Simulating and Prototyping a Formula SAE Race Car Suspension System

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Progress Report

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Role of a Race Car Suspension System

- Transfers forces from the tire contact patch to accelerate a car:
  - Kinematics:
    - relative motion between the ground, tire/wheel and car body
    - governs manner of force transfer
    - concerned with geometry
  - Dynamics:
    - forces between the tires and the car
    - behavior of the car
    - concerned with rates

Assumptions

- Sprung and unsprung masses
- Front/rear mass distribution
- Center of gravity height
- Rigid frame
- Assumed maximum accelerations:
  - 1.5 G cornering
  - 1.2 G braking
  - < 1 G acceleration

Major Components

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Kinematics
Dynamics
Reliability
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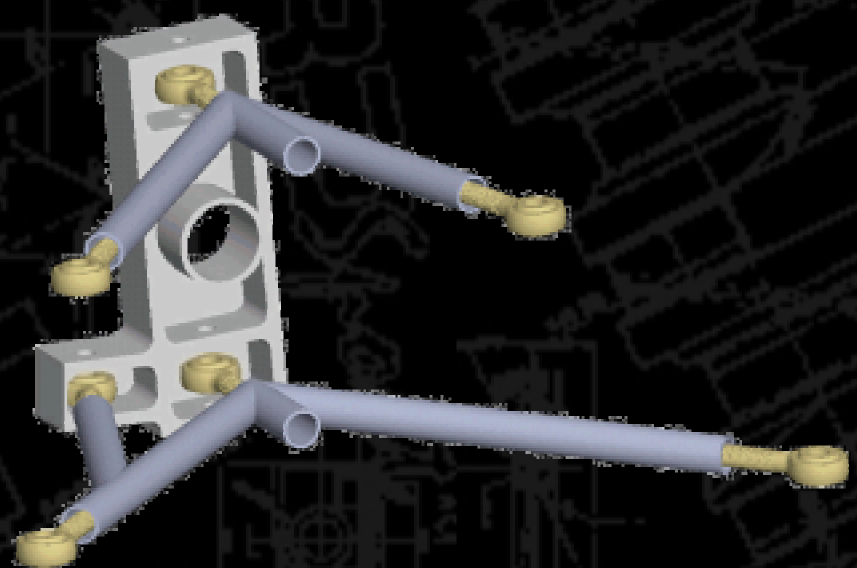
Summary

- Control arms
  - Rigid suspension links
- Upright
  - Interface between control arms and wheels
- Spring and damper (shock absorber)



Basic Design

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Summary

- Independent double A-arms
  - Flexibility in choosing parameters
  - Mostly axial loading
  - Common race car design
- Outboard springs and dampers
  - Reduced complexity
  - Sufficient adjustability

Suspension Kinematics

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- **Bottom line:**
  - **Maximize tire contact patch utilization**
  - **Correct geometry between tire and ground**

Camber

- **Affects tire's ability to generate lateral (cornering) forces**

Camber

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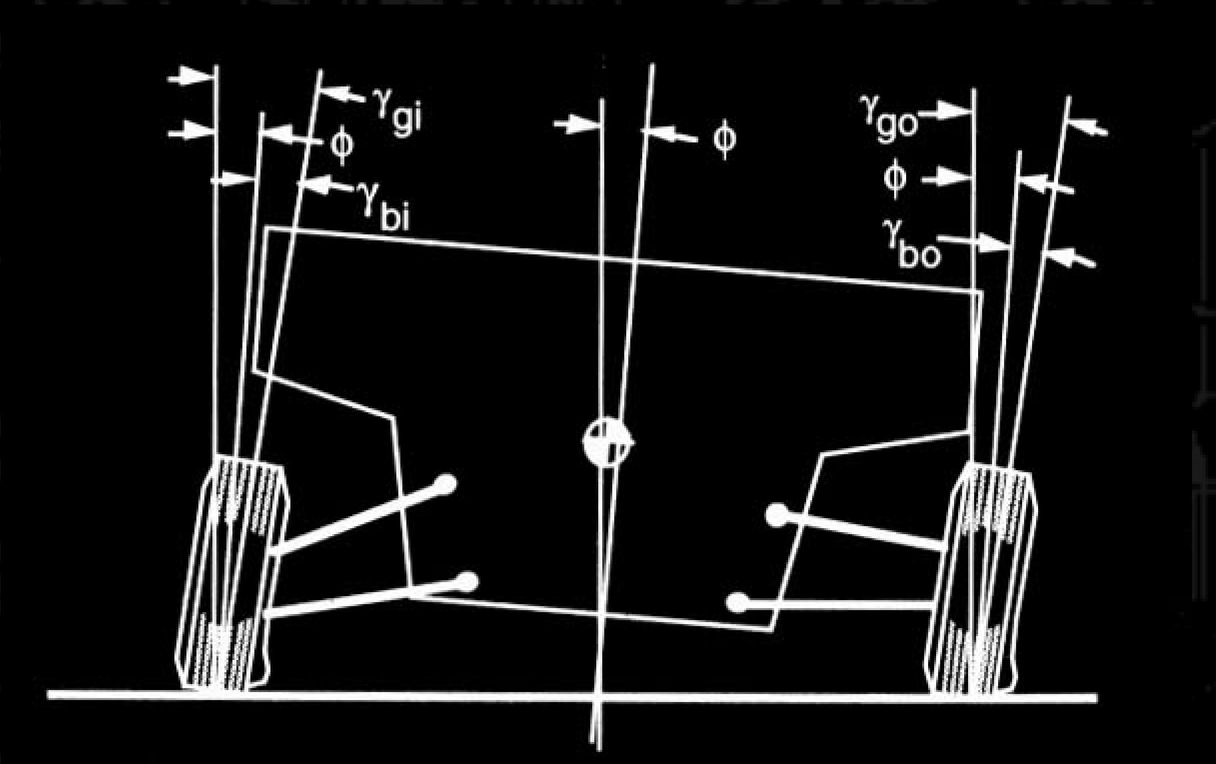
- Camber needs to change with wheel travel because car rolls to the side during cornering



Camber Gain

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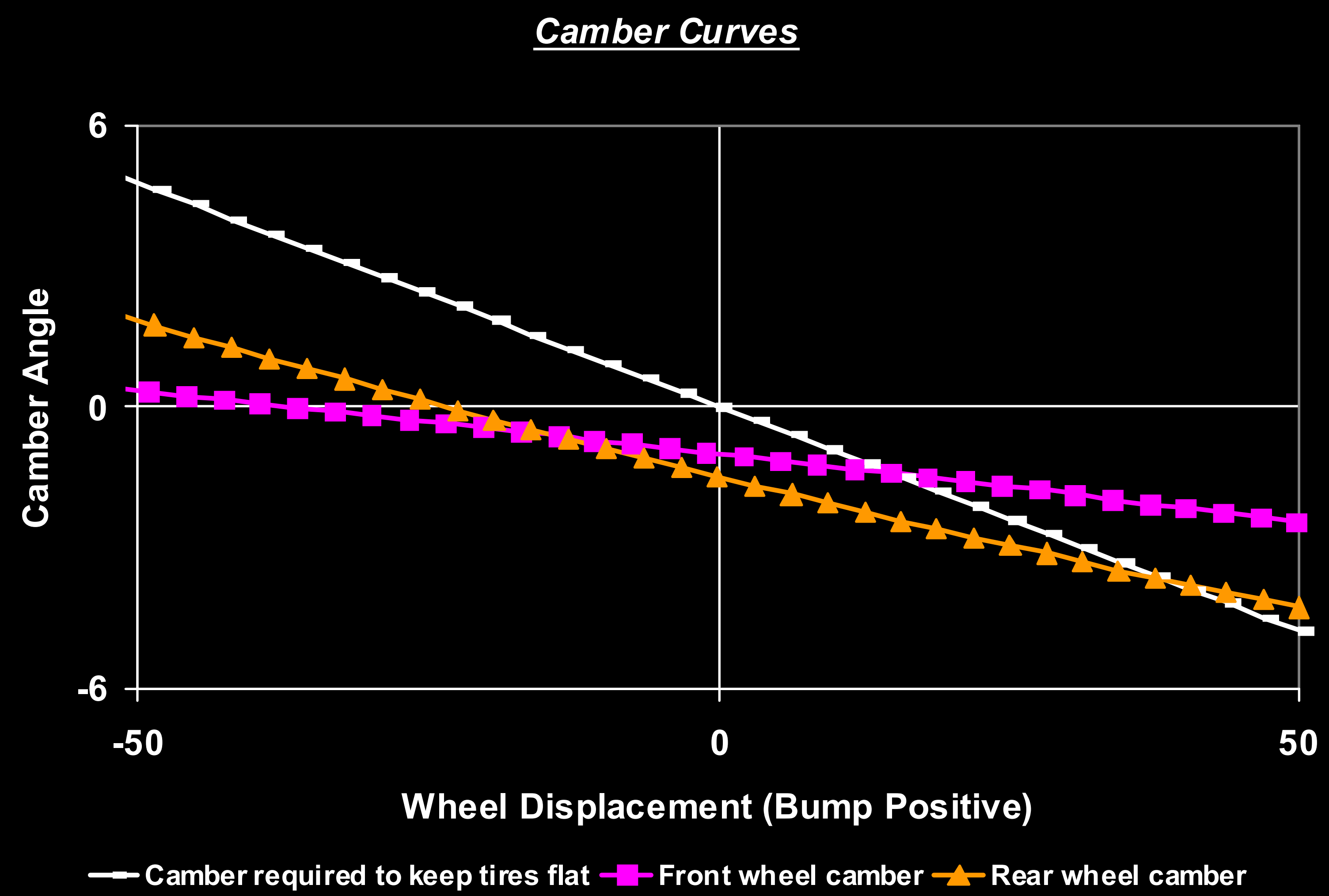
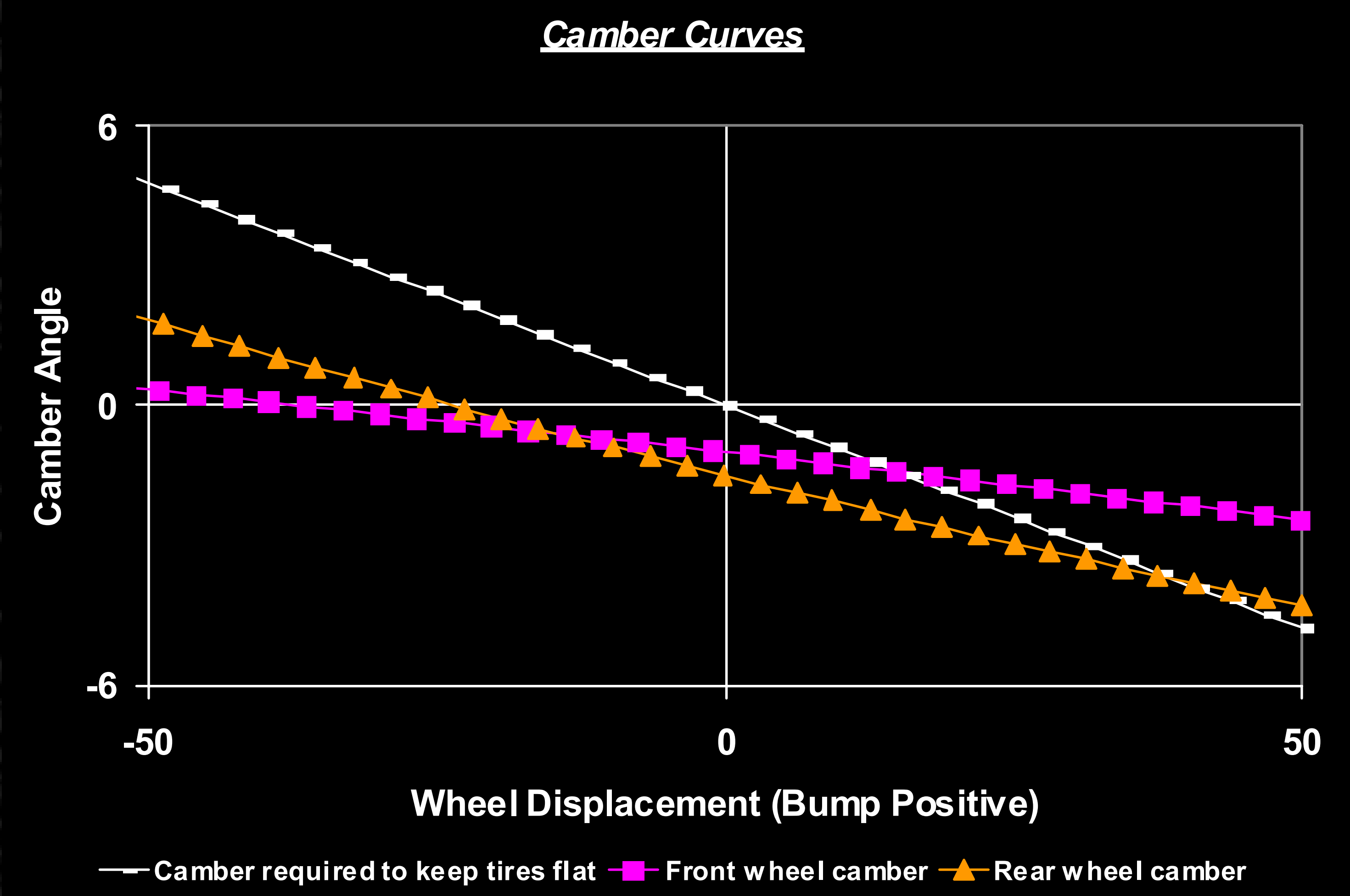
- Different for front and rear suspension



Caster

- Caster centers steered front wheels
- Also introduces camber change on steered front wheels

Caster and Camber



Roll Center

- Front and rear roll centers define roll axis of vehicle
  - Determines amount of body roll and load transfer distribution
  - Jacking effects

Jacking

"Anti" Effects

- Reduce pitching during accelerating and braking
- Anti-dive: 12%
- Anti-lift: 5%
- Anti-squat: 12%

Compromises

- Roll center and camber objectives often conflict
- Other parameters to optimize:
  - Tire scrub
  - Scrub radius
  - Kingpin inclination
  - Trail
  - Bump steer
  - Many others!

Reynard Kinematics

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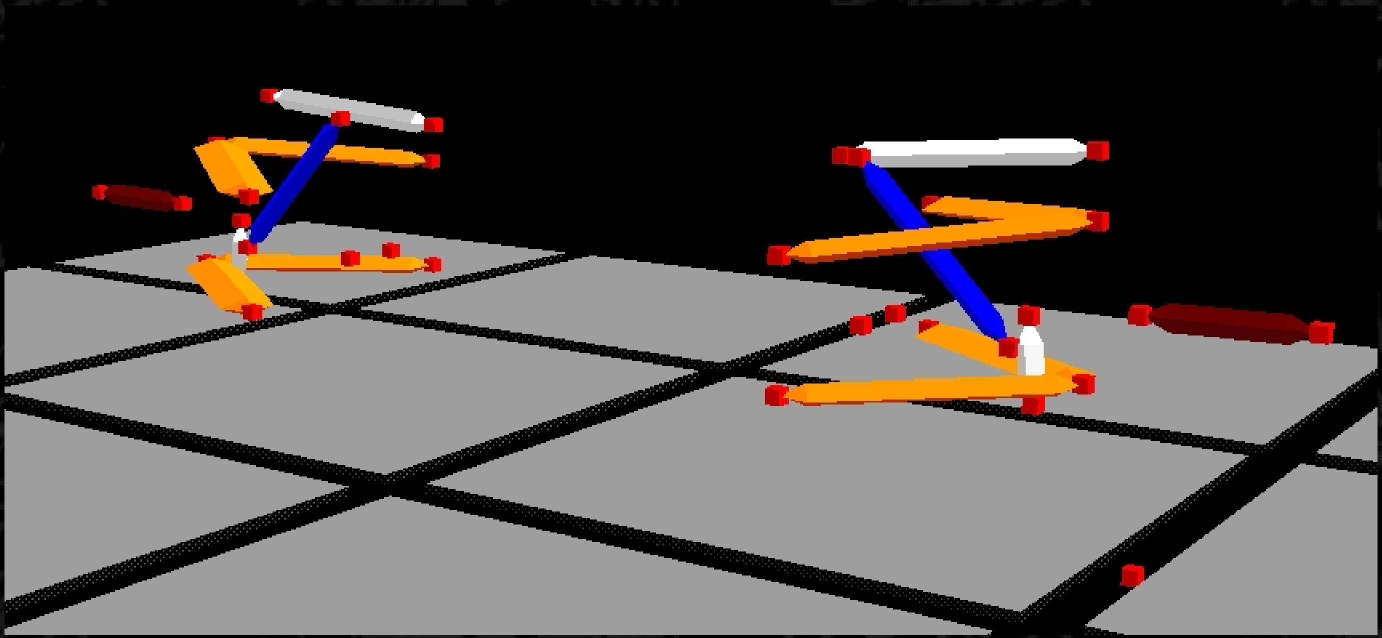
- Free evaluation software from Reynard Motorsport
- Parametric kinematics



Suspension Dynamics

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- Behavior of the car undergoing accelerations
- Bottom line:
  - Choose spring, damper, and other rates to optimize among a set of compromises

Reduce Body Roll

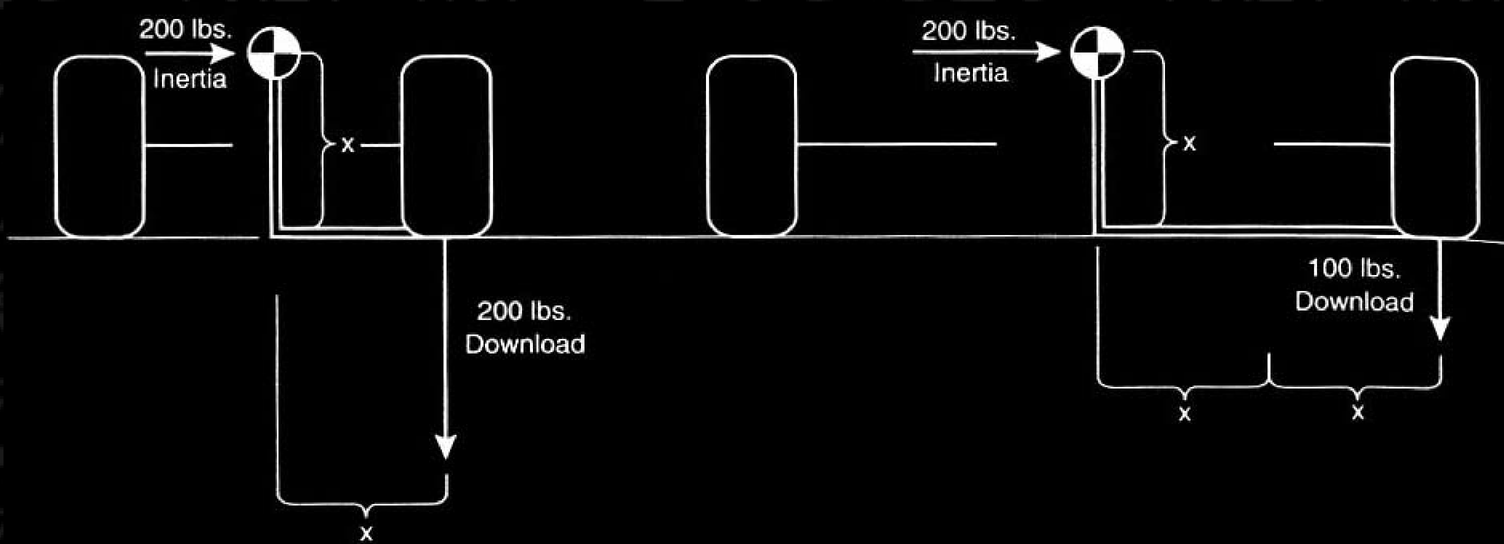
- Especially important for tight Formula SAE courses
  - Body roll slows transient response
- Shorten distance between roll center and center of gravity
  - Results in high roll center and jacking effect

Reduce Load Transfer

- Tire coefficient of friction decreases with vertical load
  - Different from elementary physics
- Net grip is best when tires share the total vertical load evenly
  - Minimize load transfer from one tire to another

Reducing Load Transfer

- **Widen track, wheelbase**
- **Lower center of gravity**

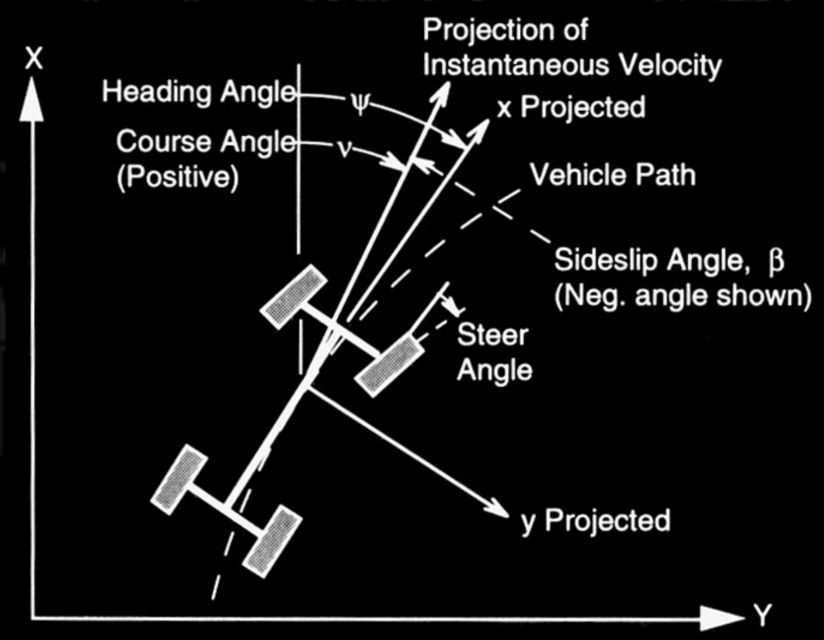


Cornering Behavior

- Understeer
  - Turning radius larger than intended
    - car "plows"
  - Stable
  - Too much load (transfer) on front tires
- Oversteer
  - Turning radius smaller than intended
    - car "spins out"
  - Unstable
  - Too much load (transfer) on rear tires

Cornering Behavior

- Neutral steer
  - Car stays on track
  - Unlimited cornering capability
  - Requires fine balance of load distribution



Adjusting Cornering Behavior

- Axle that resists roll the most usually has less cornering ability than the other axle
- Vary front/rear spring and damper rates
  - Also reduces body roll
- Anti-roll bar
  - Couples left and right wheels together to resist opposite motion

Dynamics Calculations

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- Used Microsoft Excel to determine rates

Description	Units	Design Intent (FR)	Design Intent (RR)	With Worst Case RC (FR)	With Worst Case RC (RR)	With 15% lower ride frequency (FR)	With 15% lower ride frequency (RR)	With 10% Greater Sprung Weight (FR)	With 10% Greater Sprung Weight (RR)	With Sprung Mass Distr
Basic Vehicle Lengths and CG Vertical Location										
CG height	in	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
wheelbase	mm	1750	1750	1750	1750	1750	1750	1750	1750	1750
wheelbase	in	68.898	68.898	68.898	68.898	68.898	68.898	68.898	68.898	68.898
track	mm	1200	1200	1200	1200	1200	1200	1200	1200	1200
track	in	47.244	47.244	47.244	47.244	47.244	47.244	47.244	47.244	47.244
average track	in	47.244	47.244	47.244	47.244	47.244	47.244	47.244	47.244	47.244
average track	mm	1200	1200	1200	1200	1200	1200	1200	1200	1200
Spring and Damper Mounting Orientation										
chassis to spring mounting point	mm	154.0	132.0	154.0	132.0	154.0	132.0	154.0	132.0	154.0
chassis to lower ball joint	mm	225.0	261.0	225.0	261.0	225.0	261.0	225.0	261.0	225.0
linkage ratio perpendicular	-	not used	not used	not used	not used	not used	not used	not used	not used	not used
spring/damper mounting angle from perpendicular	deg	not used	not used	not used	not used	not used	not used	not used	not used	not used
spring/damper mounting angle from perpendicular	rad	not used	not used	not used	not used	not used	not used	not used	not used	not used
motion ratio (net calculated approximation)	-	not used	not used	not used	not used	not used	not used	not used	not used	not used
motion ratio (according to Reynard Kinematics)	-	0.489	0.383	0.489	0.383	0.489	0.383	0.489	0.383	0.489
Vehicle Weights and Weight Distribution										
1 axle sprung weight	lb	225	275	225	275	225	275	247.5	302.5	175
2 axle sprung weight	lb	500	500	500	500	500	500	550	550	500
1 axle unsprung weight	lb	45	45	45	45	45	45	45	45	45
2 axle sprung weight	lb	90	90	90	90	90	90	90	90	90
1 axle total weight	lb	270	320	270	320	270	320	292.5	347.5	220
2 axle total weight	lb	590	590	590	590	590	590	640	640	590
sprung mass CG	in	12.518	12.518	12.518	12.518	12.518	12.518	12.470	12.470	12.518
sprung mass distribution	%	45.0	55.0	45.0	55.0	45.0	55.0	45.0	55.0	35.0
overall mass distribution	%	45.8	54.2	45.8	54.2	45.8	54.2	45.7	54.3	37.3
Derived Rates										
ride frequency	Hz	2.0	2.2	2.0	2.2	1.7	1.9			
ride frequency	cpm	120	132	120	132	102	112.2			
ride frequency ratio	-	1.1	1.1	1.1	1.1	1.1	1.1			
ride rate	lb/in	46	68	46	68	33	49	46	68	46
tire rate	lb/in	1200	1200	1200	1200	1200	1200	1200	1200	1200
tire static loaded radius	in	9.125	9.125	9.125	9.125	9.125	9.125	9.125	9.125	9.125
wheel center rate	lb/in	48	72	48	72	34	51	48	72	48
spring rate	lb/in	200	491	200	491	143	349	210	556	200
Roll Geometry and Rates										
roll center height	mm	24.4	52.9	-126.8	-7.4	24.4	52.9	24.4	52.9	24.4
roll center height	in	0.961	2.083	-4.992	-0.291	0.961	2.083	0.961	2.083	0.961
rolling moment lever arm	in	10.940	10.940	14.924	14.924	10.940	10.940	10.893	10.893	10.828
rolling moment per g lateral acceleration	lb-ft/g	456	456	622	622	456	456	499	499	451
1 axle spring roll rate	lb-ft/deg	75	110	75	110	54	80	75	110	75
2 axle spring roll rate	lb-ft/deg	185	185	185	185	134	134	185	185	185
roll gradient with springs alone	deg/g	2.5	2.5	3.4	3.4	3.4	3.4	2.7	2.7	2.4
Anti-Roll Bar Geometry										
ARB shear modulus		1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07
ARB inner radius		0.100	0.000	0.100	0.000	0.100	0.000	0.100	0.000	0.100
ARB outer radius		0.140	0.000	0.140	0.000	0.140	0.000	0.140	0.000	0.140
ARB area moment of inertia		4.464E-04	0.000E+00	4.464E-04	0.000E+00	4.464E-04	0.000E+00	4.464E-04	0.000E+00	4.464E-04
ARB lever arm length		4.000	6.000	4.000	6.000	4.000	6.000	4.000	6.000	4.000
chassis to ARB attachment point		350.0	300.0	350.0	300.0	350.0	300.0	350.0	300.0	350.0
ARB linkage ratio		2.273	2.273	2.273	2.273	2.273	2.273	2.273	2.273	2.273
ARB length		700.0	600.0	700.0	600.0	700.0	600.0	700.0	600.0	700.0
Anti-Roll Bar Contribution										
ARB twist rate	lb-ft/deg	2.36E-01	0.00E+00	2.36E-01	0.00E+00	2.36E-01	0.00E+00	2.36E-01	0.00E+00	2.36E-01
ARB rate	lb-ft/deg									
ARB roll rate	lb-ft/deg	42	0	42	0	42	0	42	0	42
2 axle ARB roll rate	lb-ft/deg	42	42	42	42	42	42	42	42	42
Net Roll Characteristics										
axle roll rate	lb-ft/deg	117	110	117	110	96	80	117	110	117
2 axle roll rate	lb-ft/deg	227	227	227	227	176	176	227	227	227

White cells are for data entry.

Gray cells are calculated or dervied values

ARB dimensions are on approximate and are used only to generate additional roll stiffness values for balancing load distribution.

CarSim Educational

- Simulates vehicle behavior
- Can help to analyze sensitivity of parameters
  - Deviations from design intent
- Complement design with road testing

Reliability

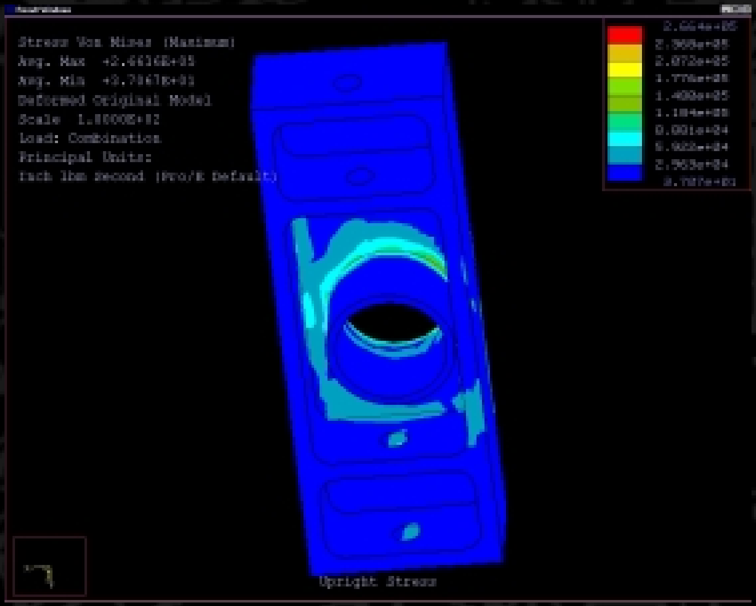
- Importance of completing all the dynamic events
  - Ability to engineer next iteration based on successes and failures
- Structural strength to maintain intended kinematics and dynamics

A-arm Load Analyses

- 1.5G cornering and 1.2G braking
- Maximum tensile stress: 57 MPa
  - under cornering
- Maximum compressive stress: 42 MPa
  - front suspension under braking
- All loads under 650 MPa yield strength of 4130 chromoly steel

Loads on Front Upright

- A-arm loads resolved into loads on upright
- No severe stresses
  - Modeling is not representative of braking forces
- Constrained hub carrier and applied previous loads
  - Hub carrier not yet fully designed



Manufacturing

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- **Upright:**
  - **CNC machined from 6061-T6 aluminum**
- **Control arms**
  - **Welded 4130 chromoly steel tubing**
- **Mounting brackets**
  - **Welded 4130 chromoly rectangular tubing**
- **Purchased items:**
  - **Wheels**
  - **Dampers**
  - **Various hardware**

Summary

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- Analyzed suspension design in context of Formula SAE requirements
  - Compromised among parameters for best first year car
- Combine with testing
- Next semester:
  - Complete suspension construction
  - Minor changes to suspension
  - Brakes
  - Steering

Questions