll



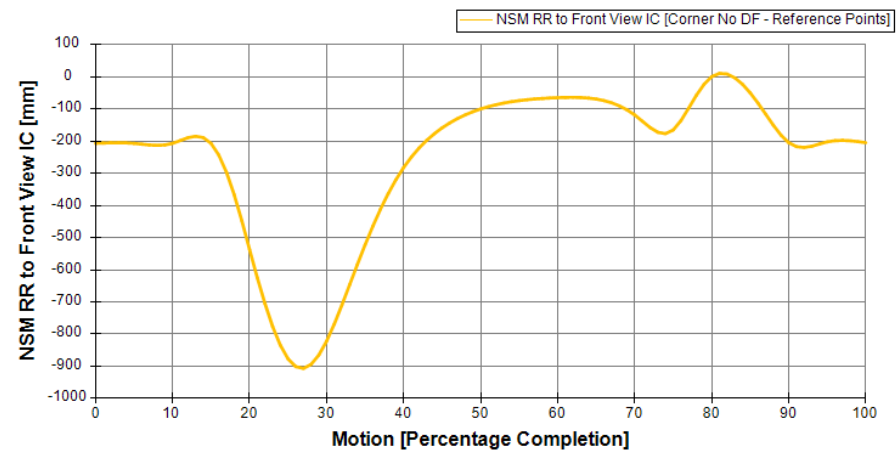
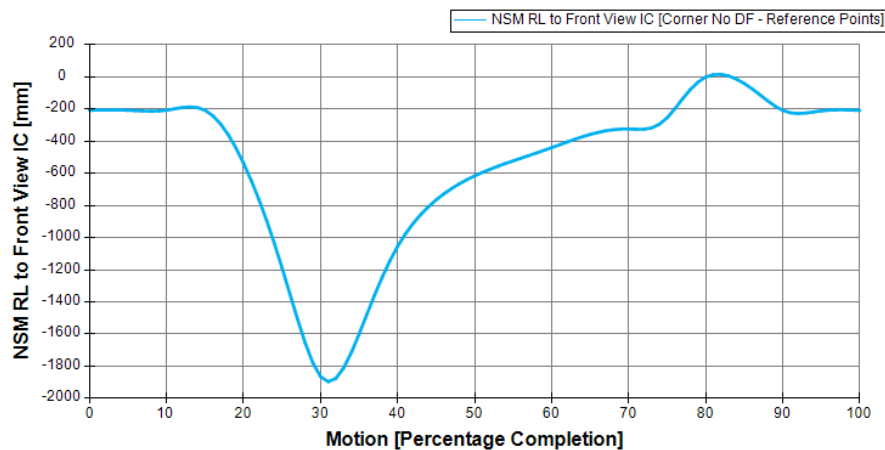
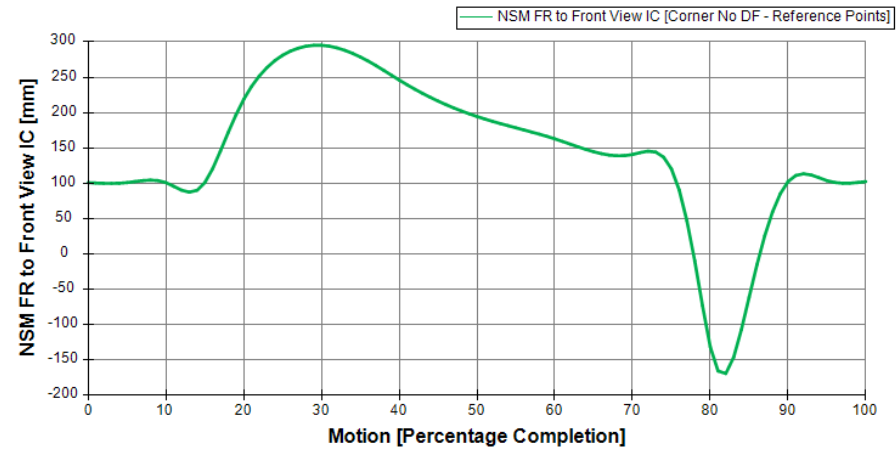
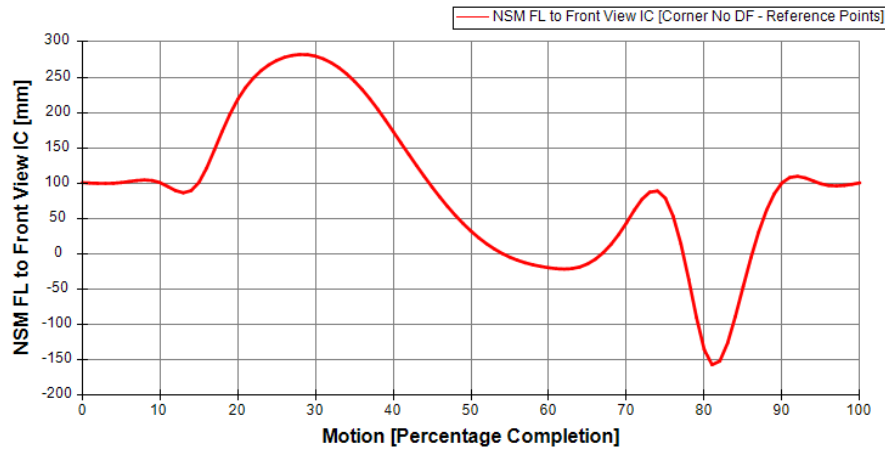
Front View IC to NSM CG Distance- Pitch



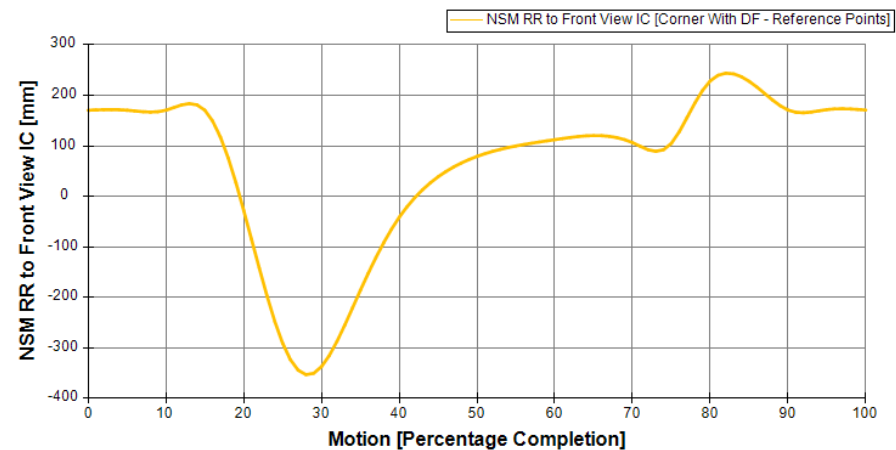
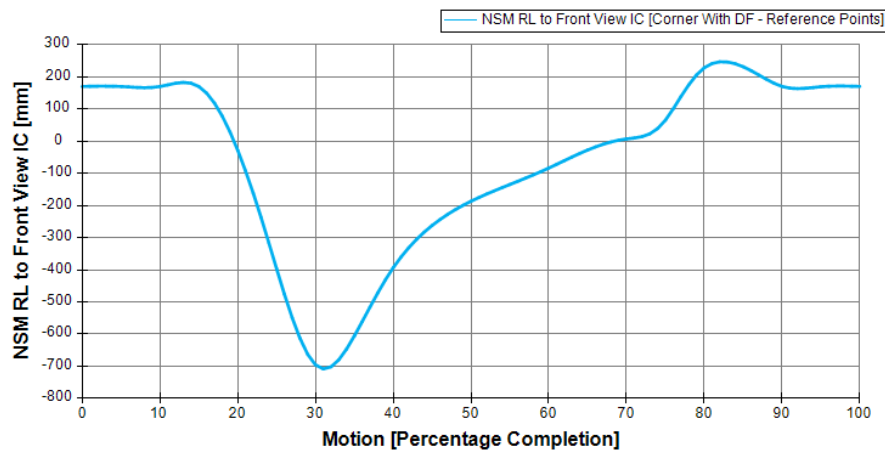
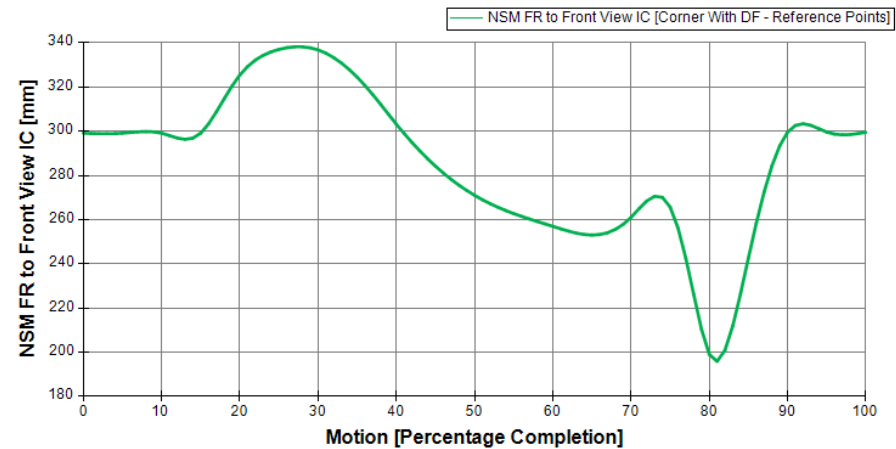
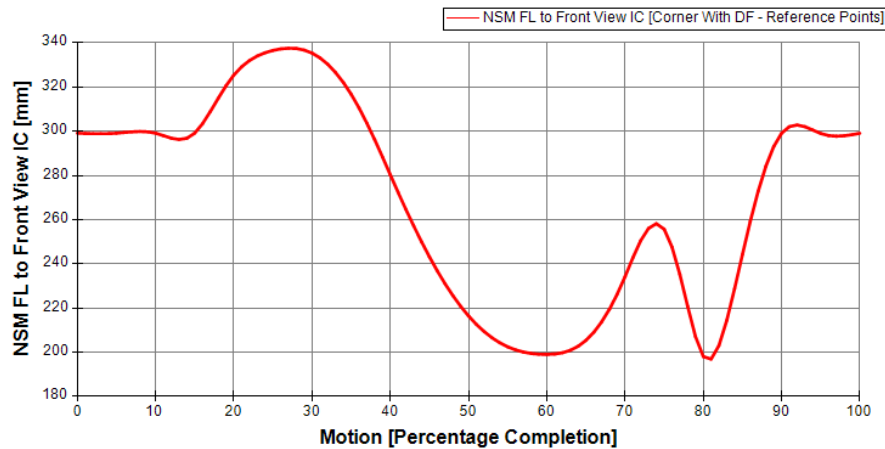
Front View IC to NSM CG Distance- Steering



Front View IC to NSM CG Distance- Corner without Downforce



Front View IC to NSM CG Distance- Corner with Downforce

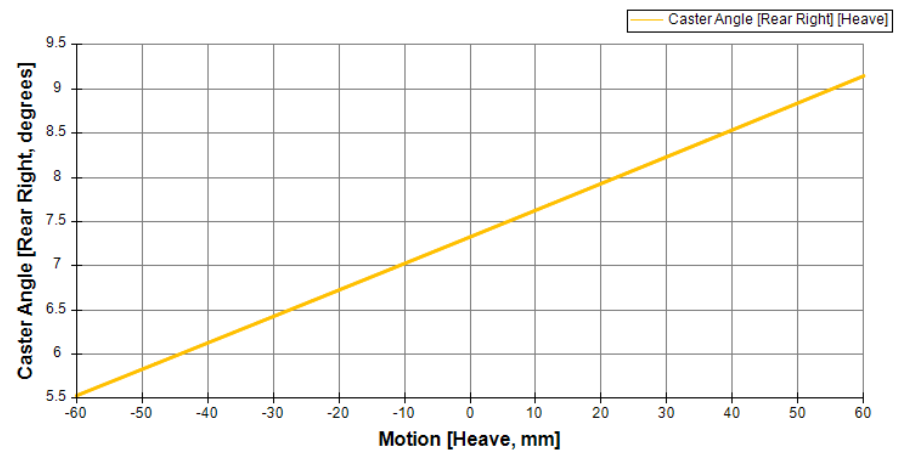
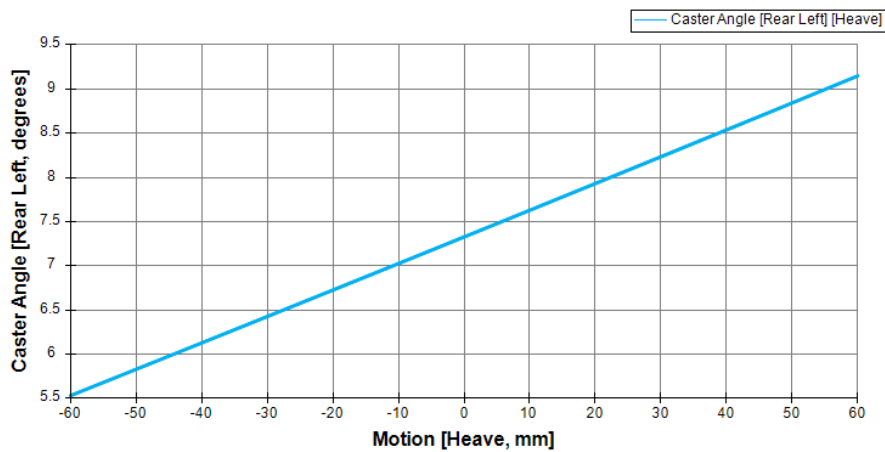
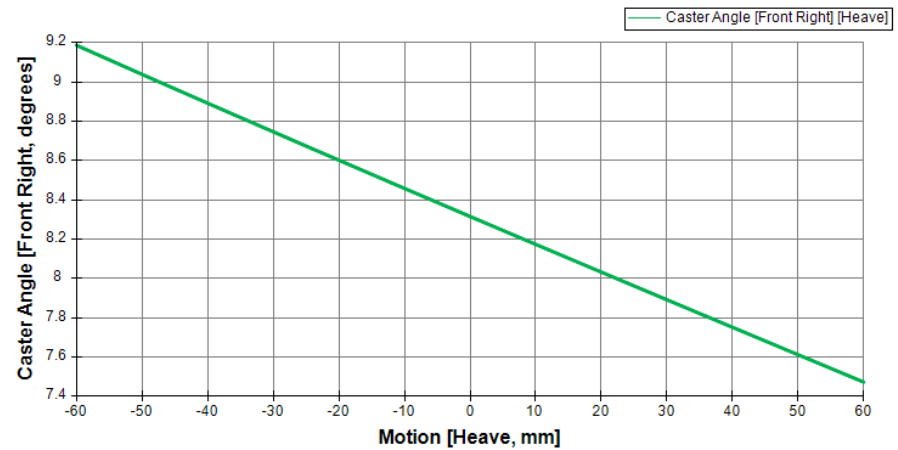
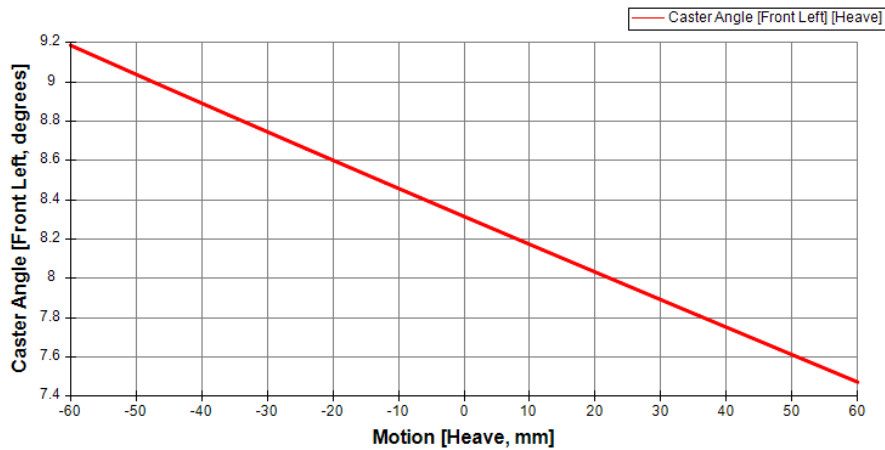


Front View IC to NSM CG Distance– Comments

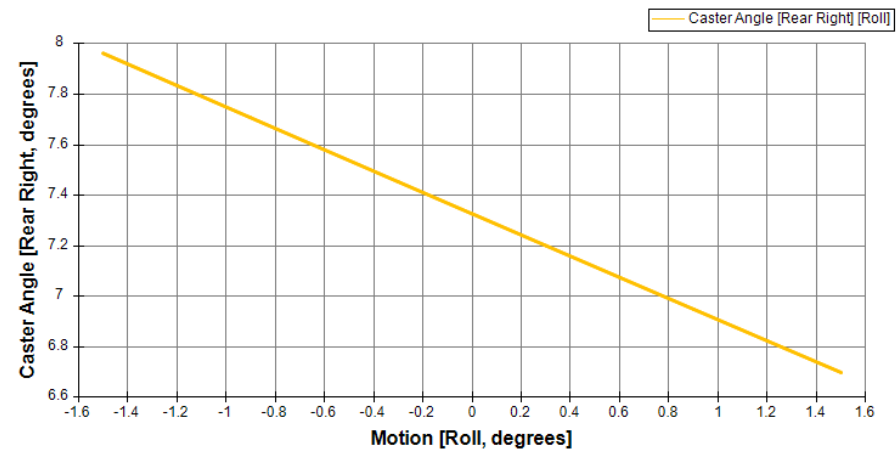
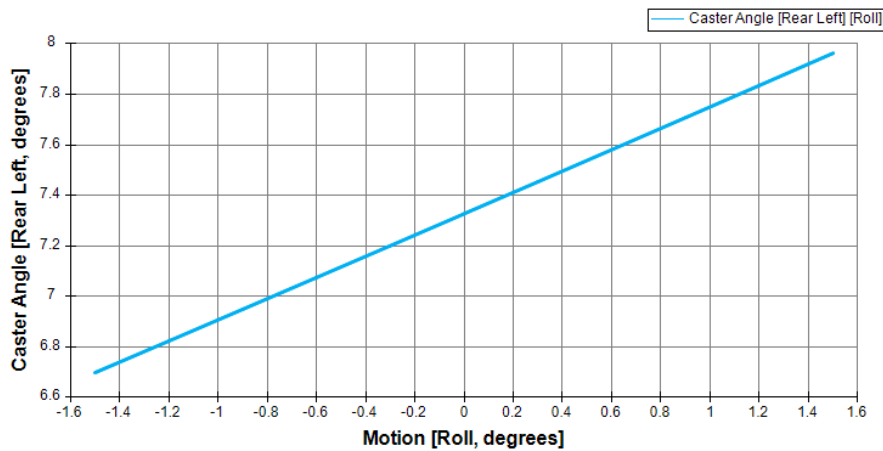
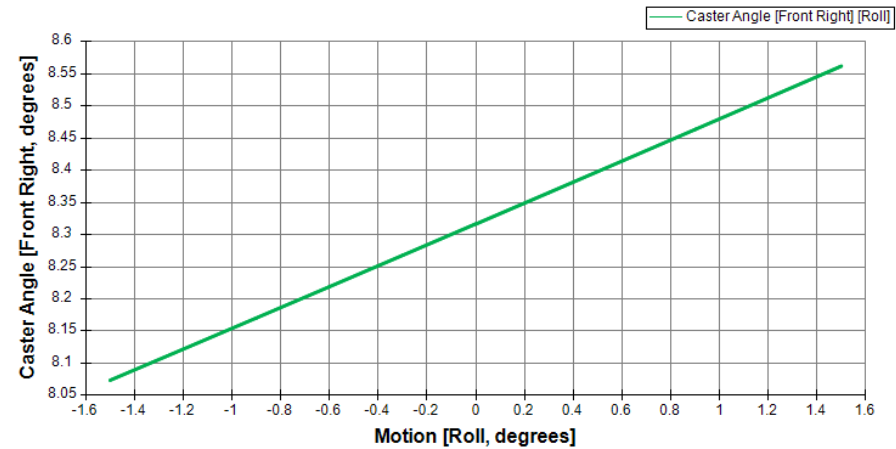
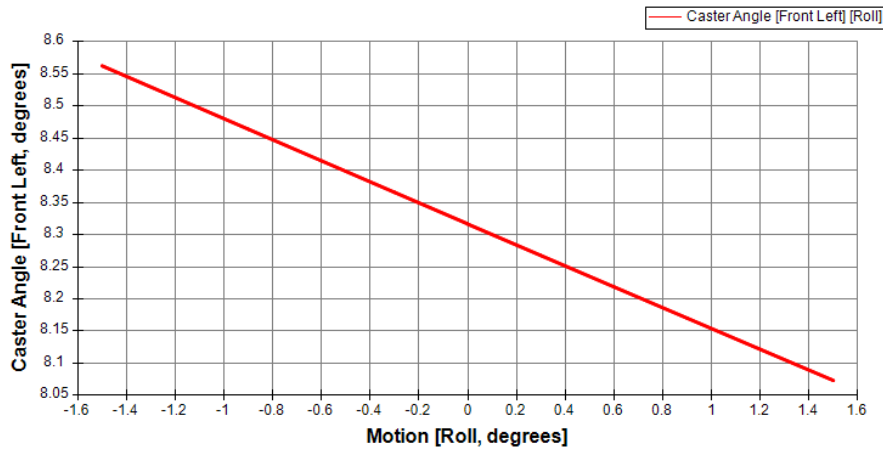
Transient tire contact patch load variation due to this effect depends on-

- Magnitude (and direction) of Sprung Mass roll moment and inertia
- Magnitude (and direction) of Non-Sprung Mass roll moment about IC and inertia
- Damper response

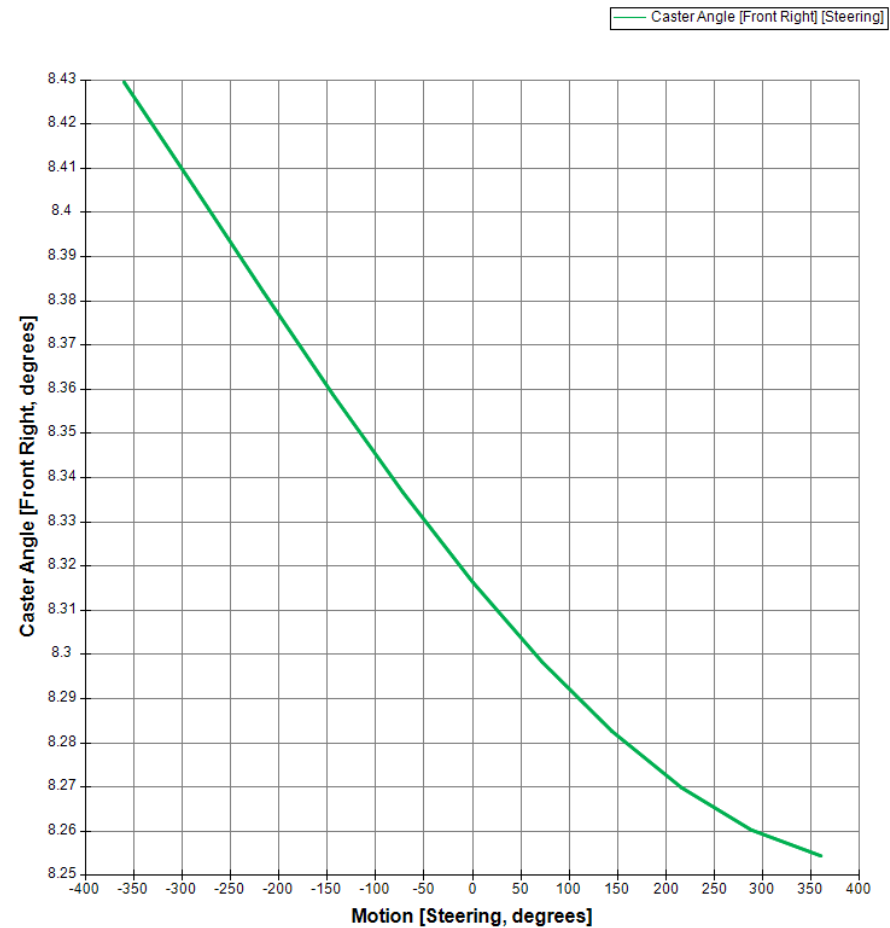
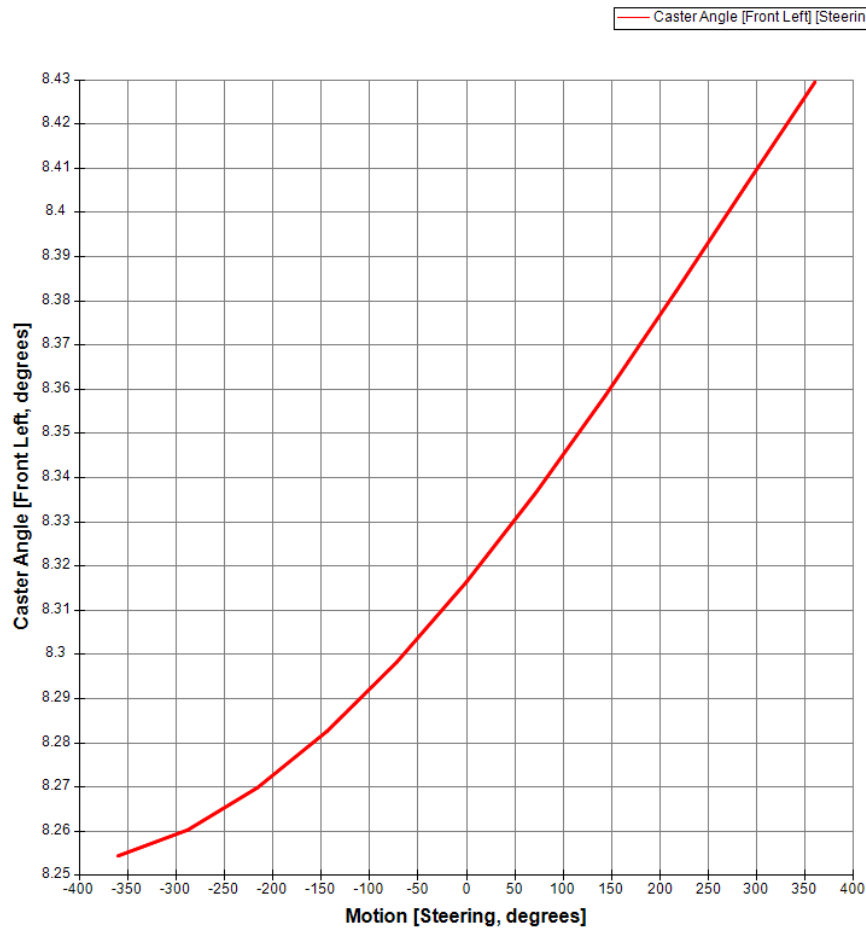
Caster Angle - Heave



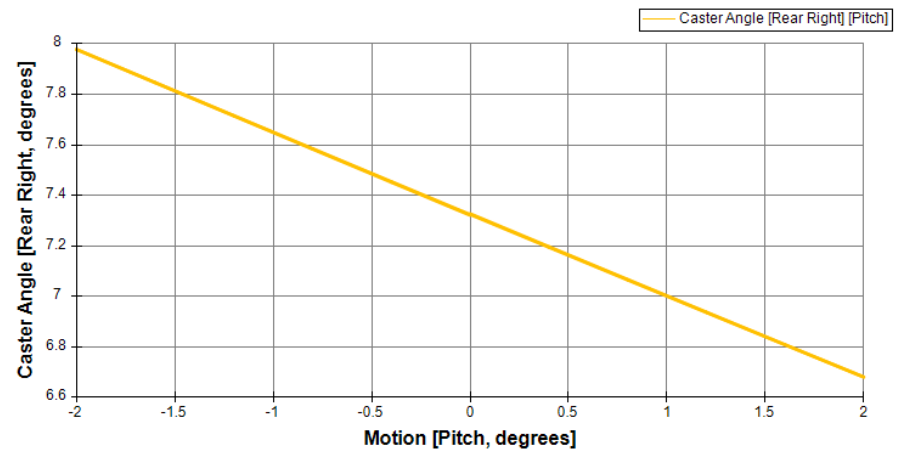
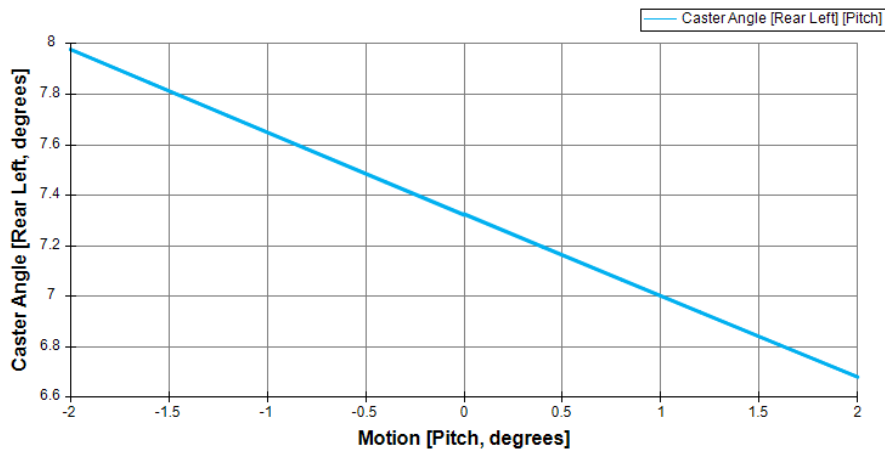
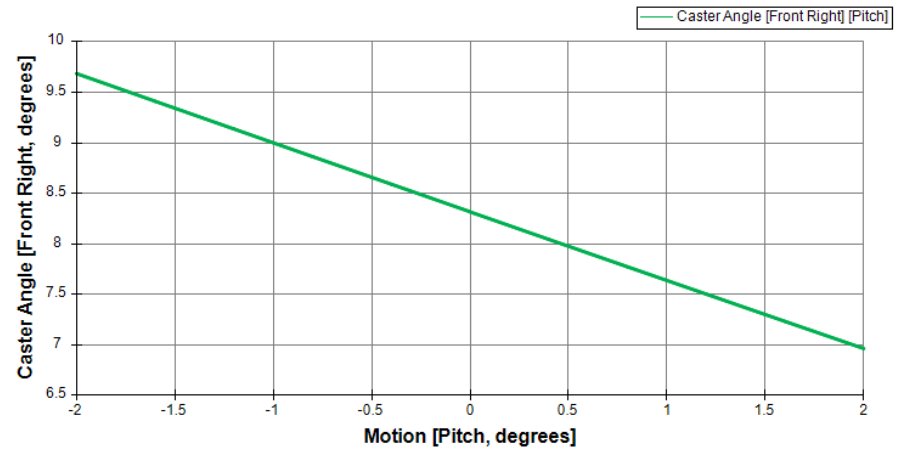
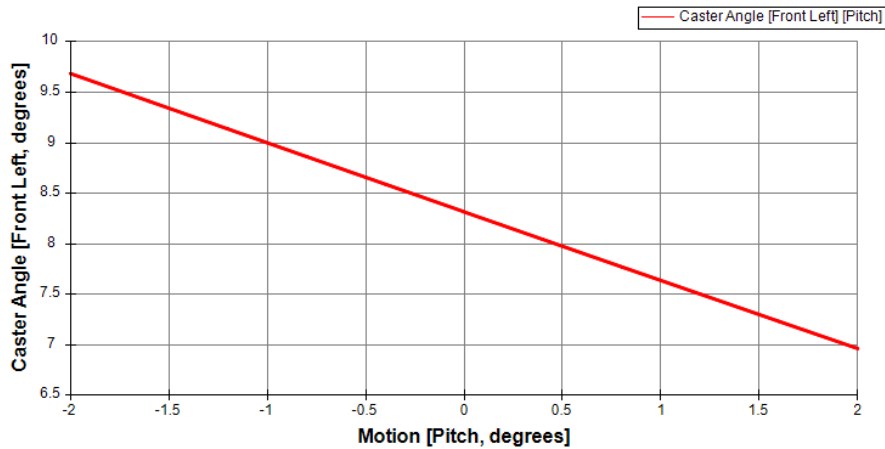
Caster Angle - Roll



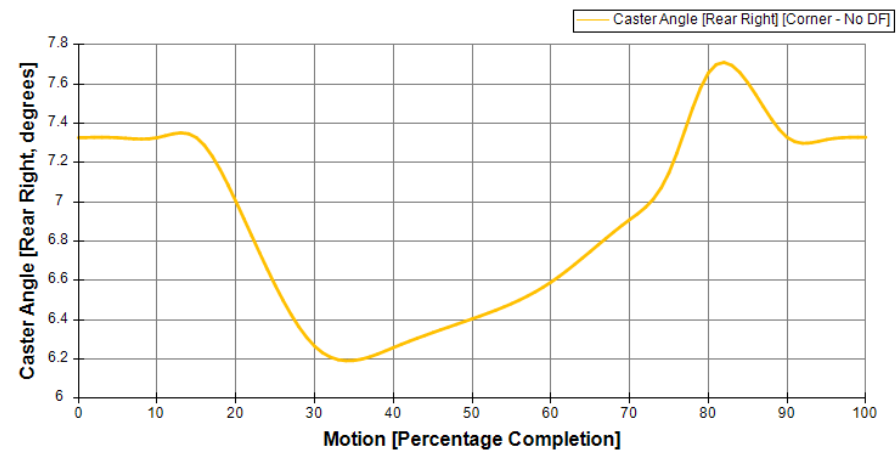
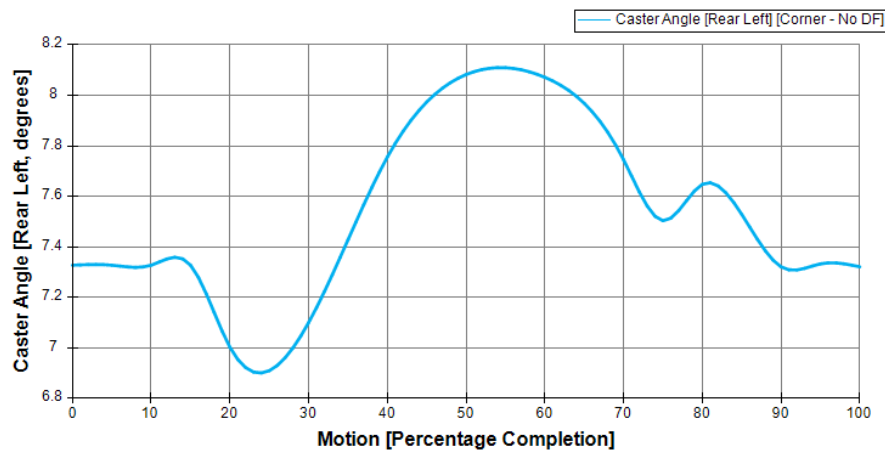
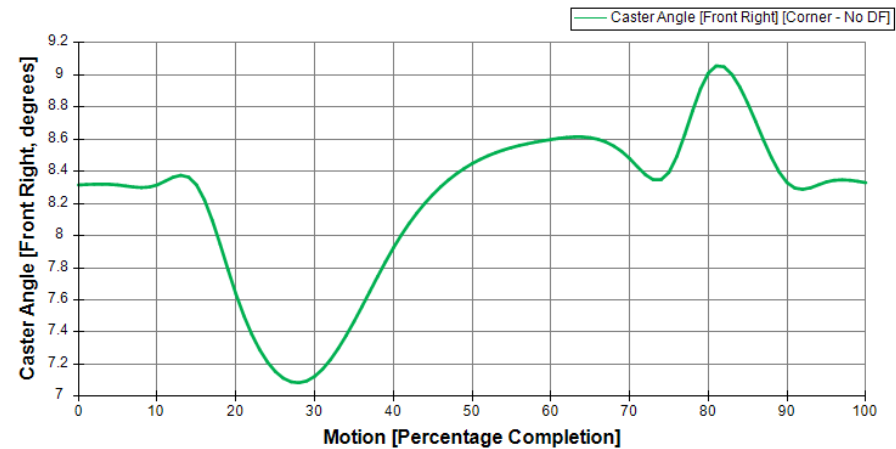
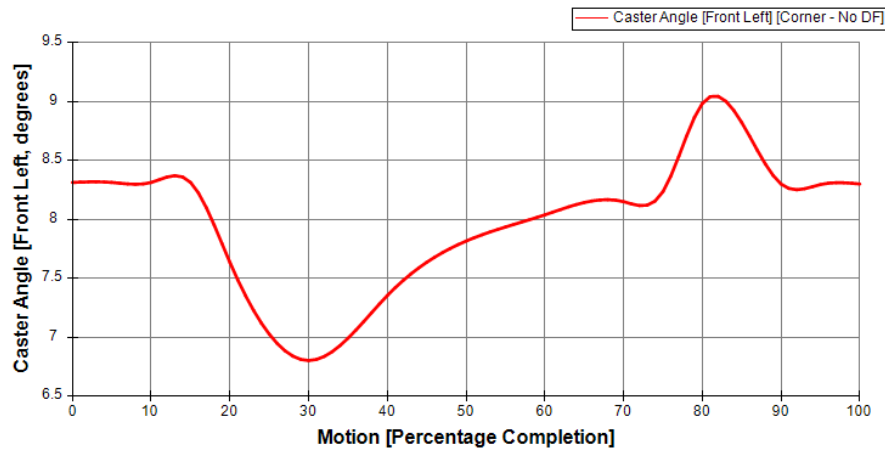
Caster Angle - Steering



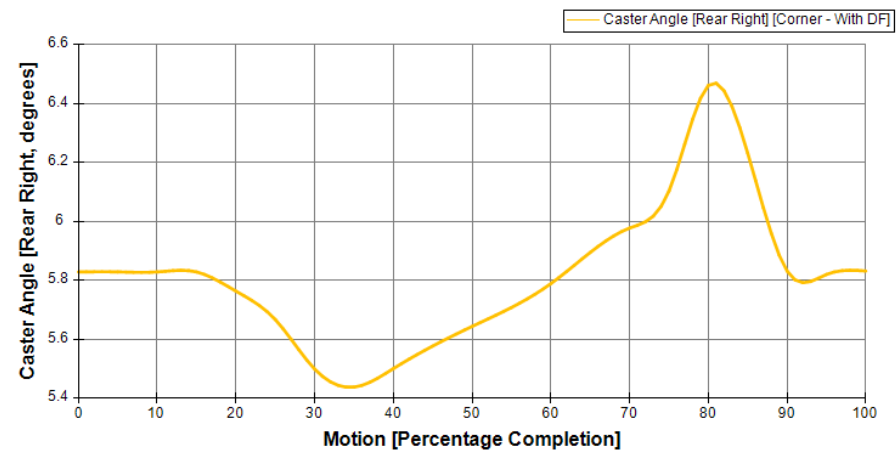
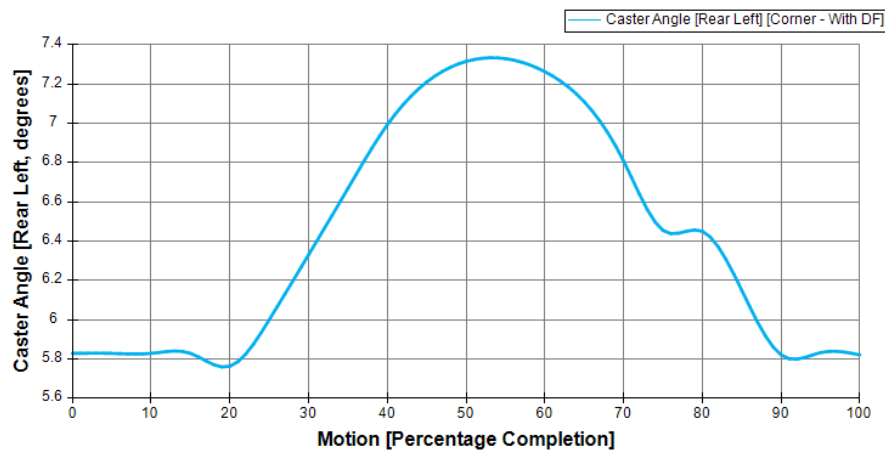
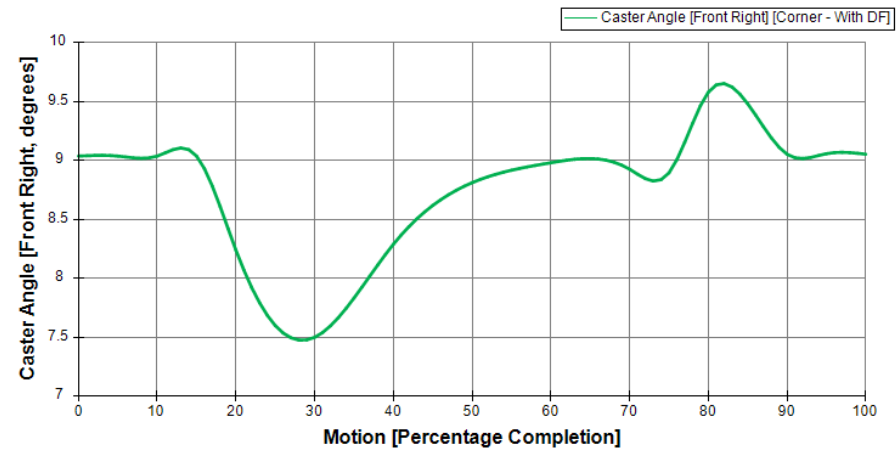
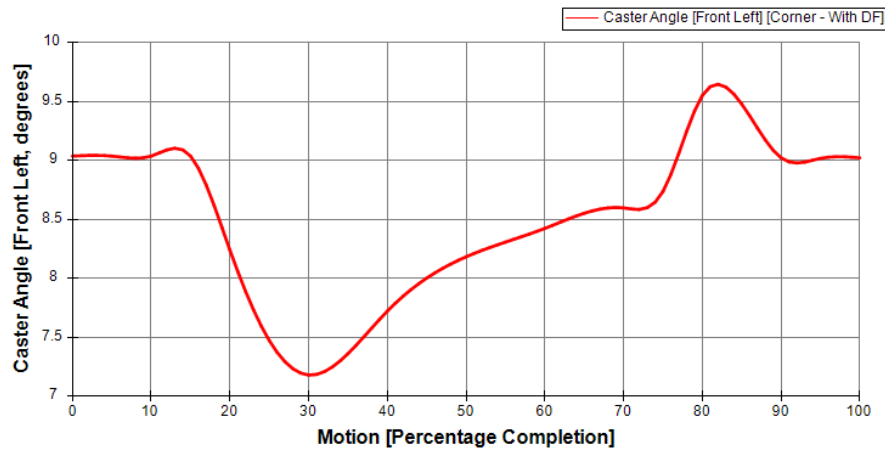
Caster Angle - Pitch



Caster Angle - Corner Without Downforce

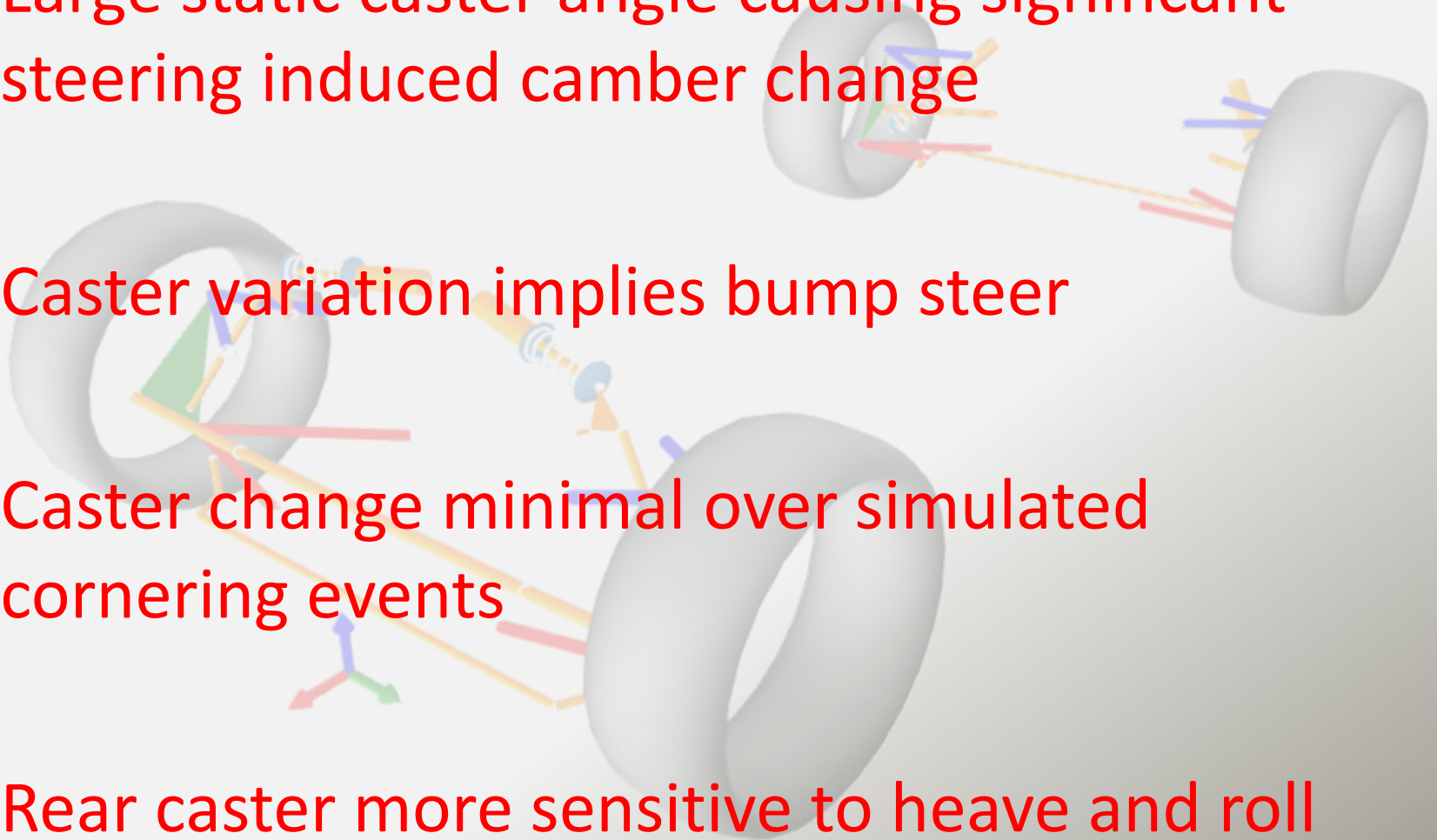


Caster Angle - Corner With Downforce

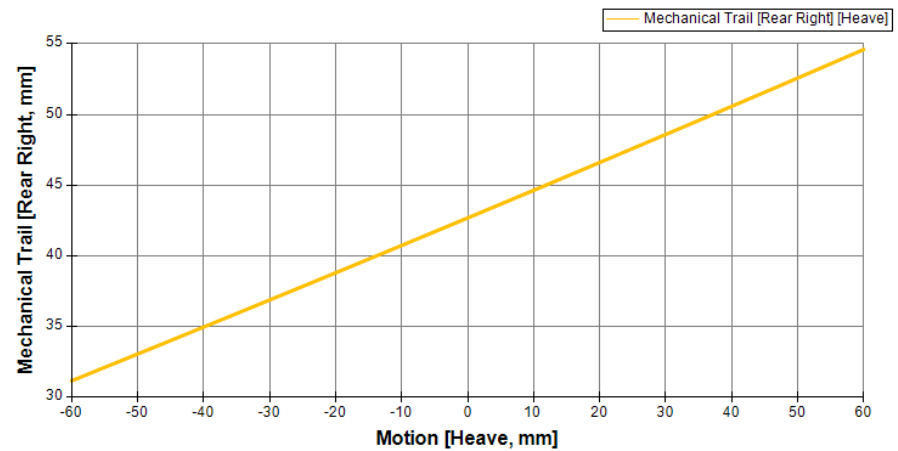
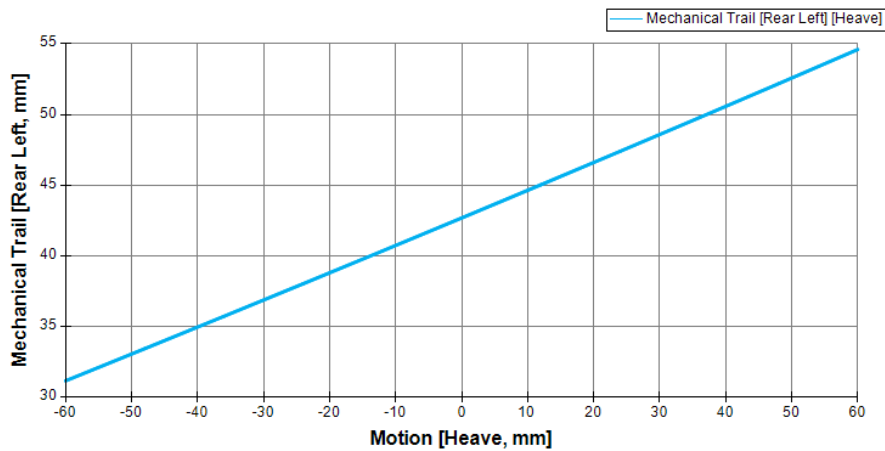
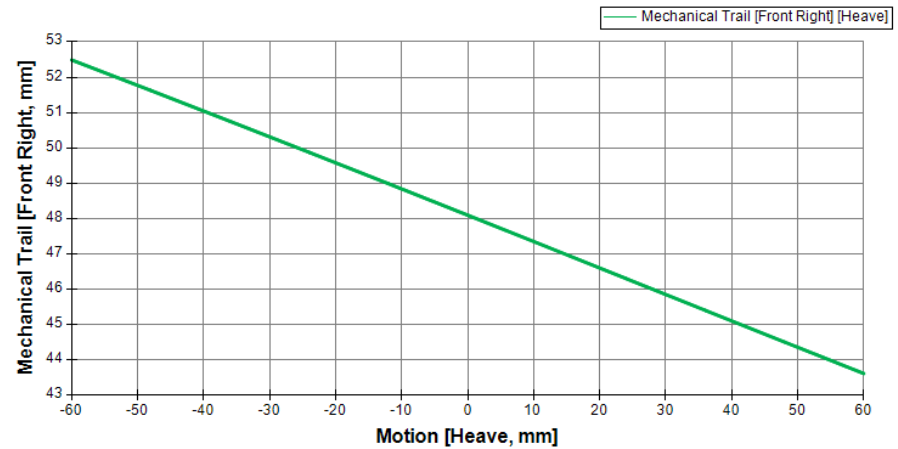
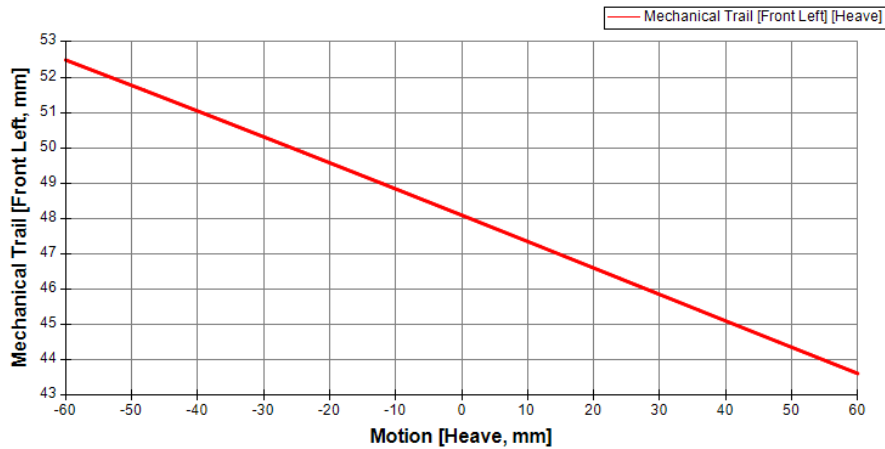


Caster Angle – Comments

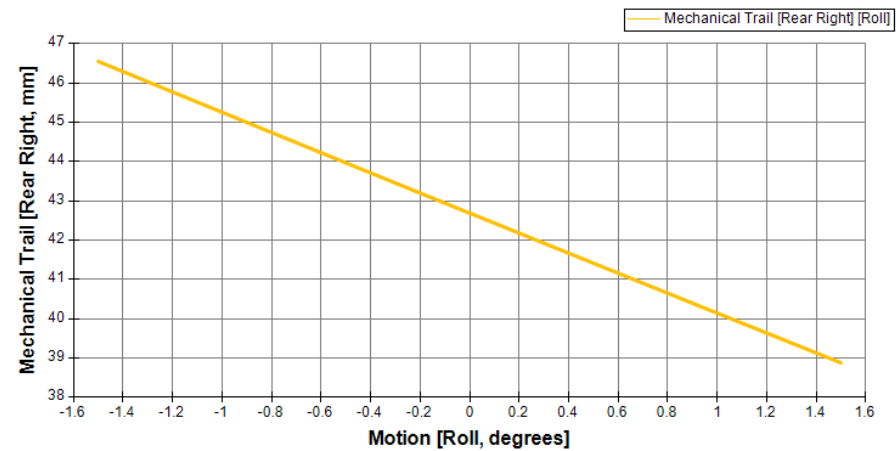
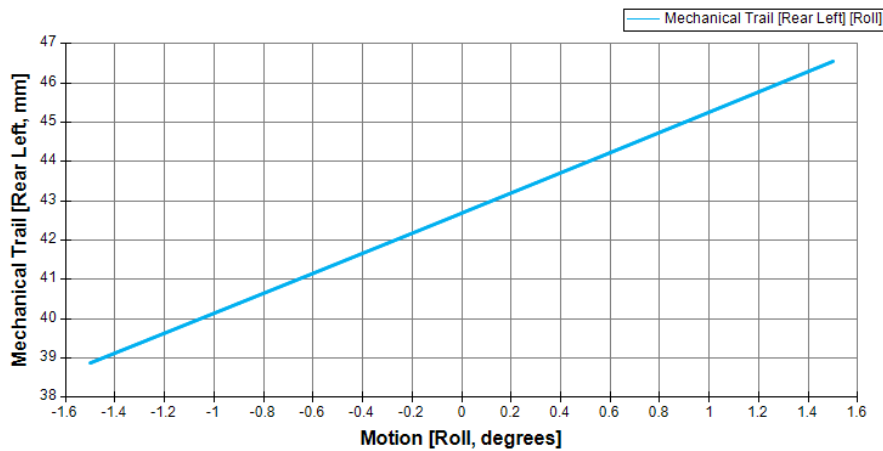
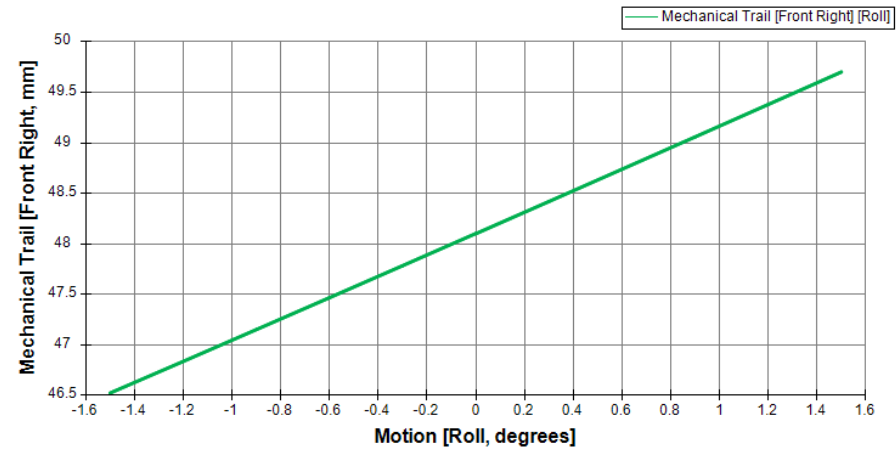
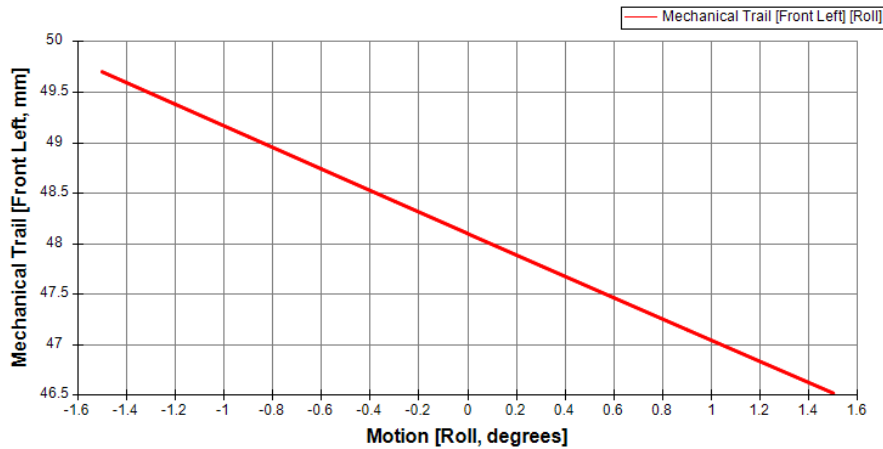
- Large static caster angle causing significant steering induced camber change
- Caster variation implies bump steer
- Caster change minimal over simulated cornering events
- Rear caster more sensitive to heave and roll than front



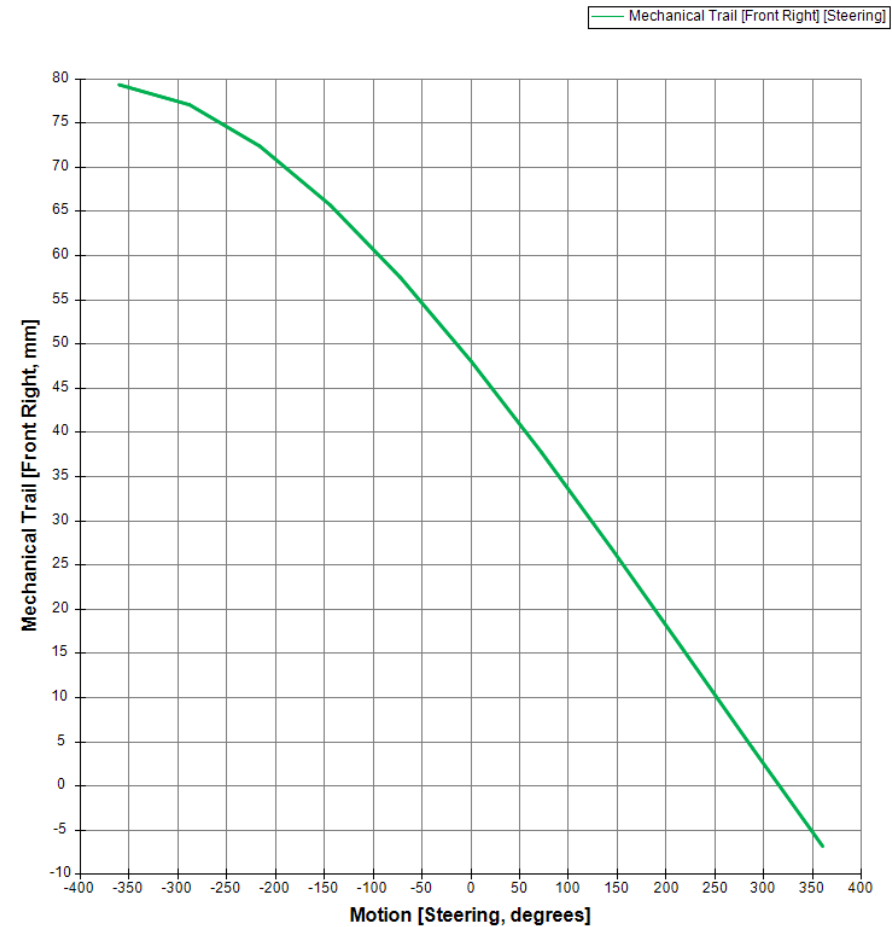
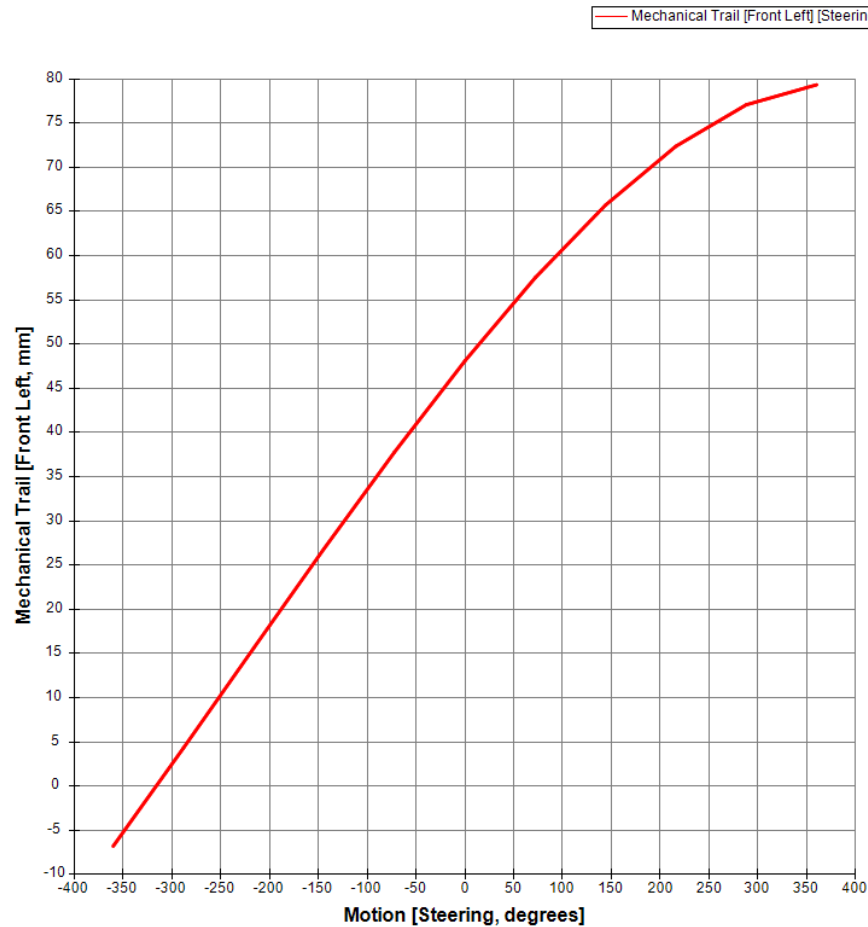
Mechanical Trail - Heave



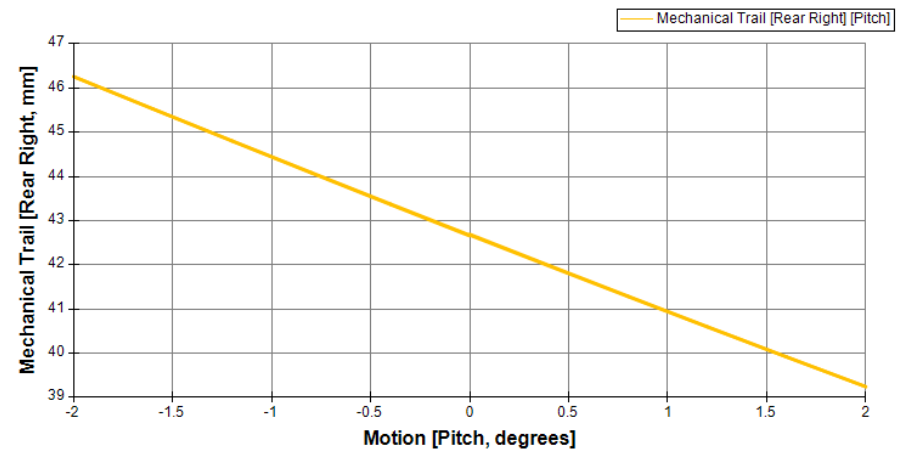
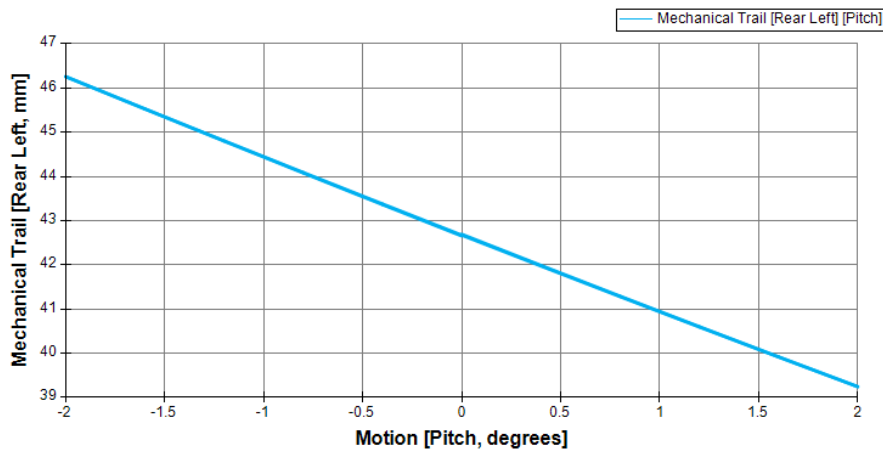
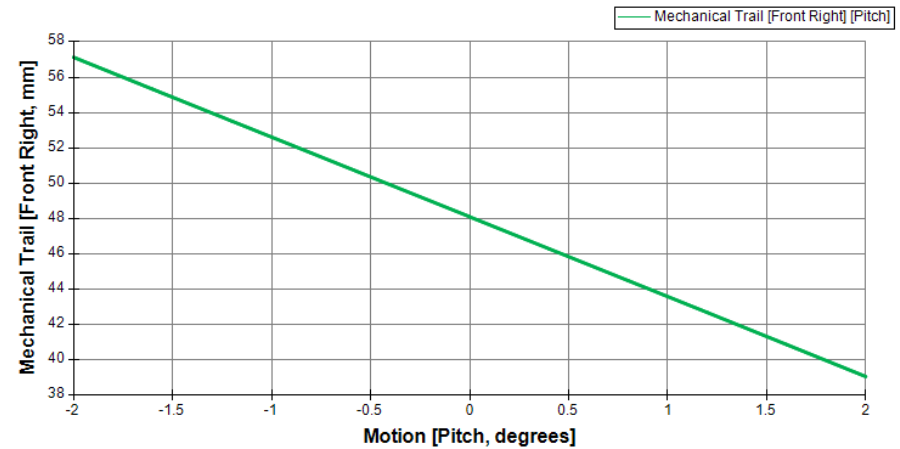
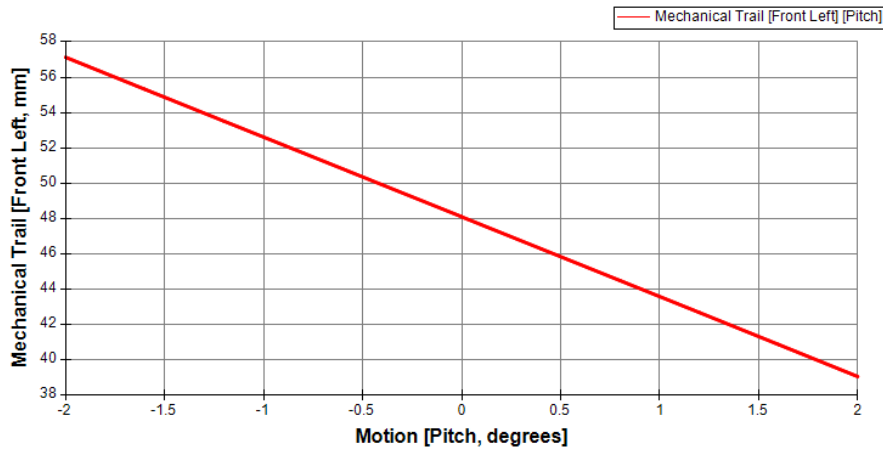
Mechanical Trail - Roll



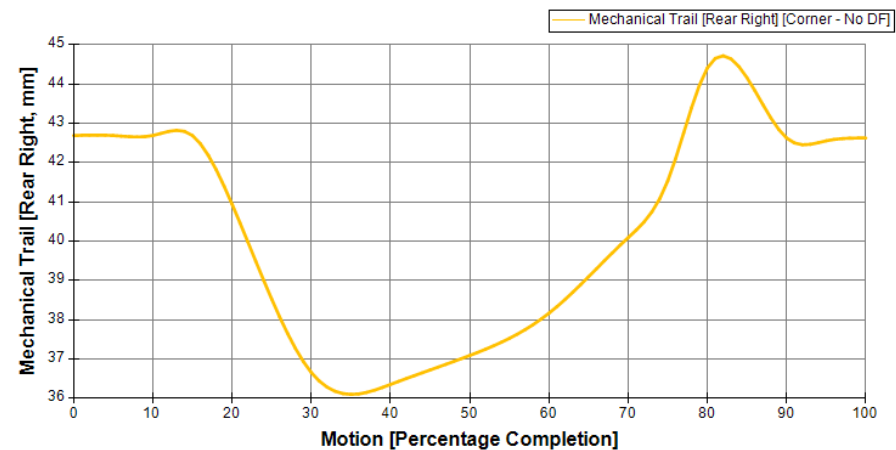
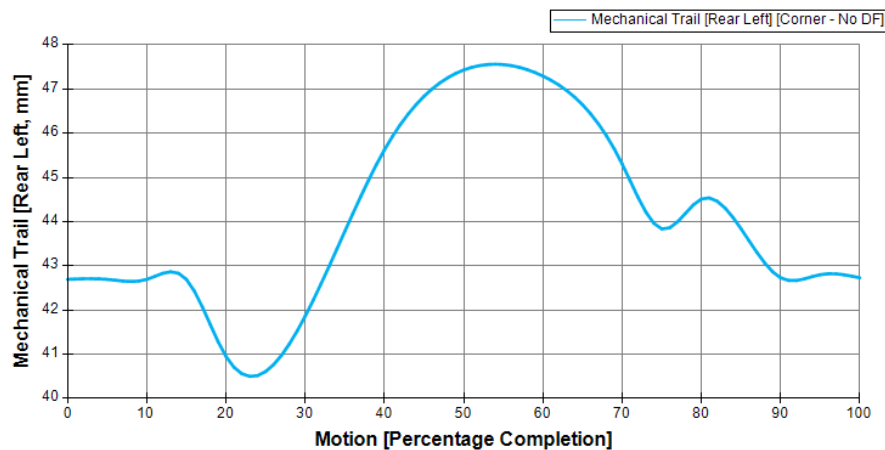
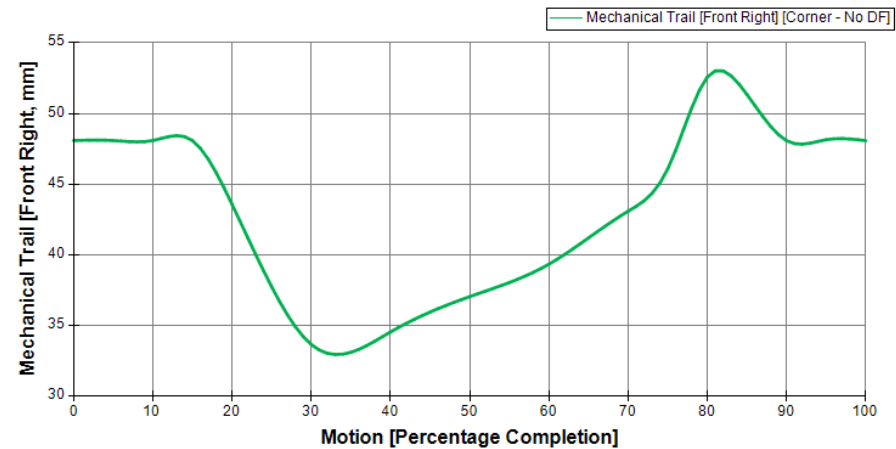
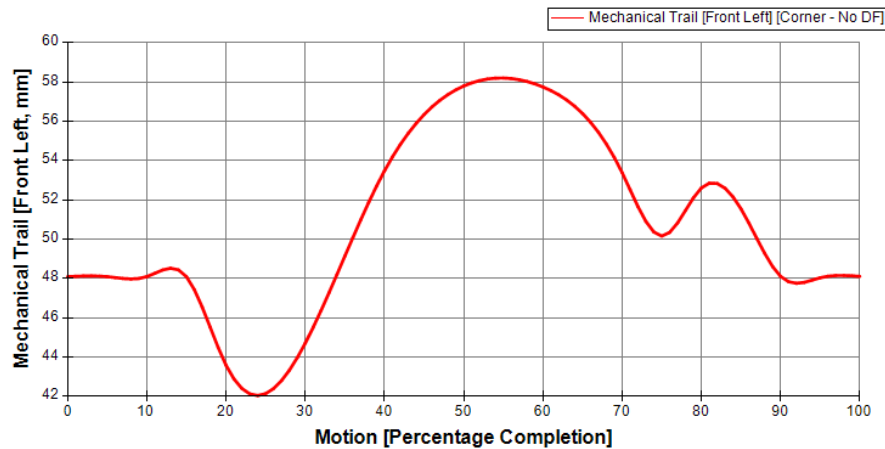
Mechanical Trail - Steering



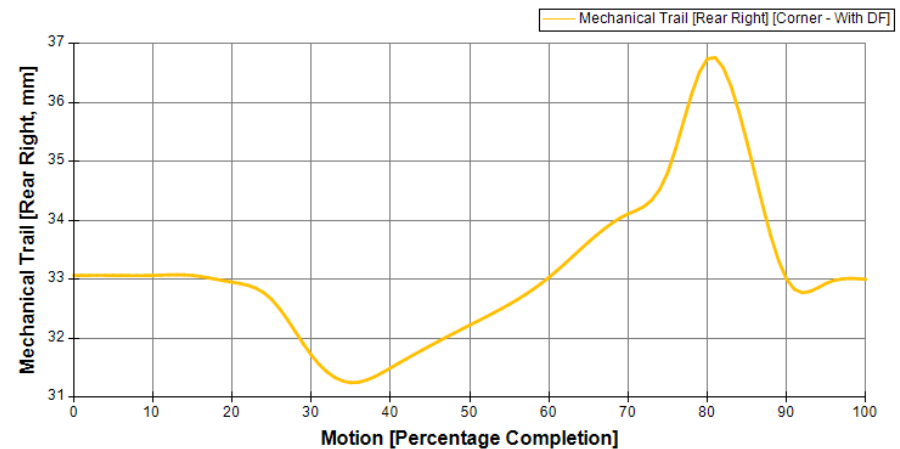
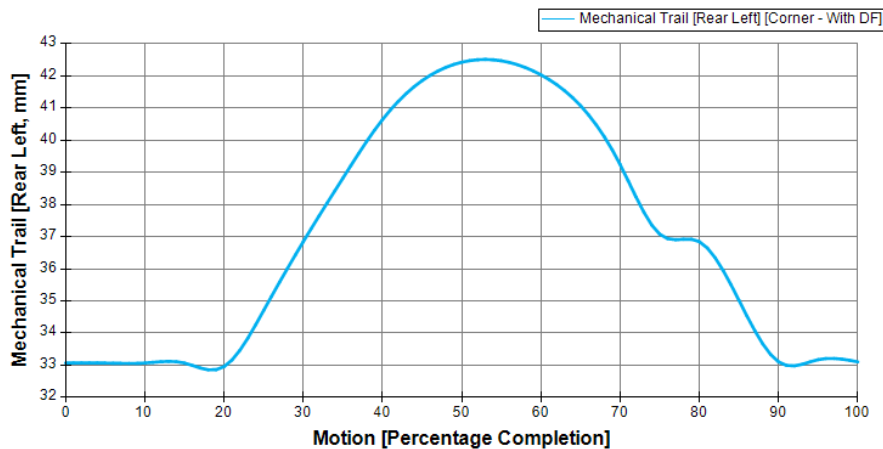
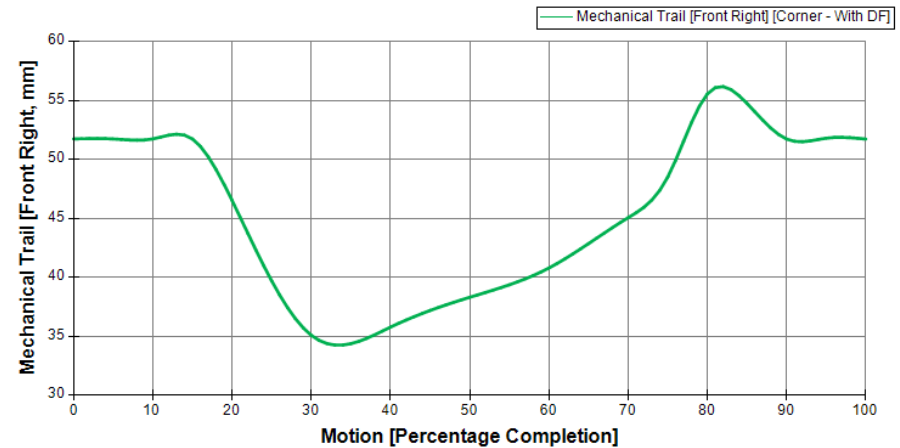
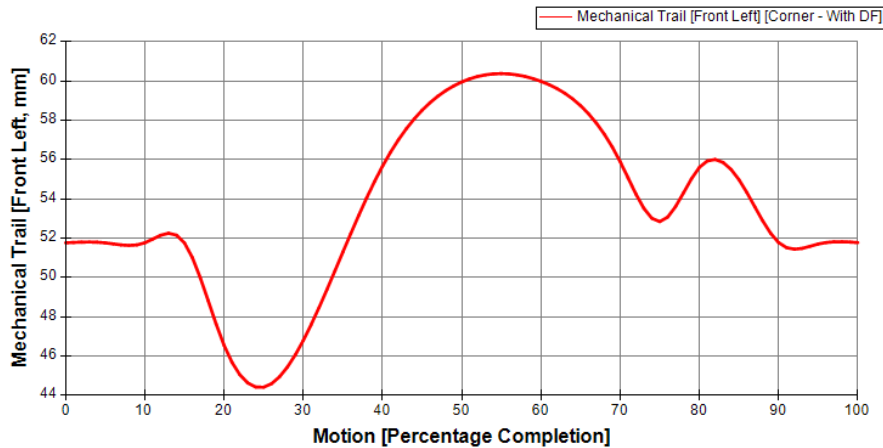
Mechanical Trail - Pitch



Mechanical Trail - Corner Without Downforce

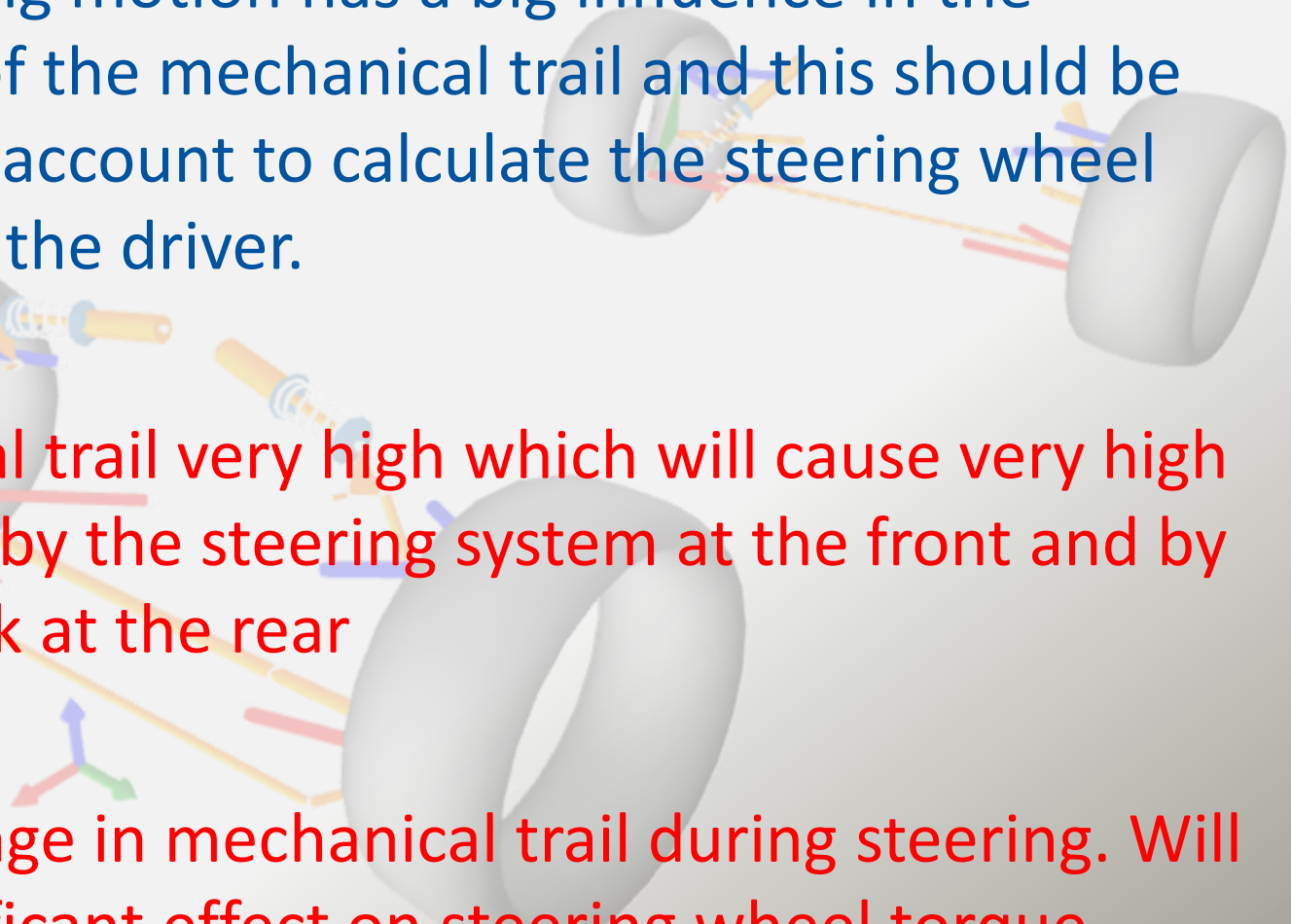


Mechanical Trail - Corner With Downforce

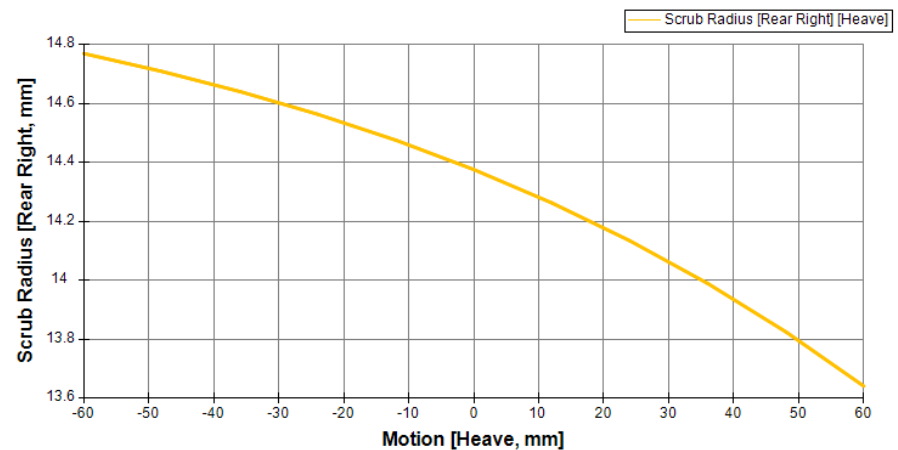
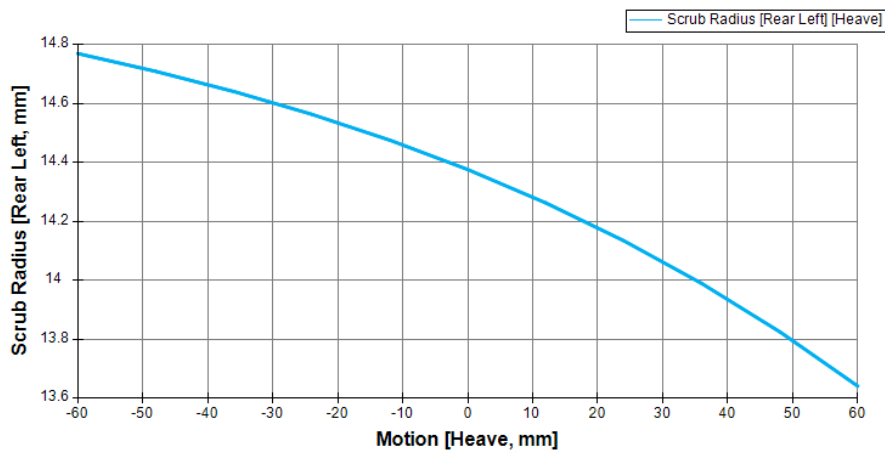
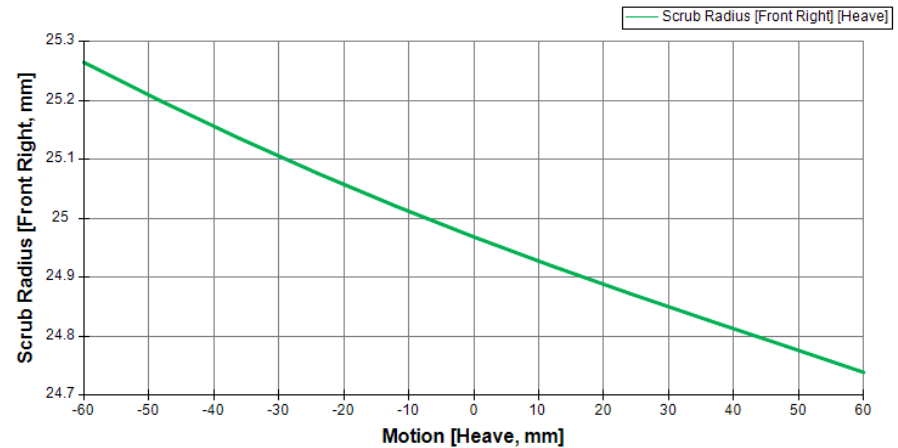
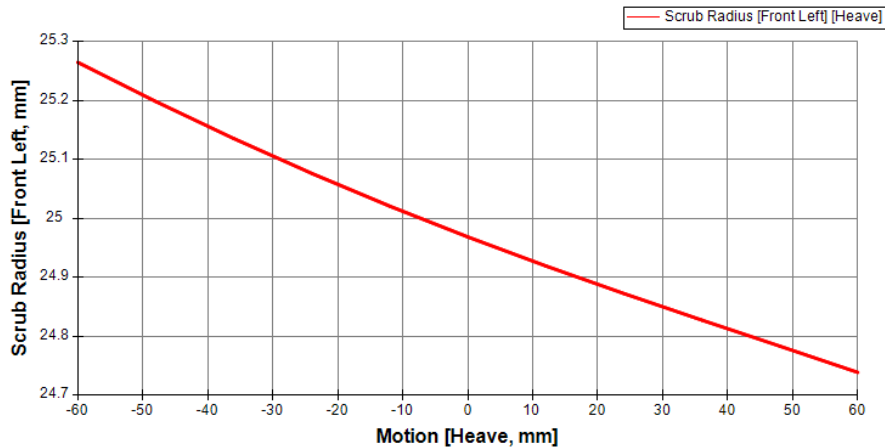


Mechanical Trail – Comments

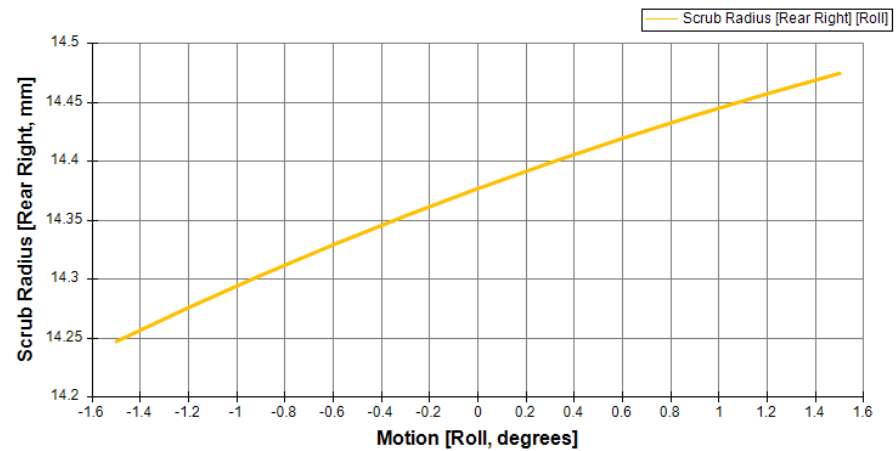
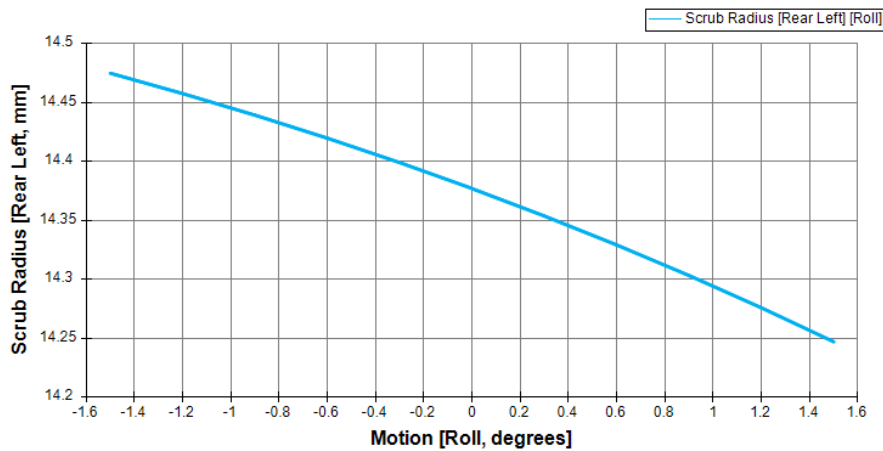
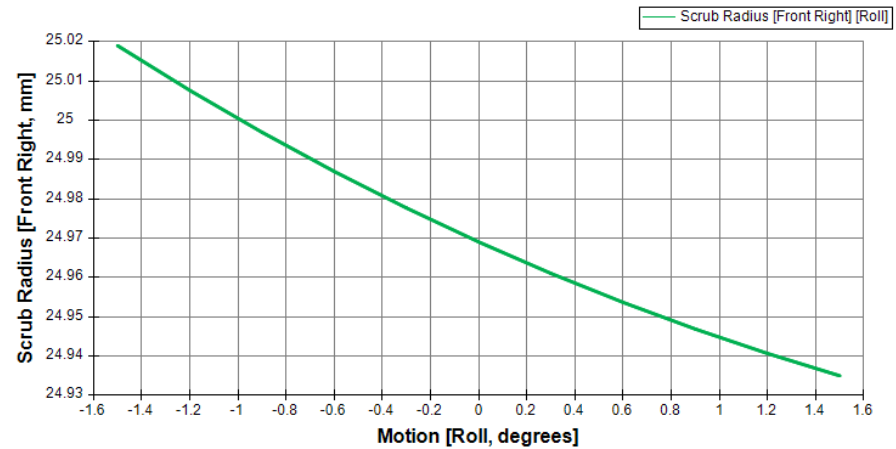
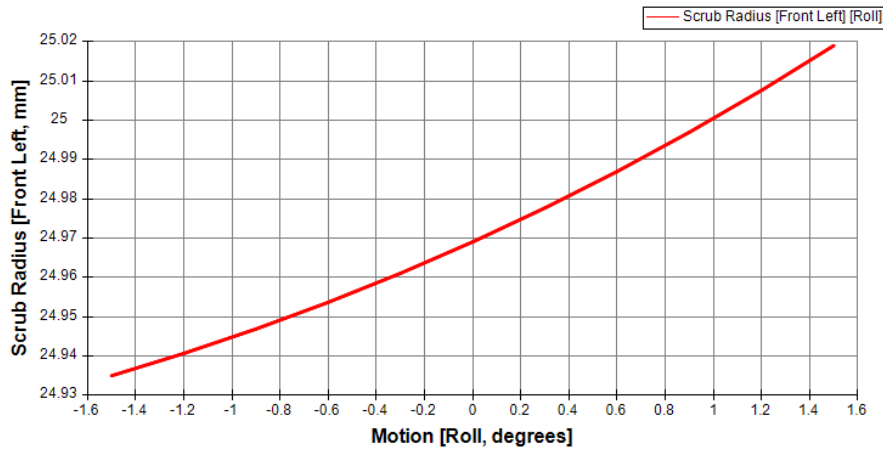
- The steering motion has a big influence in the variation of the mechanical trail and this should be taken into account to calculate the steering wheel torque for the driver.
- Mechanical trail very high which will cause very high forces felt by the steering system at the front and by the toe link at the rear
- Large change in mechanical trail during steering. Will have significant effect on steering wheel torque feedback to driver.



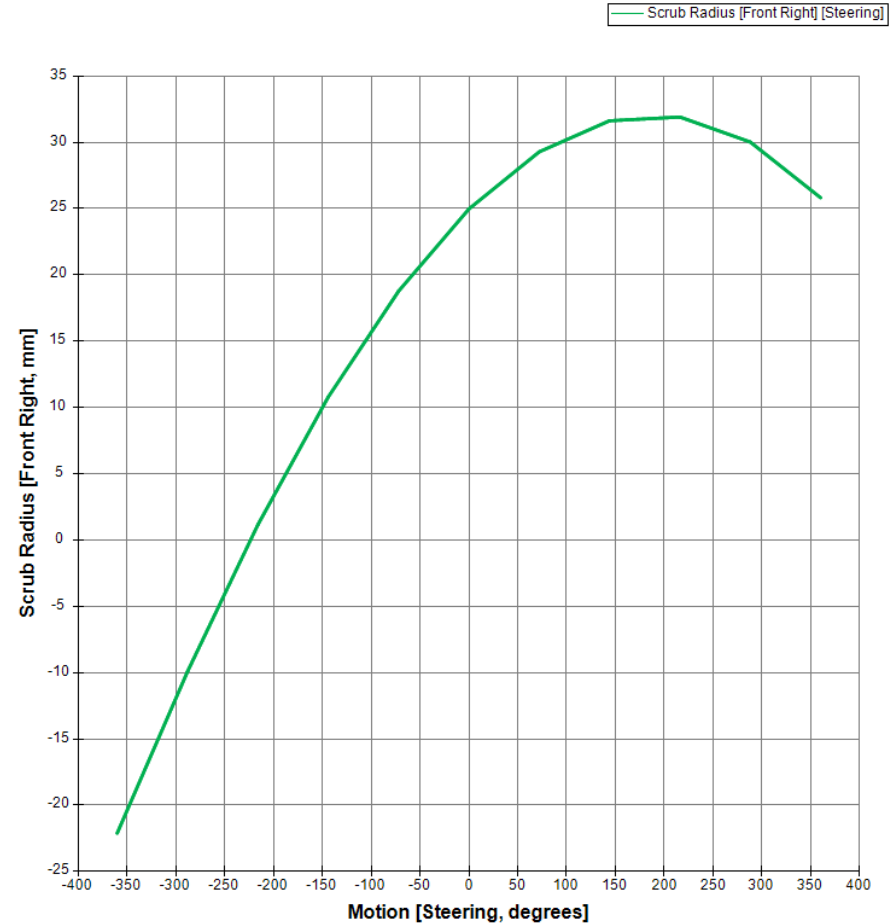
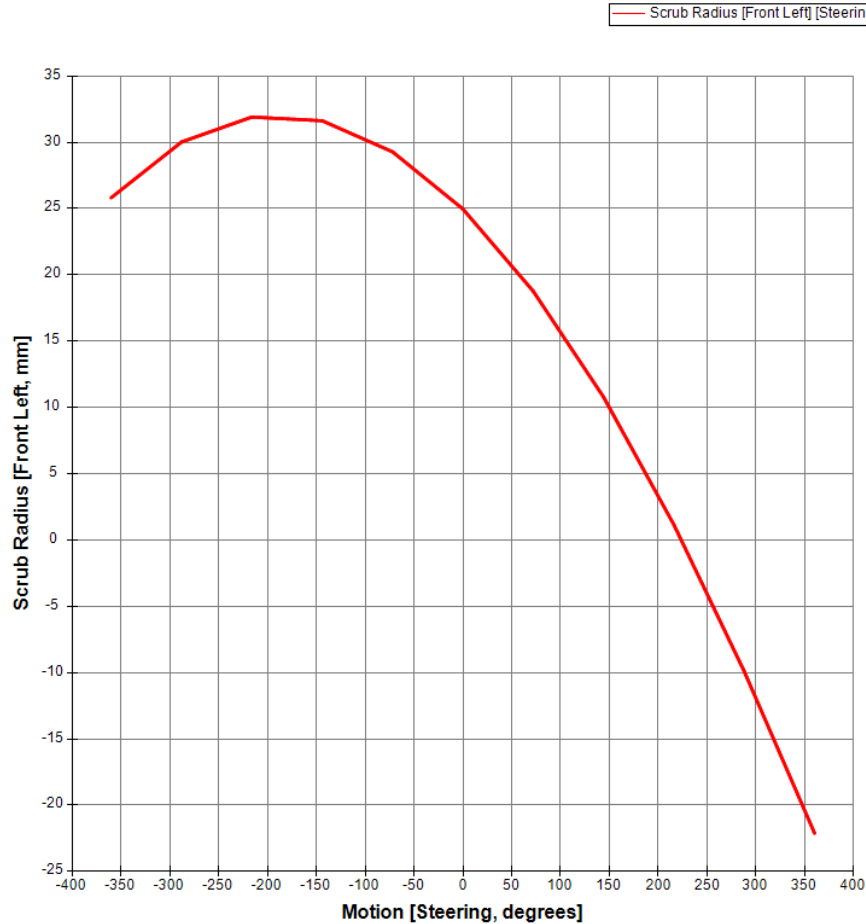
Scrub Radius - Heave



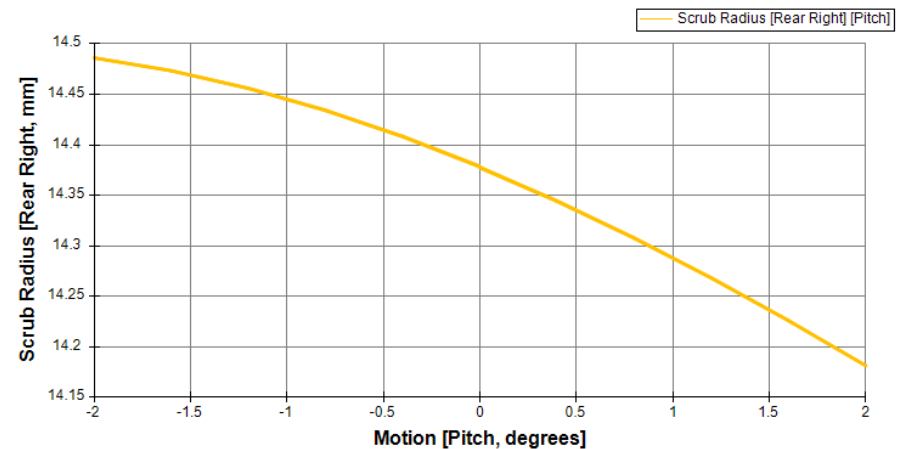
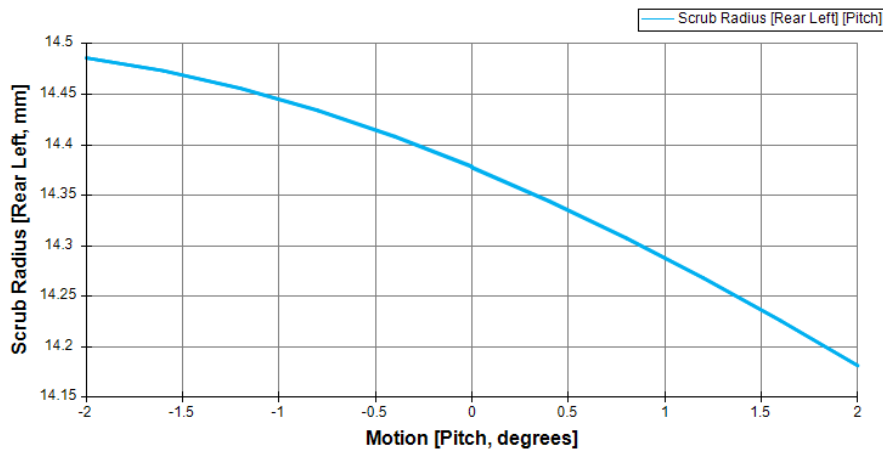
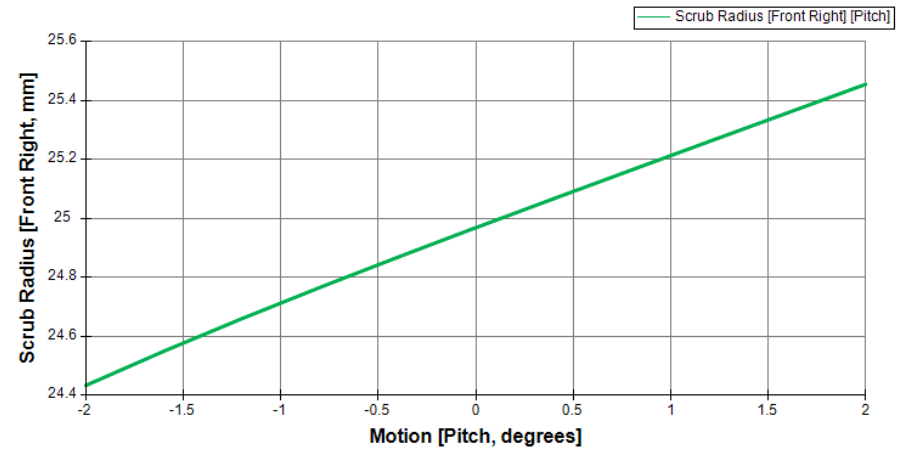
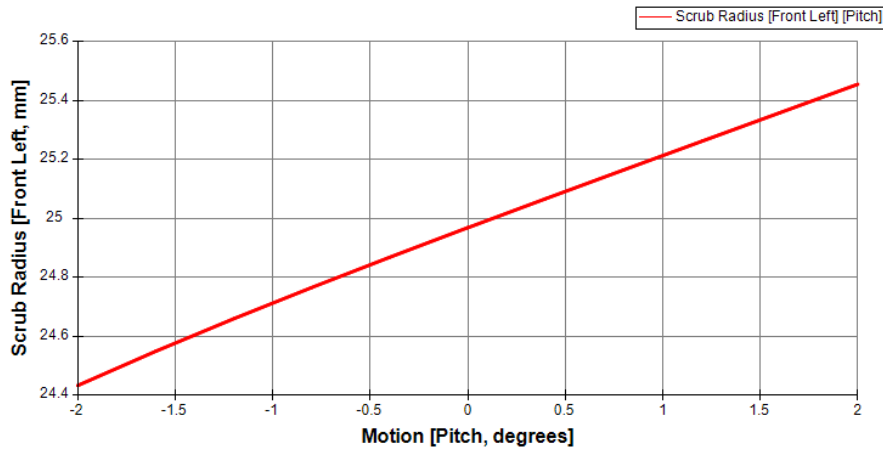
Scrub Radius - Roll



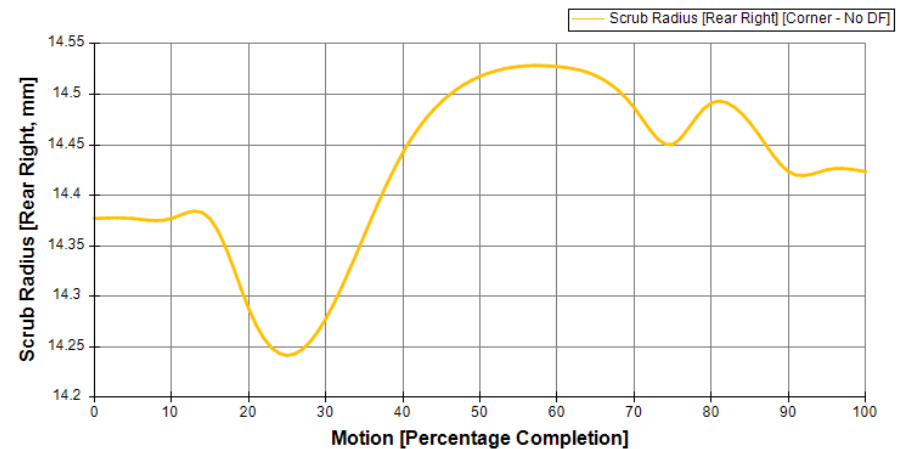
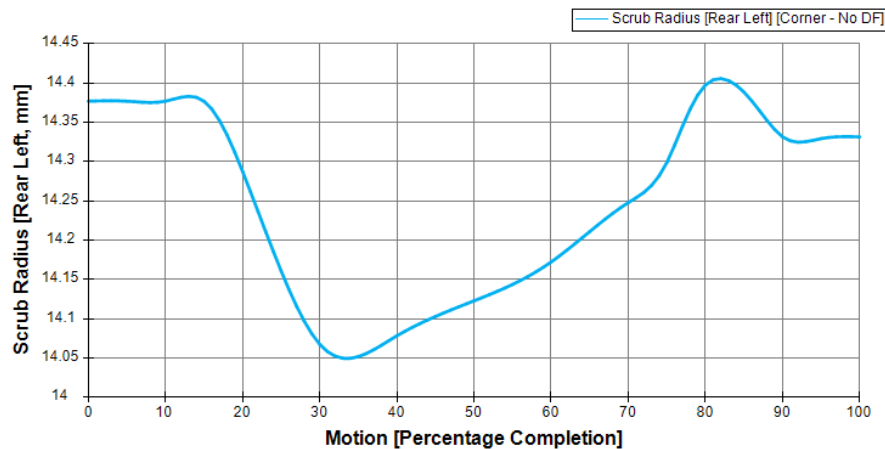
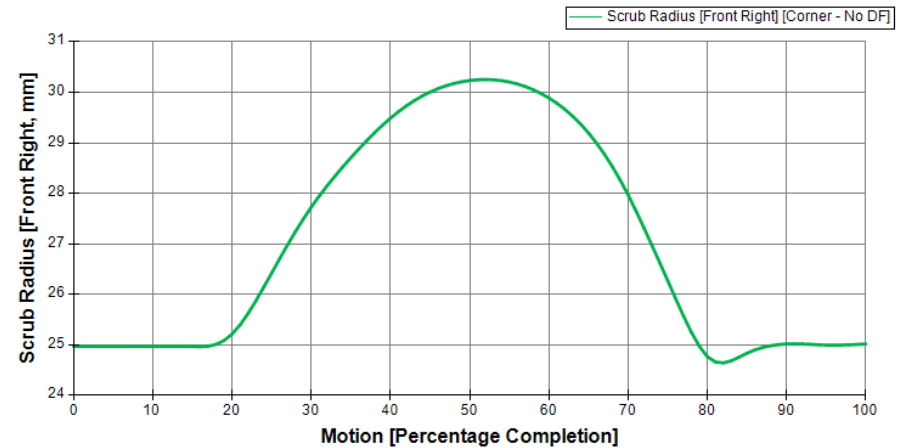
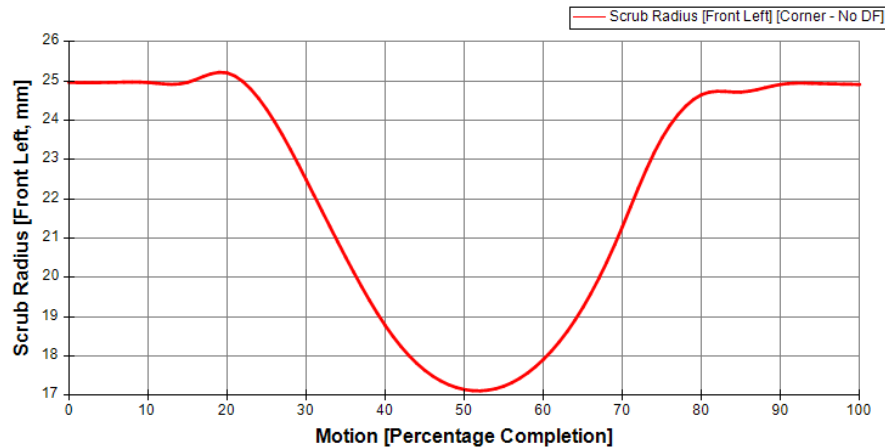
Scrub Radius - Steering



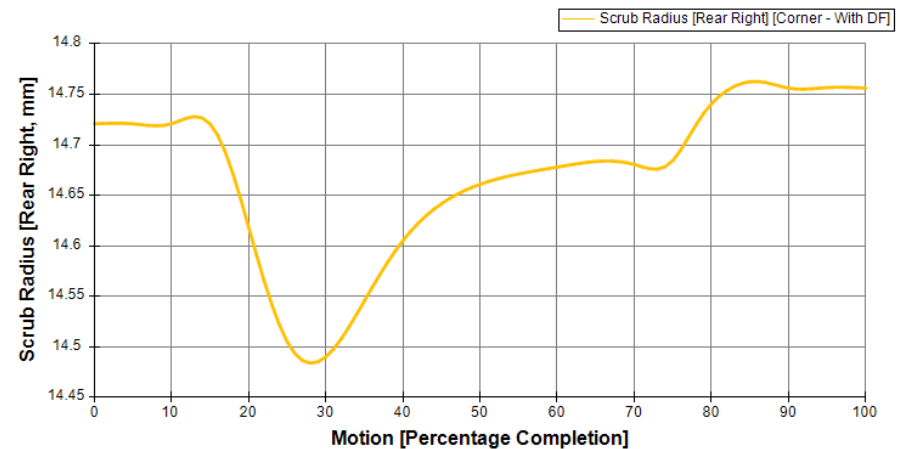
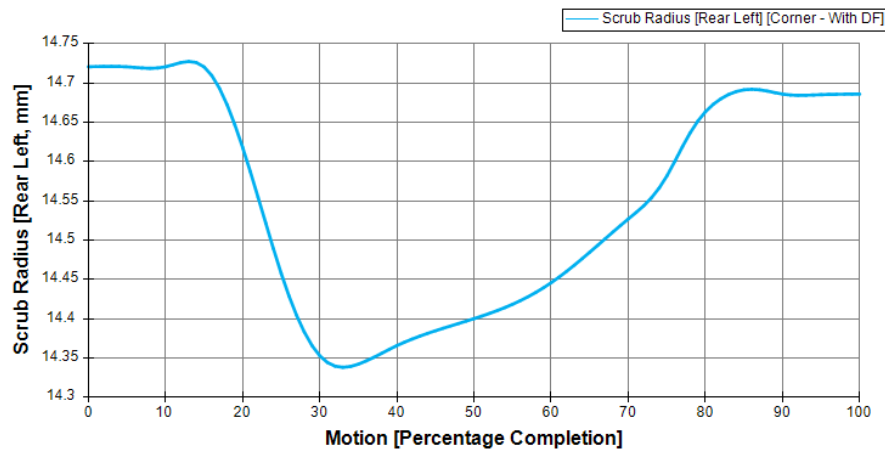
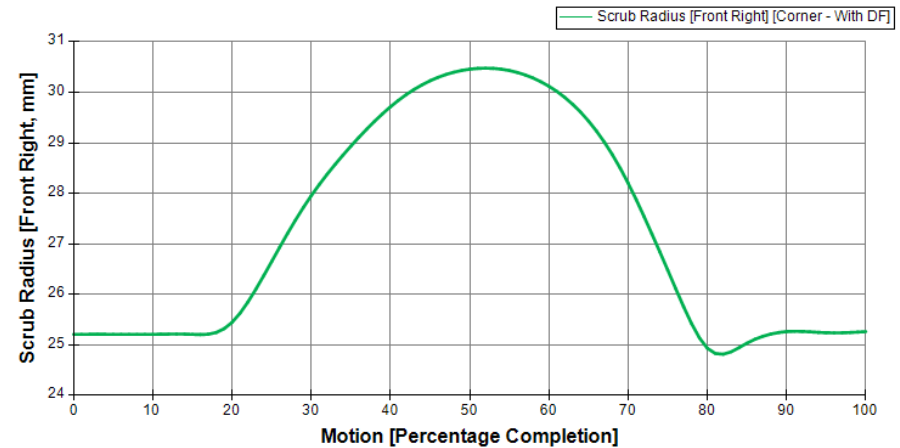
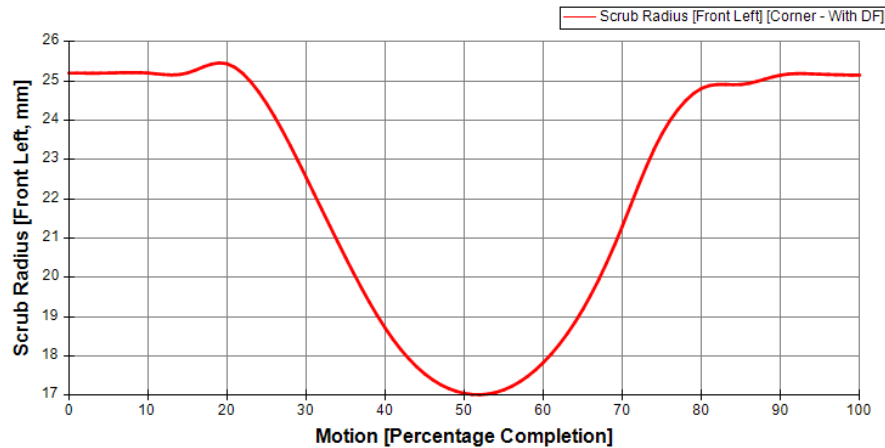
Scrub Radius - Pitch



Scrub Radius - Corner Without Downforce

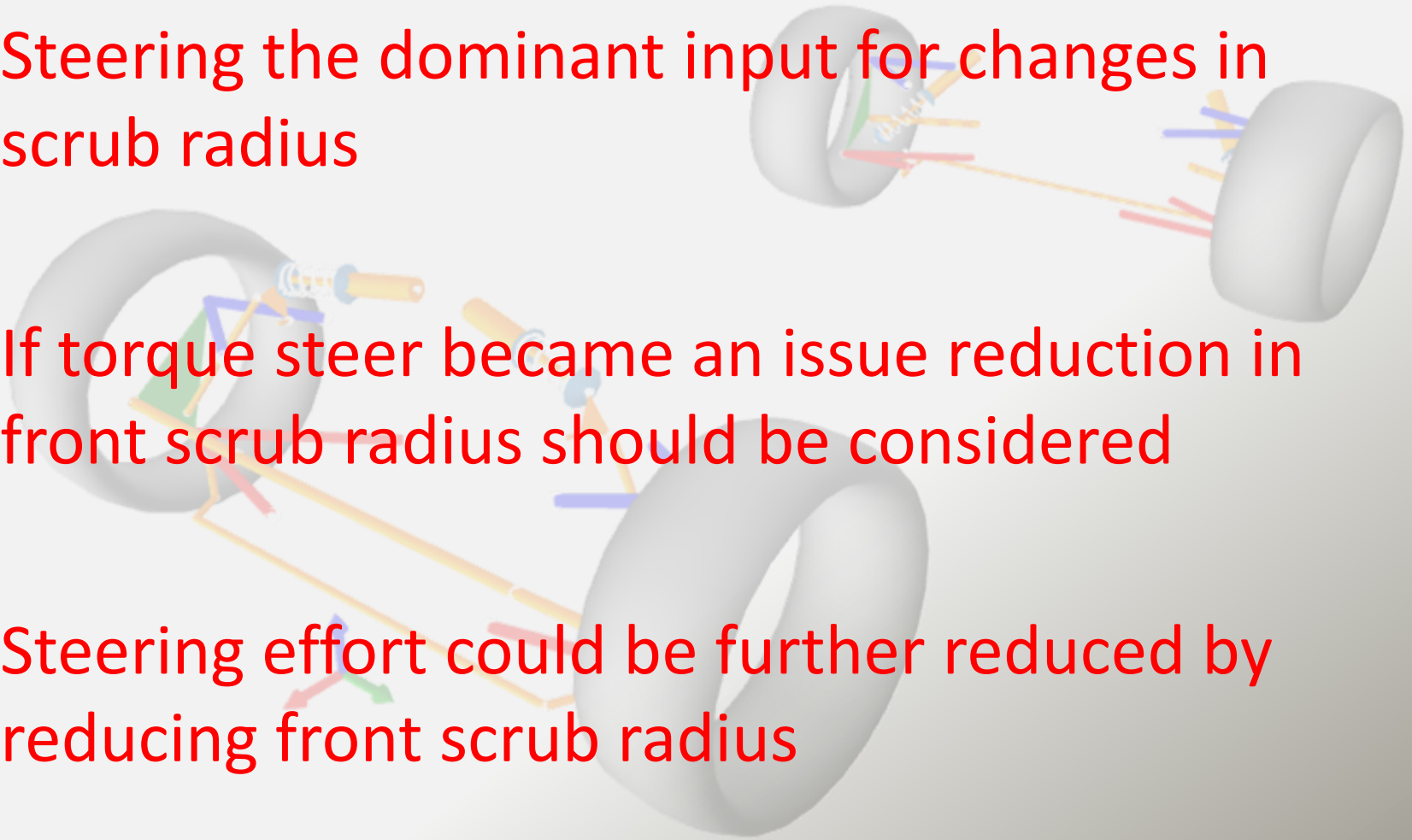


Scrub Radius - Corner With Downforce

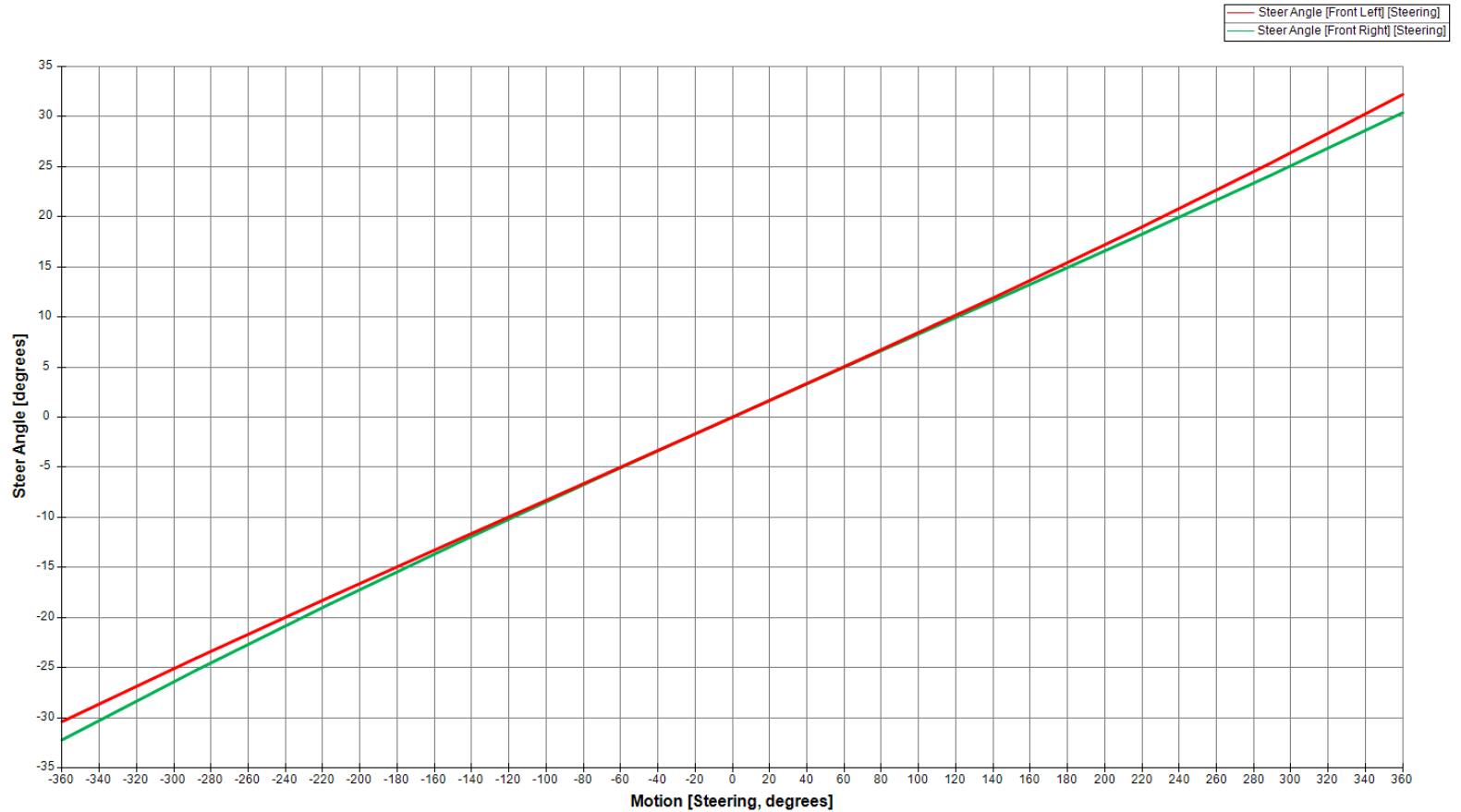


Scrub Radius– Comments

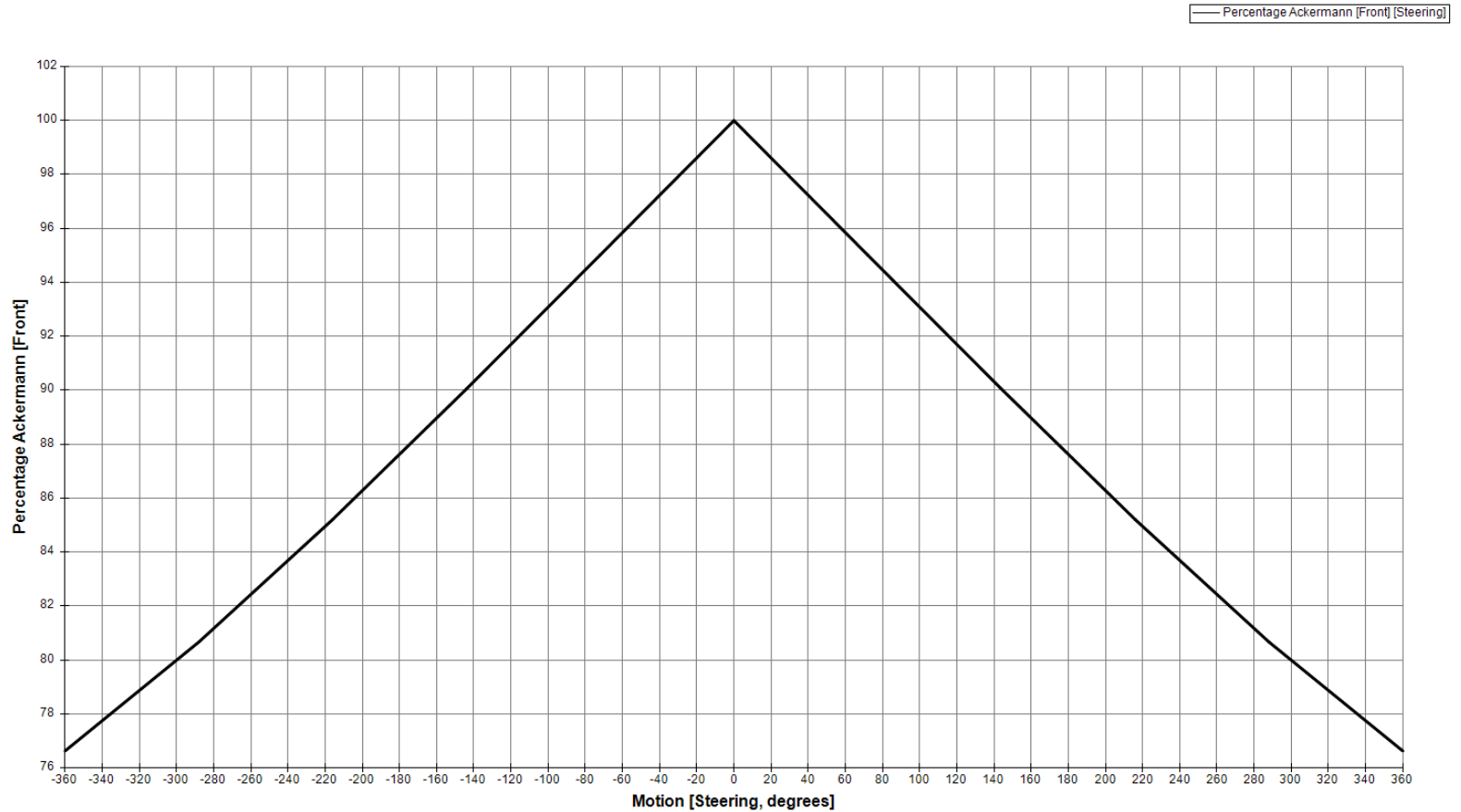
- Steering the dominant input for changes in scrub radius
- If torque steer became an issue reduction in front scrub radius should be considered
- Steering effort could be further reduced by reducing front scrub radius



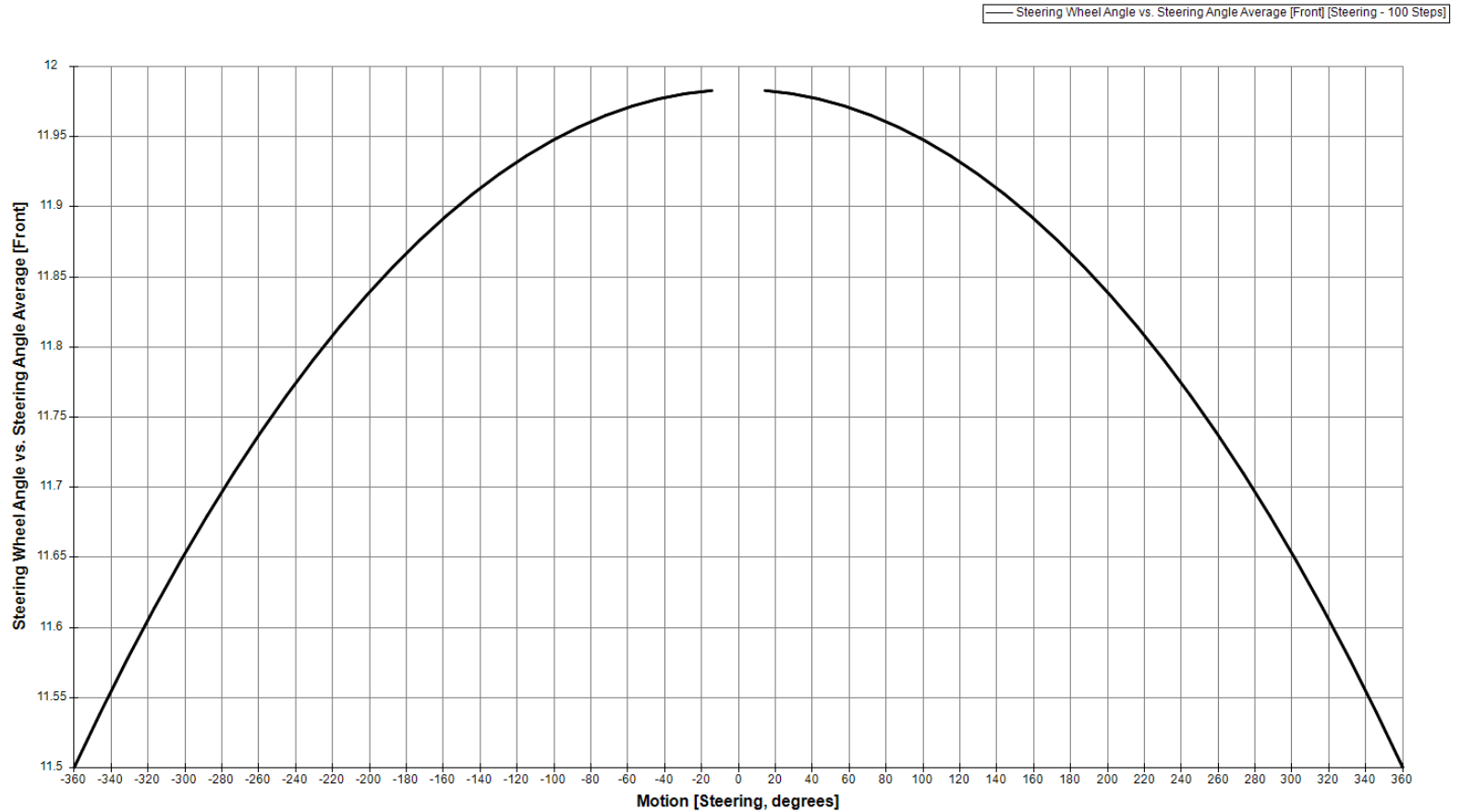
Steering Angle



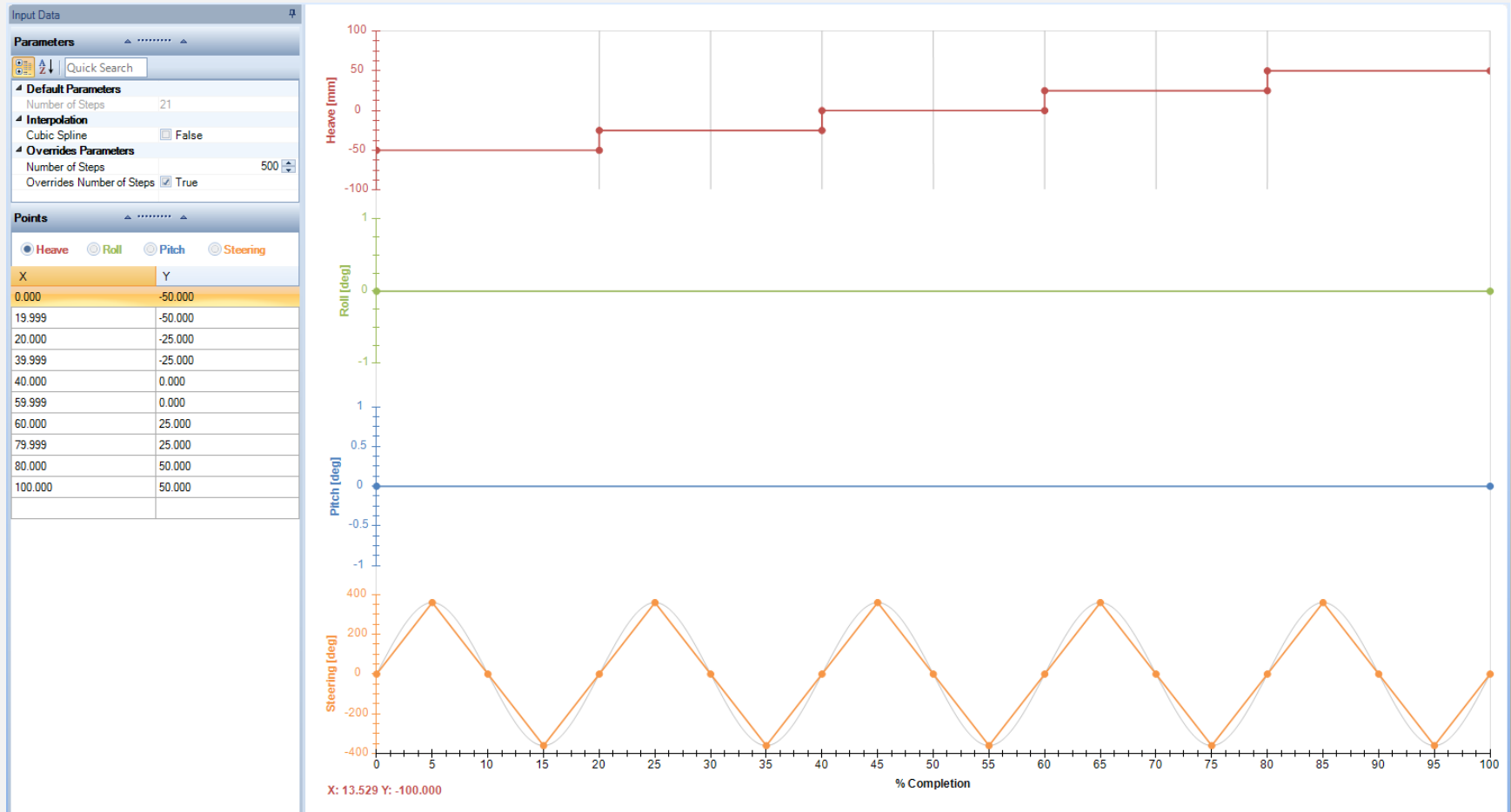
Percent Ackermann



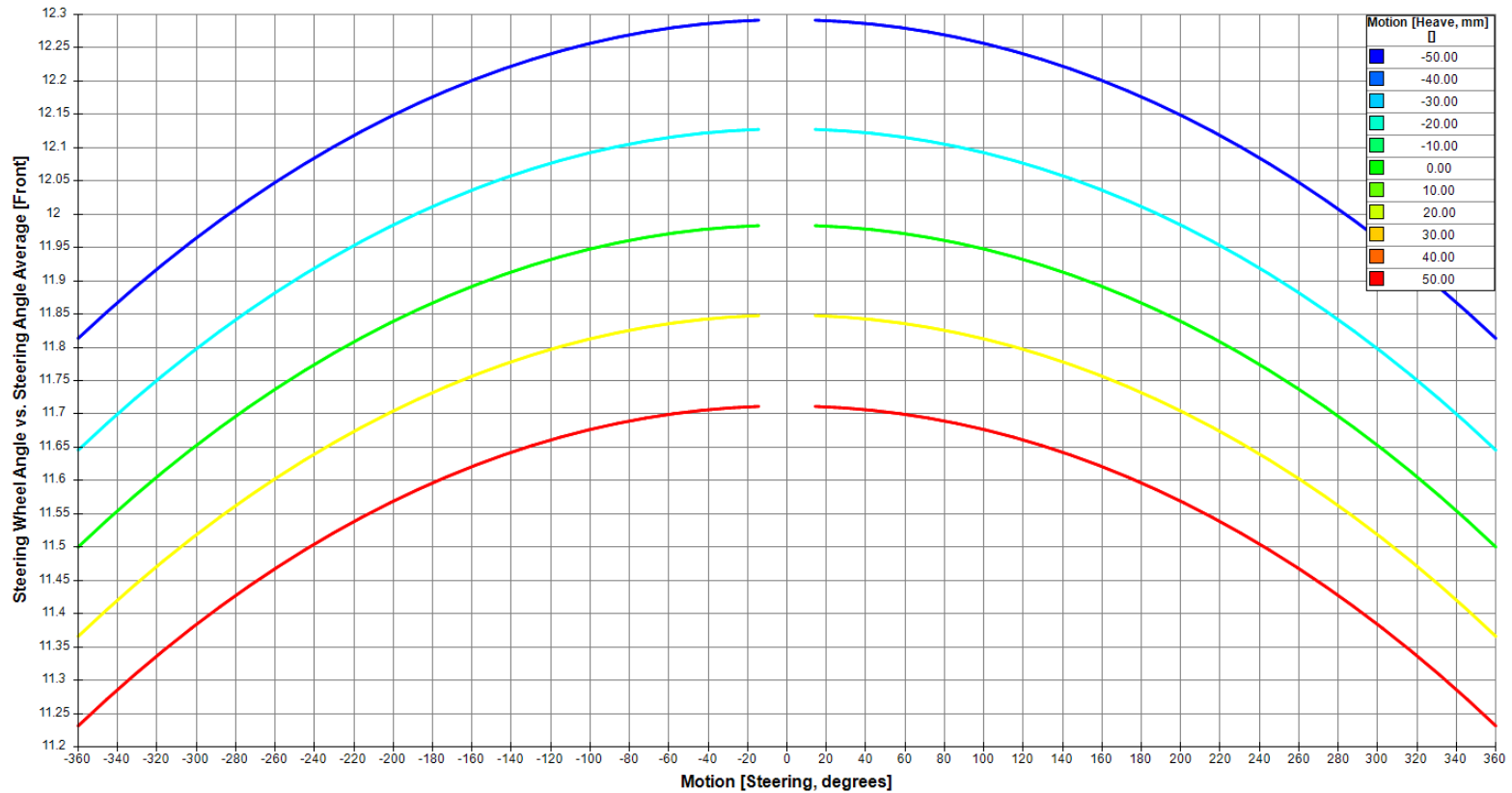
Steering Ratio Average



Steering Ratio Average for Different Heave Displacements - Input

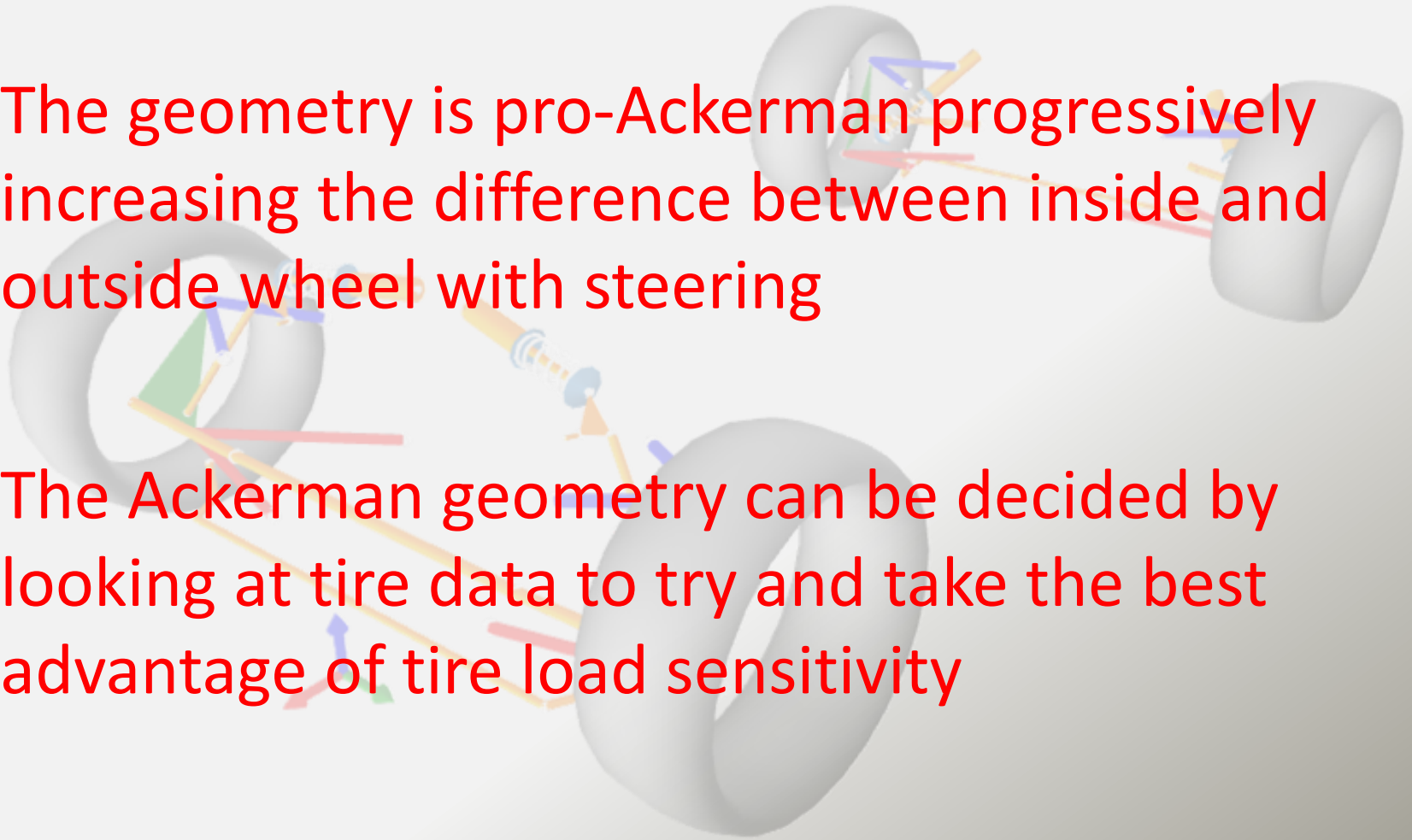


Steering Ratio Average for Different Heave Displacements - Output

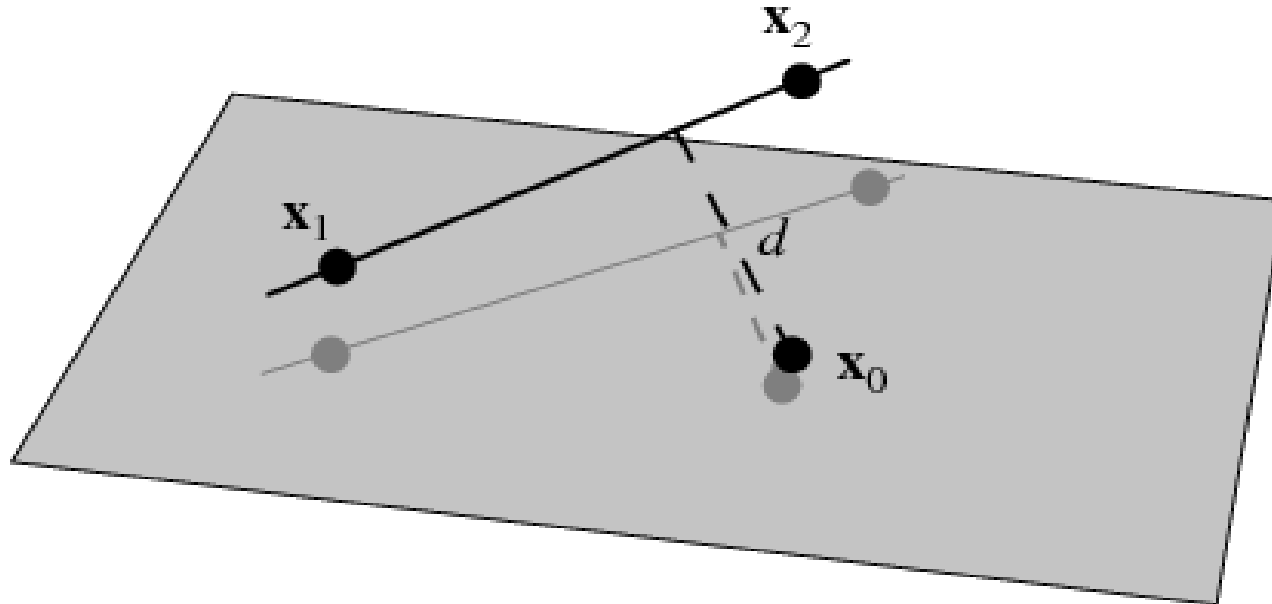


Steering – Comments

- The geometry is pro-Ackerman progressively increasing the difference between inside and outside wheel with steering
- The Ackerman geometry can be decided by looking at tire data to try and take the best advantage of tire load sensitivity



Definition of Shortest Distance Between a Line and a Point



Let a line in three dimensions be specified by two points $\mathbf{x}_1 = (x_1, y_1, z_1)$ and $\mathbf{x}_2 = (x_2, y_2, z_2)$ lying on it, so a vector along the line is given by

$$\mathbf{v} = \begin{bmatrix} x_1 + (x_2 - x_1)t \\ y_1 + (y_2 - y_1)t \\ z_1 + (z_2 - z_1)t \end{bmatrix}$$

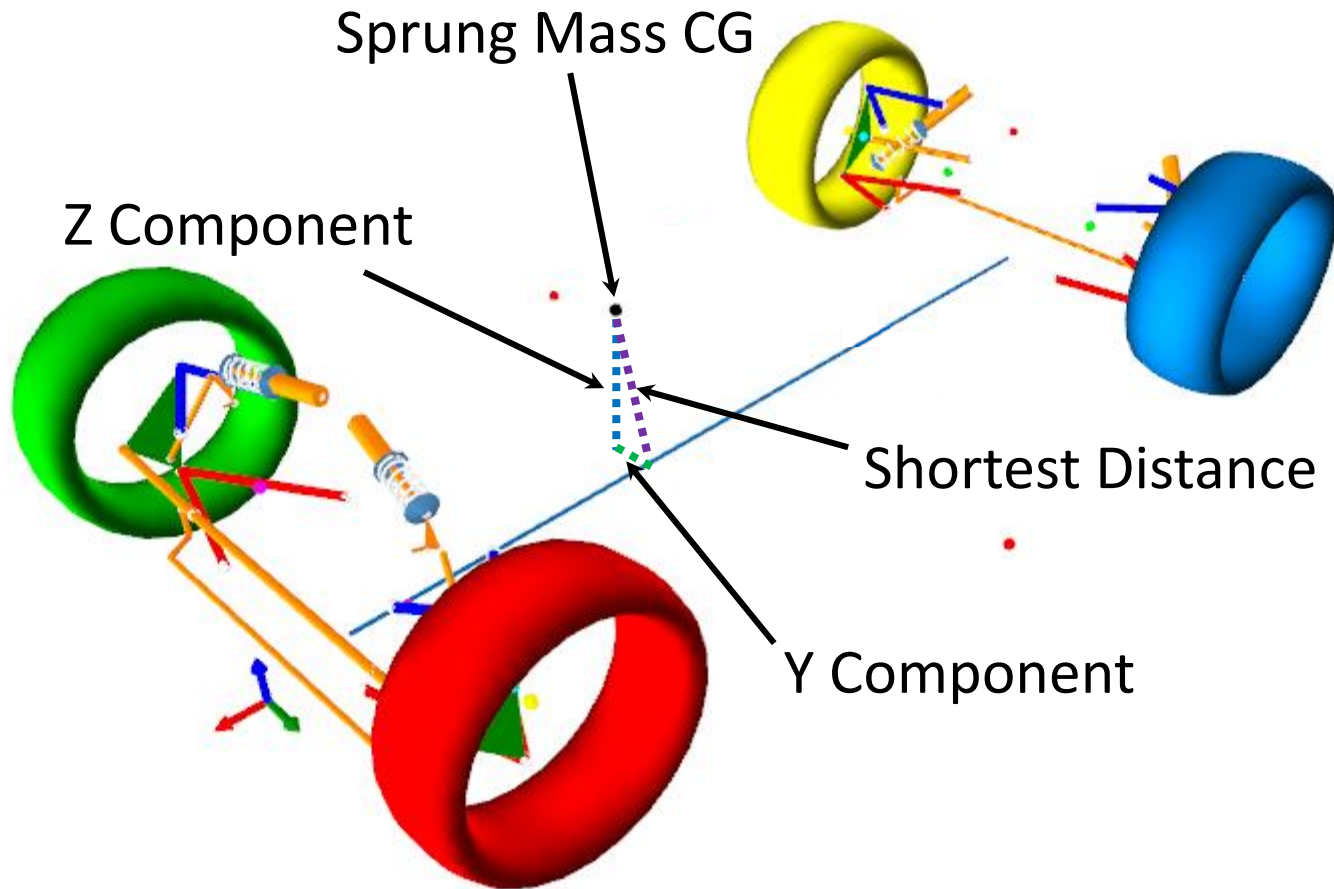
$$= \frac{|\mathbf{x}_1 - \mathbf{x}_0|^2 |\mathbf{x}_2 - \mathbf{x}_1|^2 - [(\mathbf{x}_1 - \mathbf{x}_0) \cdot (\mathbf{x}_2 - \mathbf{x}_1)]^2}{|\mathbf{x}_2 - \mathbf{x}_1|^2}$$

$$\xrightarrow{\text{red arrow}} d = \frac{|(\mathbf{x}_2 - \mathbf{x}_1) \times (\mathbf{x}_1 - \mathbf{x}_0)|}{|\mathbf{x}_2 - \mathbf{x}_1|}$$

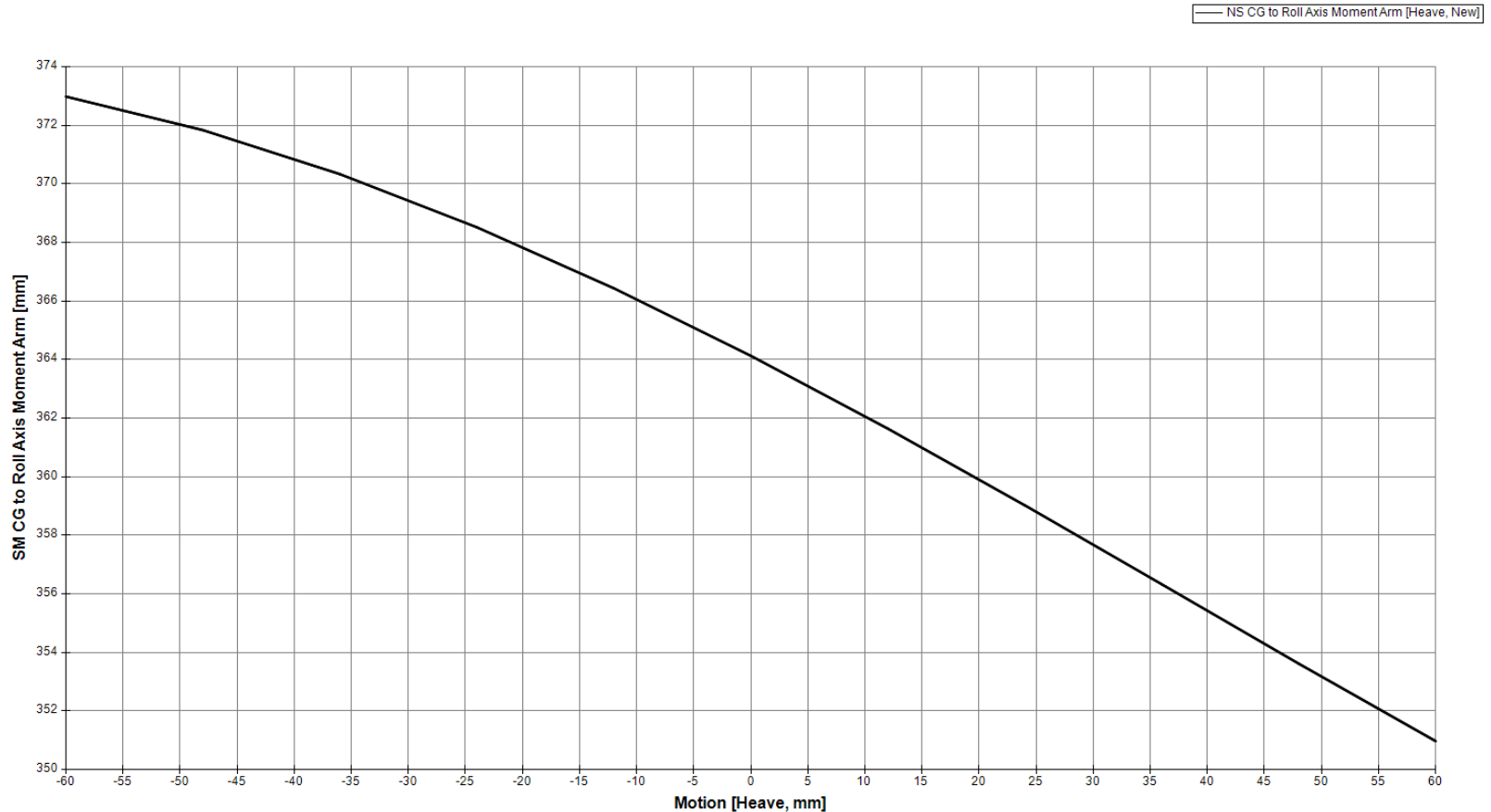
$$= \frac{|(\mathbf{x}_0 - \mathbf{x}_1) \times (\mathbf{x}_0 - \mathbf{x}_2)|}{|\mathbf{x}_2 - \mathbf{x}_1|}$$

Source: <http://mathworld.wolfram.com/Point-LineDistance3-Dimensional.html>

Shortest Distance Between Roll Axis and SM CG



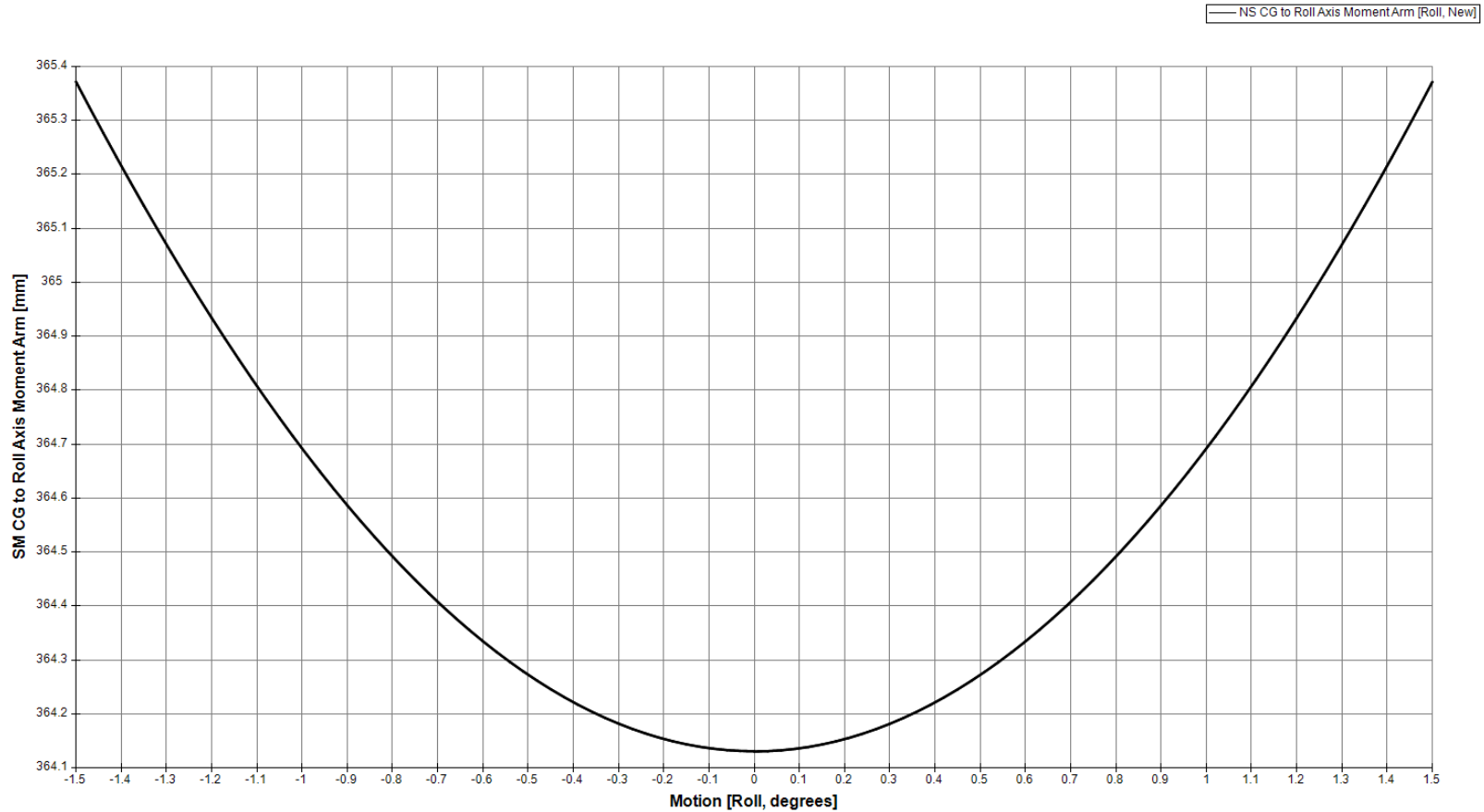
Shortest Distance Between Roll Axis and SM CG- Heave



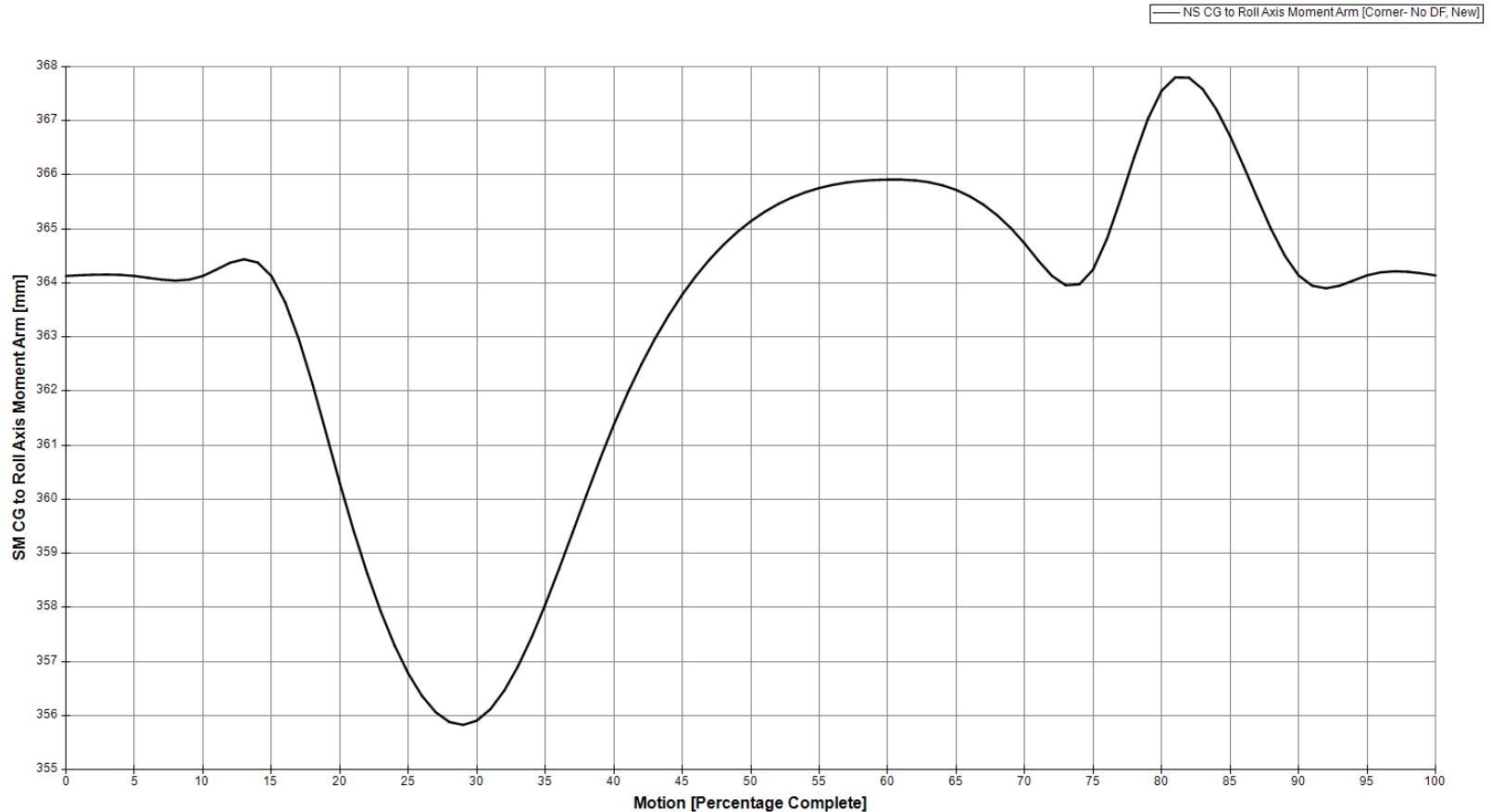
Shortest Distance Between Roll Axis and SM CG- Pitch



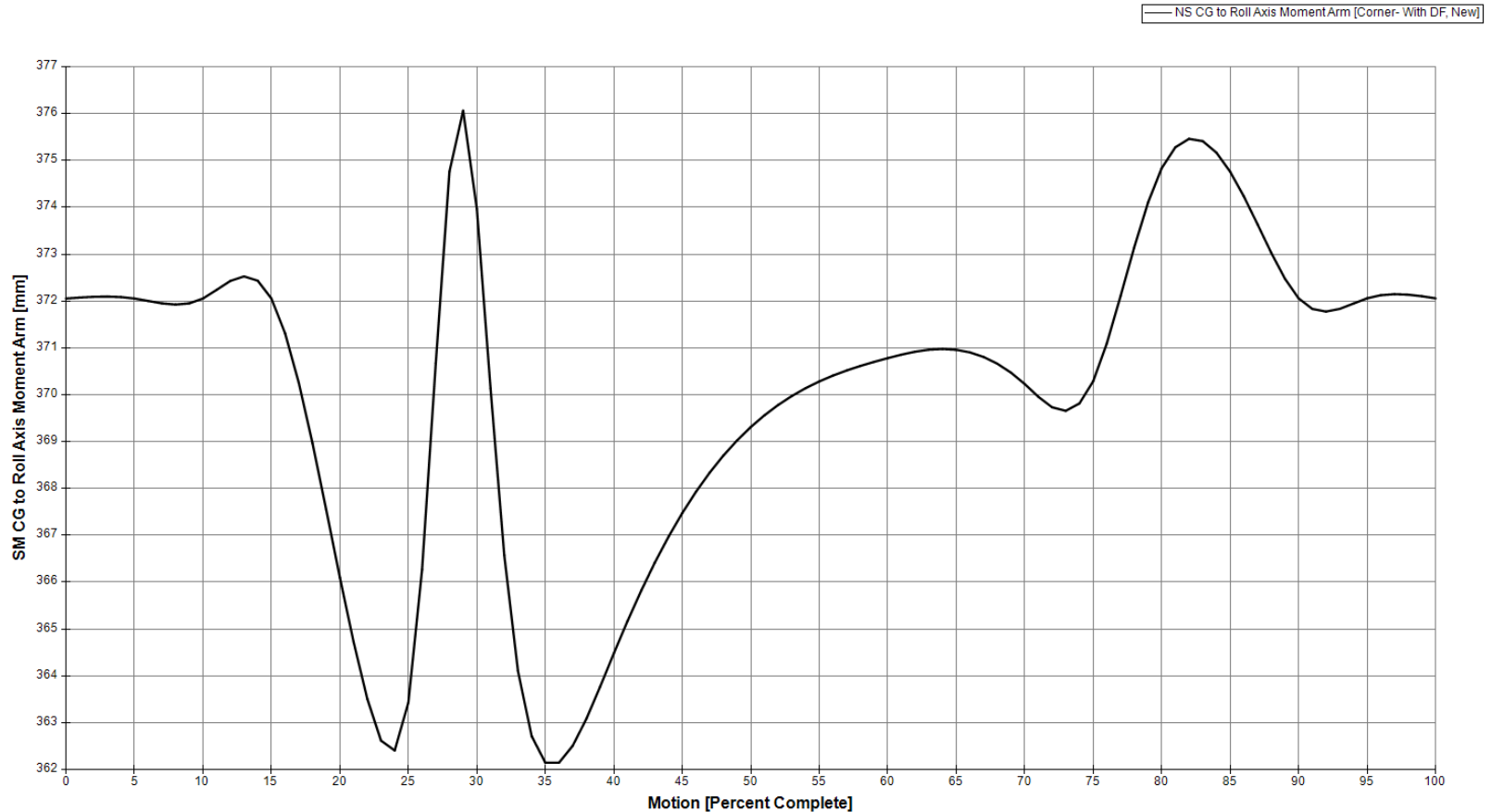
Shortest Distance Between Roll Axis and SM CG- Roll



Shortest Distance Between Roll Axis and SM CG- Corner No Downforce



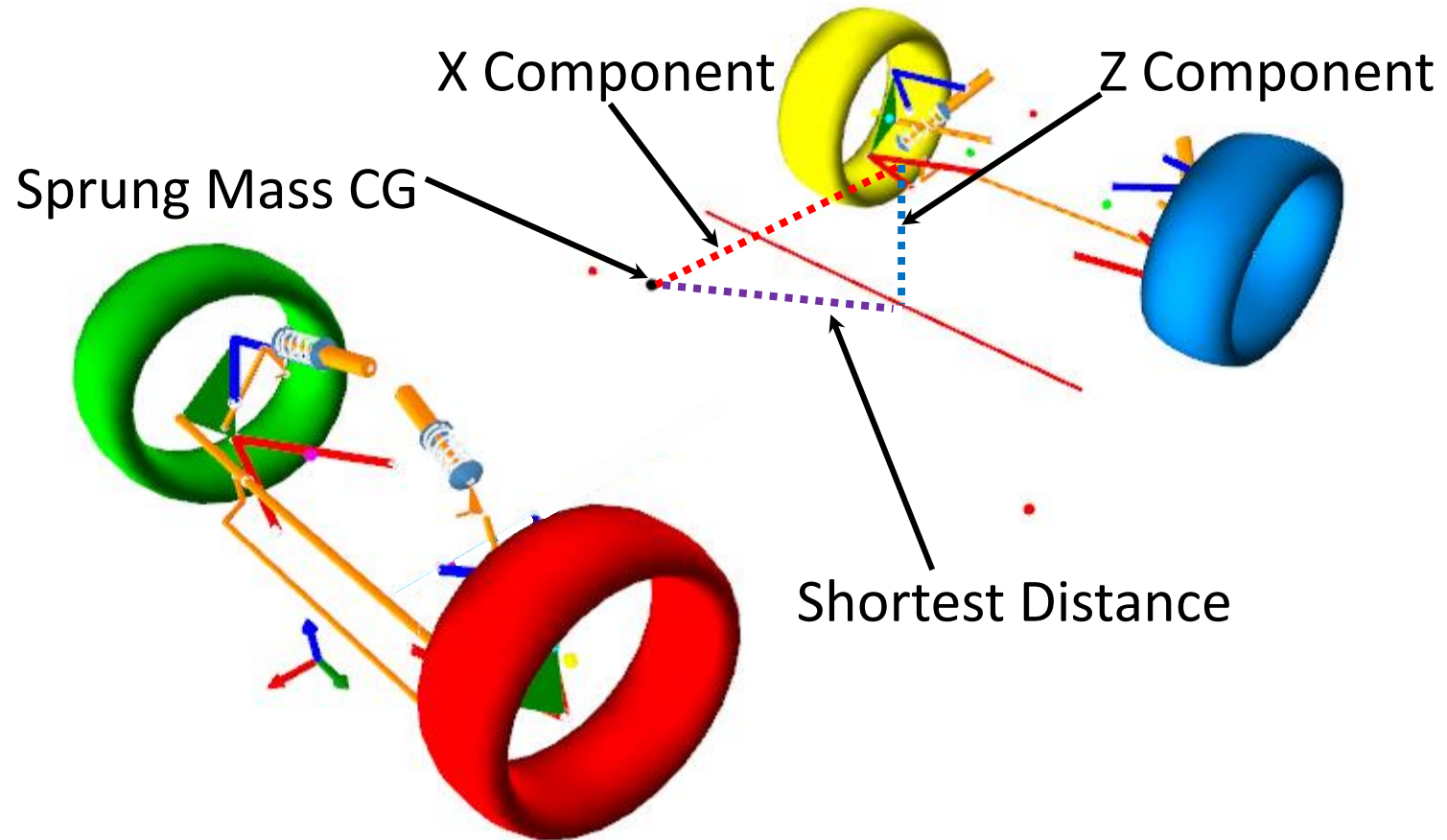
Shortest Distance Between Roll Axis and SM CG- Corner Downforce



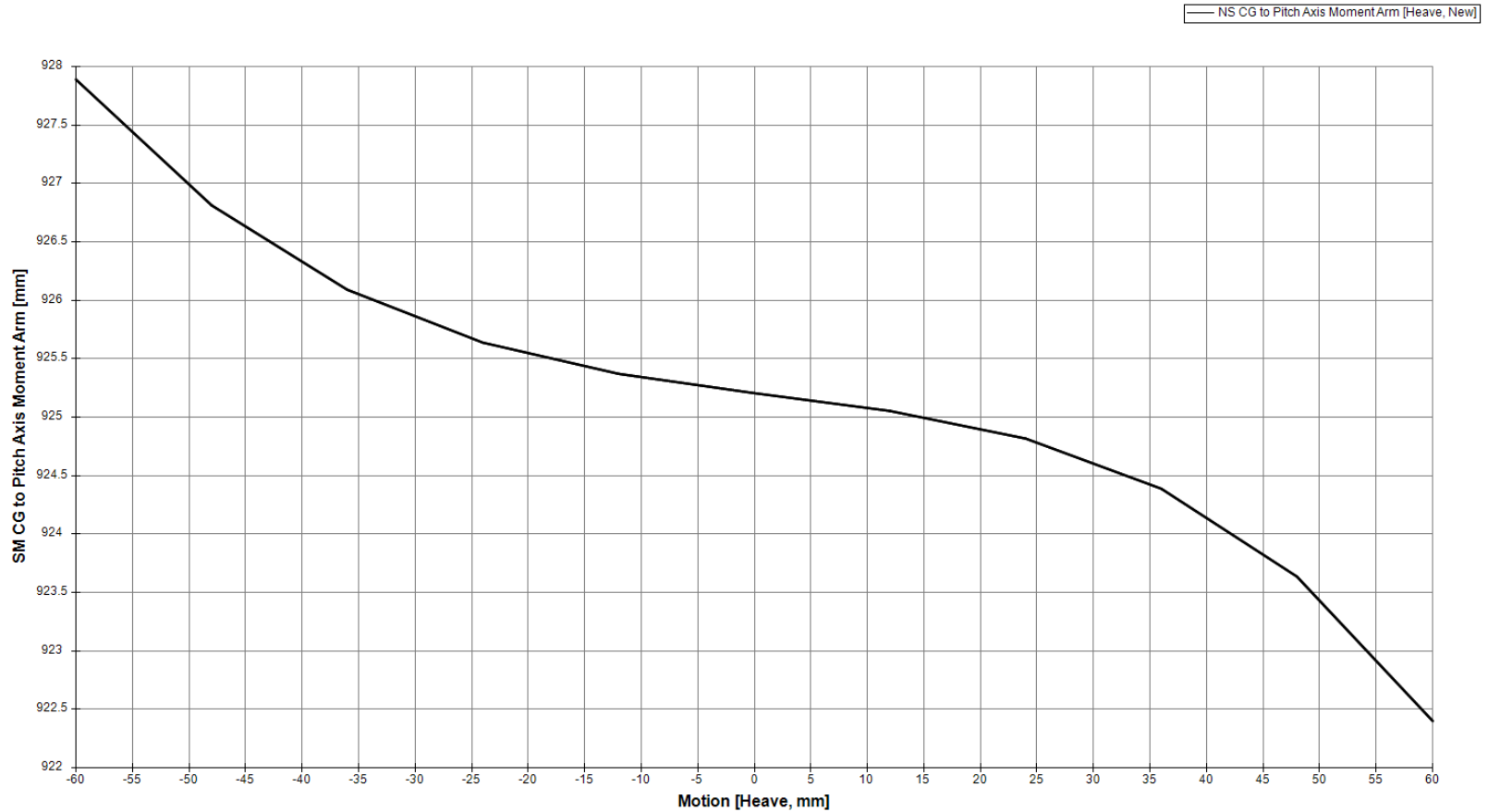
Shortest Distance Between Roll Axis and SM CG

- The evolution of the moment arm between the roll axis and the sprung mass center of gravity through a cornering sequence gives an indication of the relationship between lateral kinematic and elastic weight transfer. Change in this moment arm affects the roll inertia.
- Only the vertical component of the moment arm affects the elastic to kinematic weight transfer relationship.
- The magnitude of this moment arm should be considered in conjunction with the roll center migration results
- The cornering simulation with downforce shows the distance between sprung mass center of gravity and the roll axis changing by approximately 15 mm over the duration

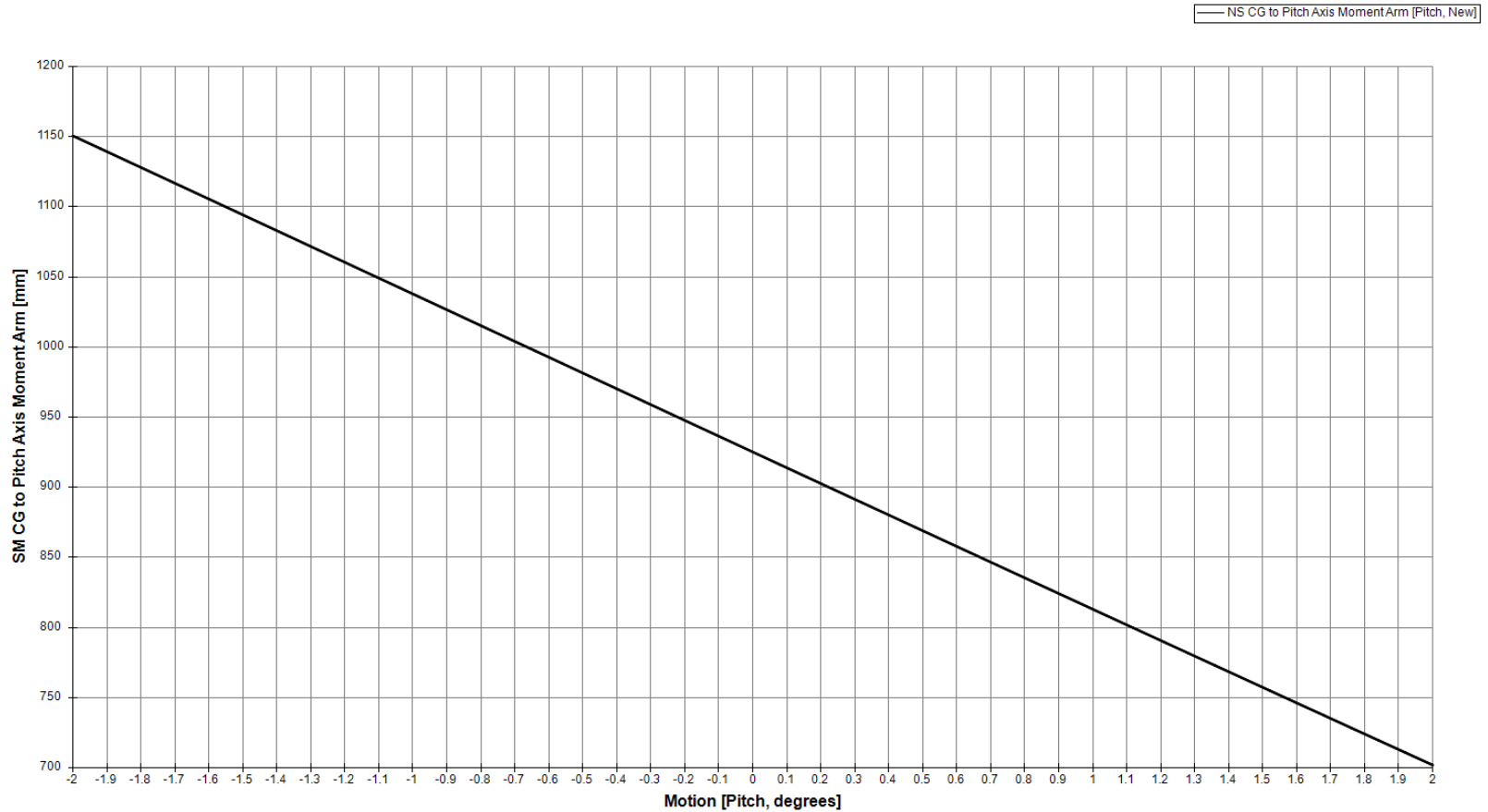
Shortest Distance Between Pitch Axis and SM CG



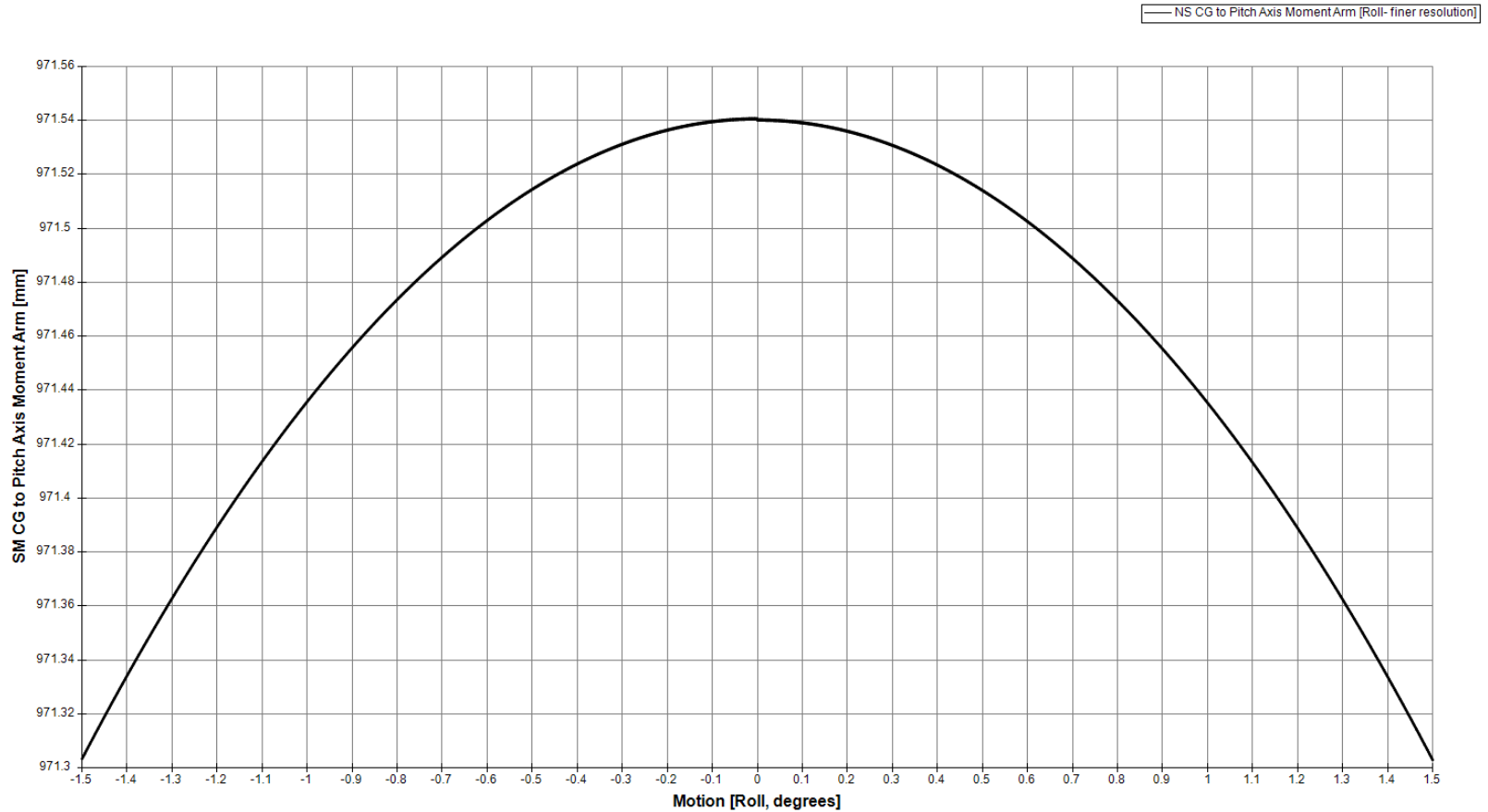
Shortest Distance Between Pitch Axis and SM CG- Heave



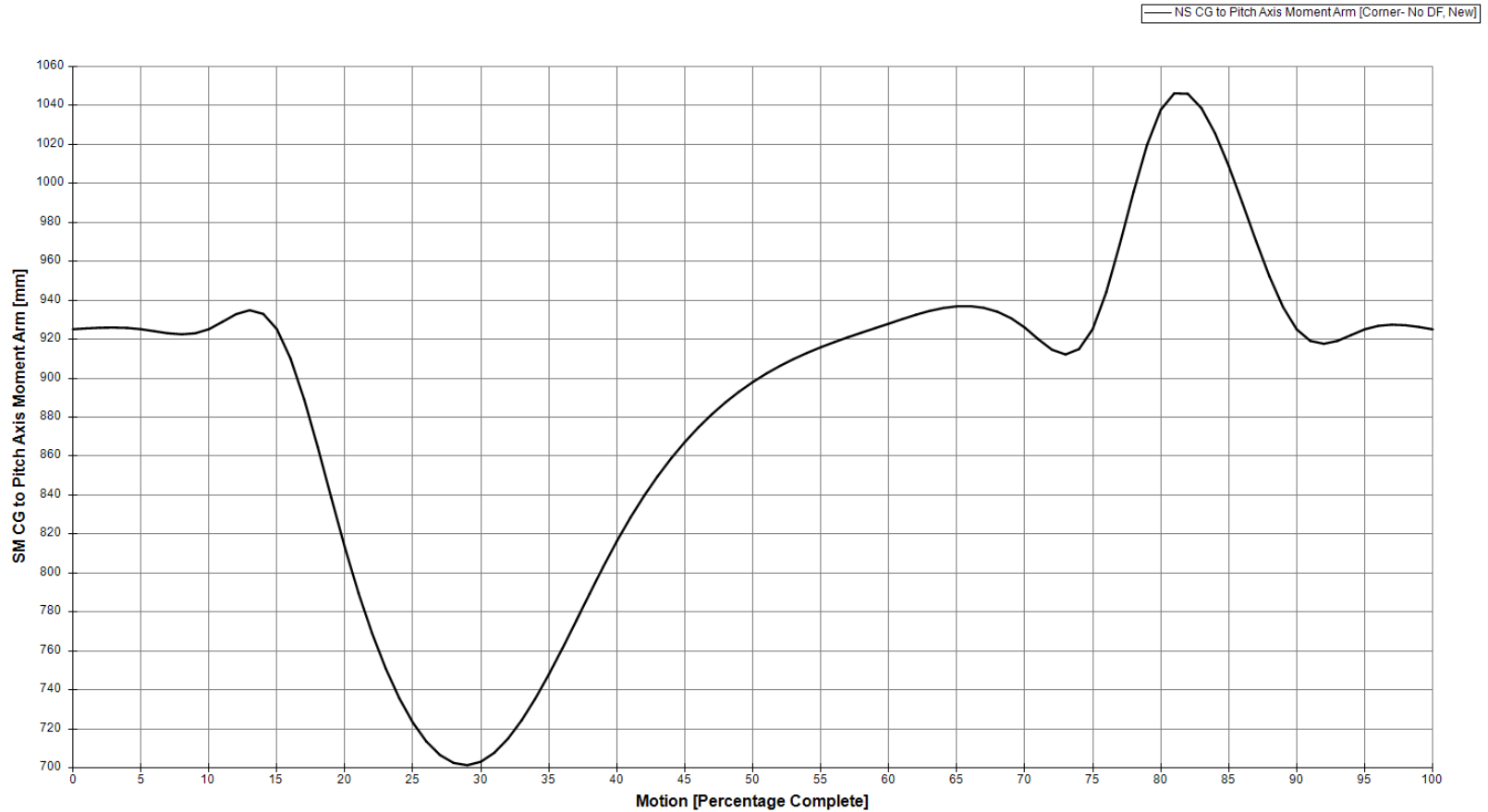
Shortest Distance Between Pitch Axis and SM CG- Pitch



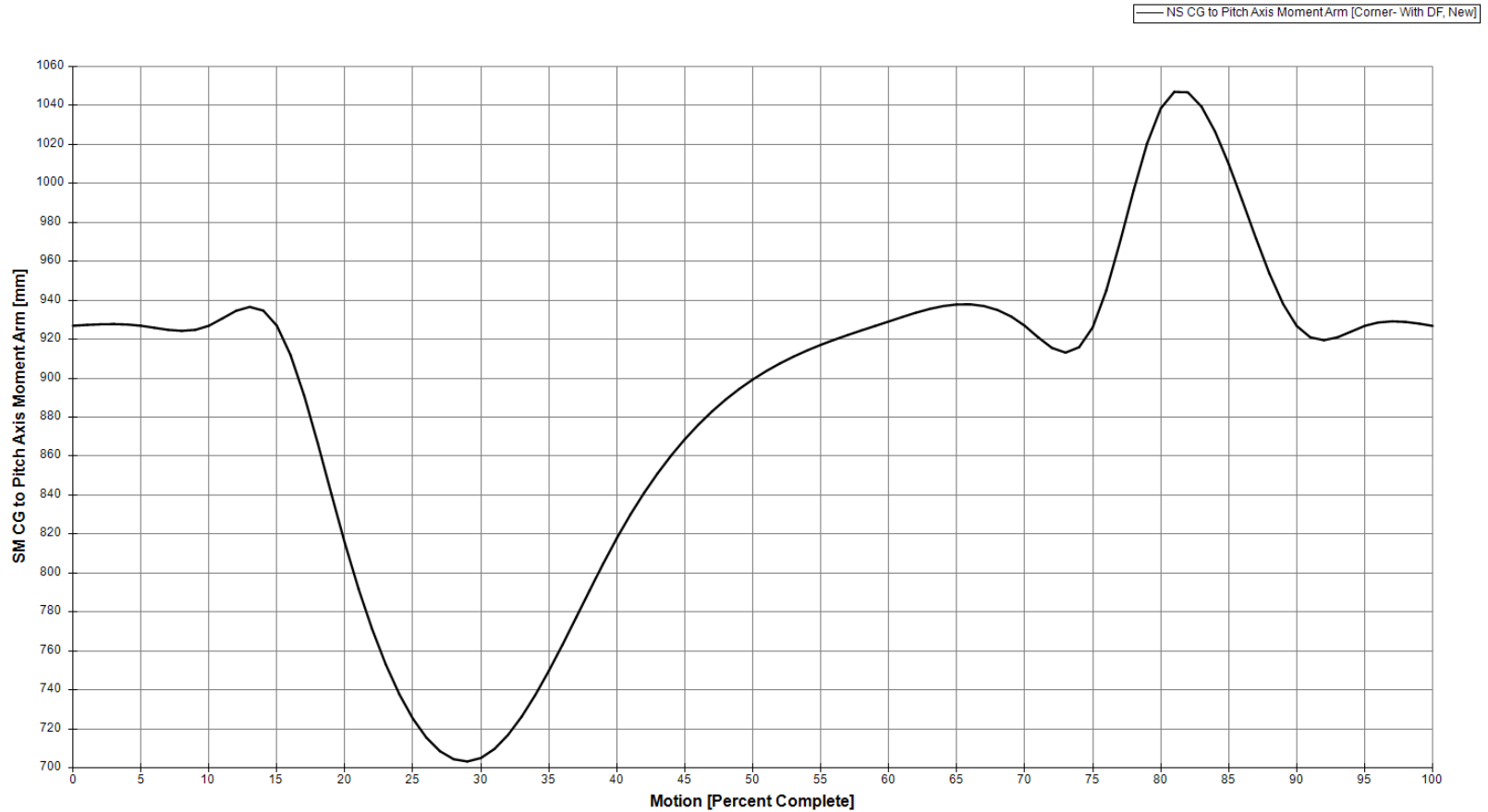
Shortest Distance Between Pitch Axis and SM CG- Roll



Shortest Distance Between Pitch Axis and SM CG- Corner No Downforce



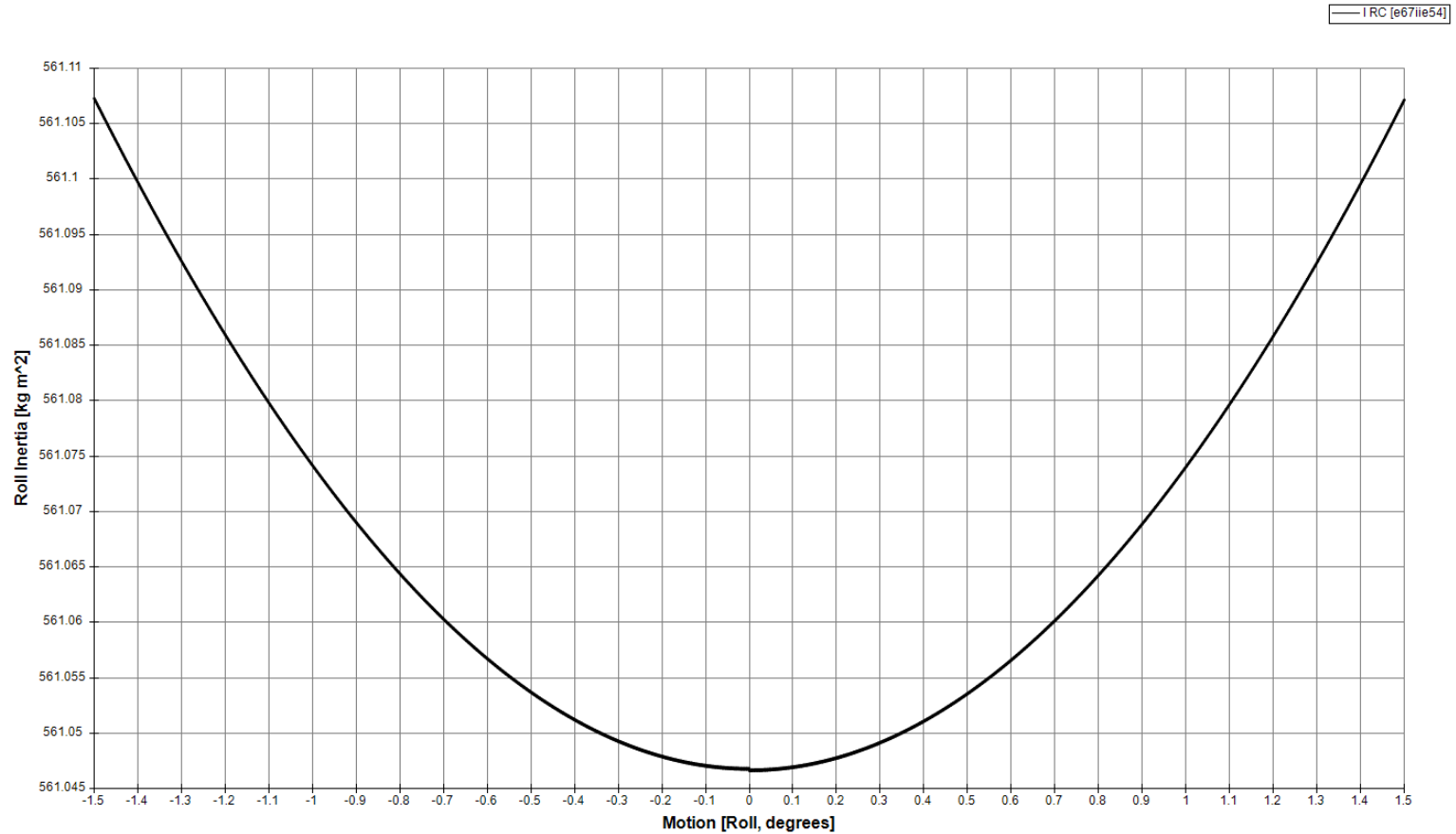
Shortest Distance Between Pitch Axis and SM CG- Corner Downforce



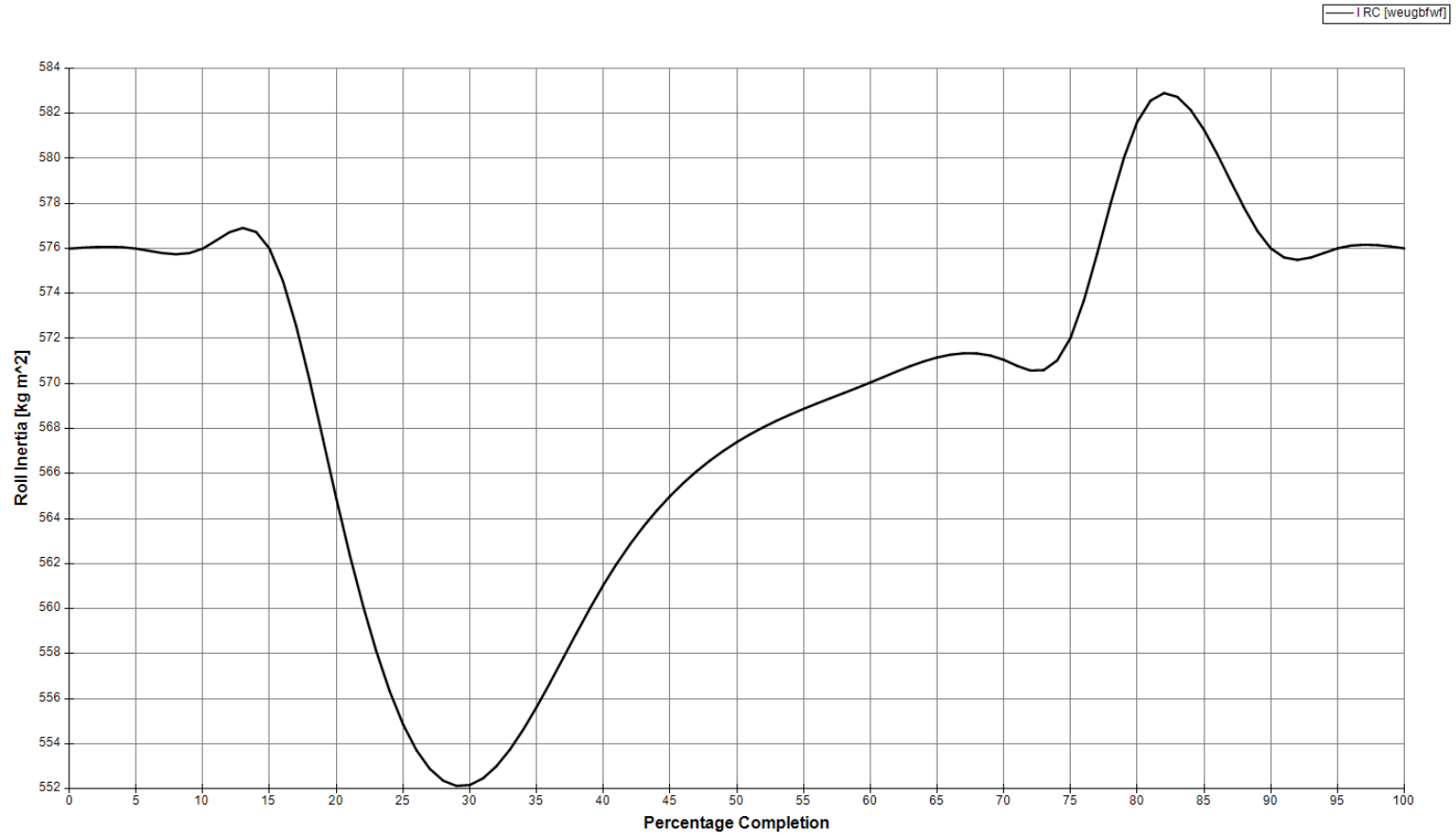
Shortest Distance Between Pitch Axis and SM CG

- The evolution of the moment arm between the pitch axis and the sprung mass center of gravity through a cornering sequence gives an indication of the relationship between longitudinal kinematic and elastic weight transfer. Change in this moment arm affects the pitch inertia of the sprung mass.
- Only the vertical component of the moment arm affects the elastic to kinematic weight transfer relationship.
- The magnitude of this moment arm should be considered in conjunction with the pitch center migration results
- During the pitch simulation there is a large change in the pitch center to sprung mass center of gravity moment arm of approximately 400 mm

Roll Inertia Change - Roll



Roll Inertia Change – Corner with DF



Pitch Inertia Change - Pitch

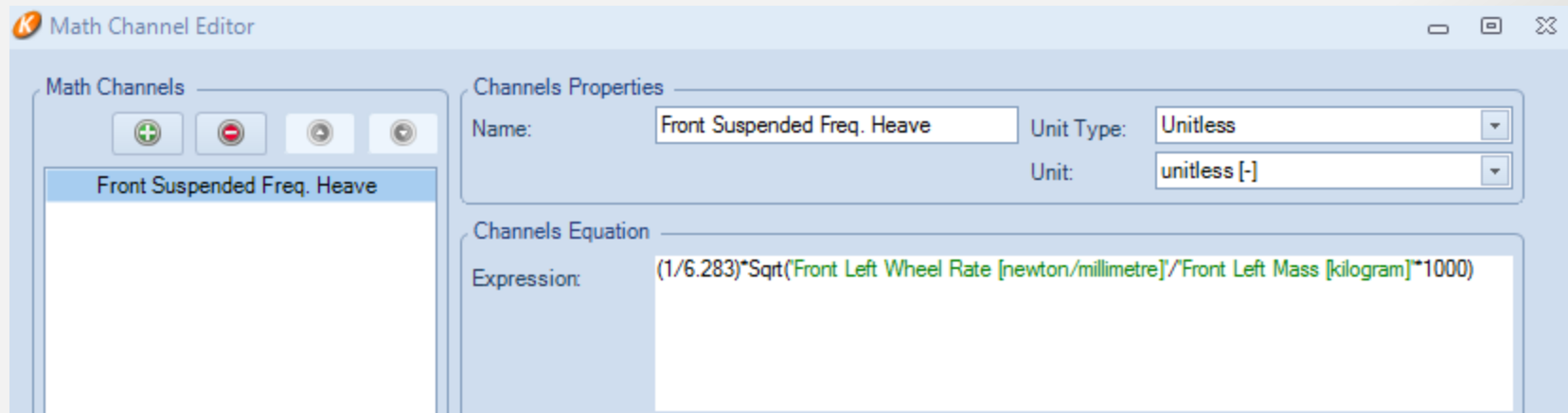
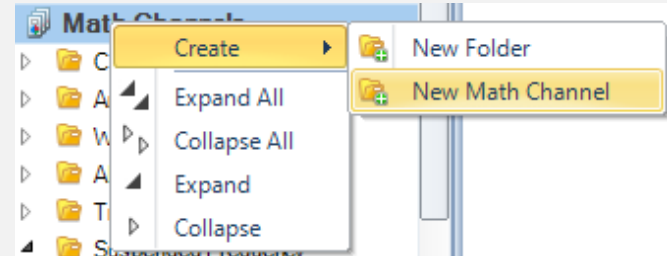
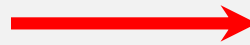


Inertia Change – Comments

- Changes in inertia throughout a given movement will change the transient response of the sprung mass
- Roll inertia essentially unchanged in roll simulation, small change in roll inertia during corner simulation.
- Significant changes in pitch inertia due to large movement of pitch center during pitch simulation

Creating Suspended Mass Frequency Math Channel- Heave

Create new math
channel and name



Wheel rate including
motion ratio

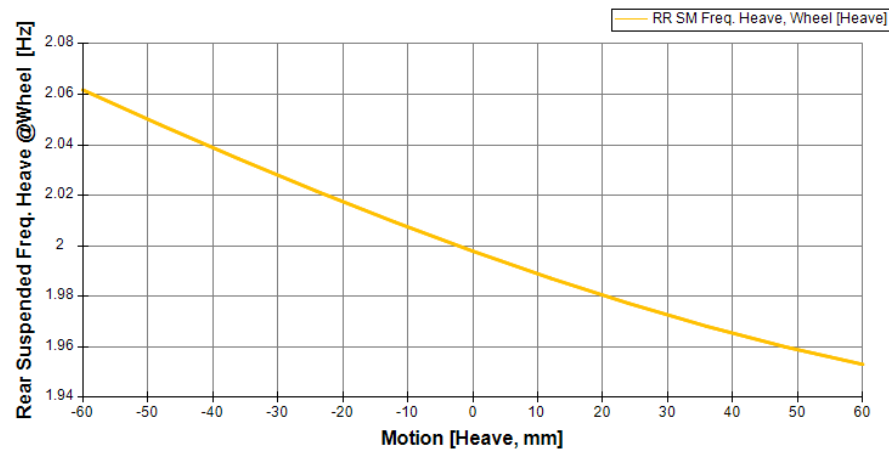
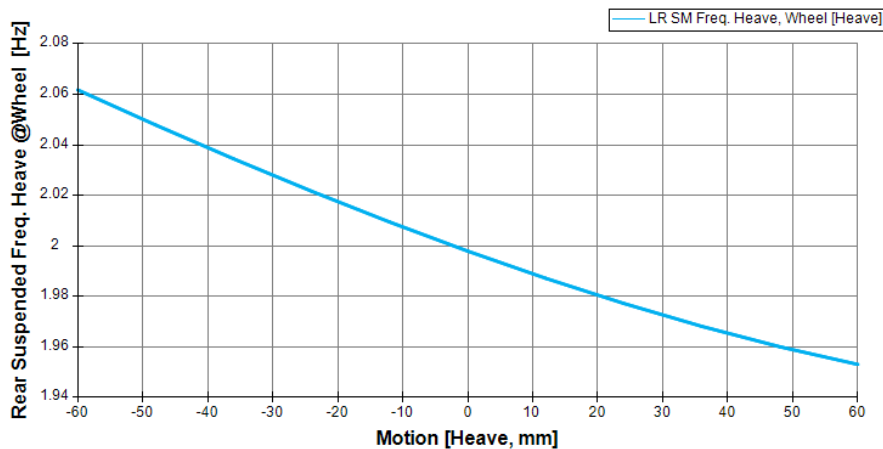
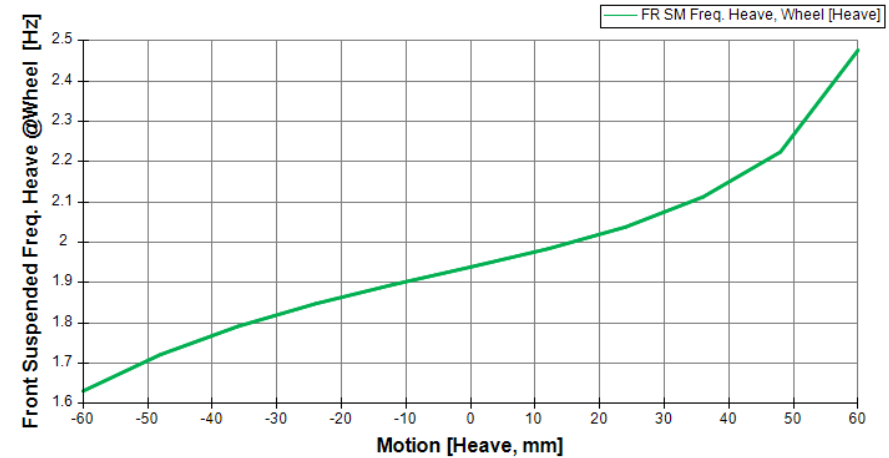
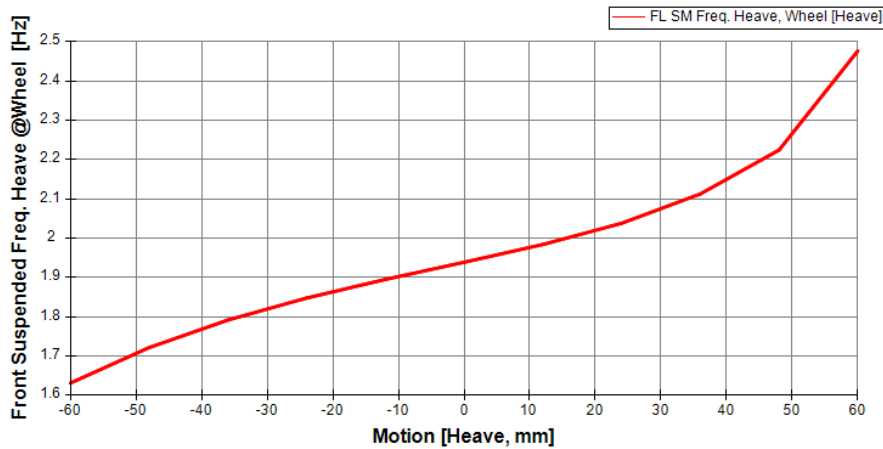


Suspended mass of
left front corner

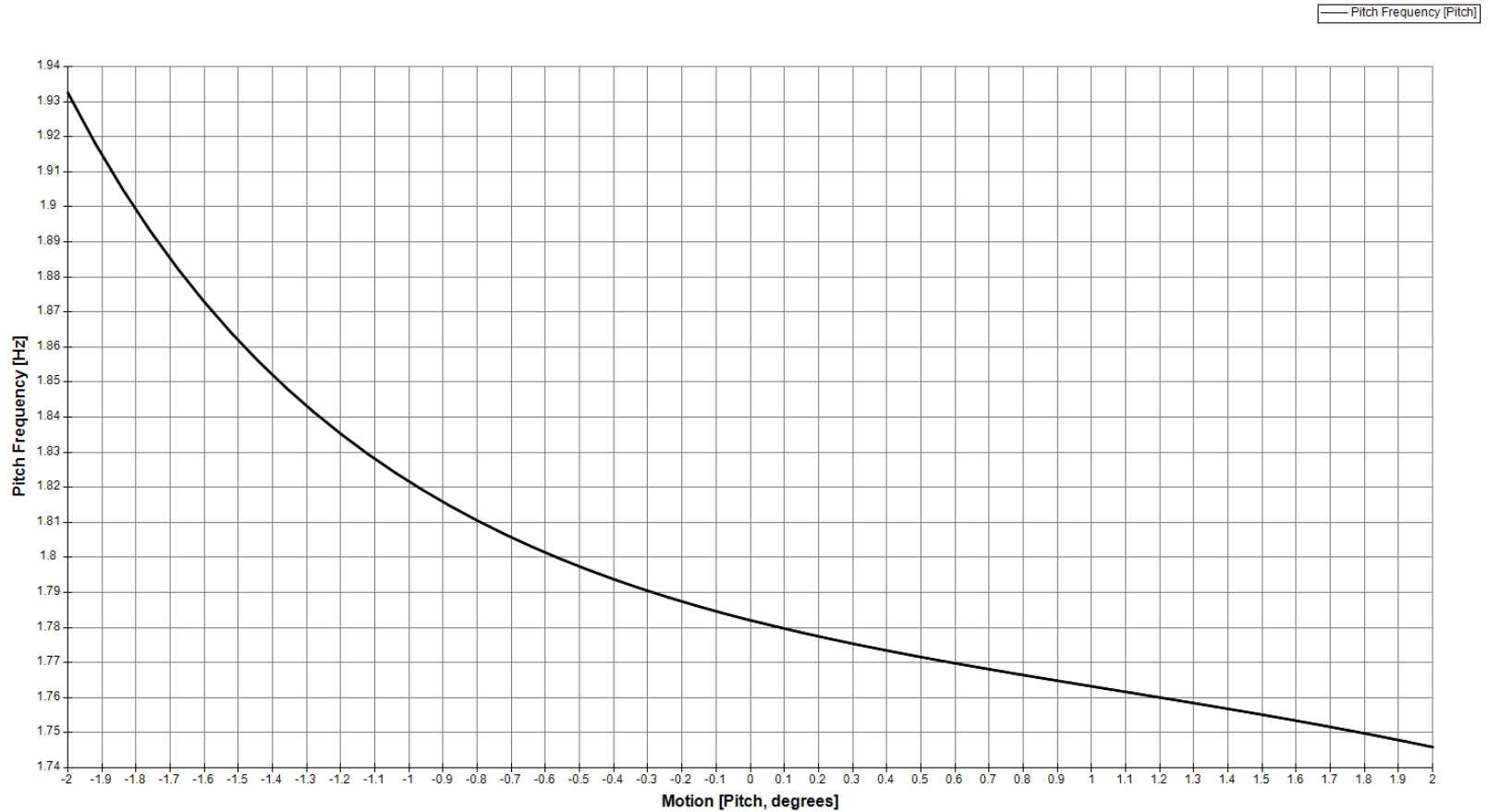


$$(1/6.283)*\text{Sqrt}(' \text{Front Left Wheel Rate [newton/millimetre]} / \text{Front Left Mass [kilogram]} * 1000)$$

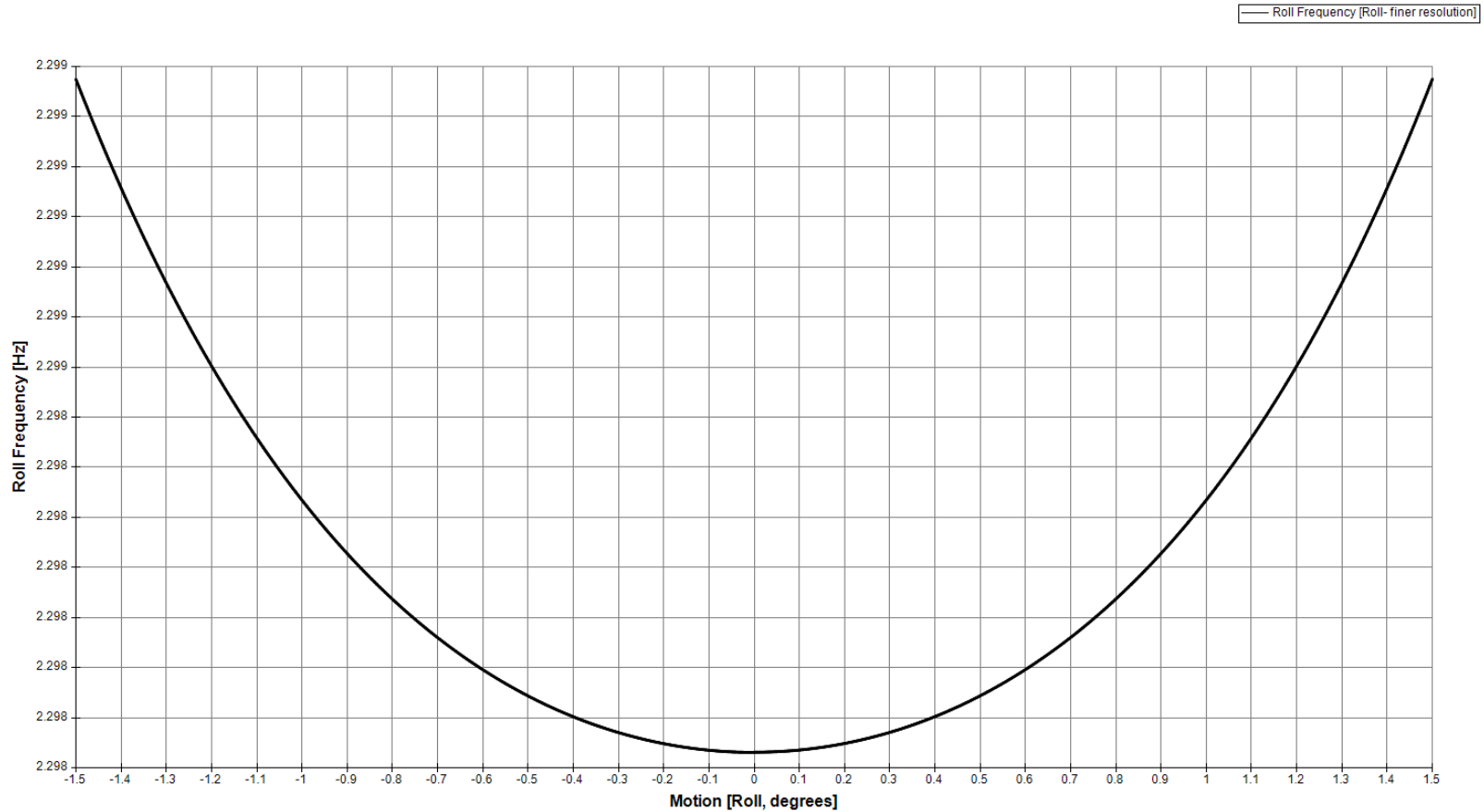
Suspended Mass Frequency- Heave



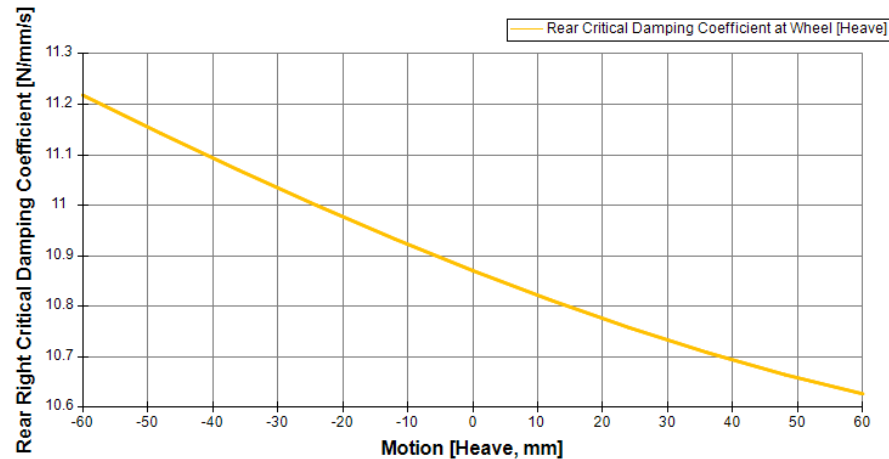
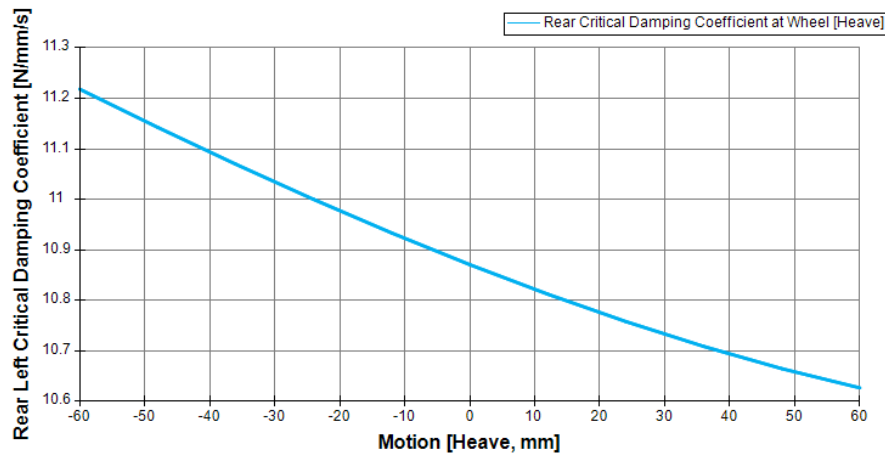
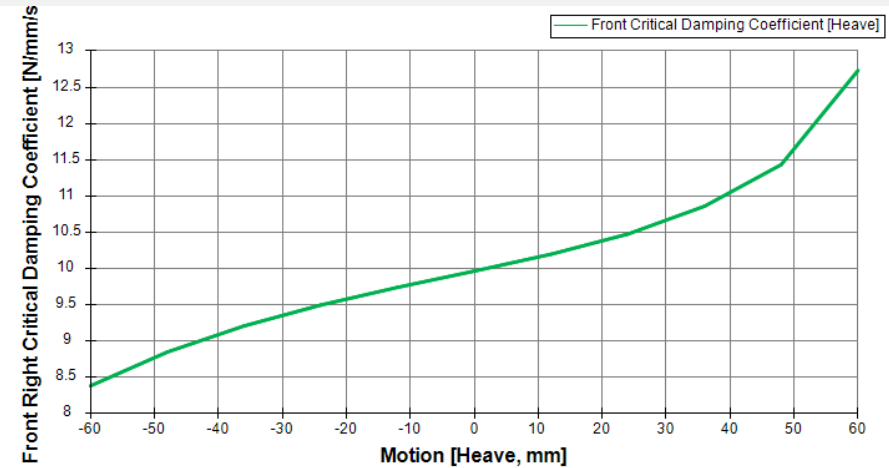
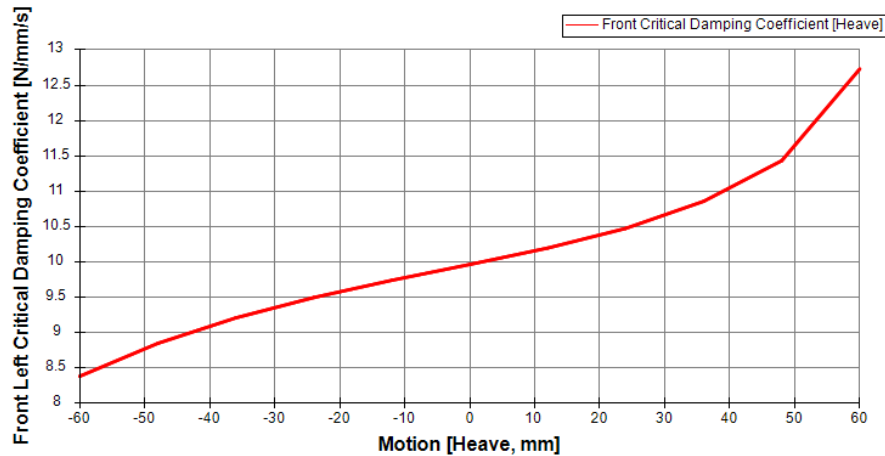
Suspended Mass Frequency- Pitch



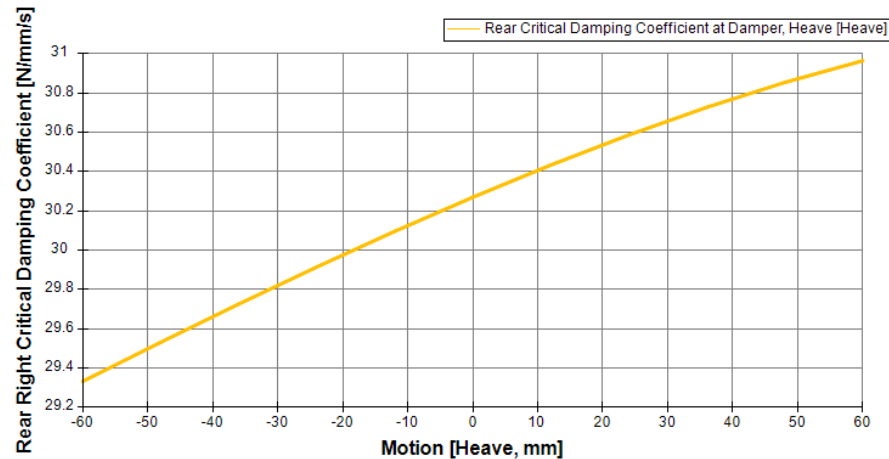
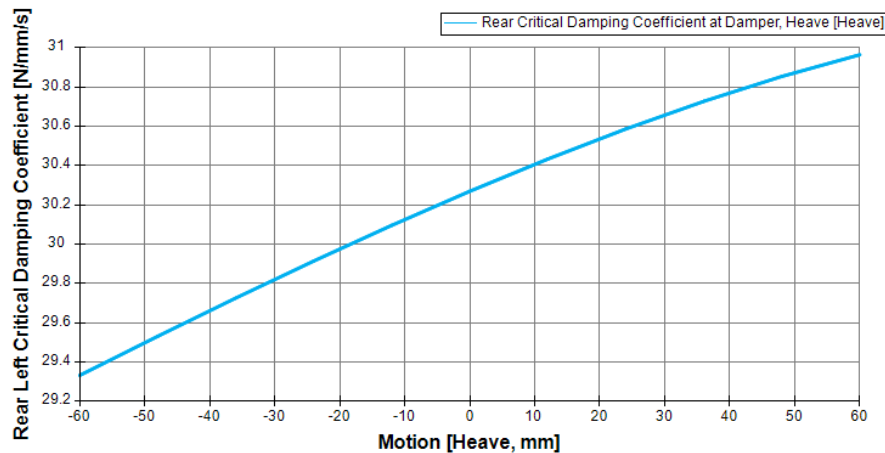
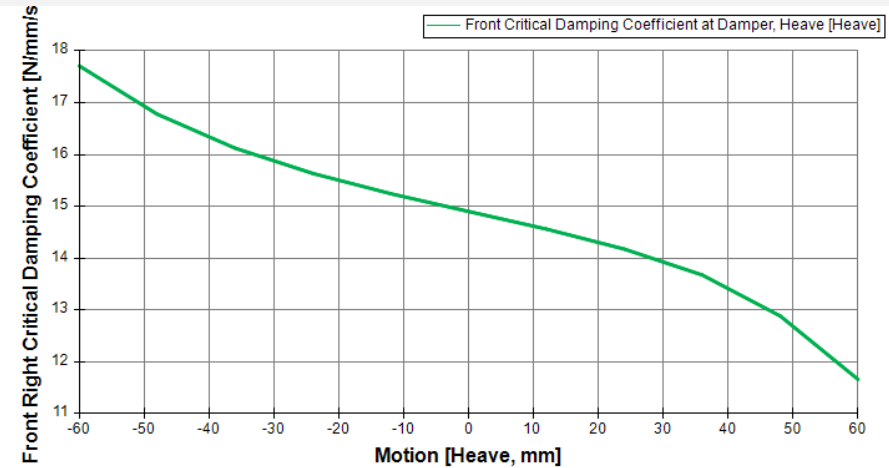
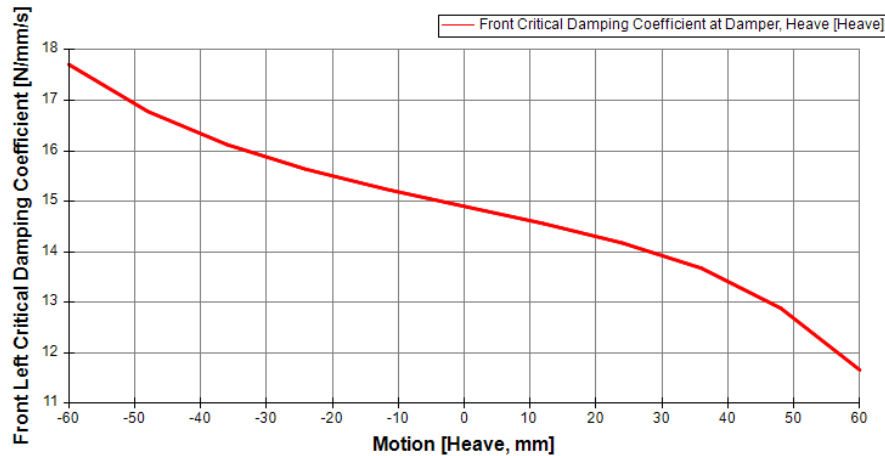
Suspended Mass Frequency- Roll



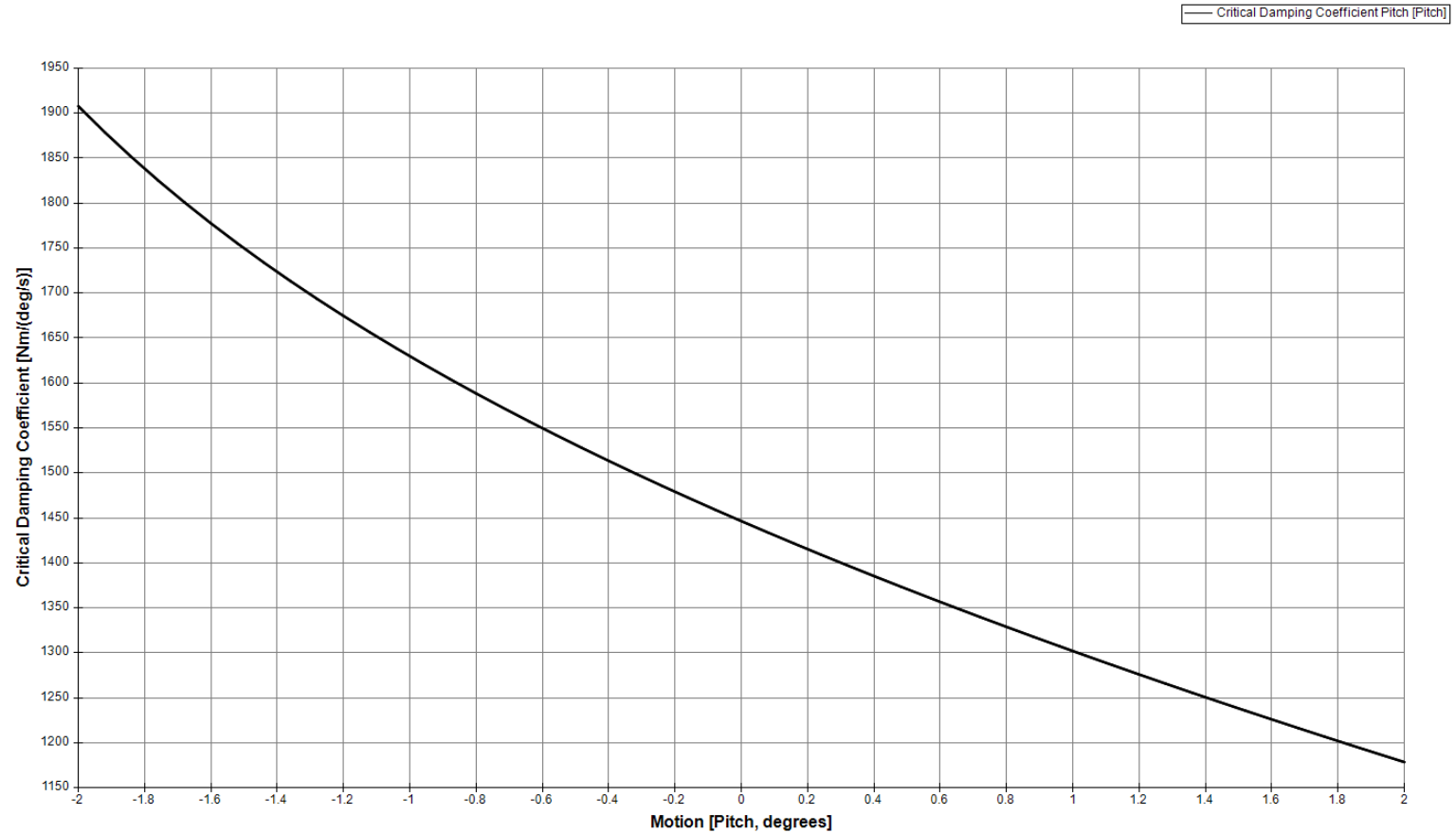
Suspended Mass Critical Damping- Heave At Wheel



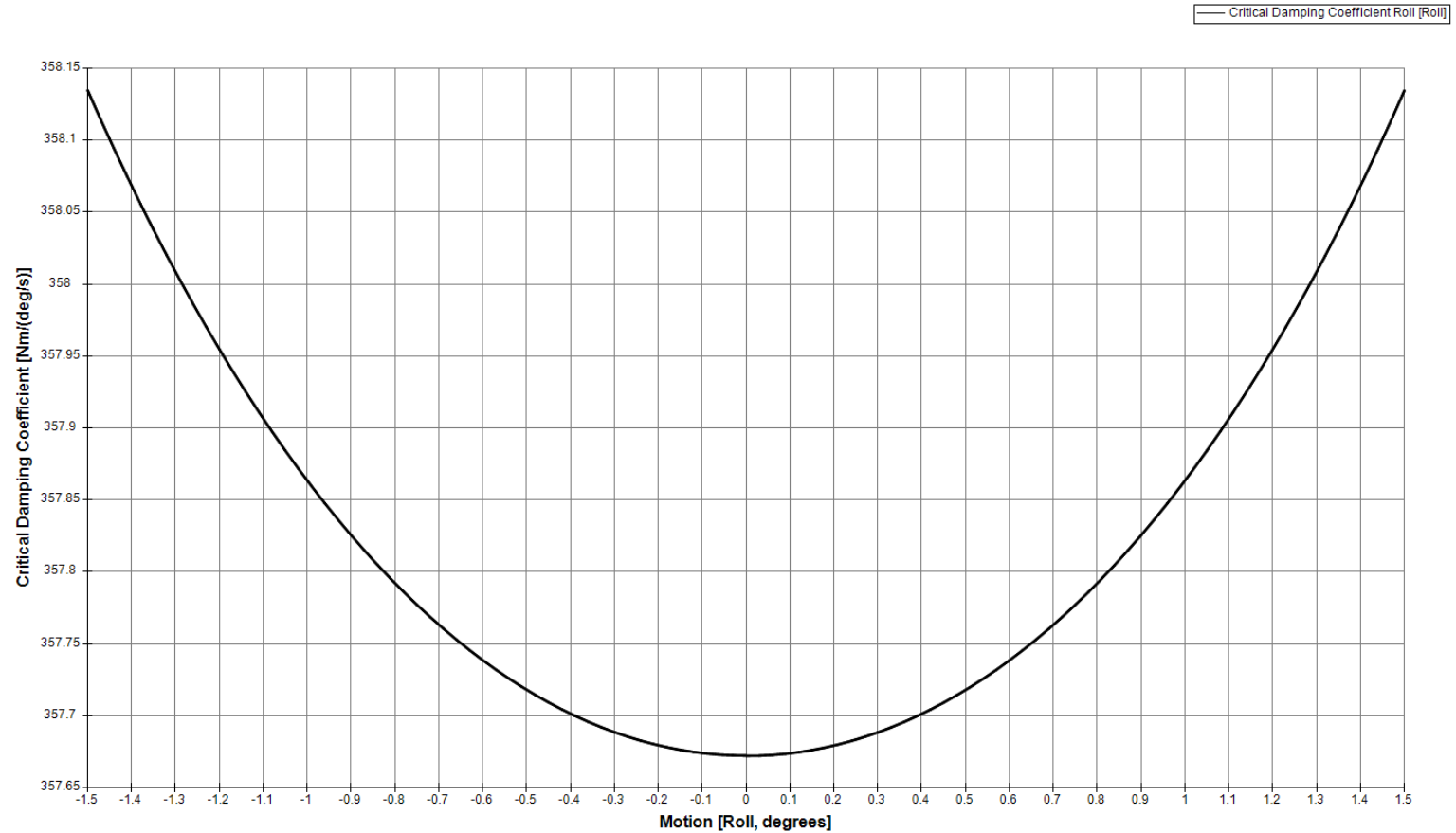
Suspended Mass Critical Damping- Heave At Damper



Suspended Mass Critical Damping- Pitch

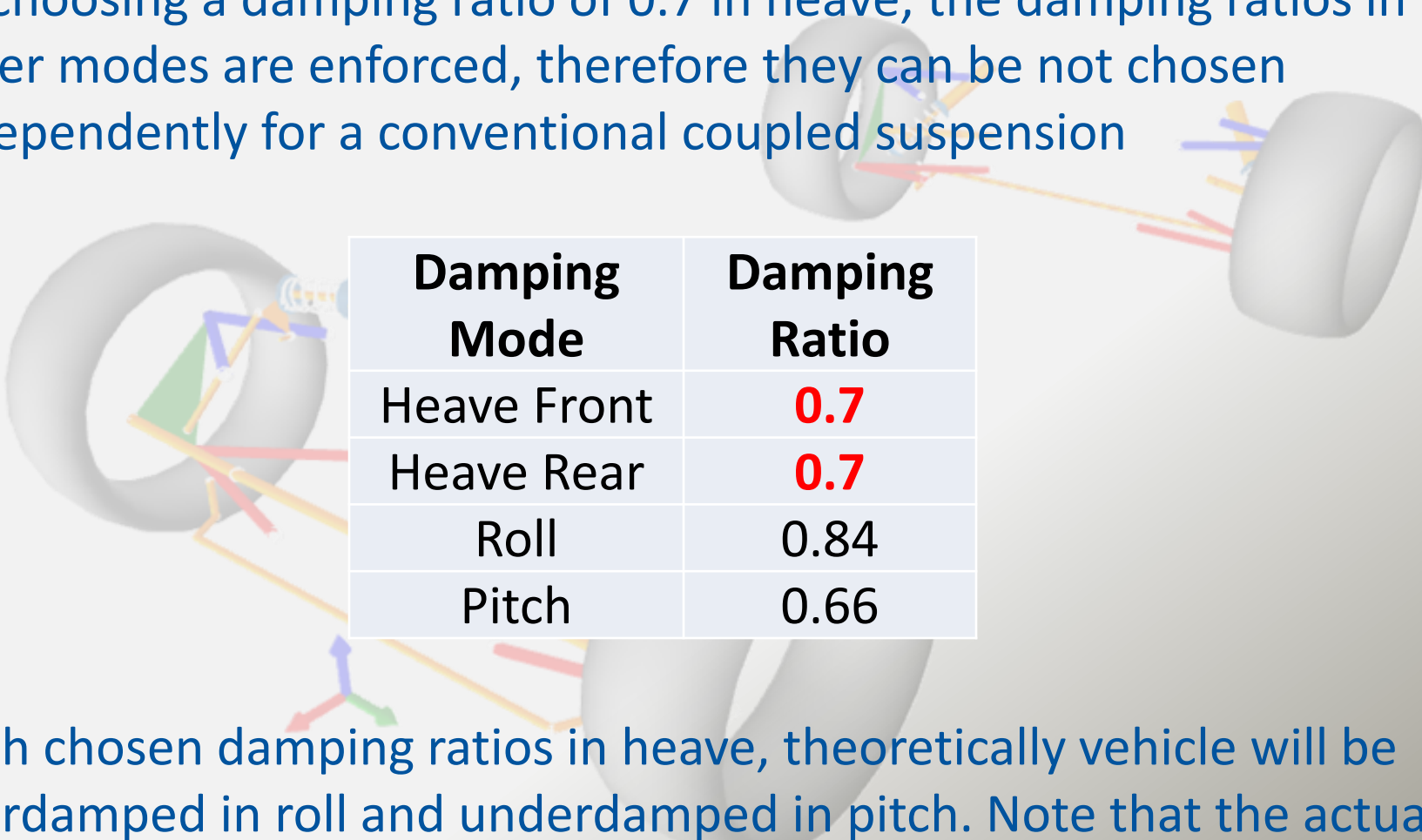


Suspended Mass Critical Damping- Roll



Suspended Frequency and Damping – Comments

By choosing a damping ratio of 0.7 in heave, the damping ratios in other modes are enforced, therefore they can be not chosen independently for a conventional coupled suspension



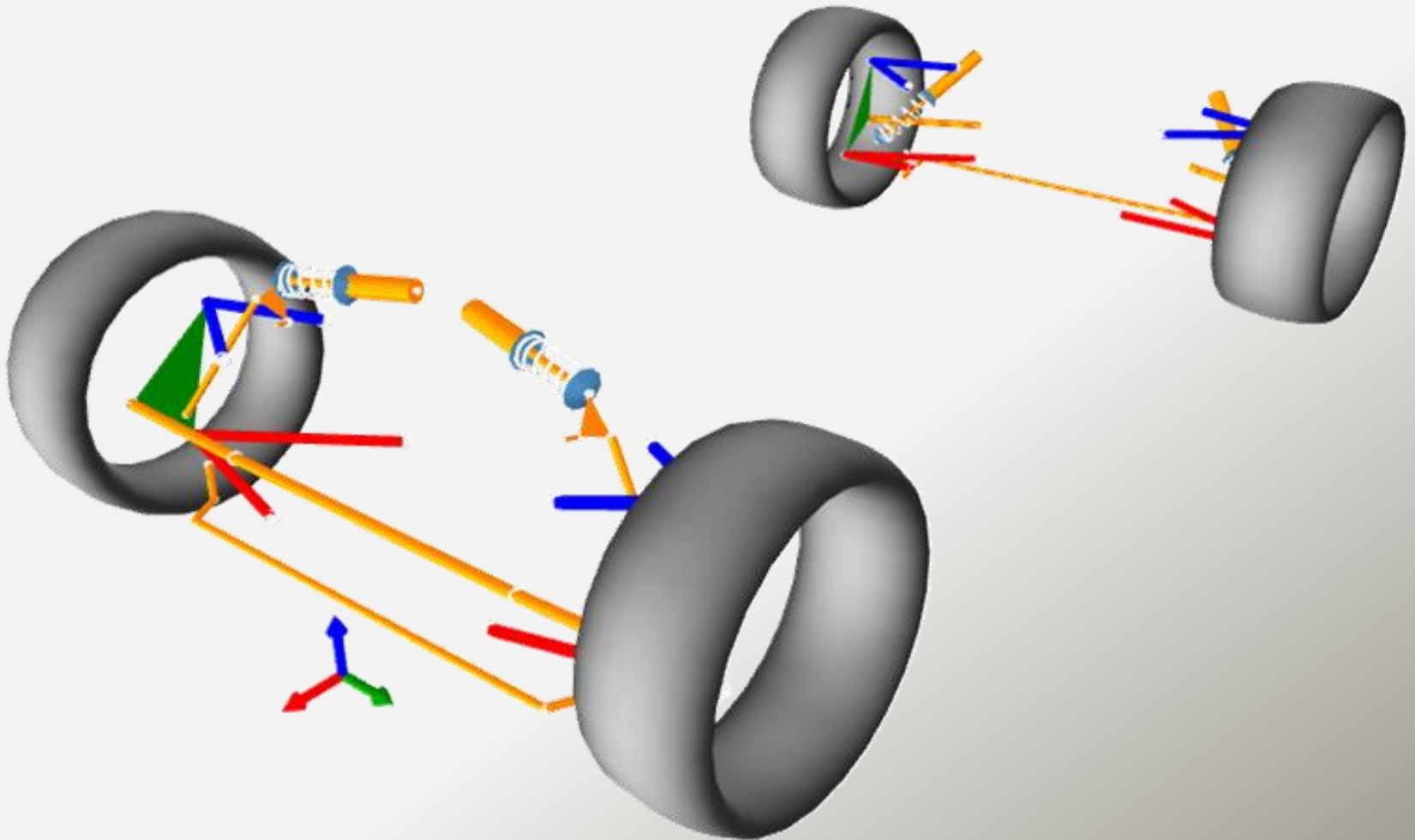
Damping Mode	Damping Ratio
Heave Front	0.7
Heave Rear	0.7
Roll	0.84
Pitch	0.66

With chosen damping ratios in heave, theoretically vehicle will be overdamped in roll and underdamped in pitch. Note that the actual damping ratios are a function of installation stiffness.

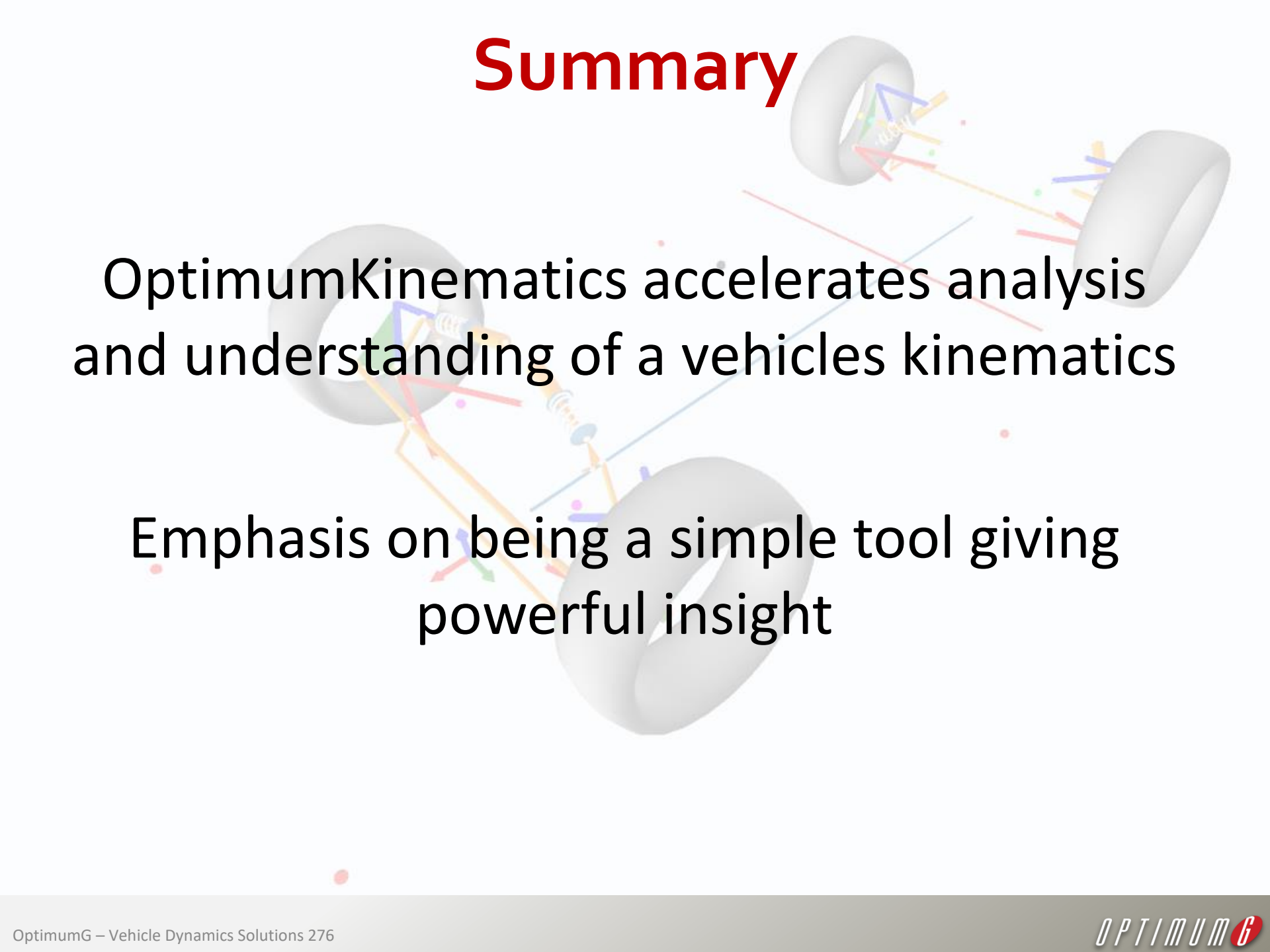
Suspended Frequency and Damping – Comments

- Damping requirements change with displacement due to motion ratios changing throughout all motions- pitch, roll and heave
- With knowledge of damping coefficients of fitted dampers, damping ratio at each position in each mode can be computed
- By simulating motion that includes variable motion ratios via the math channels, further insight into the frequency and damping response is possible than with traditional basic analysis

7. Summary



Summary

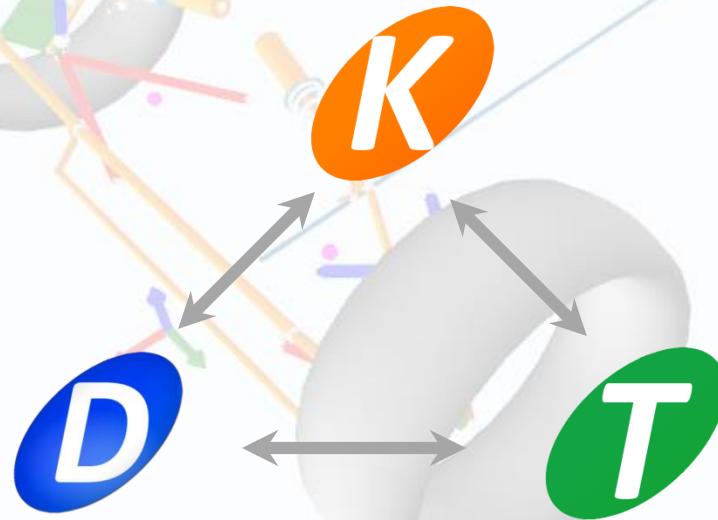


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Summary

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Questions and Enquiries-
software@optimumg.com