8-Series Suspension Demystification

One person’s dream - is another person’s nightmare

8-Series Suspension Demystification

- Presentation includes a general understanding of the dynamics of 8-series suspension by reviewing some of the basic fundamentals of Ground Vehicle Suspension System Dynamics with specific examples relevant to the 8-series suspension.

- The overview of Ground Vehicle Suspension System Dynamics will include
  - Terminology
  - Fundamentals of Vehicle Dynamics
  - Engineering formulas to analyze and estimate stock and upgrade suspension performance
  - Calculations relevant to the 8-Series suspensions

- Stock and upgrade suspension analysis
  - Vehicle suspension upgrade performance predictions are dependent on a through understanding of the installed changes
    - Spring/wheel rates, suspension natural frequencies
    - motion centers
    - roll stiffness
    - suspension travel
    - interaction of these and other suspension system elements
  - Comparisons of the stock, M-Sport, CSi and several aftermarket suspension options.

8-Series Suspension Demystification

- **Go-Cart Analysis**
  - **Suspension**
    - Tire stiffness
    - Frame flex
    - No geometries
  - **Pros:**
    - stability on smooth surface
      - Directional stability - predictable
      - Suspension "set" at tire rate
      - Ultimate cornering performance
  - **Cons:**
    - No previsions for roadway defects
      - Pitch/Bounce uncontrolled
      - Wheel hop uncontrolled
      - Cornering unpredictable on rough roadway
    - Seat cushion only occupant comfort

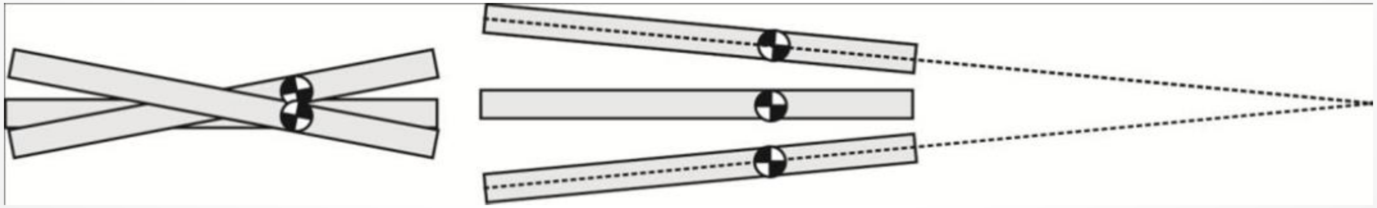
8-Series Suspension Demystification

- **Terminology**

  - **Suspension** – the term given to the system of springs, *dampeners* and linkages that connects a vehicle to its wheels and allows relative motion between the two. Suspension systems serve a dual purpose — contributing to the vehicle's ***roadholding/handling*** and braking for good active safety and driving pleasure, and keeping vehicle ***occupants* comfortable** and reasonably well isolated from ***roadway defects*** such as: road noise, bumps, and vibrations, etc. (wiki-modified)

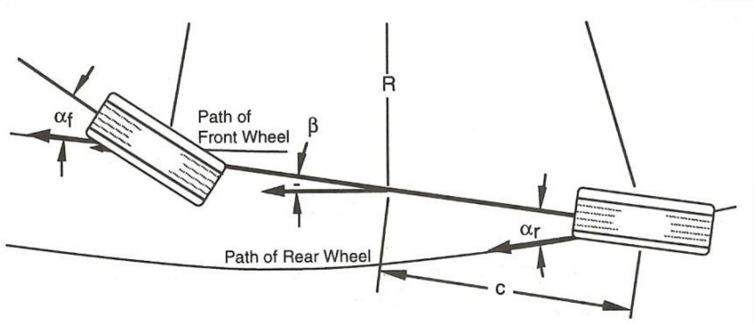
  - **Geometry** – the functions of how forces are transmitted through the suspension system and elements.
  - **Anti-Dive** – suspension geometry that counteracts nose dive with braking - weight transfer
  - **Anti-Lift** – suspension geometry that counteracts tail lift with braking - weight transfer
  - **Anti-Pitch** - suspension geometry that counter acts pitch motion – accel/decel weight transfer
  - **Anti-Squat** - suspension geometry that counteracts tail squat - acceleration weight transfer
  - **Pitch Motion** – when the front and rear body motion is moving in opposite directions, out of phase
  - **Bounce Motion** – vertical motion of the body with the front and rear in phase
  - **Motion Center** – location of bounce/Pitch motion center with respect to vehicle axles

Pitch **Bounce**



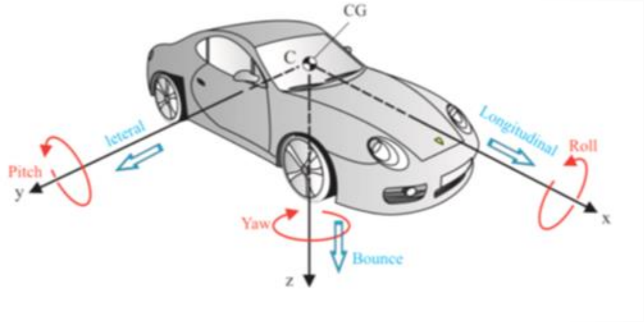
8-Series Suspension Demystification

- **Terminology -** continued
  - **Natural Frequency** – free vibration of a system, i.e., wheel rate, sprung weight oscillations, Hz
  - **Neutral Steer** – equal front and rear wheel slip angle change with an increase in speed
  - **Understeer** – increase in front wheel slip angle with increase in speed – skid pad
  - **Oversteer** – increase in rear wheel slip angle with increase in speed
  - **Spring Rate** – change in load on a spring per unit deflection i.e., lbs/in
  - **Spring Installation/Motion Ratio** – suspension geometry ratio between wheel motion, spring and or dampener deflection
  - **Wheel Rate** – spring rate times the suspension installation/motion ratio
  - **Roll Center** – axle center of rotation defined by the suspension type & geometry
  - **Roll Axis** – vehicle center of rotation defined by the front & rear roll centers
  - **Roll Stiffness** – the suspensions resistance to roll
  - **Set** – (Taking a set) the point at which the max weight transfer has occurred with a change in force
  - **Slip Angle** – difference angle between the tire/wheel and direction of travel due to centrifugal force



8-Series Suspension Demystification

- **Terminology** - continued
  - **Vehicle Motion Coordinate** – Longitudinal = X , Lateral = Y, Bounce = Z
  - **Vehicle Motion Axis** – Roll = X, Pitch = Y, Yaw = Z



  - **Weight transfer** – change in tire/suspension loading due to the forced of accel/decel and cornering *(roadway inclination*)
    - **Longitudinal** – acceleration and braking force
    - **Lateral** – steering & cornering forces

8-Series Suspension Demystification

- ***Fundamentals of Vehicle Dynamics***
  - Acceleration – power/traction limited, weight transfer,
  - Braking – forces, tire-road friction. proportioning, anti-lock, efficiency
  - Road Loads – aerodynamics/drag/wind/yaw moment, rolling resistance/tire
  - **Ride** – road roughness, vehicle components (inc,-tire, driveline & engine vibrations)
  - **Steady-State Cornering** – steering response, under/over and neutral steer
  - **Suspension systems** – axle types - solid, independent, linkages, geometries - anti-dive/squat/pitch
  - Steering system – recirculating ball, rack and pinion
  - Rollover - propensity
  - Tires – vertical load - suspension, longitudinal – accel & decel, lateral - cornering

8-Series Suspension Demystification

- ***Fundamentals of Vehicle Dynamics*** *– detail*
  - **Ride** – quality, passenger comfort, suspension compliance
    - Road roughness – tactual vibration, noise
    - Tire/wheel – balance/shape/stiffness
    - Drivetrain – engine/driveline vibrations
    - **Suspension** – quarter-car model, isolation, damping, spring/wheel rates
    - ***Bounce/Pitch*** – half-car model - frequencies, motion centers, Maurice Olley Criteria
  - **Steady-State Cornering** – under/over and neutral steer
    - **Under-steer** – front roll stiffness > rear, push - considered most stable for average driver
    - **Over-steer** – front roll stiffness < rear, loose - wild ride least stable
    - **Neutral-steer** - front roll stiffness = rear, performance driver preference
  - **Suspension System Geometry** – MacPherson with multi-link rear
    - **Geometry Advantages** – Instantaneous vs. spring element weight transfer
    - **Y Axis Geometries** - Anti-dive/squat/pitch geometries
    - **X Axis Geometries** - Roll centers/axis/stiffness, anti-roll

8-Series Suspension Demystification

- **Suspension system performance upgrades can be accurately predicted:**
  - **Comparative Analysis** - original equipment suspension engineering comparison to the proposed suspension system changes (note: accuracy is everything & suspension geometry is complex)

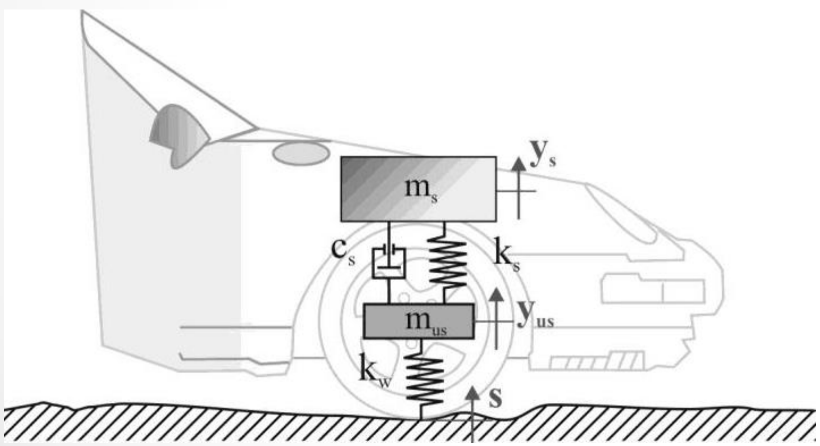
  - **Suspension values unchanged**
    - **suspension geometries** - Suspension linkage angle changes may affect reaction force
    - **sprung/unsprung-weights** -
    - **roll centers/roll axis** - may change slightly with reduced ride height (roll center to CG)
    - **weight transfer** - may change slightly with reduced ride height (tire contact to CG)

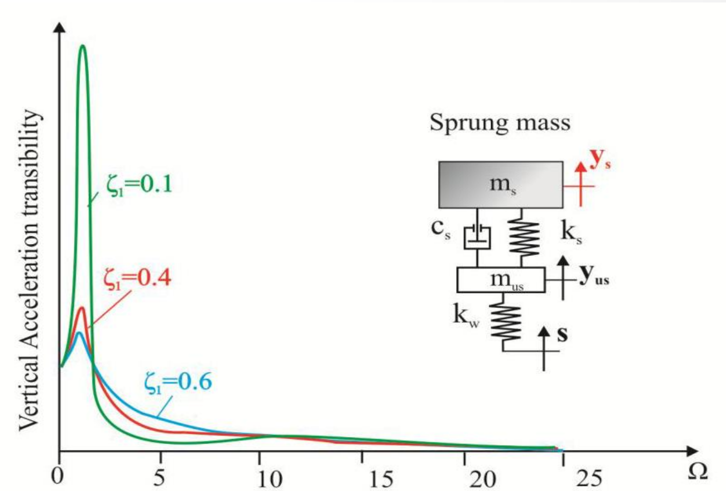
  - **Suspension values changes**
    - **reduced ride height/suspension travel**
    - **Increase spring/tire/bump stop rates**
    - **Pitch/bounce natural frequencies and motion center location**
    - **Increase role & swaybar rates**
    - **Increase damping rates**
    - **suspension dynamic factors -** those relevant to passenger comfort and performance.

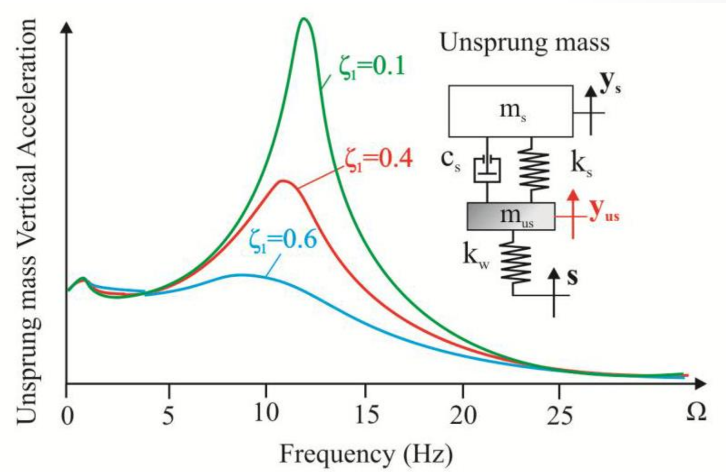
  - **In other words:** when the original equipment suspension performance is analyzed - upgrades can provide predictable performance changes

8-Series Suspension Demystification

- **Ride - Suspension**
  - **Quarter-Car Model**
    - ¼ Sprung weight = m_s
    - Unsprung weight = m_{US}
    - spring rate = k_s
    - Dampener rate = c_s
    - Ride Rate = $k_s + k_t$
    - Isolation = ride rate/sprung mass
    - Natural Frequency = Hz
    - Spring Installation Ratio = IR



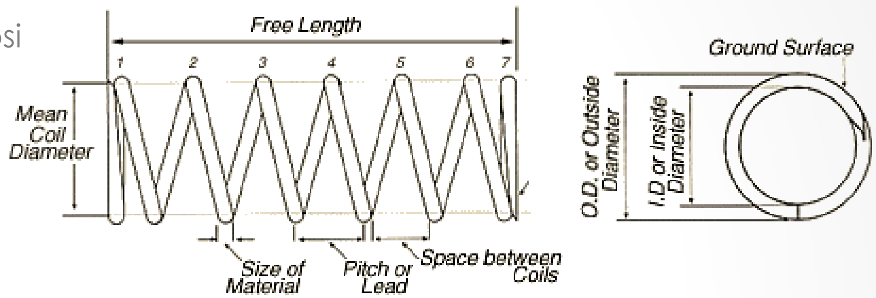




8-Series Suspension Demystification

- **Ride - Suspension**
  - **Spring Rate Calculation**
    - ***k*** = spring rate = lbs/in
    - ***G*** = Modulus of torsion = 11.5×10^6 psi
    - ***d*** = diameter of wire
    - ***D*** = diameter of coil
    - ***N*** = number of active coils

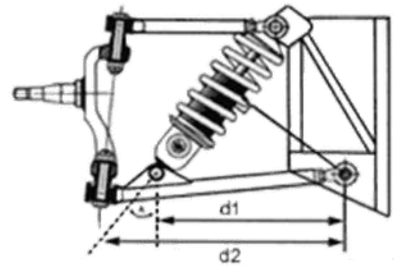
$$k = \frac{d^4 G}{8 N D^3}$$

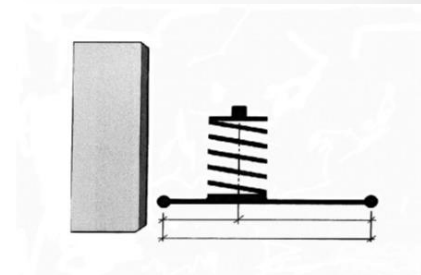


  - **Spring Rate Measurement**
    - Spring Dyno

8-Series Suspension Demystification

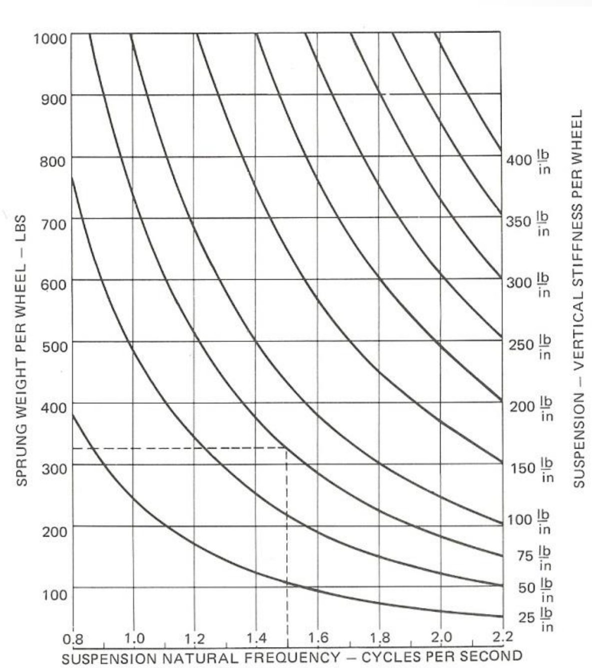
- **Ride - Suspension**
  - **Wheel Rate Calculation**
    - Installation = motion ratio = d1/d2
    - Wheel rate = SR * $(d1/d2)^2$ cos (alpha)
    - Wheel rate = SR * $(d1/d2)^2$





  - **Ride – Natural Frequency -**
    - f = natural frequency
    - K = wheel rate
    - M = sprung weight of ¼ car

$$f = 1/(2\pi)\sqrt{\frac{K}{M}}$$



8-Series Suspension Demystification

- Rod's massive E-31 Suspension Excel Spreadsheet - w/13 worksheets & plots galore

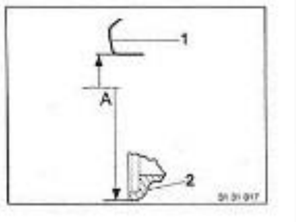
850Ci Coil Spring Calculation

FRONT - EDCIII	Spring wire dia. d^4	G	Number of coils	Active coils +.5 -1.5	Spring coil Dia. D^3	K=lbs./in Wheel Rate	Measured Inst. Ratio	% change	% Front/Rear	Free Length	Front Unsprung Weight	Ride Height	Ride Height Drop	Actual Suspension Frequency @ Speed	Test 1.07	Unladen Ride Height	Ride Height Drop	Test-L Ride Height	Ride Height Drop	Test-H Ride Height	Ride Height Drop	Ride Height	Ride Height Drop	Ride Height	Ride Height Drop
														Actual F Hz	Calc F/Rea	945	945	995	995	1045	1045	1200	1200	1300	1300
H&R - set	0.551	11500000	4.375	3.625	6.05	165	161.00				1050			80	MPH		-1.42	0.34	-1.76		-2.10		-3.14		-3.81
	0.0921736				221.45	149	0.90	32%	42%	11.75	1135	5.39	-1.42	1.18	1.23	5.39	-1.42	5.05	-1.32	4.72	-1.21	3.67	-0.88	3.00	-0.66
Dinan - set 1	0.59	11500000	5.75	5.25	6.00	154	161.00										-1.27		-1.64		-2.00		-3.12		-3.84
	0.1211736				216.00	138	0.90	23%	44%	12.38		5.54	-1.27	1.14	1.16	5.54	-1.27	5.18	-1.19	4.82	-1.11	3.69	-0.85	2.97	-0.69
Dinan - set 2	0.625	11500000	6.625	6.125	6.00	166											-1.40		-1.73		-2.07		-3.10		-3.77
	0.1525879				216.00	149	0.90	32%	34%	11.75		5.42	-1.40	1.18	1.44	5.42	-1.40	5.08	-1.29	4.75	-1.18	3.71	-0.84	3.04	-0.62
Eibach						220	225.00																		
	0.61		5.5			198	0.90	76%	54%	10.60		5.83	-0.99	1.36	1.12										
Cobra																									
						400		255%						1.93											
AC Schnitzer	0.620	11500000	5.5	5	6.00	197																			
	0.1477634				216.00	177	0.90	43%	52%	10.25		4.91	-1.90	1.29											
Bryson					other	550																			
						440		291%						2.03											
850 M-Sport	0.585	11500000	4.625	3.625	6.50	169	172.00										-0.27	0.33	-0.60		-0.93				
31 33 1 138 735	0.117118	D=15.5mm			274.63	152	0.90	35%	44%	12.75		6.54		1.19	1.20	6.54	-0.27	6.21	-0.16	5.88	-0.04				
850CSi	0.605	11500000	4.5	3.5	6.63	189	200.00										-0.11	0.29	-0.40		-0.70				
31 33 2 227 470	0.1339743				290.78	170	0.90	51%	41%	12.25		6.70	-0.11	1.26	1.35	6.70	-0.11	6.41	0.04	6.11	0.19				
840Ci stock	0.575	11500000	5.625	4.625	6.63	117											-0.17		-0.65		-1.12		-2.60		-3.55
33 31 1 137 954	0.1093129				290.78	105	0.90	-7%	41%	15.63		6.64	stock	0.99	1.06	6.64	-0.17	6.16	-0.21	5.69	-0.24	4.21	-0.34	3.26	-0.40
850Ci stock	0.585	11500000	5.625	4.625	6.63	125	123.00										0.00		-0.44		-0.89		-2.26		-3.15
31 33 1 137 956	0.117118				290.78	113	0.90	0%	43%	15.20		6.81	stock	1.03	1.06	6.81	0.00	6.37	0.00	5.93	0.00	4.55	0.00	3.66	0.00
Test Values - 1																									
Dinan - set 1	0.59	11500000	5.75	5.25	6.00	154											-1.27		-1.64		-2.00		-3.12		-3.84
850Ci stk - Cut 1	0.1211736				216.00	138	0.90	23%	47%	12.38		5.54	-1.27	1.14	1.10	5.54	-1.27	5.18	-1.19	4.82	-1.11	3.69	-0.85	2.97	-0.69
Test Values - 2																									
H&R	0.551	11500000	4.375	3.625	6.05	165											-1.42		-1.76		-2.10		-3.14		-3.81
850Ci stk - Cut 1.5	0.0921736				221.45	149	0.90	32%	47%	11.75		5.39	-1.42	1.18	1.12	5.39	-1.42	5.05	-1.32	4.72	-1.21	3.67	-0.88	3.00	-0.66
														Actual	Test										

REAR - EDCIII	Spring wire dia. d^4	G	Number of coils	Active coils +.5 -1.5	Spring coil Dia. D^3	K=lbs./in Wheel Rate	Measured Inst. Ratio	% change	% Front/Rear	Free Length	Rear Unsprung Weight	Loaded Spring length	Ride Height Drop	Suspension Frequency	1.16	Unladen Ride Height	Ride Height Drop	Ride Height	Height Drop	Ride Height	Height Drop	Ride Height	Height Drop	Ride Height	Height Drop
											1090					930	930	975	975	1125	1125	1200	1200	1300	1300
H&R - set	0.551	11500000	8.65	7.15	3.79		1.66			Meas. =	424	12.50					-0.03		-0.25		-0.98		-1.34		-1.83
	0.0921736				54.35	341	335	-17%		13.10		11.86	-0.71			11.02	-0.40	10.24	-0.98	9.80	-1.05	9.58	-1.09	9.29	-1.14
						205	0.60	38%	58%	20.75		17.51	0.27	1.36		18.29	-0.03	18.07	0.05	17.34	0.33	16.97	0.47	16.49	0.66
Dinan - set 1	0.625	11500000	8.5	7	3.99		1.66			Meas. =	812	11.00					-0.72		-0.97		-1.80		-2.22		-2.78
	0.1525879				63.52	493	510	20%		12.50		11.64	-0.92			10.76	-0.66	10.52	-0.70	10.22	-0.63	10.07	-0.60	9.86	-0.56
						179	0.36	20%	56%	18.26		16.71	-0.53	1.27		17.60	-0.72	17.35	-0.66	16.51	-0.49	16.09	-0.41	15.54	-0.29
Dinan - set 2	0.6875	11500000	7.5	7	3.85		1.66										-3.24		-3.39		-3.91		-4.17		-4.51
	0.2234039				57.07	804	no data	96%		11.00		10.47	-2.09			9.84	-1.57	9.79	-1.43	9.60	-1.25	9.51	-1.16	9.38	-1.04
						292	0.36	96%	66%	18.26		16.81	-0.43	1.62		15.08	-3.24	14.92	-3.09	14.41	-2.60	14.15	-2.35	13.81	-2.02
Eibach							1.66																		
						457	433	12%																	
					166.00	166	0.36	12%	46%					1.22											
Cobra	0.625	11500000	8.85	8.35	3.75		1.66																		
	0.1525879				52.73	498	no data	22%		14.00		13.15	0.58												
						181	0.36	22%	31%	23.24		20.90	3.66	1.28											
AC Schnitzer	0.595	11500000	8.25	7.75	3.75		1.66																		
	0.1253337				52.73	441	no data	8%		11.80		10.84	-1.73												
						160	0.36	8%	48%	19.59		16.94	-0.30	1.20											
Bryson					other	1200	1.66																		
						800	no data	95%																	
						291	0.36	95%						1.62											
850 M-Sport	0.627	11500000	7.875	7.875	3.76		1.66			Meas. =	707.6	11.00					-1.21		-1.44		-2.22		-2.61		-3.13
33 53 1 138 738	0.1545504	D=16mm			53.16	531	530	30%		12.00		11.20	-1.36			10.58	-0.84	10.16	-1.06	9.88	-0.97	9.74	-0.93	9.55	-0.88
						193	0.36	30%	56%	18.26		16.28	-0.96	1.32		17.11	-1.21	16.87	-1.14	16.10	-0.91	15.71	-0.80	15.19	-0.64
850CSi	0.67	11500000	8.75	7.25	3.88		1.66			Meas. =	707.6	11.00					-0.95		-1.13		-1.73		-2.03		-2.43
33 53 2 227 719	0.2015112				58.19	687	670	68%		12.00		11.38	-1.18			10.68	-0.74	10.58	-0.64	10.36	-0.49	10.25	-0.42	10.11	-0.32
						249	0.36	68%	59%	18.26		16.73	-0.51	1.50		17.37	-0.95	17.19	-0.83	16.59	-0.42	16.29	-0.22	15.89	0.06
850/840Ci stock	0.59	11500000	9.5	8	3.76		1.66			Meas. =	691.4	12.00					0.00		-0.30		-1.31		-1.81		-2.49
33 53 1 137 958	0.1211736				53.16	410	400	0%		13.60		12.56	Stock			11.42	0.00	11.22	0.00	10.85	0.00	10.67	0.00	10.43	0.00
						149	0.36	0%	57%	19.92		17.24	Stock	1.16		18.32	0.00	18.01	0.00	17.01	0.00	16.50	0.00	15.83	0.00
Test Values - 1																									
850Ci stk - Cut 1	0.59	11500000	8.5	7.5	3.76		1.67										-3.34		-3.63		-4.57		-5.04		-5.67
33 53 1 137 958	0.1211736				53.16	437	no data	7%		12.50		11.53	-1.04			10.37	-1.05	10.27	-0.95	9.93	-0.93	9.75	-0.92	9.52	-0.90
H&R						159	0.36	7%	53%	20.83		18.16	0.92	1.19		14.97	-3.34	14.69	-3.32	13.75	-3.26	13.27	-3.23	12.64	-3.19
Test Values - 2																									
850Ci stk - Cut 1.5	0.59	11500000	8.5	7	3.78		1.67										-3.46		-3.73		-4.62		-5.07		-5.67
33 53 1 137 958	0.1211736				54.01	461	no data	12%		12.25		11.33	-1.24			10.23	-1.19	10.13	-1.09	9.81	-1.05	9.65	-1.02	9.43	-1.00
H&R						167	0.36	12%	53%	20.42		17.88	0.64	1.23		14.86	-3.46	14.59	-3.42	13.70	-3.31	13.25	-3.25	12.65	-3.18

8-Series Suspension Demystification

- **Suspension system**
  - **Comparative Analysis - Suspension values changes**
    - Stock vs Reduced ride height - front



Front axle - ride height E31

Ride height in normal position (measured from the lower tape edge of the wheel rim to the bottom of the wheel house to the perpendicular passing through the center of the wheel)

The difference in the deviation from the set point between all wheels	max. mm (in)	10 (.39)
standard		
rim 16 '	mm (in)	599 (23.58)
rim 17 "	mm (in)	614 (24.17)
M-Sports suspension, low-slung		
rim 16 '	mm (in)	584 (22.99)
rim 17 "	mm (in)	599 (23.58)
CSi suspension, low-slung		
rim 17 "	mm (in)	600 (23.62)
rim 18 '	mm (in)	613 (24.13)
Dinan		
rim 17 "	mm (in)	583 (22.94)

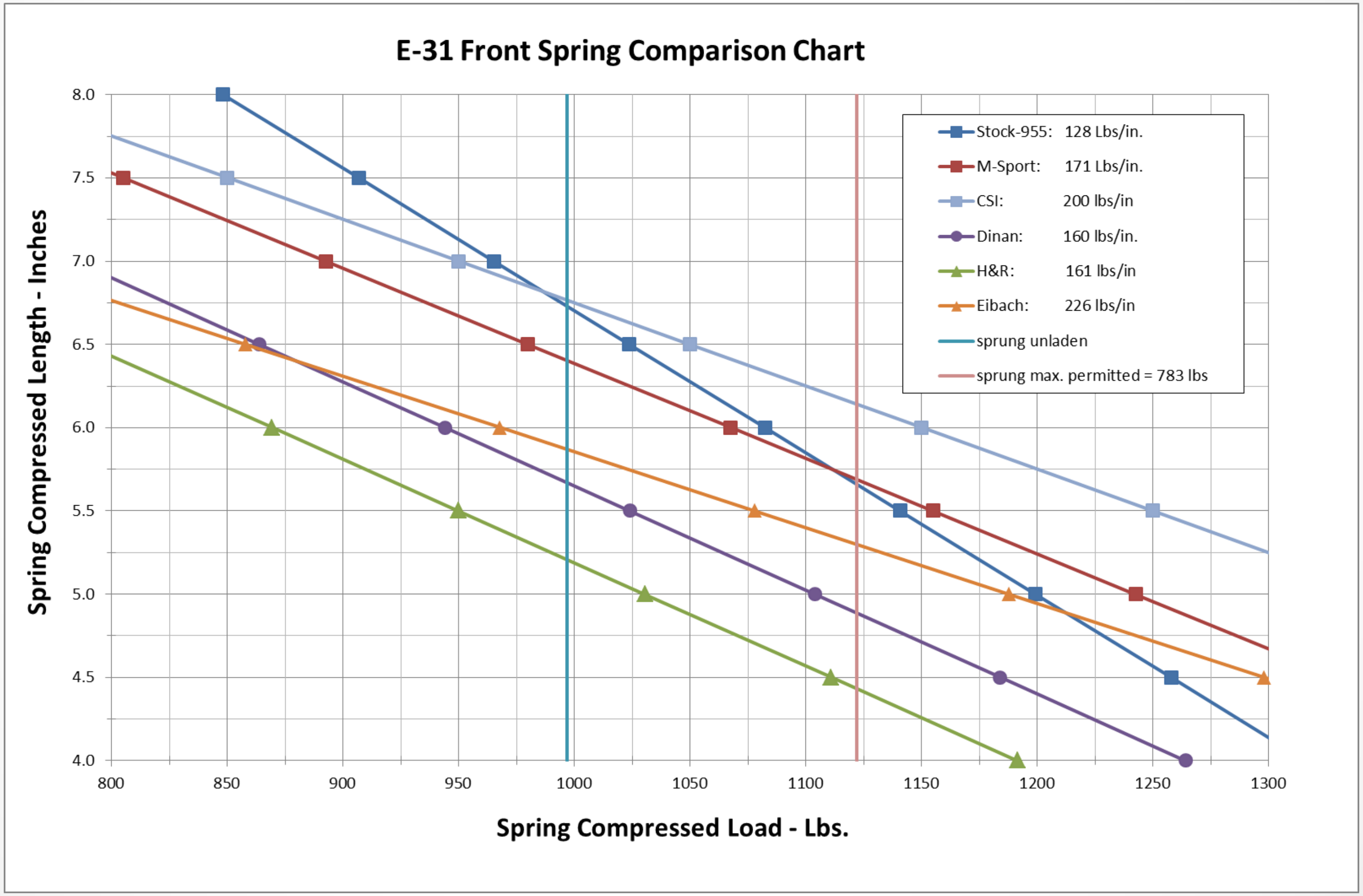
8-Series Suspension Demystification

- **Suspension system**
  - **Comparative Analysis - Front Suspension values**
    - **Stock Ride Height Spring Length = 7.0"**
    - **Suspension Travel – Front w/CSi bump stop**
      - Stock = 3.75"
      - M-Sport = 3.13"
      - CSi = 3.05"
      - Dinan = 2.55"
    - **Suspension Travel – Front, M-Sport w/ CSi Additional Shock Absorber**
      - **M-Sport = 3.13 – 2.49 = .64"**
    - **Additional Shock Absorber - Bump Stops**

Absorber- Crush lbs @ measurement						
FRONT	stock	CSi-used	CSi-new		M5/M6	M6-Comp
Series	E31	E31	E31		E60/63	E63
P/N:	140-140	226-674	226-674		283-182	284-082
Length		2.49	2.56		2.31	
Crush/lbs						
1/4"		32	44		52	
1/2"		103	119		87	
3/4"		149	187		115	
1"		250	292		172	

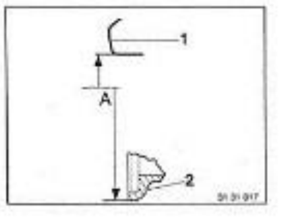
8-Series Suspension Demystification

- **Front Spring Data-** calculated/measured spring compression



8-Series Suspension Demystification

- **Suspension system**
  - **Comparative Analysis - Suspension values**
    - Stock vs Reduced ride height - rear



Rear axle - ride height E31

Ride height in normal position (measured from the lower tape edge of the wheel rim to the bottom of the wheel house to the perpendicular passing through the center of the wheel)

The difference in the deviation from the set point between all wheels	max. mm (in)	10 (.39)
standard		
Rim 16 '	mm B (in)	569 (22.40)
rim 17 "	mm B (in)	581 (22.87)
M-Sports suspension, low-slung		
Rim 16 '	mm B (in)	554 (21.81)
rim 17 "	mm B (in)	566 (22.28)
CSi suspension, low-slung		
rim 17 "	mm B (in)	570 (22.44)
rim 18 "	mm B (in)	583 (22.95)
Dinan		
rim 17 "	mm B (in)	578 (22.75)

8-Series Suspension Demystification

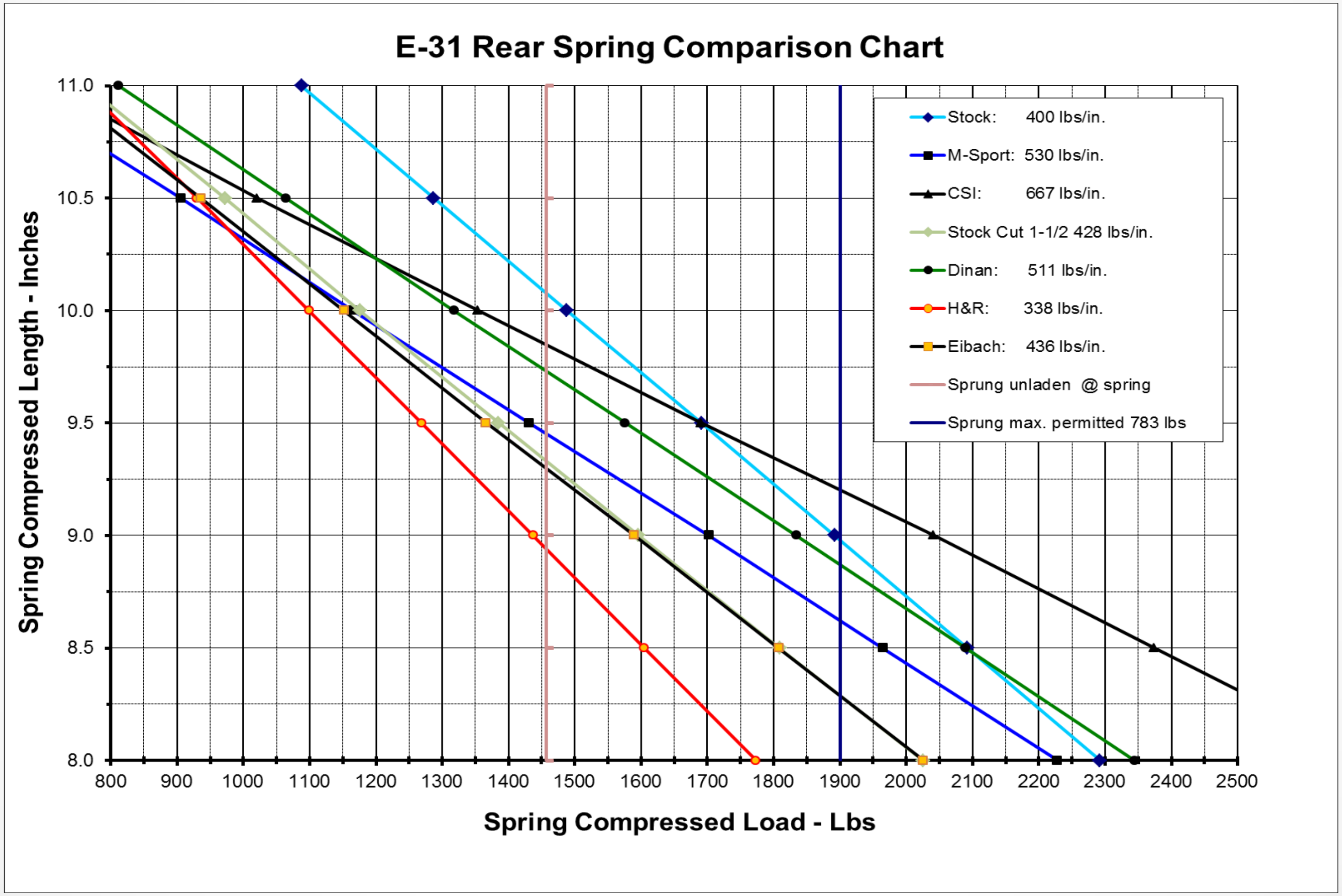
- **Suspension system**
  - **Comparative Analysis - Rear Suspension values**
    - **Stock Measured spring Length = 10-1/8"**
    - **Suspension Travel – Rear, w/o Additional Shock Absorber**
      - Stock = 4.68"
      - M-Sport = 4.13"
      - CSi = 4.25"
      - Dinan = 4.56"
    - **Suspension Travel – Rear, M-Sport w/M5 Additional Shock Absorber**
      - **M-Sport = 4.13 – 2.31 = 1.82"**
    - **Additional Shock Absorber - Bump Stops**

Absorber - Crush lbs @ measurement

REAR	Stock	CSi	M5-used	740-Sport	M5	M6
Series	E31	E31	E34	E38	E60	E63
P/N:	134-043	226-186	226-351	227-093	282-524	283-183
Length			2.31	3.25	3.0	
Crush/lbs						
1/4"			87	73	35	
1/2"			180	161	65	
3/4"			280	237	85	
1"			467	321	127	

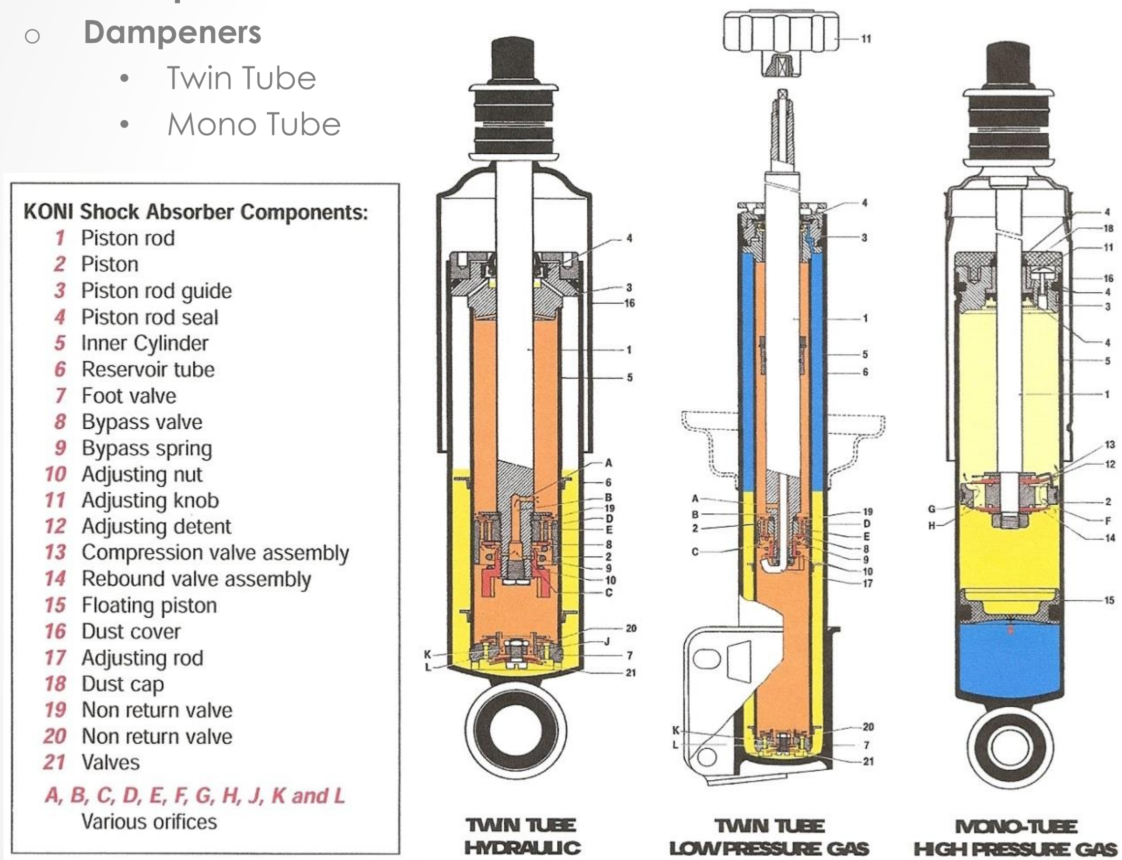
8-Series Suspension Demystification

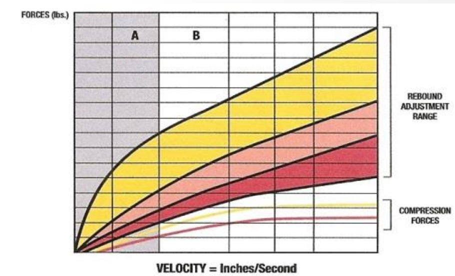
- **Rear Spring Data** – calculated/measured spring compression



8-Series Suspension Demystification

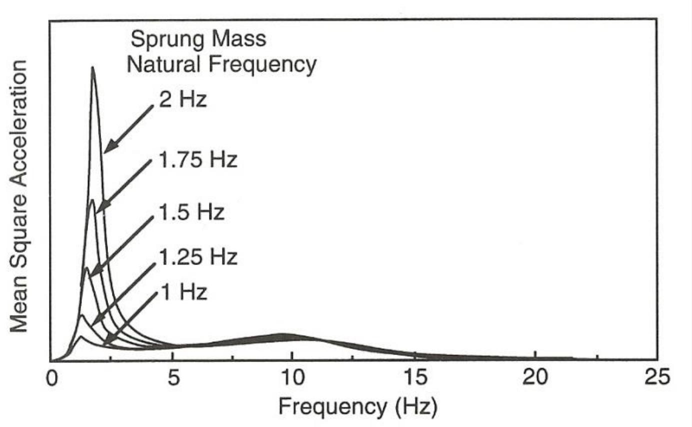
- **Ride - Suspension**
  - **Dampeners**
    - Twin Tube
    - Mono Tube

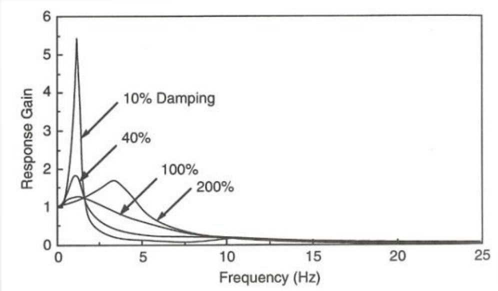


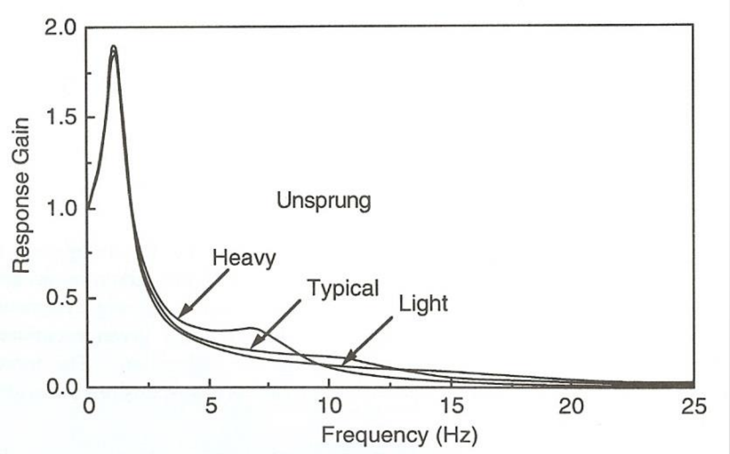


8-Series Suspension Demystification

- **Ride - Suspension**
  - **Dampener** - Shock
    - Control/reduce sprung weight/chassis motion/overshoot and wheel hop
    - Rebound rate – sprung Hz
    - Compression rate – unsprung Hz
    - Rebound typically 3-6 times the compression
    - Driver induces forces on suspension
      - Brake, acceleration & steering - low
    - Road induces forces on suspension
      - Defects in roadway - high
    - Typical Damping factor = 40%
    - Dampener Design
      - Twin Tube – Low Pressure
      - Mono Tube – High Pressure
        - Extensions force – 60-80 lbs
        - Increase ride height = Ef/WR





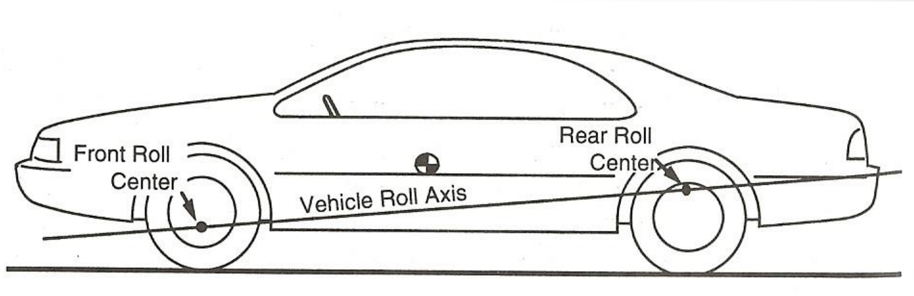


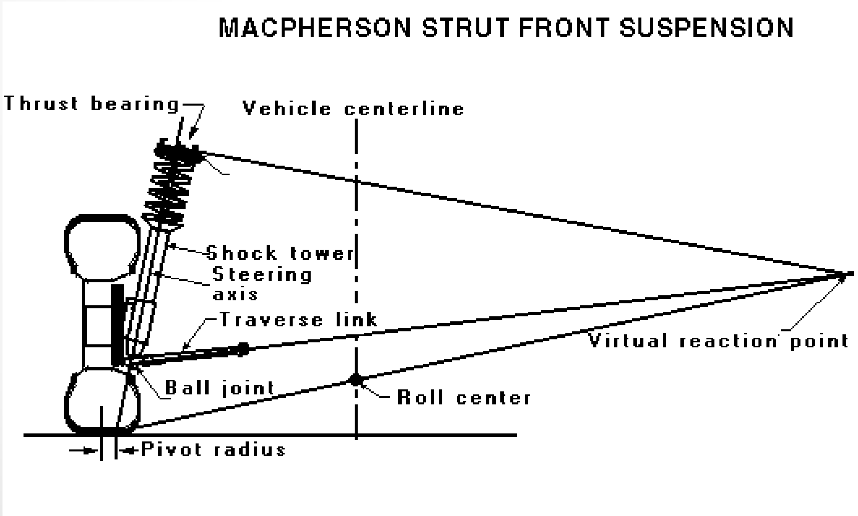
8-Series Suspension Demystification

- **Ride - Suspension**
  - **Dampener** – Shock - Selections
    - **Options - Low Pressure Gas**:
      - M-sport
      - CSi
      - EDC – comfort/sport, best of both worlds
      - Koni – Front with modifies strut, rear M-sport/CSI
    - **Options - High Pressure Gas:**
      - Bilstein – Sport, re-valve, extension force = ride height increase

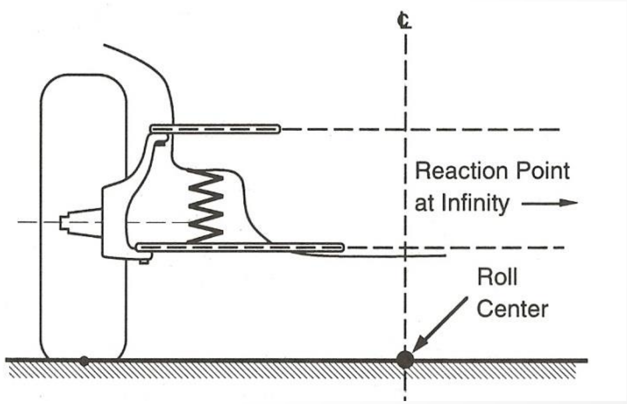
8-Series Suspension Demystification

- **Suspension System - Geometry**
  - **Chassis Roll Factors**
    - Roll center – front & rear axles
    - Roll Axis – line through centers
    - Anti-Roll – geometries
    - Distance between Roll Axis & CG





5-Link Rear Suspension



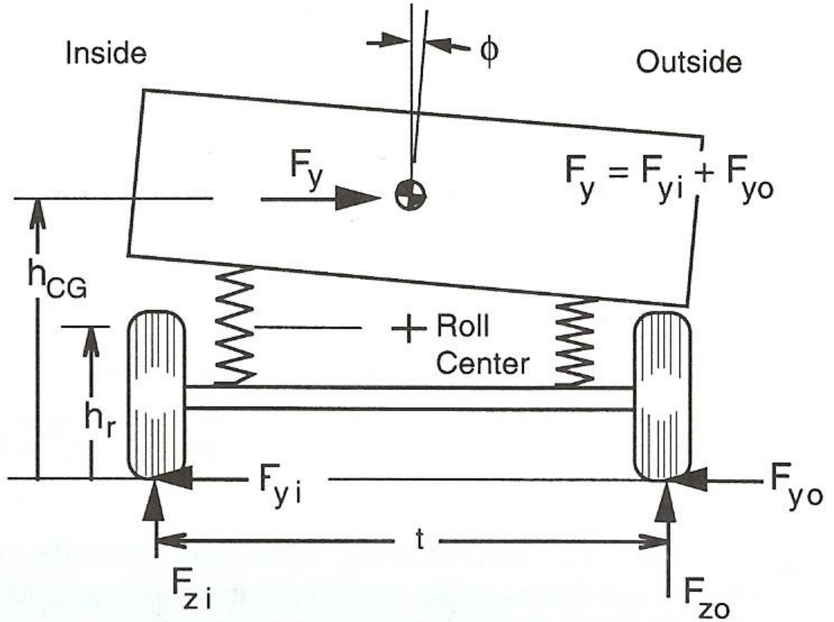
8-Series Suspension Demystification

- **Suspension System Geometry**
  - **Roll Stiffness**

$$K_\phi = 0.5\, K_s\, s^2$$

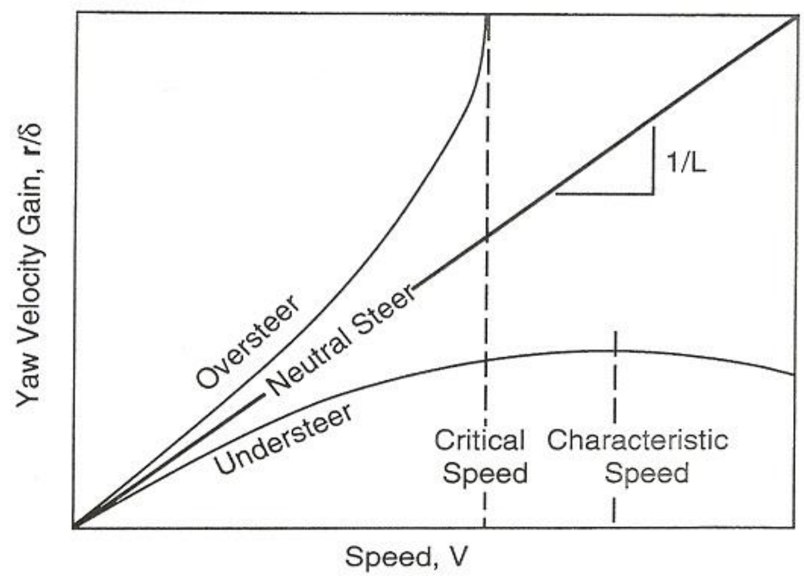
where:

K_ϕ = Roll stiffness of the suspension
K_s = Vertical rate of each of the left and right springs
s = Lateral separation between the springs



8-Series Suspension Demystification

- **Suspension System Geometry - Steady State Cornering**
  - **Roll Stiffness** – Front & Rear effects steering
  - **Under/over/Neutral Steer**
    - **Under-steer** – front roll stiffness > rear, push/tight - considered most stable for average driver
    - **Over-steer** – front roll stiffness < rear, loose - wild ride least stable, can be throttle induced
    - **Neutral-steer** - front roll stiffness = rear, performance preference



Yaw velocity gain as a function of speed.

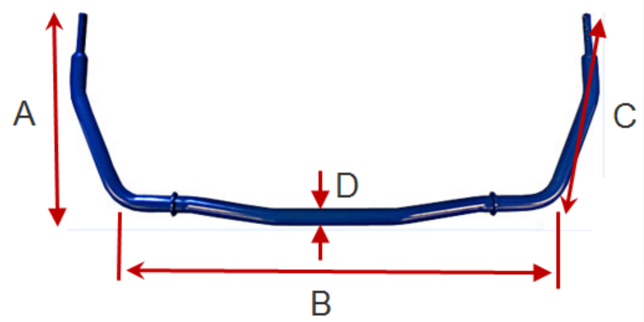
8-Series Suspension Demystification

- **Suspension Systems Geometry**
  - **Roll Stiffness adjustment –** Anti-Roll Bar - Swaybar
  - **Swaybar rate calculation -**

$$K_{swaybar\_Puhn} = \frac{5000000 \cdot D^4}{0.4244 \cdot A^2 \cdot B + 0.2264 C^3}$$

Sway bar stiffness in $\frac{lbf}{in}$

Length of end perpendicular to B (A)
Length of center section (B)
Length of end section (C)
Diameter (D)



  - **Swaybars** – flawed analysis
    - Analysis between vehicles ignores suspension wheel rates differences and the other 3 swaybar dimensions

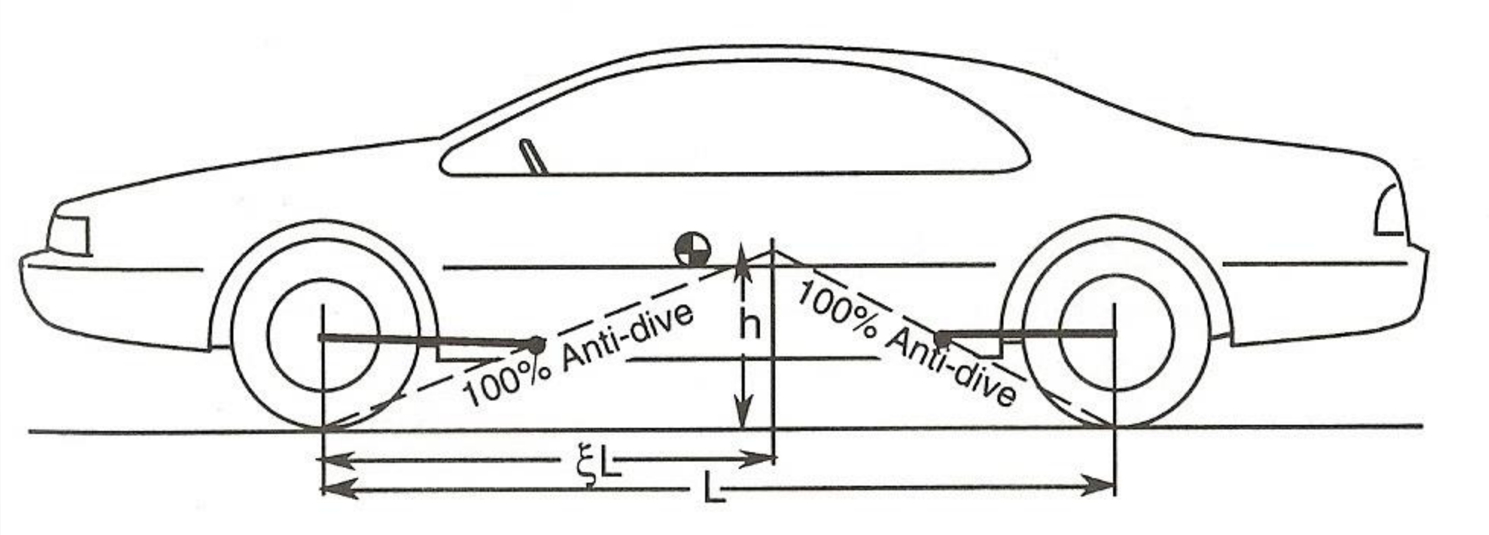
	Front Diameter (mm)	Rear Diameter (mm)	Front/Rear Stiffness Bias
850i (Stock)	24.0	13.0	1.85 (most understeer)
850Ci (Stock)	24.0	15.5	1.55
850CSi (Stock)	27	17.0	1.59
BMW e34 M5 (stock)	25	18	1.39
BMW e36 M3 (stock)	23	20	1.15 (least understeer)

8-Series Suspension Demystification

- **Suspension System Geometry**
  - **Geometry Correction**
    - Strut spacer – anti-roll

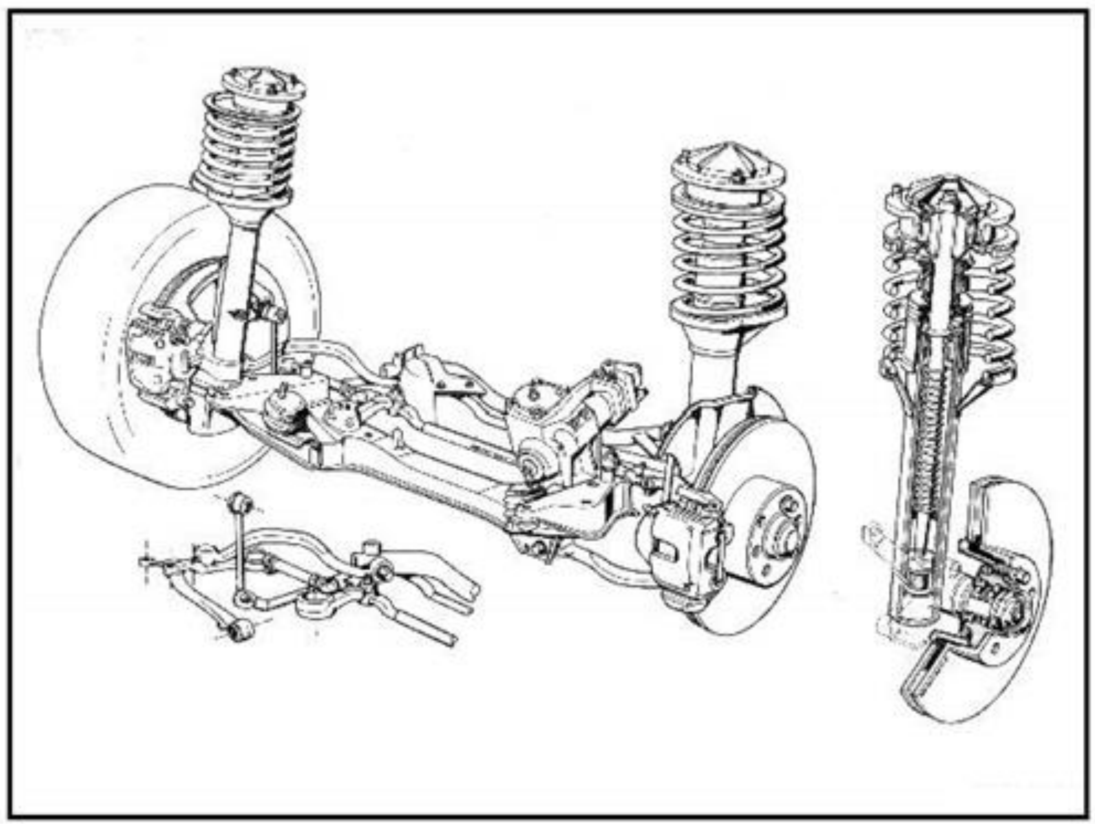
8-Series Suspension Demystification

- **Suspension System Geometry**
  - **Anti-Dive – Upper Thrust Arm/ Control Arm front suspension**
    - reaction to front brake torque
  - **Anti-Squat – Trailing Arm rear suspension**
    - reaction to rear axle torque
  - **Anti-Pitch – front Thrust Arm and rear Trailing Arm suspension**
    - reaction to brake torque and bias on front & rear axles
  - **Anti-Roll – Lower Wishbone/Control Arm Front suspension**
    - reaction to lateral forces



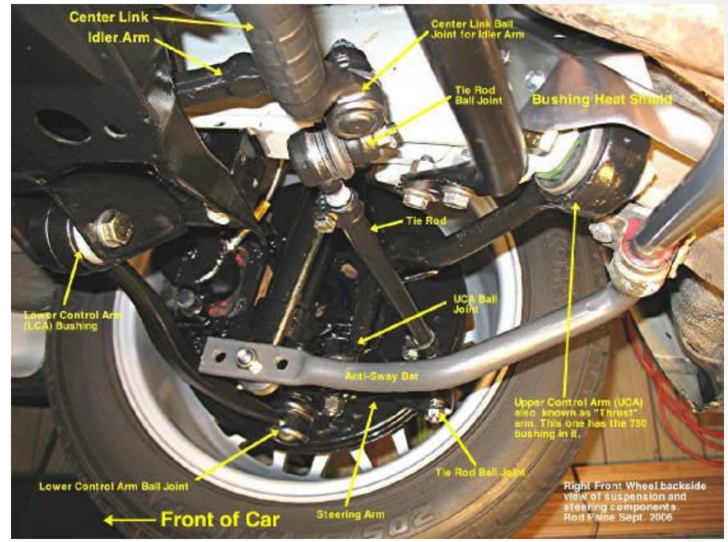
8-Series Suspension Demystification

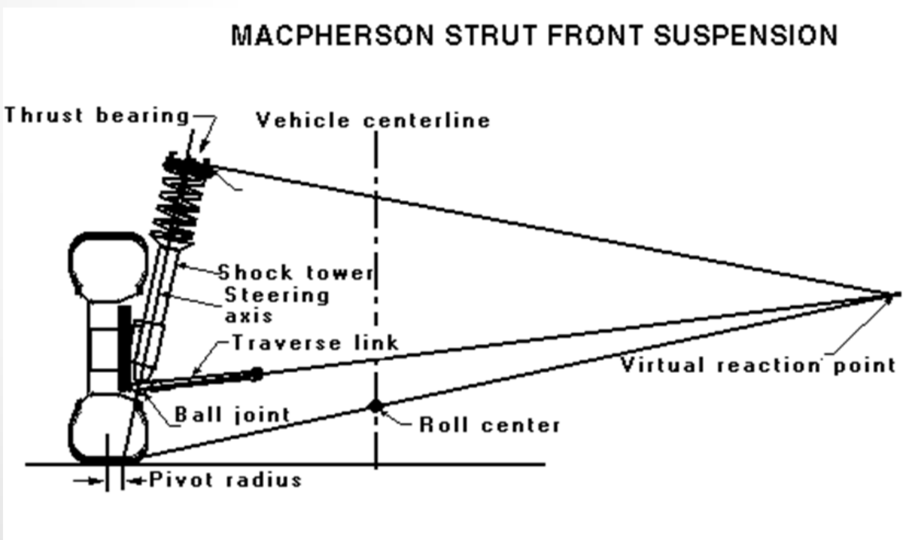
- **Suspension System Geometry**
  - **Macpherson Front suspension**
    - **Strut**
    - **control arms**
    - **Steering arm**

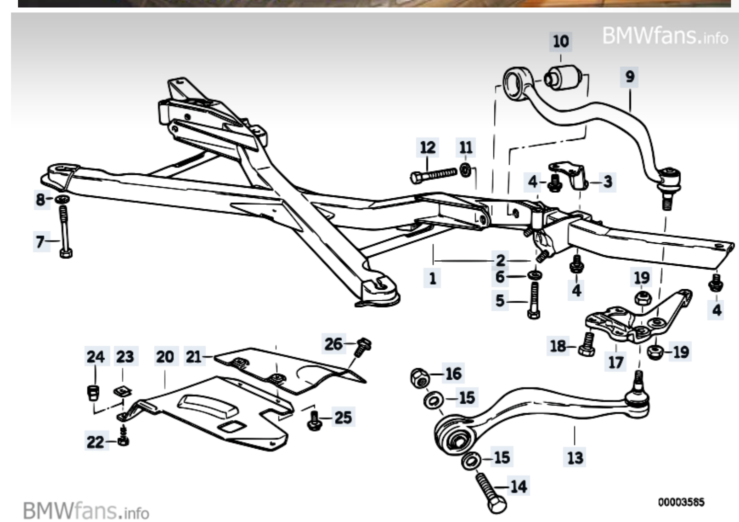


8-Series Suspension Demystification

- **Suspension System Geometry**
  - **Macpherson Front suspension – E-31 (E32 & E34)**
    - Strut - steering angle, camber, caster
    - Lower control arm – anti-roll
    - Upper control arm/thrust rod – anti-dive
    - Steering arm

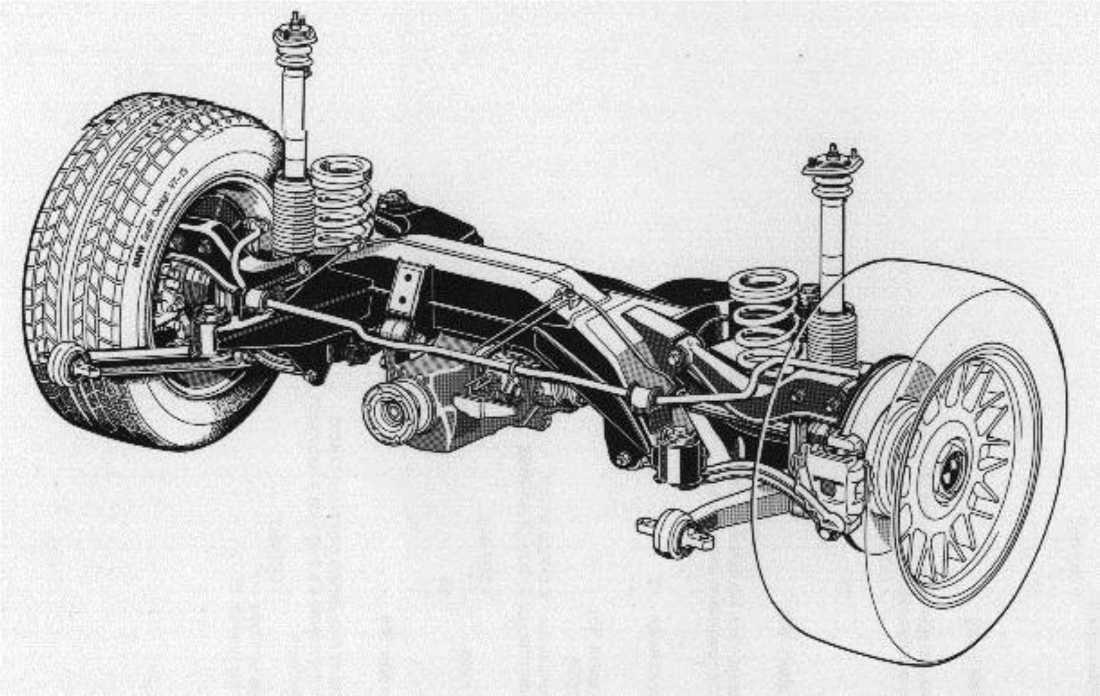






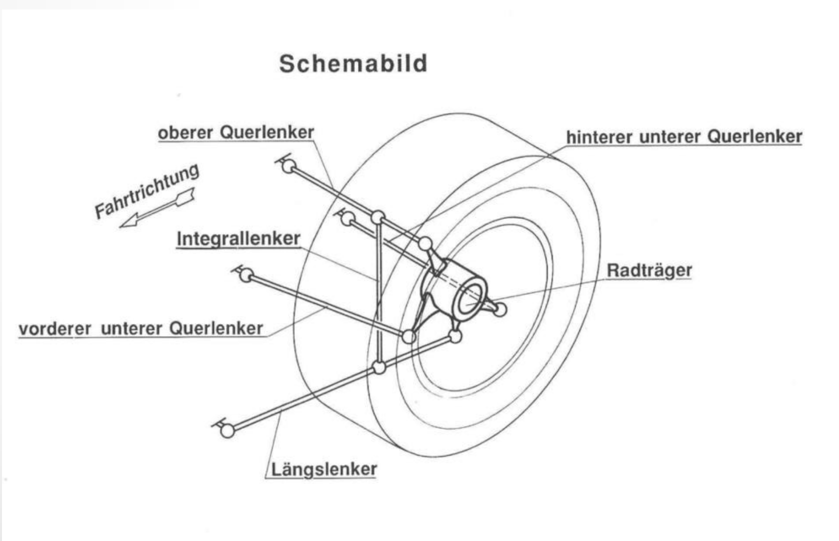
8-Series Suspension Demystification

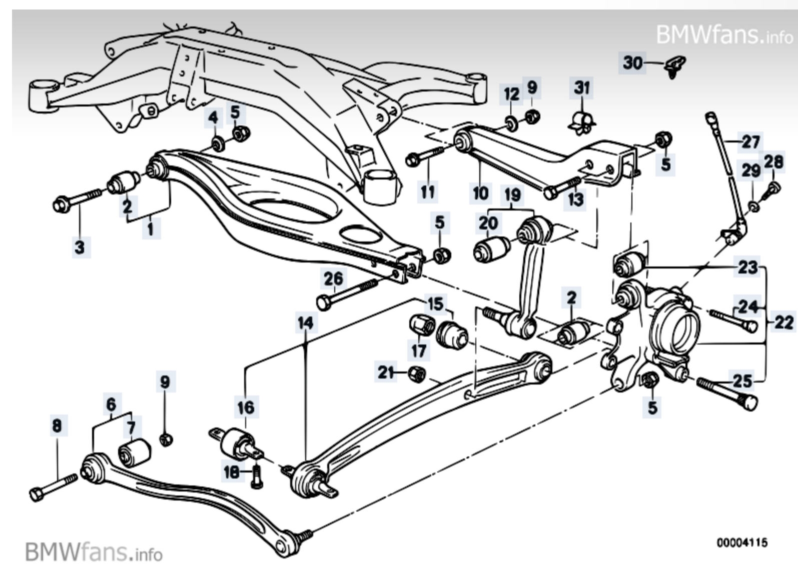
- **Suspension System Geometry**
  - **5-Link rear suspension**



8-Series Suspension Demystification

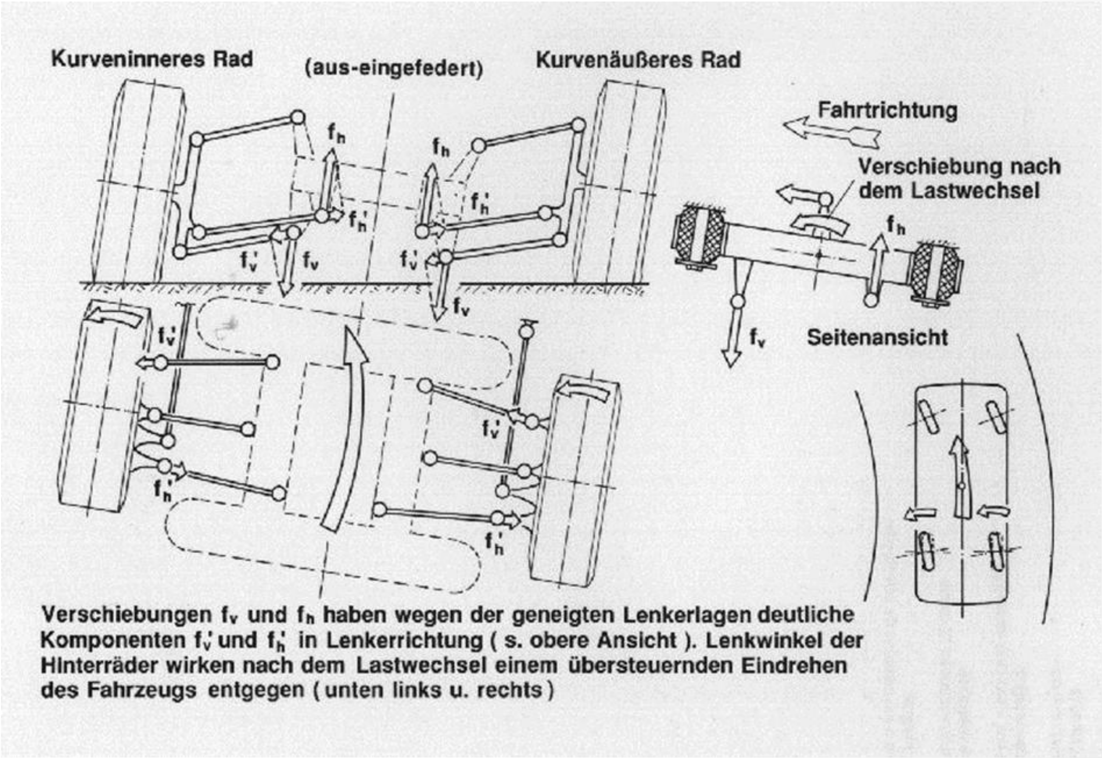
- **Suspension System Geometry**
  - **5-Link rear suspension – E31 only**
  - schematic picture - Schemabild
    - Upper wishbone (10) - oberer querlenker (roll steer)
    - front lower wishbone (6) – vorderer unterer querlenker (roll steer)
    - rear Lower Wishbone (1)– hinterer unterer querlenker (roll steer)
    - Integrel Link (19)– Integrallenker
    - trailing arm (14)- Längslenker – anti-squat
    - wheel carrier (22)– Radträger





8-Series Suspension Demystification

- **Suspension System Geometry**
  - **E31 Rear Suspension Dynamics - Roll steer** – Shifts f_v and f_h have because of the inclined arm positions distinct components f_v^1 and f_h^1 in link direction (s, top view). Steering angle of the rear wheels act according to the load change over a controlling oversteering counter (bottom left & right)

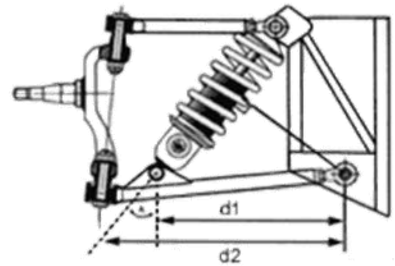


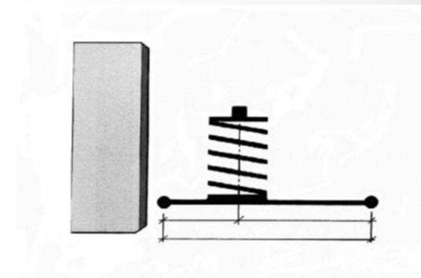
8-Series Suspension Demystification

- **Suspension System Geometry**
  - **Weight transfer - Anti-Feature Geometries**
    - instantaneous weight transfer equivalent to the anti-feature installation ratio < 1:1
    - Anti-Pitch, Nose Dive, Squat - reaction to longitudinal forces
      - acceleration
      - braking
    - Anti-Roll - reaction to lateral forces
      - steering
    - Anti-Features aid spring elements - “Taking a Set”.
  - **Weight transfer at natural frequency rate – spring elements**
    - Wheel rates
    - Pitch rate
    - Bounce Rate
    - Roll Rate
  - **Suspension Anti-Features and spring elements manage/control**
    - body mass
    - motion

8-Series Suspension Demystification

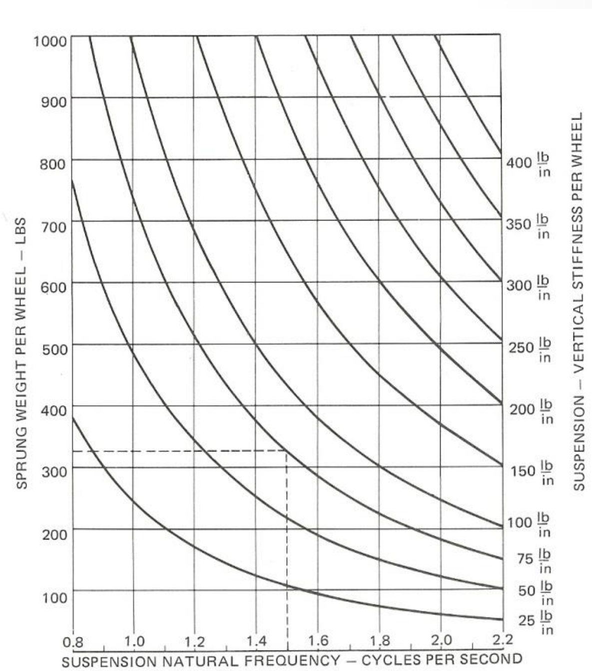
- **Ride - Suspension**
  - **Quarter-Car Model**
  - **Wheel Rate Calculation**
    - motion ratio = d1/d2
    - Wheel rate = SR * $(d1/d2)^2$ cos (alpha)
    - Wheel rate = SR * $(d1/d2)^2$





  - **Ride – Natural Frequency -**
    - f = natural frequency
    - K = wheel rate
    - M = sprung weight of ¼ car

$$f = 1/(2\pi)\sqrt{\frac{K}{M}}$$



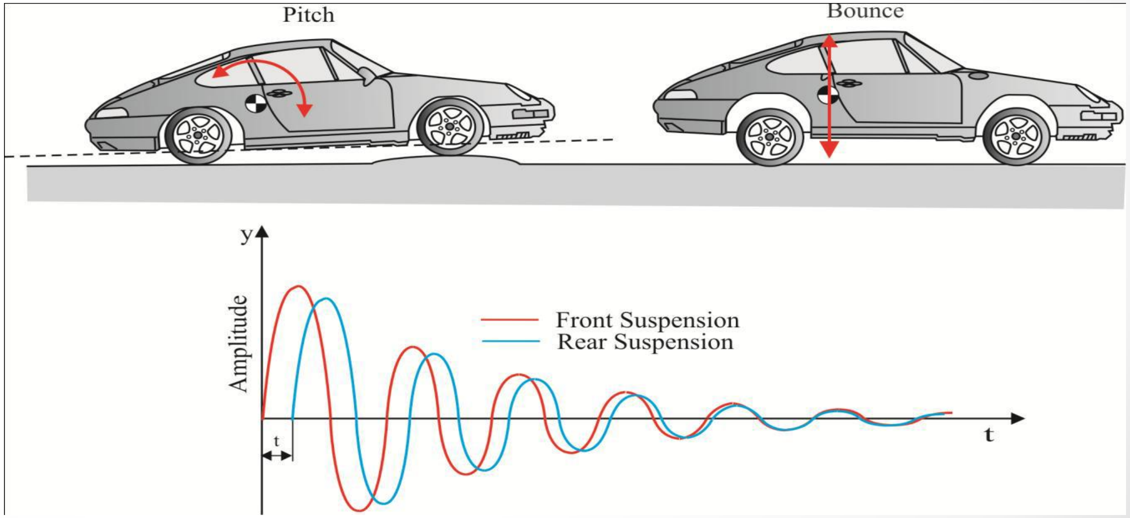
8-Series Suspension Demystification

- **Ride - Rigid Body Bounce/Pitch Motion**

Maurice Olley Suspension Criteria: (1930's)

- Front suspension should have a 30% lower ride rate (Hz) than the rear suspension rate
- The pitch and bounce frequency should be close together : the bounce frequency should be less than 1.2 times the pitch frequency (ratio = pitch/bounce)
- Neither frequency should be higher then 1.3Hz
- The roll frequency should be approximately equal to the pitch and bounce frequency
- The rule that the rear suspension should have a higher natural frequency is rationalized by the observation that vehicle bounce motion is less annoying than pitch motion. Since the suspension excitation input from the road affects the front wheels first, the higher rear to front ratio of frequencies will tend to introduce bounce.

- Pitch/Bounce Motions
- Olley criteria: Front wheel rate < rear



8-Series Suspension Demystification

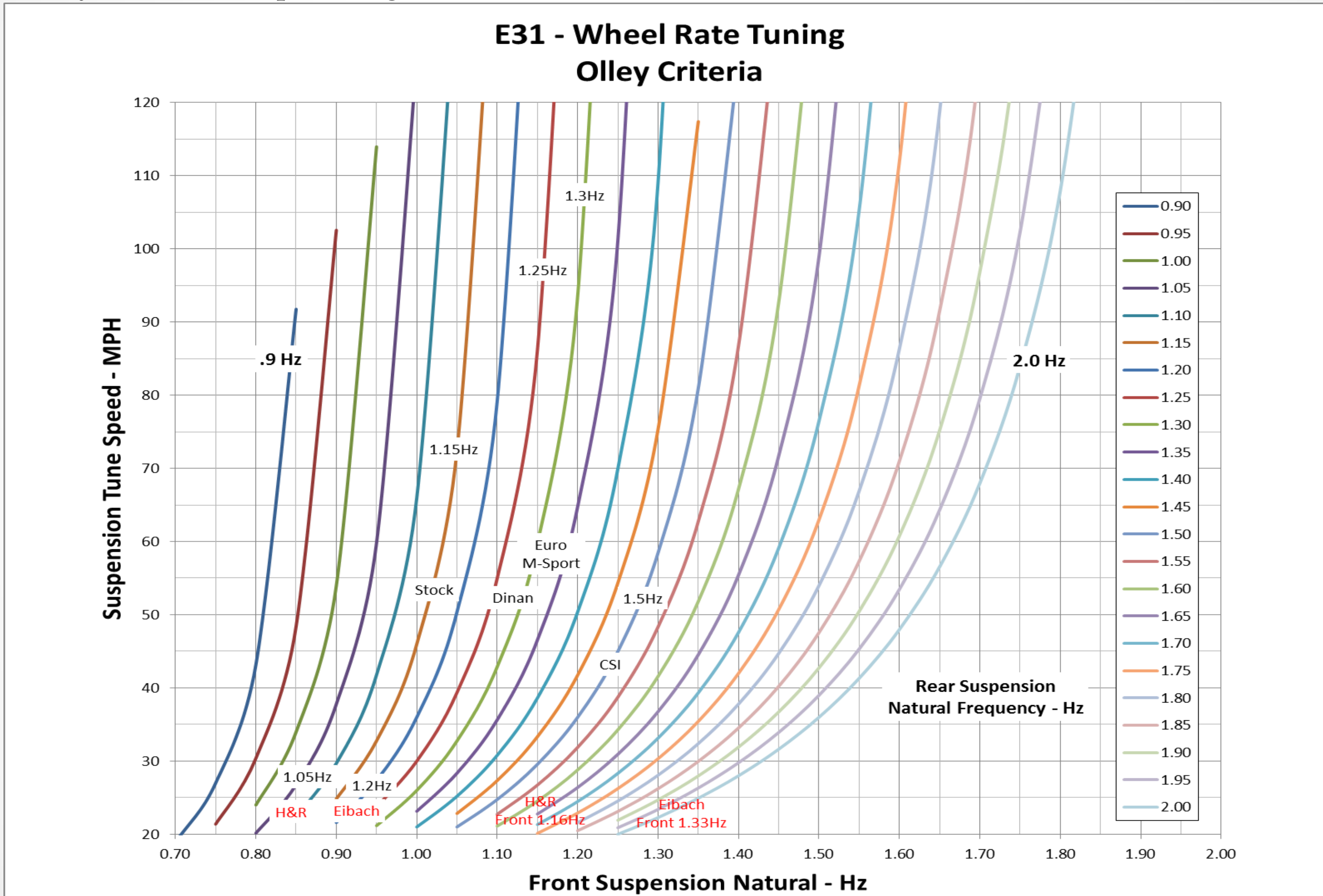
- **Ride - Suspension**
  - **E31 Front & Rear wheel rates with listed springs, lbs/in & Hz**
    - Stock – 850/840
    - Euro M-Sport
    - CSi
    - Dinan Stage 1
    - H&R
    - Eibach
    - AC Schnitzer
    - H&R Front + M-Sport Rear
    - H&R Front + Stock Cut 1-1/2 coil
    - CSi calculated with 80mph tune
  - **Front to Rear Natural Hz with Speed Tuning**

$$F_{Hz} = \frac{1}{\left(\frac{.0568 * \text{wheelbase}}{\text{Speed}}\right) + \left(\frac{1}{R_{Hz}}\right)}$$

Load = Driver + Passenger + Luggage = 520 lbs	Front Wheel Rate	Rear Wheel Rate
Stock 850/840	117	149
Hz	1.03	1.18
Euro M-Sport	152	193
Hz	1.17	1.34
CSI	170	249
Hz	1.24	1.52
Dinan	138	179
Hz	1.11	1.29
H&R	149	124
Hz	1.16	1.08
Eibach	198	166
Hz	1.33	1.24
AC Schnitzer	177	160
Hz	1.26	1.22
H&R + M-Sport	149	193
Hz	1.16	1.34
H&R + Cut 1-1/2	149	167
Hz	1.16	1.25

8-Series Suspension Demystification

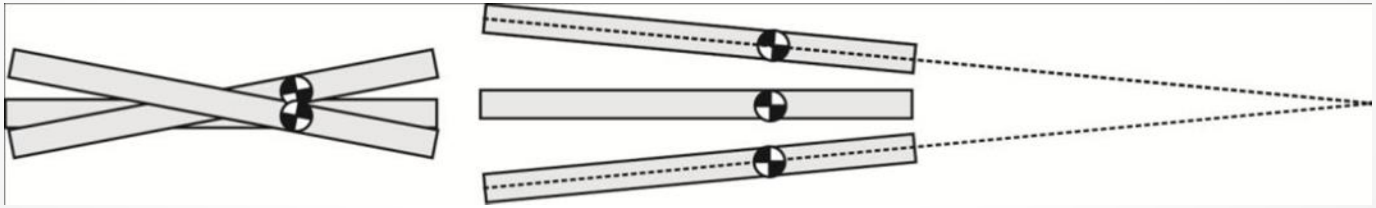
Olley Criteria Graph using wheelbase



8-Series Suspension Demystification

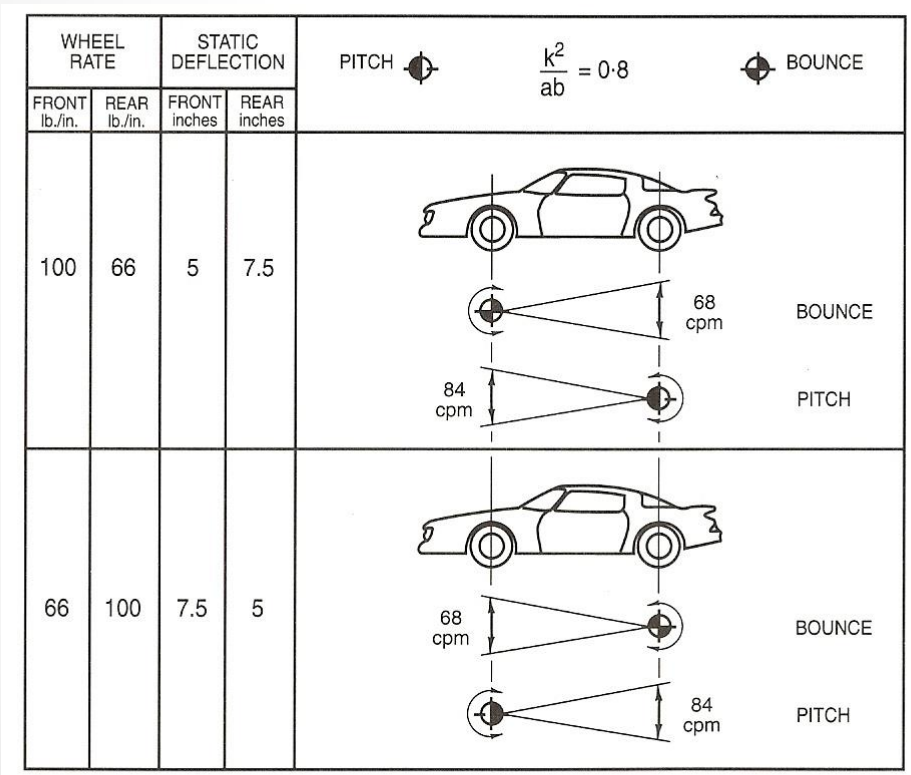
- **Ride - Rigid Body Bounce/Pitch Motion**
  - **Suspension System Criteria** – order of design
    - **Suspension Axle Type & Geometry** – 1st elements of suspension design
      - anti-features
      - installation ratios
    - **Natural Frequency** – 2nd wheel/spring rates
    - **Dampeners** – 3rd rebound and compression rates
    - **Roll stiffness** – 4th under/oversteer compensation with roll bars
  - **Motion Center Locations** – Olley Criteria for wheel rate/natural frequencies front to rear
    - The MCL *outside wheelbase* it is called the *bounce* center and is associated with the bounce frequency
    - The MCL *inside wheelbase* it is called the *pitch* center and is associated with the pitch frequency (usually higher than bounce).
    - A lower front natural frequency puts the bounce center behind the rear wheels
  - **Motion Center**

Pitch **Bounce**

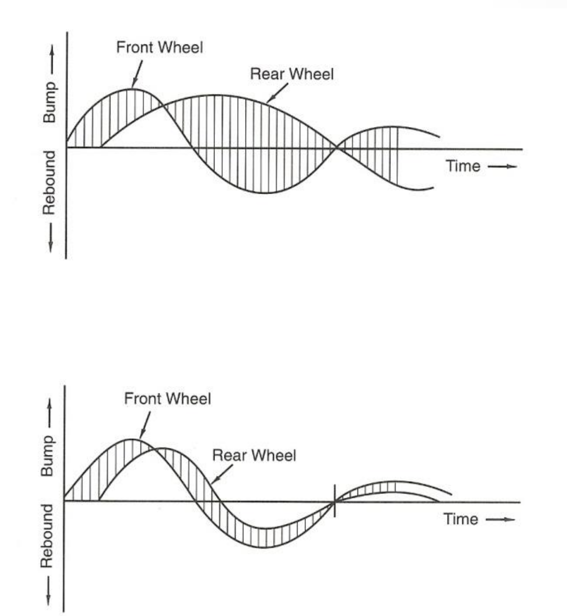


8-Series Suspension Demystification

- **Ride - Rigid Body Bounce/Pitch Motion**
  - **Pitch dominant** – Front wheel rate > Rear and Front = Rear wheel rate
  - **Bounce dominant** – Front wheel Rate < Rear



Chassis Motion Response



8-Series Suspension Demystification

- What ride frequencies are common today - Steve Lyman, Formula SAE Lead Design Judge
  DaimlerChrysler Corporation

	Front Suspension					Rear Suspension					
Vehicle	Ride Rate w/o tire (lb/in)	Corner Weight (lb)	Unsprung Weight (lb)	Sprung Weight (lb)	**Frequency (hertz)**	Ride Rate w/o tire (lb/in)	Corner Weight (lb)	Unsprung Weight (lb)	Sprung Weight (lb)	**Frequency (hertz)**	Ride Ratio Rr/Frt
99 Volvo V70 XC	119	1032	100	932	**1.12**	131	832	100	732	**1.32**	1.18
2001 MB E320 4-Matic	117	991	100	891	**1.13**	148	964	100	864	**1.29**	1.14
Jeep KJ Liberty	126	1036	85	951	**1.14**	181	914	85	829	**1.46**	1.28
97 NS Chrysler T&C	148	1173	85	1088	**1.15**	145	880	85	795	**1.34**	1.16
Pacifica	160	1286	85	1166	**1.16**	153	1074	85	989	**1.23**	1.06
99 MB E320 4-Matic	121	985	100	885	**1.16**	150	960	100	860	**1.31**	1.13
97 Peugeot 306 GTI	110	850	85	765	**1.19**	113	468	85	383	**1.7**	1.43
99 Audi A 6 Quattro	152	1070	100	970	**1.24**	172	864	100	764	**1.48**	1.2
2001 MB E320 2WD	131	907	85	822	**1.25**	144	969	85	884	**1.26**	NA
	99	907	85	822	**1.09**						
95 BMW M3	113	783	85	698	**1.26**	159	790	85	705	**1.48**	1.18
2001 VW Passat	163	1060	100	960	**1.29**	136	670	100	570	**1.53**	1.19
2000 Neon	134	836	75	761	**1.31**	127	510	65	445	**1.67**	1.27
2001 JR	161	1009	85	924	**1.31**	136	607	85	522	**1.6**	1.22
99 LH Dodge Intrepid	185	1125	85	1040	**1.32**	152	651	85	566	**1.62**	1.23
02 Jeep WG Grand Cherokee	197	1170	85	1085	**1.33**	184	1005	85	920	**1.4**	1.05
2000 VW Golf	107	797	85	712	**1.21**	105	586	85	501	**1.43**	1.18

8-Series Suspension Demystification

- Ride - Suspension
  - Half-Car Model

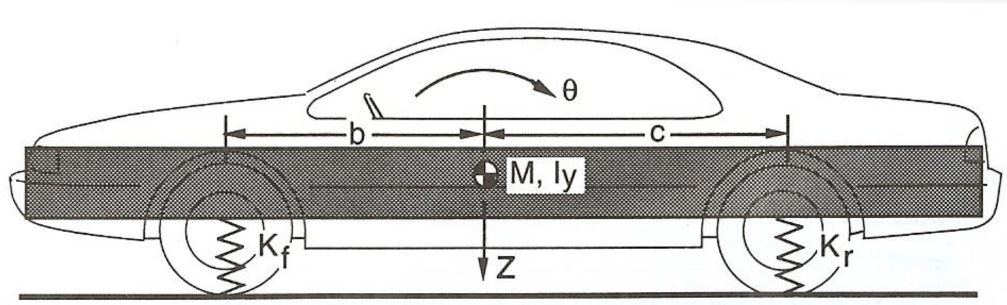
$\alpha = (K_f + K_r)/M$

$\beta = (K_r c - K_f b)/M$

$\gamma = (K_f b^2 + K_r c^2)/M k^2$

where:

K_f = Front ride rate
K_r = Rear ride rate
b = Distance from the front axle to the CG
c = Distance from the rear axle to the CG
I_y = Pitch moment of inertia
k = Radius of gyration = $\sqrt{I_y / M}$



  - Rigid Body Bounce/Pitch Motion

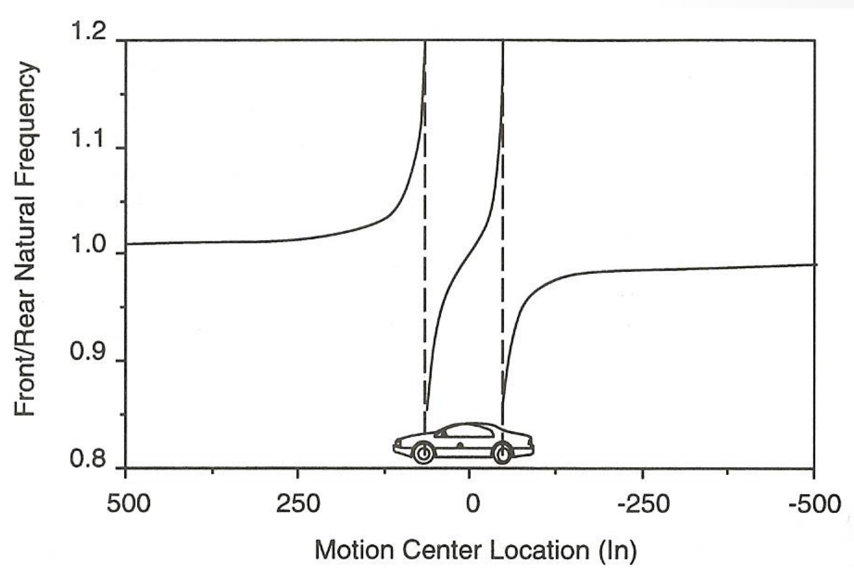
$$(\omega_{1,2})^2 = \frac{(\alpha+\gamma)}{2} \pm \sqrt{\frac{(\alpha+\gamma)^2}{4} - \left(\alpha\gamma - \beta^2/k^2\right)}$$

$$= \frac{(\alpha+\gamma)}{2} \pm \sqrt{\frac{(\alpha-\gamma)^2}{4} + \beta^2/k^2}$$

$$\omega_1 = \sqrt{\frac{(\alpha+\gamma)}{2} + \sqrt{(\alpha-\gamma)^2/4 + \beta^2/k^2}}$$

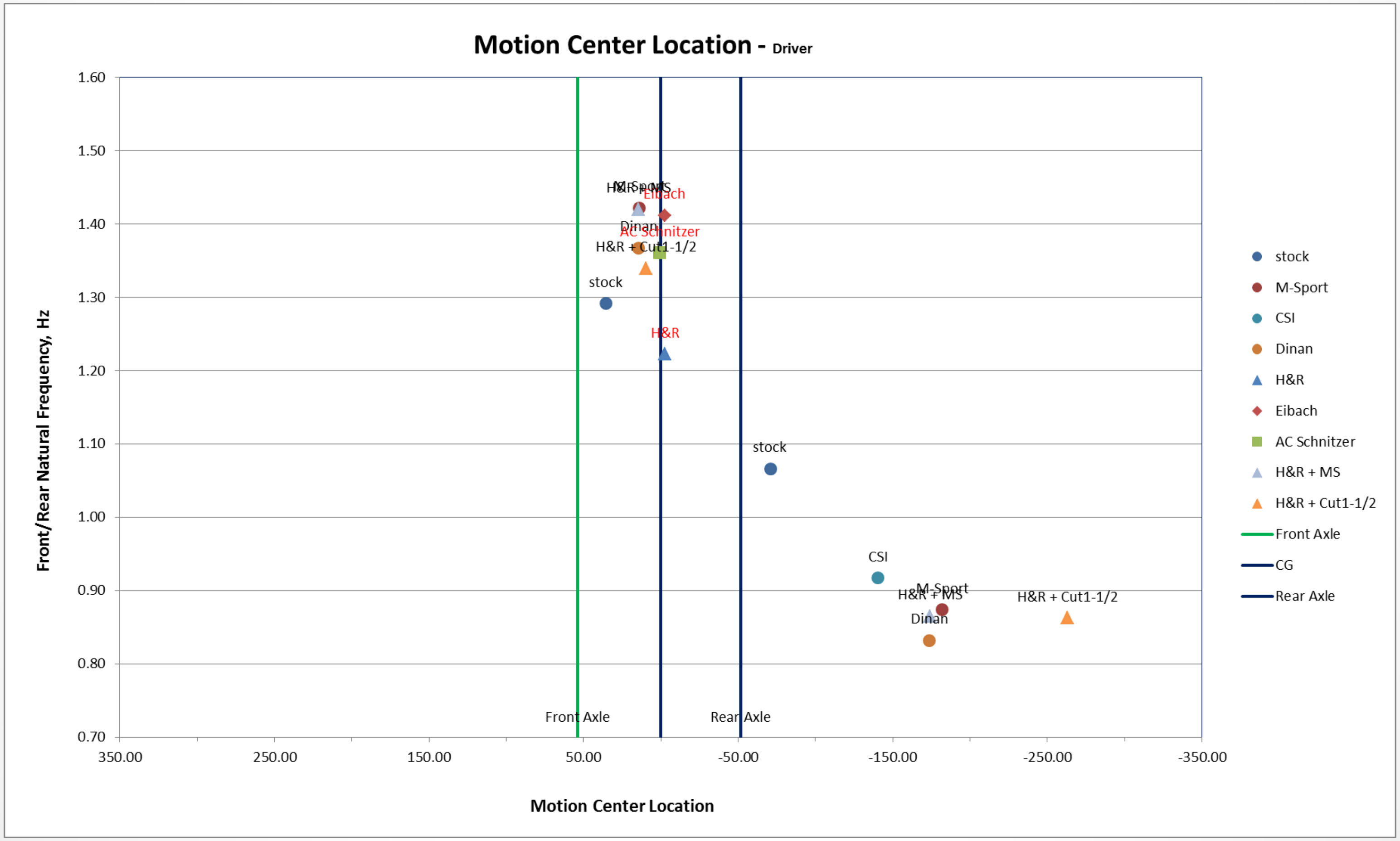
$$\omega_2 = \sqrt{\frac{(\alpha+\gamma)}{2} - \sqrt{(\alpha-\gamma)^2/4 + \beta^2/k^2}}$$

$Z/\theta = -\beta/(\alpha - \omega^2)$



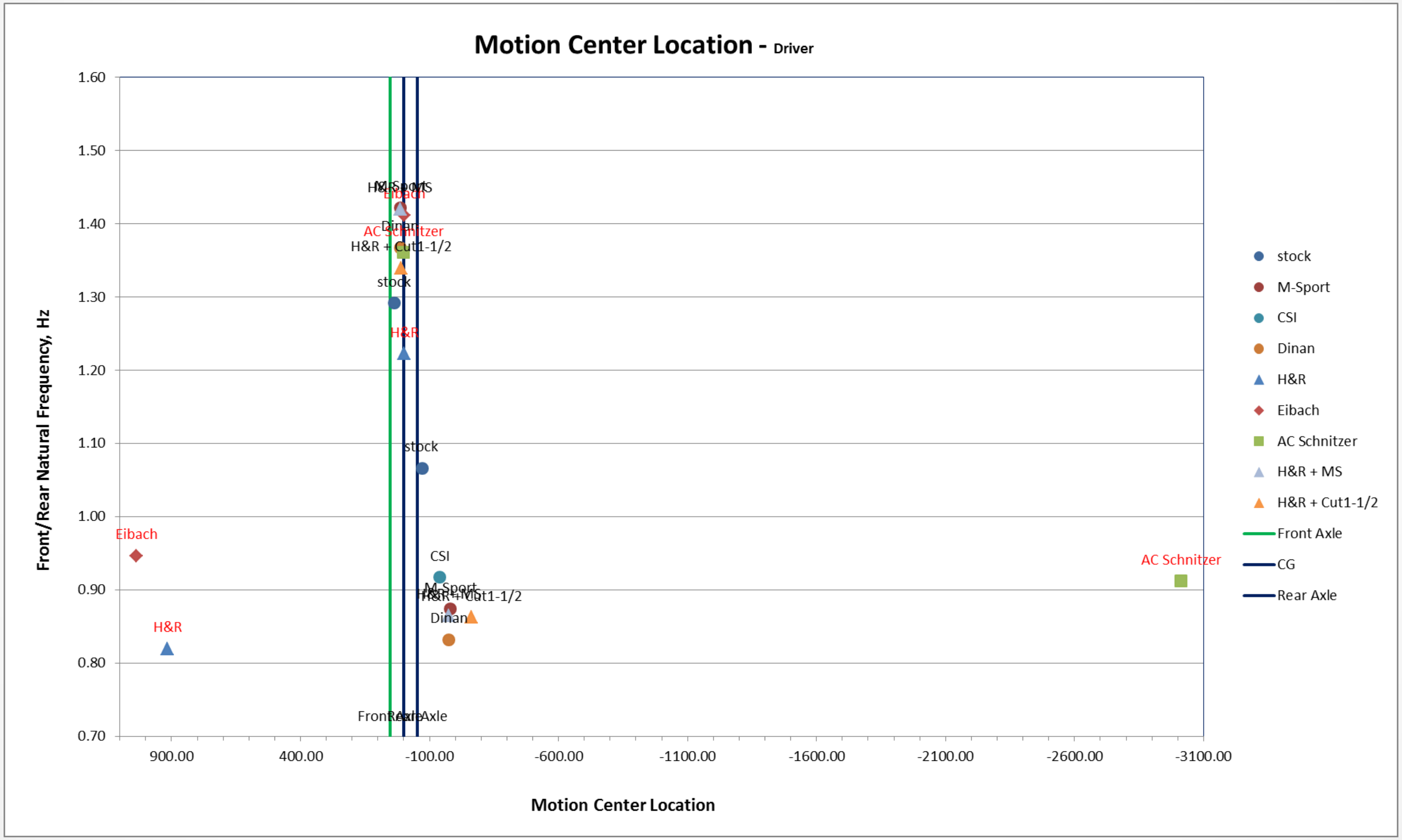
8-Series Suspension Demystification

- Driver = 210 lbs.



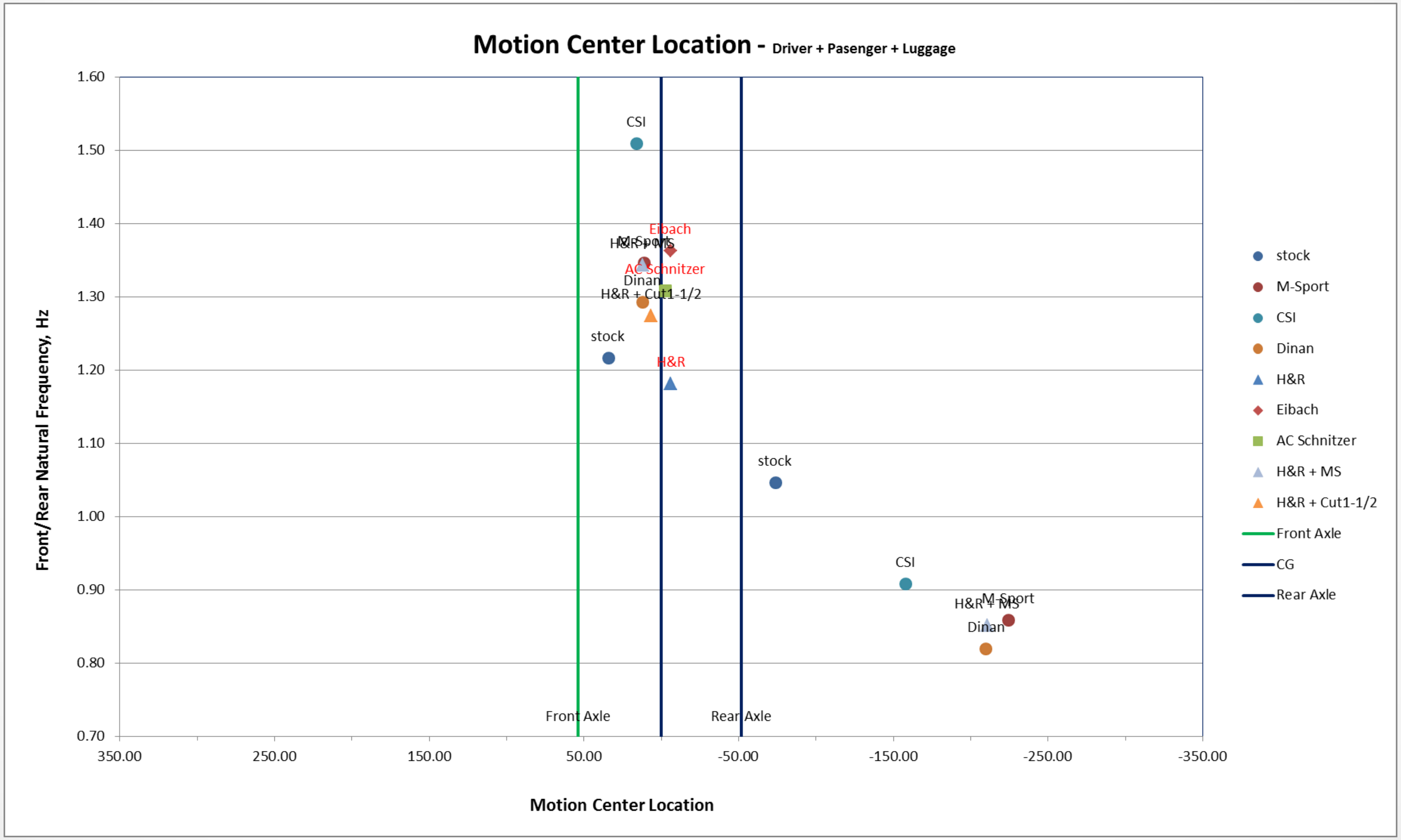
8-Series Suspension Demystification

- Driver = 210 lbs.



8-Series Suspension Demystification

- Driver + Passenger = 370 lbs + Luggage = 150 lbs – Total = 520 lbs.



8-Series Suspension Demystification

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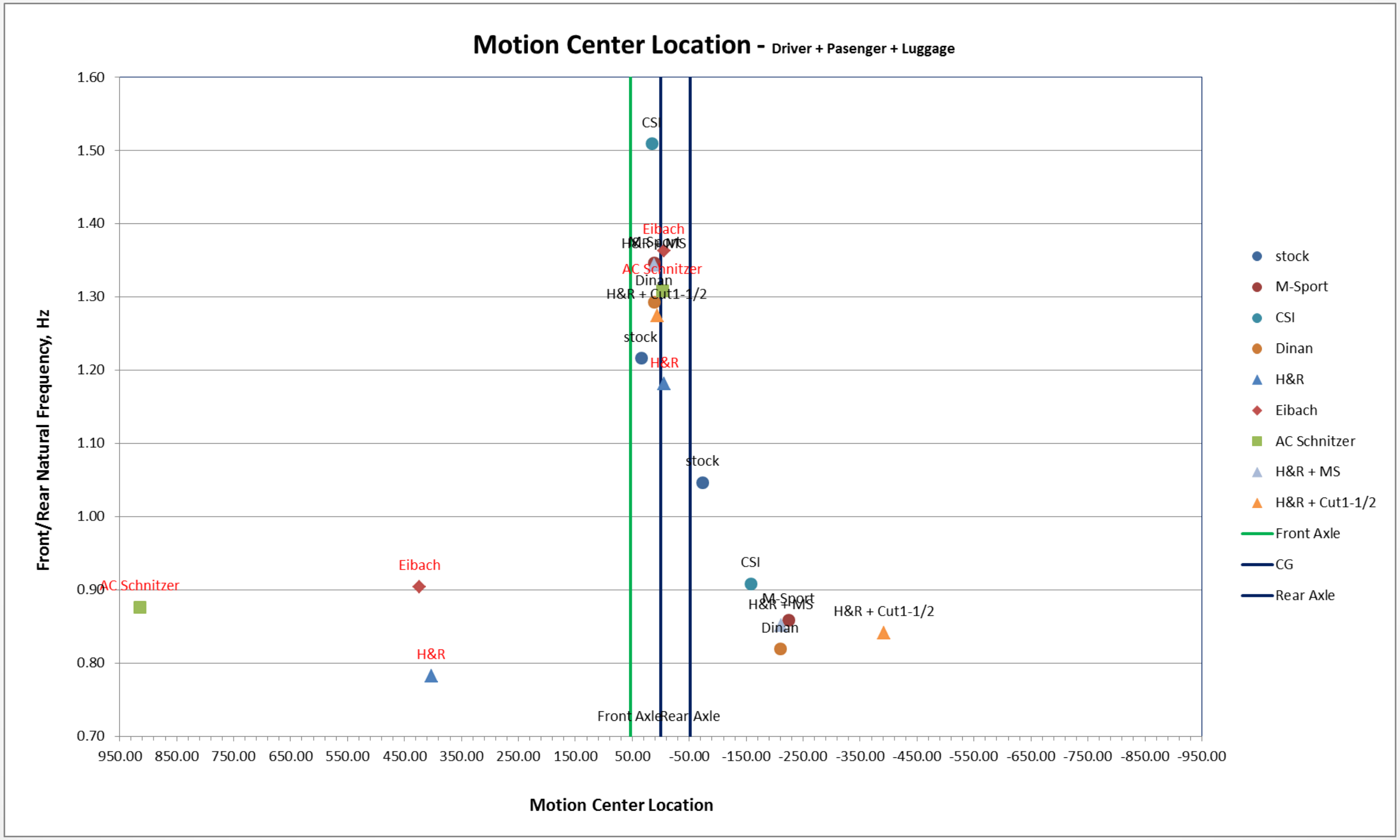
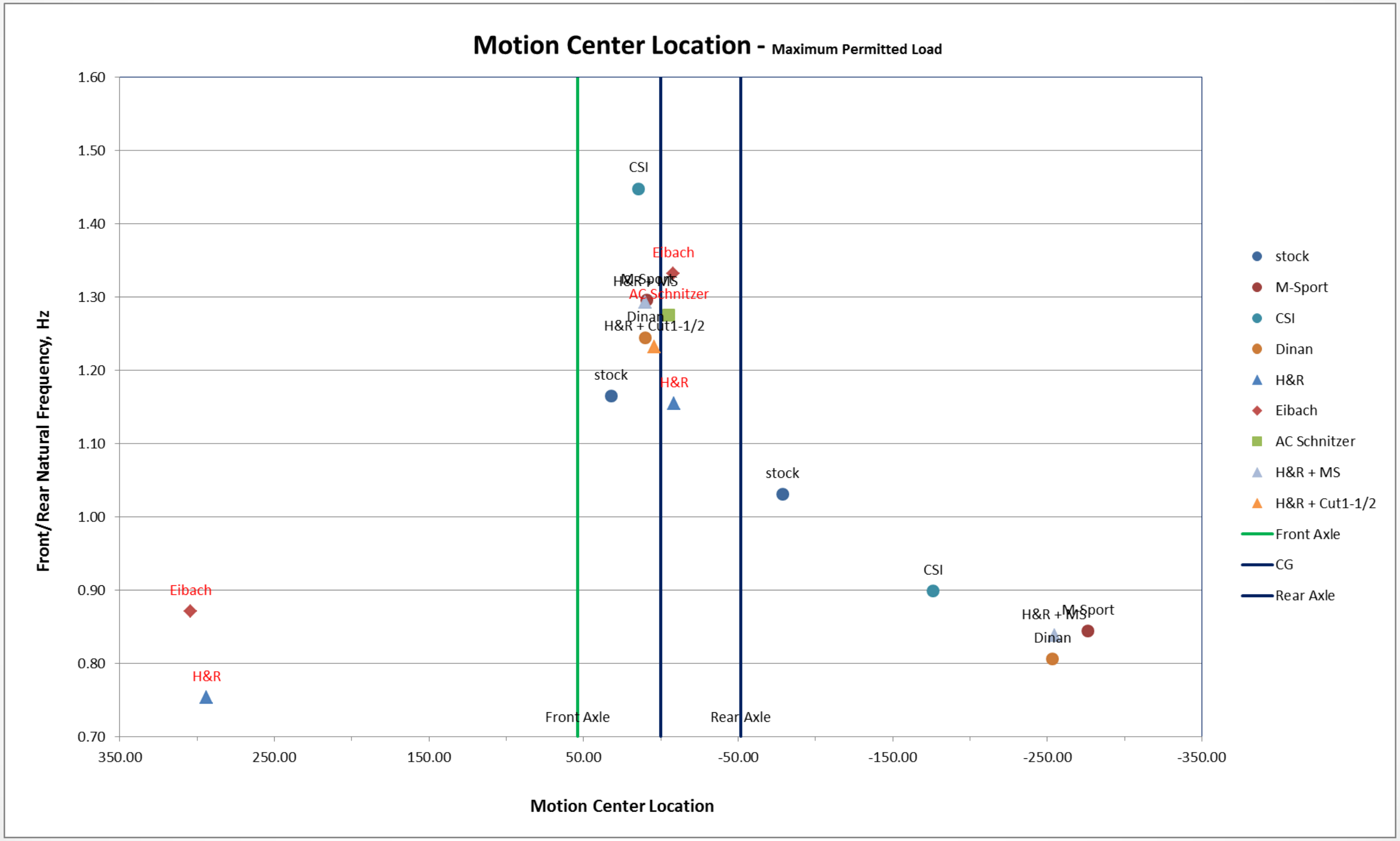


8-Series Suspension Demystification

- Maximum Permitted Load = 783 lbs.



8-Series Suspension Demystification

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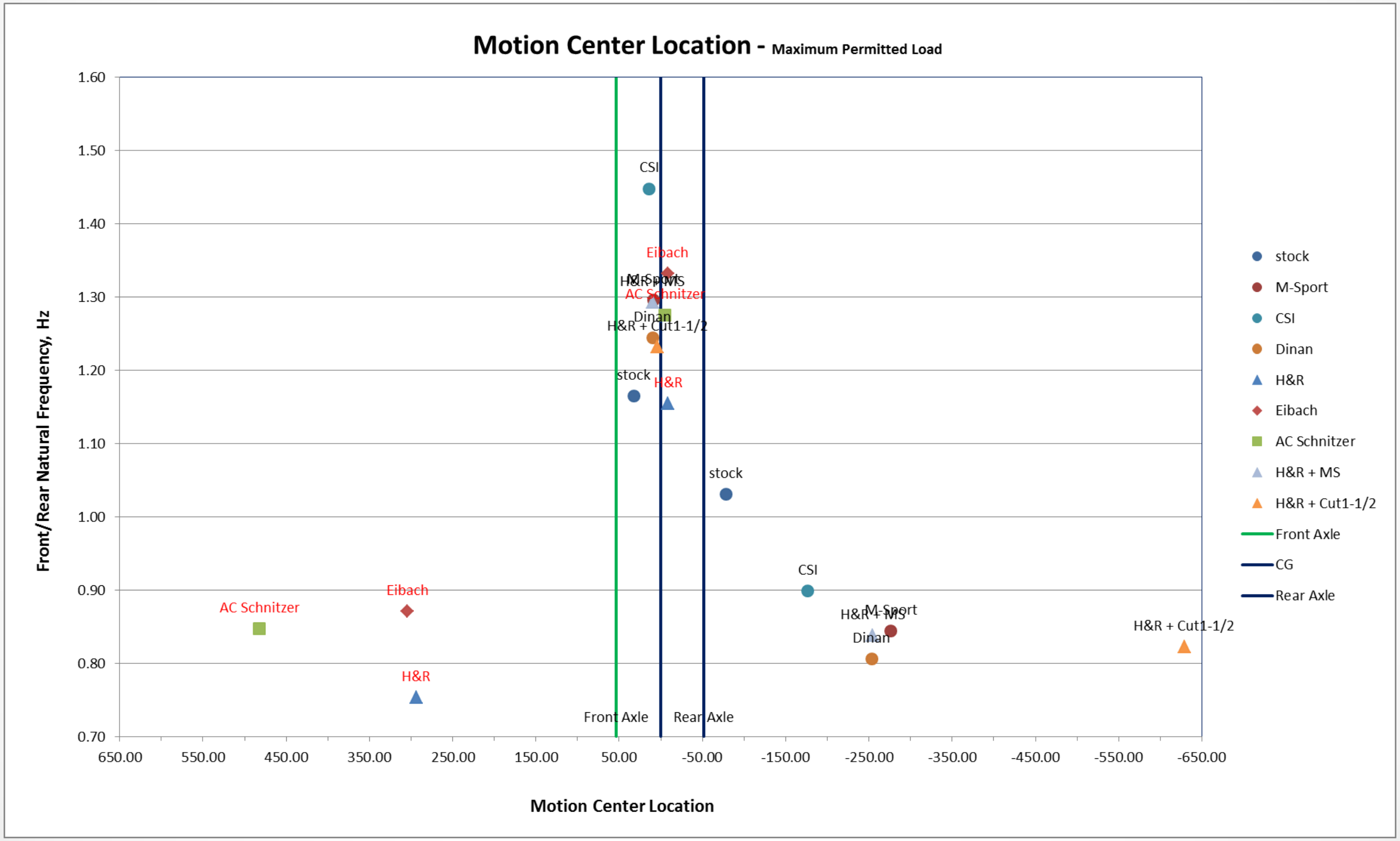

8-Series Suspension Demystification

- **Conclusion:**
  - Comparative analysis provided the opportunity to explore
    - BMW E31 suspension setups
    - Various aftermarket suspension offerings
  - Deselect the off normal performance topologies
    - Less then ideal pitch/bounce motion center
    - Less than desired ride height
    - Less than desired suspension travel
    - Less then adequate spring/wheel rates

- **Questions ????????/**

8-Series Suspension Demystification

Euro M-Sport Suspension

- **Part number:** 33 32 9 059 315 - Set (NLA)

Part number:	Name:	Supplement:	Quantity:
31 20 6 777 788	Dust protection collar	D=83MM	2
31 21 1 128 336	Collar nut		2
31 22 1 139 345	Wheel hub, front, symmetric	D=83MM	2
31 31 1 139 653	Left front spring strut		1
31 31 1 139 654	Front right spring strut		1
31 33 1 138 735	Front coil spring		2
31 33 1 138 769	Additional damper, front		2
31 35 1 136 068	Stabilizer rubber mounting D=25MM		2
33 52 1 137 474	Shock absorber, rear		2
Additional parts:			
33 53 1 138 738	Rear coil spring		2
Sway Bars:			
31 35 2 226 379	Front E32 Sport Suspension <-4/92	D= 26mm	1
31 35 2 227 364	Front (CSi) - 4/92->	D= 27mm	1
33 56 1 090 399	Rear – <-9/92	D= 15.5mm	1
33 55 2 227 321	Rear (CSi) - 9/92->	D= 17mm	1

8-Series Suspension Demystification

- References Sources:
  - How to Make Your Car Handle – Puhn – 1981 - HP Books
  - Performance Handling – Alexander – 1991 – Motorbooks International
  - Fundamentals of Vehicle Dynamics Gillespy – 1992 - SAE
  - Race Car Vehicle Dynamics – Milliken & Milliken – 1995 - SAE
  - Internet Search