# Collegiate Design Series
# *Suspension 101*


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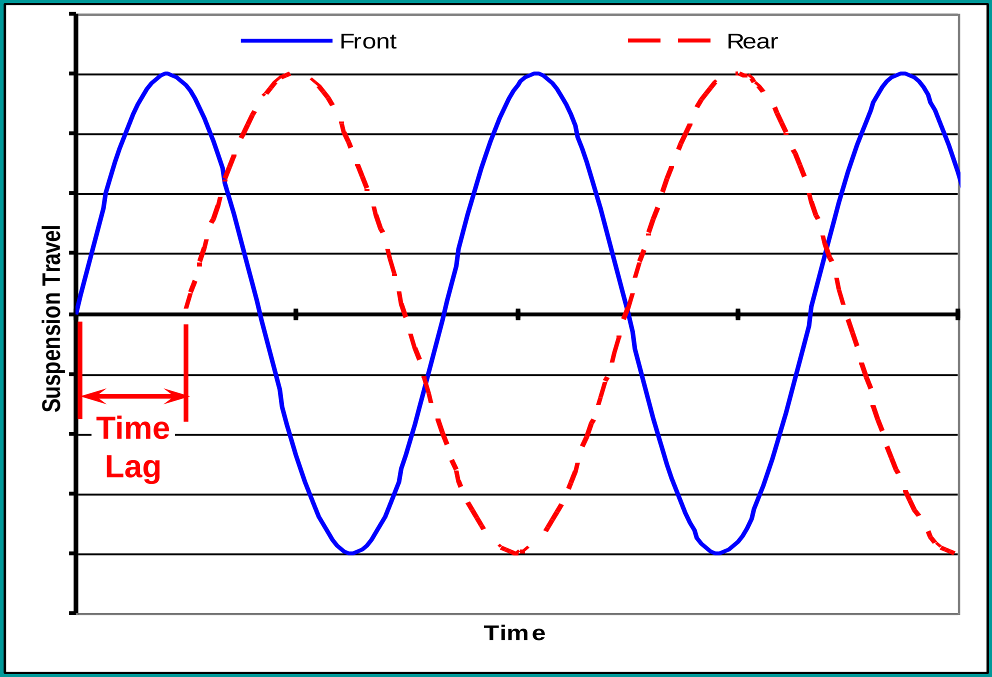
# There Are Many Solutions

- “It depends.”
- “Everything is a compromise.”

# Suspension 101

- Ride Frequency/ Balance (Flat Ride)
- Motion Ratios
- Ride Friction
- Suspension Geometry Selection
- Suspension Layouts- Double A Arm Variations and Compromises
- Dampers- A Really Quick Look

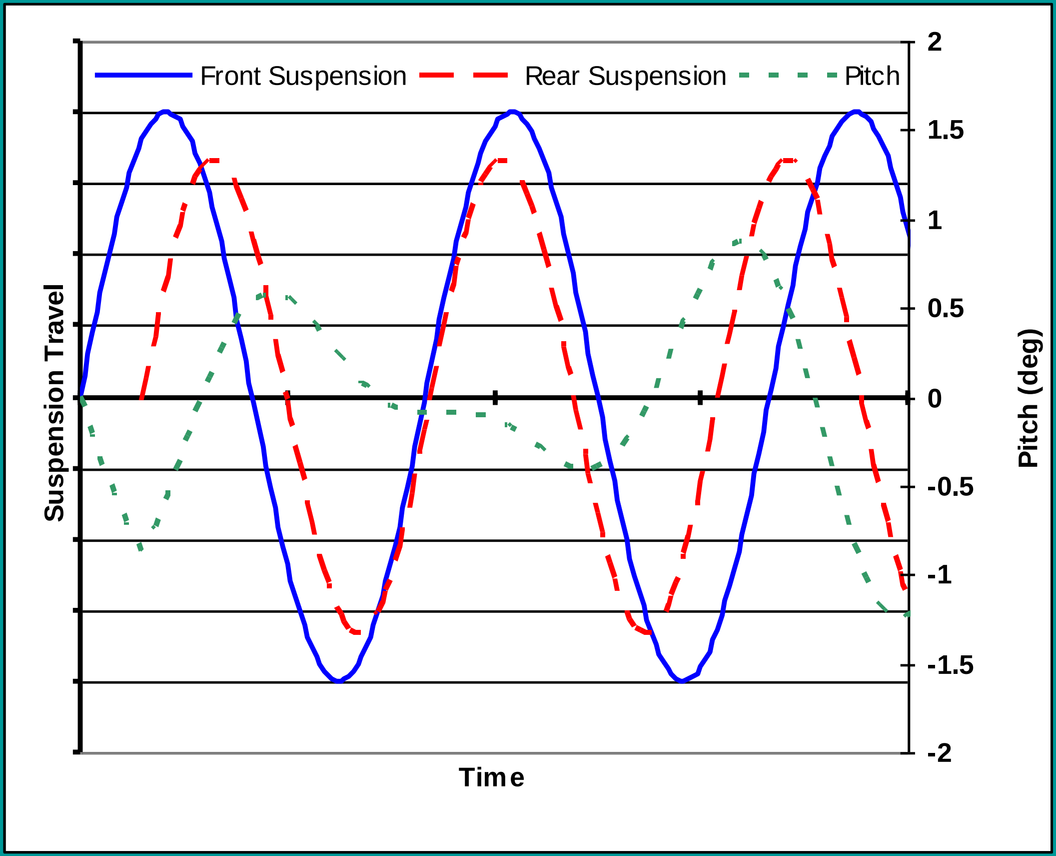
“The thing we had missed was that the excitation at front and rear did not occur simultaneously. The actual case was more like this--




--with the angle of crossing of the two wave lines representing the severity of the pitch.”

(From Chassis Design: Principles and Analysis, Milliken & Milliken, SAE 2002)

"By arranging the suspension with the lower frequency in front (by 20% to start) this motion could be changed to--




--a much closer approach to a 'flat' ride".

(From Chassis Design: Principles and Analysis, Milliken & Milliken, SAE 2002)

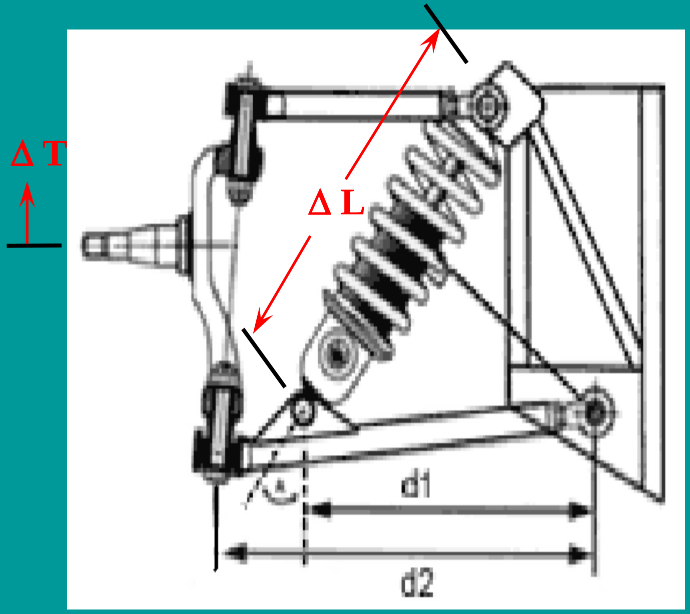
# What ride frequencies are common today?

| Vehicle | Front Suspension | | | | | Rear Suspension | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ride Rate wlo tire (Ib/in) | Corner Weight (lb) | Unsprung Weight (Ib) | Sprung Weight (lb) | **Frequency (hertz)** | Ride Rate wlo tire (Ib/in) | Corner Weight (lb) | Unsprung Weight (Ib) | 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 A6 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 |

# Does motion ratio affect forces transmitted into the body?

- Motion ratio is spring travel divided by wheel travel.
- The force transmitted to the body is reduced if the motion ratio is increased.

# Does motion ratio affect forces transmitted to the body?




Wheel Rate: 150 lb/in

Motion Ratio: 0.5 ←Not good

Force at wheel for 1” wheel travel = 150 lb

Spring deflection for 1” wheel travel=0.5”

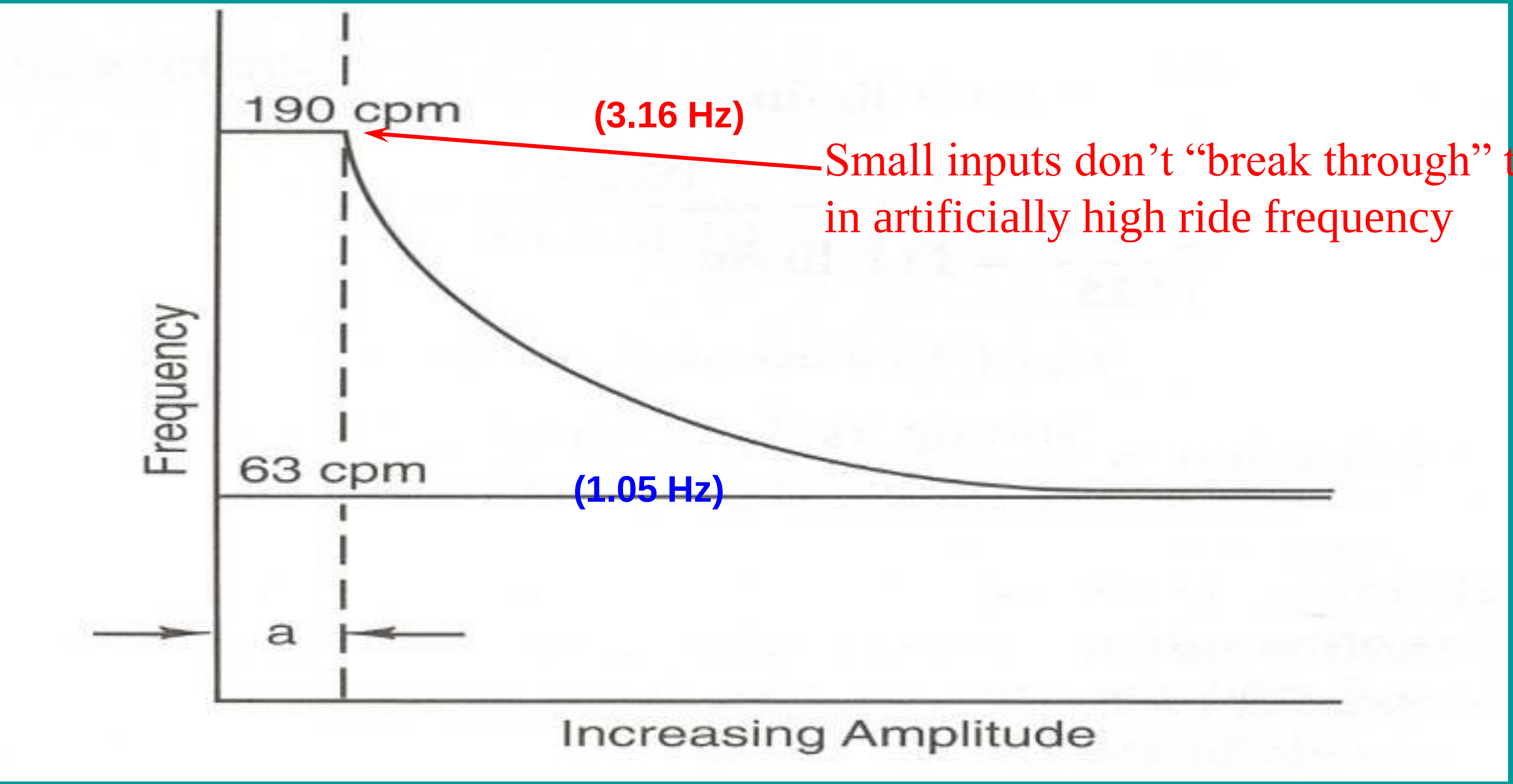
Force at spring for 1” wheel travel = 300 lb

Force at body = Force at wheel / MR

Spring Rate=300 lb / 0.5 = 600 lb/in

**Spring Rate= Wheel Rate / $MR^2$**

# How does ride friction affect frequency?




Small inputs don't "break through" the friction, resulting in artificially high ride frequency

(From Chassis Design: Principles and Analysis, Milliken & Milliken, SAE 2002)

# Ride Summary

- **Flat Ride**
  - Improves handling, acceleration, braking performance
- **Plenty of suspension travel**
  - Allows lower spring rates & ride frequencies
  - Allows progressive jounce bumper engagement
- **Good motion ratio**
  - Reduces loads into vehicle structure
  - Increases shock velocity, facilitates shock tuning
  - 1.00:1 is ideal, 0.60:1 minimum design target
- **Stiff structure (The 5$^{th}$ Spring)**
  - Improves efficiency of chassis and tire tuning
  - Provides more consistent performance on the track
  - Applies to individual attachment compliances, 5:1 minimum design target, 10:1 is ideal
  - Successful SAE designs in the 2000-3000 ft-lbs/deg range (static torsion), 2X for static bending (lbs/in)
- **Low Friction**
  - Permits dampers to provide consistent performance
  - Not masked by coulomb friction (stiction)
  - 40:1 minimum (corner weight to frictional contribution for good SLA suspension

# Suspension Geometry Setup

- Front Suspension 3 views
- Rear Suspension 3 views

# Front Suspension Front View

- Start with tire/wheel/hub/brake rotor/brake caliper package.
  - pick ball joint location.
  - pick front view instant center length and height.
  - pick control arm length.
  - pick steering tie rod length and orientation.
  - pick spring/damper location.

# FSFV: wheel/hub/brake package

- Ball joint location establishes:
  - King Pin Inclination (KPI): the angle between line through ball joints and line along wheel bearing rotation axis minus 90 degrees.
  - Scrub radius: the distance in the ground plan from the steering axis and the wheel centerline.
  - Spindle length: the distance from the steer axis to the wheel center.

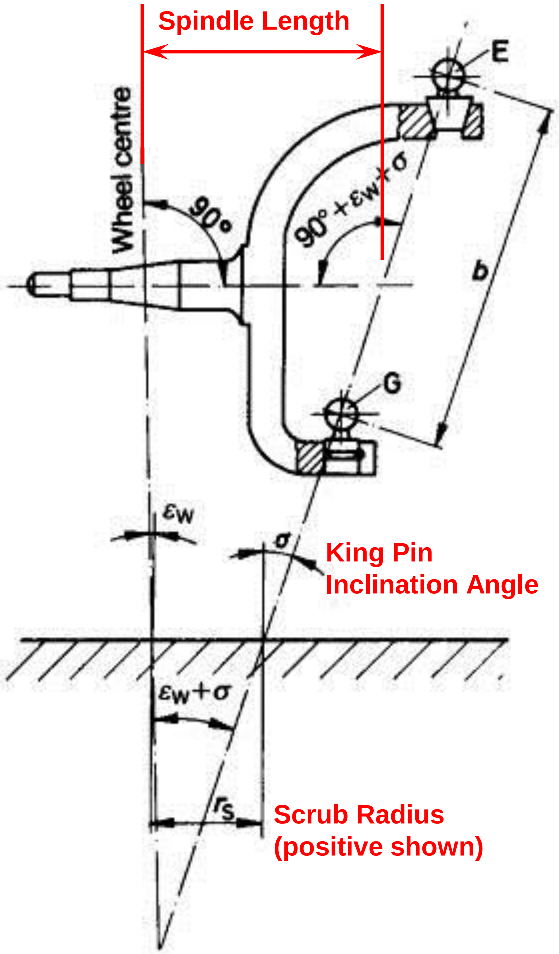



**Fig. 3.80** The precise position of the steering axis – also known as kingpin inclination axis – can only be determined if the centre points E and G of the two ball joints are known. The total angle of kingpin inclination and camber ($\sigma + \epsilon_W$) must also be included when dimensioning the steering knuckle as an individual part.

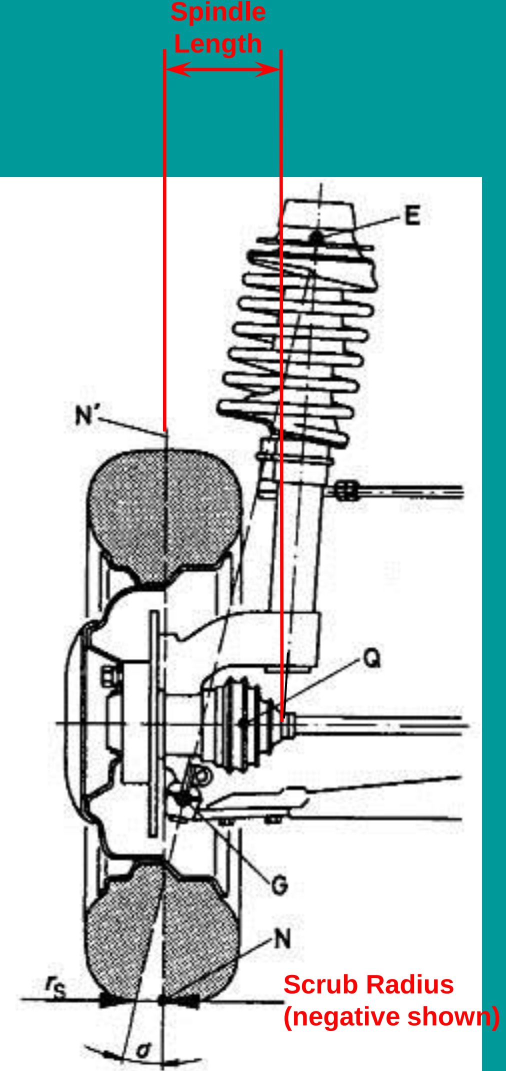



**Fig. 3.79** Left front axle of an Audi with negative kingpin offset on the ground $r_S$ = –18 mm and an almost vertical damper unit; the spring was angled to reduce the friction between the piston rod and rod guide. For reasons of space, the CV-joint centre Q had to be shifted inwards; the space for snow chains has to be considered (see Fig. 2.5b and position 10 in Fig. 1.39).

From The Automotive Chassis: Engineering Principles, J. Reimpell & H. Stoll, SAE 1996

# FSFV: wheel/hub/brake package

- KPI effects returnability and camber in turn.
- KPI is a result of the choice of ball joint location and the choice of scrub radius.

# FSFV: wheel/hub/brake package

- Scrub radius determines:
  - the sign and magnitude of of the forces in the steering that result from braking.
  - a small negative scrub radius is desired.
- Scrub radius influences brake force steer.

# FSFV: wheel/hub/brake package

- Spindle length determines the magnitude of the forces in the steering that result from:
  - hitting a bump
  - drive forces on front wheel drive vehicles
- Spindle length is a result of the choice of ball joint location and the choice of scrub radius.

# FSFV: wheel/hub/brake package

- Front view instant center is the instantaneous center of rotation of the spindle (knuckle) relative to the body.
- Front view instant center length and height establishes:
  - Instantaneous camber change
  - Roll center height (the instantaneous center of rotation of the body relative to ground)

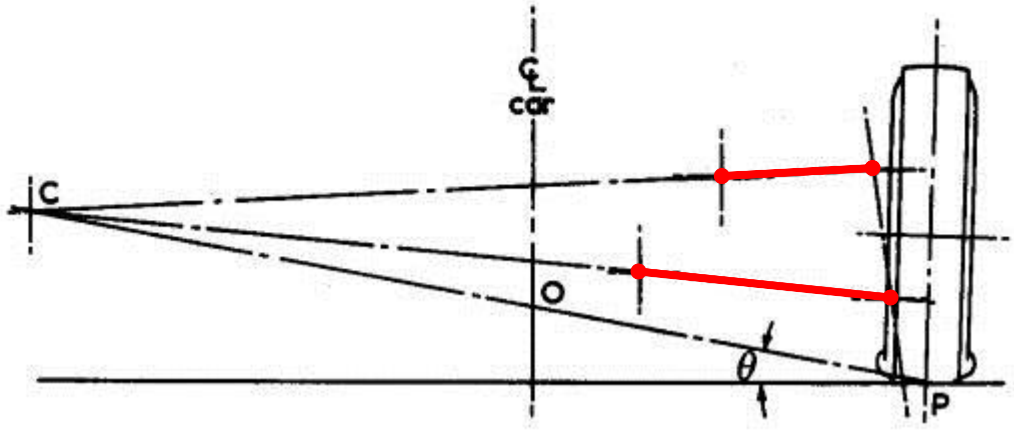



*Fig.* 5·2 The roll centre derivation for a double wishbone suspension, in this case arranged to give some swing axle effect, is shown

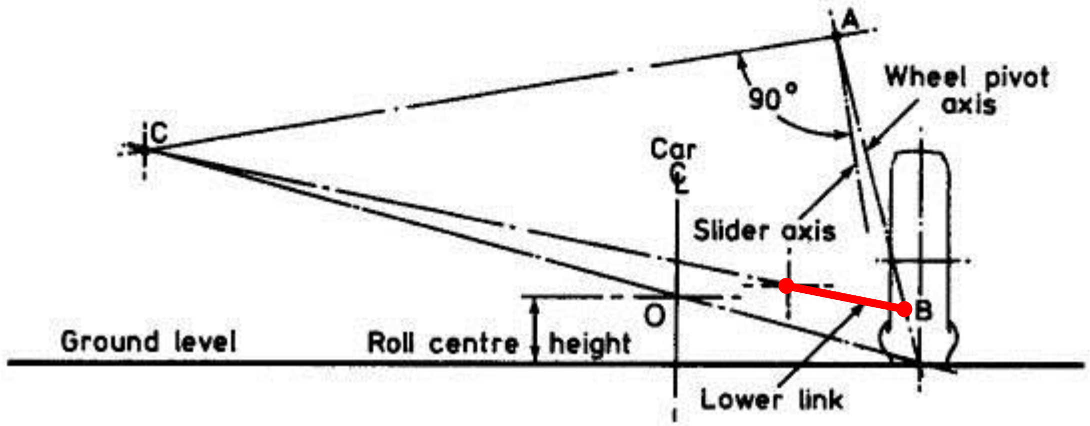



*Fig.* 5·3 The derivation of the roll centre height for a strut and link type suspension is shown. The 'kingpin' axis is defined by the pivot-attachment point of the slider, *A*, and *B*, the outer end of the lower link. The slider axis could, but more often does not, lie along this axis. *C* is the instantaneous centre of the linkage, the intersection point of the perpendicular to the slider axis from its attachment point and the centre line of the lower link continued

From Car Suspension and Handling 3rd Ed, D. Bastow & G. Howard, SAE 1993

# FSFV: wheel/hub/brake package

- The upper control arm length compared to the lower control arm length establishes:
  - Roll center movement relative to the body (vertical and lateral) in both ride and roll.
  - Camber change at higher wheel deflections.

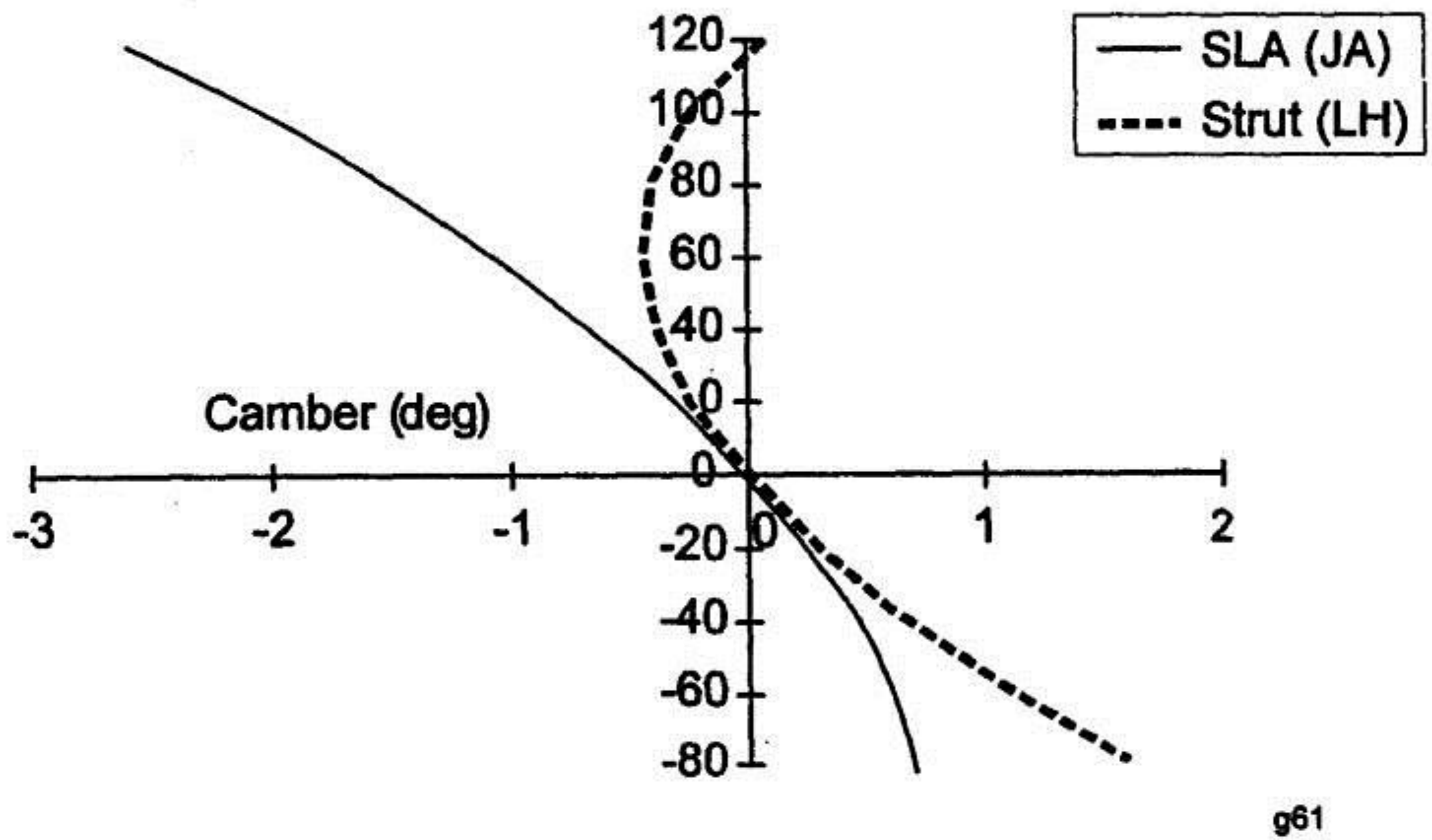



*Figure 64 Camber Patterns Of SLA And Strut Suspensions*

(From Suspension Geometry and Design, John Heimbecher, DaimlerChrysler Corporation)

# FSFV: Roll Center Movement

- Ride and roll motions are coupled when a vehicle has a suspension where the roll center moves laterally when the vehicle rolls.
- The roll center does not move laterally if in ride, the roll center height moves 1 to 1 with ride (with no tire deflection).

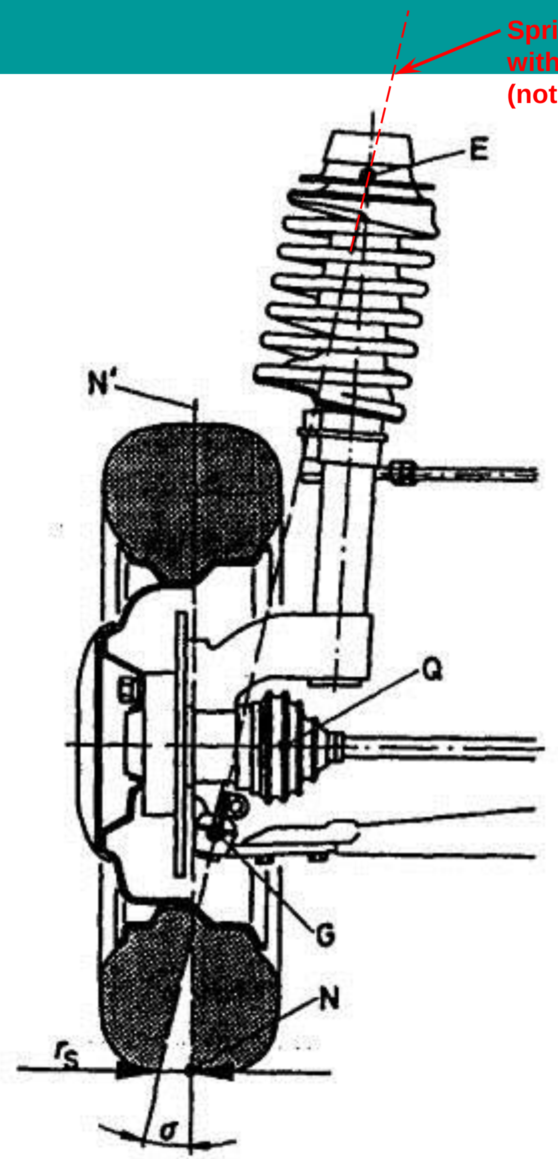
# FSFV: wheel/hub/brake package

- The steering tie rod length and orientation (angle) determines the shape (straight, concave in, concave out) and slope of the ride steer curve.

# FSFV: wheel/hub/brake package

- The spring location on a SLA suspension determines:
  - the magnitude of the force transmitted to the body when a bump is hit (the force to the body is higher than the force to the wheel)
  - the relationship between spring rate and wheel rate (spring rate will be higher than wheel rate)
  - how much spring force induces c/a pivot loads
- An offset spring on a strut can reduce ride friction by counteracting strut bending (Hyperco gimbal-style spring seat).

**Fig. 3.79** Left front axle of an Audi with negative kingpin offset on the ground $r_S$ = −18 mm and an almost vertical damper unit; the spring was angled to reduce the friction between the piston rod and rod guide. For reasons of space, the CV-joint centre Q had to be shifted inwards; the space for snow chains has to be considered (see Fig. 2.5b and position 10 in Fig. 1.39).




From The Automotive Chassis: Engineering Principles, J. Reimpell & H. Stoll, SAE 1996

# Front Suspension Side View

- Picking ball joint location and wheel center location relative to steering axis establishes:
  - Caster
  - Caster trail (Mechanical Trail)

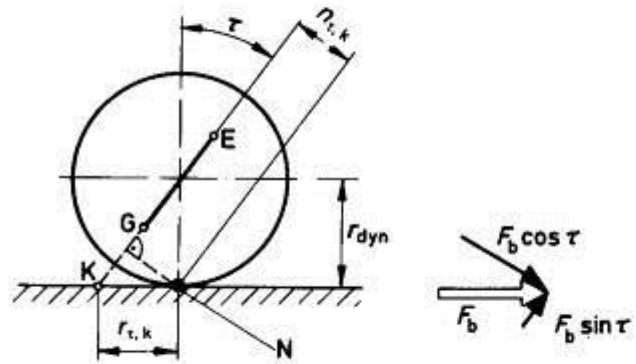



**Fig. 3.88** If the extension of the steering axis goes through the ground at point K in front of the wheel centre, the distance arising is the kinematic caster trail $r_{\tau,k}$ (Case 1). A vertical to $\overline{EG}$, drawn through the centre of tyre contact N, when projected onto the $xz$-plane, gives the lateral force lever $n_{\tau,k}$ (Equation 3.30).

Longitudinal forces which arise, such as the braking force $F_b$ (or the rolling resistance $F_R$), must be resolved at the centre of tyre contact (or as $F3'_R$ in the wheel centre, Fig. 3.86) by the angle $\tau$.

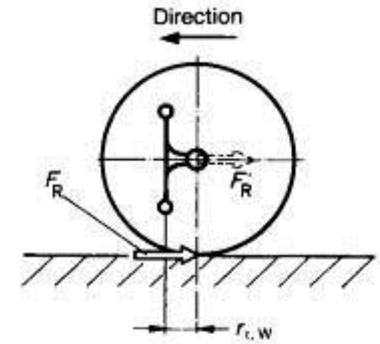



**Fig. 3.89** Caster can also be achieved by shifting the wheel centre behind the steering axis (Case 2); if this is vertical, as shown, the (here) positive caster offset is equal to the lever: $r_{\tau,W} = r_{\tau,k} = +n_{\tau,k}$. Rolling resistance forces $F_R$ acting at the centre of tyre contact must be observed as $F'_R$ in the wheel centre.

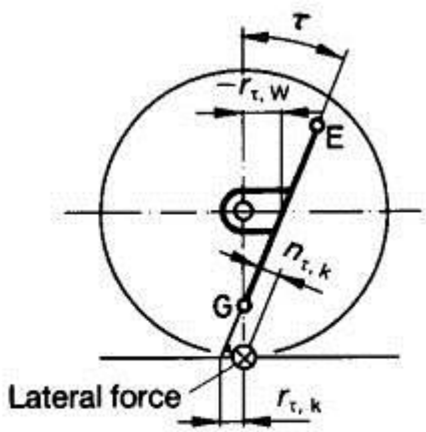



**Fig. 3.91** Front axle properties can be improved by a negative caster offset $r_{\tau,W}$; the caster trail $r_{\tau,k}$ on the ground shortens by this amount and the camber alteration when the wheels are turned becomes more favourable.

From The Automotive Chassis: Engineering Principles, J. Reimpell & H. Stoll, SAE 1996

# Front Suspension Side View

- Picking the side view instant center location establishes:
- Anti-dive (braking)
- Anti-lift (front drive vehicle acceleration)

# Anti Dive/Anti Squat CS Transparency

# Suspension Variations Tranparencies-CS

# Front Suspension Side View

- Anti-dive (braking):
  - Instant center above ground and aft of tire/ground or below ground and forward of tire/ground.
  - Increases effective spring rate when braking.
  - Brake hop if distance from wheel center to instant center is too short.

# Front Suspension Plan View

- Picking steer arm length and tie rod attitude establishes:
  - Ackermann
  - recession steer
  - magnitude of forces transmitted to steering

# Front Suspension: Other Steering Considerations

- KPI and caster determine:
  - Returnability
    - The steering would not return on a vehicle with zero KPI and zero spindle length
  - camber in turn

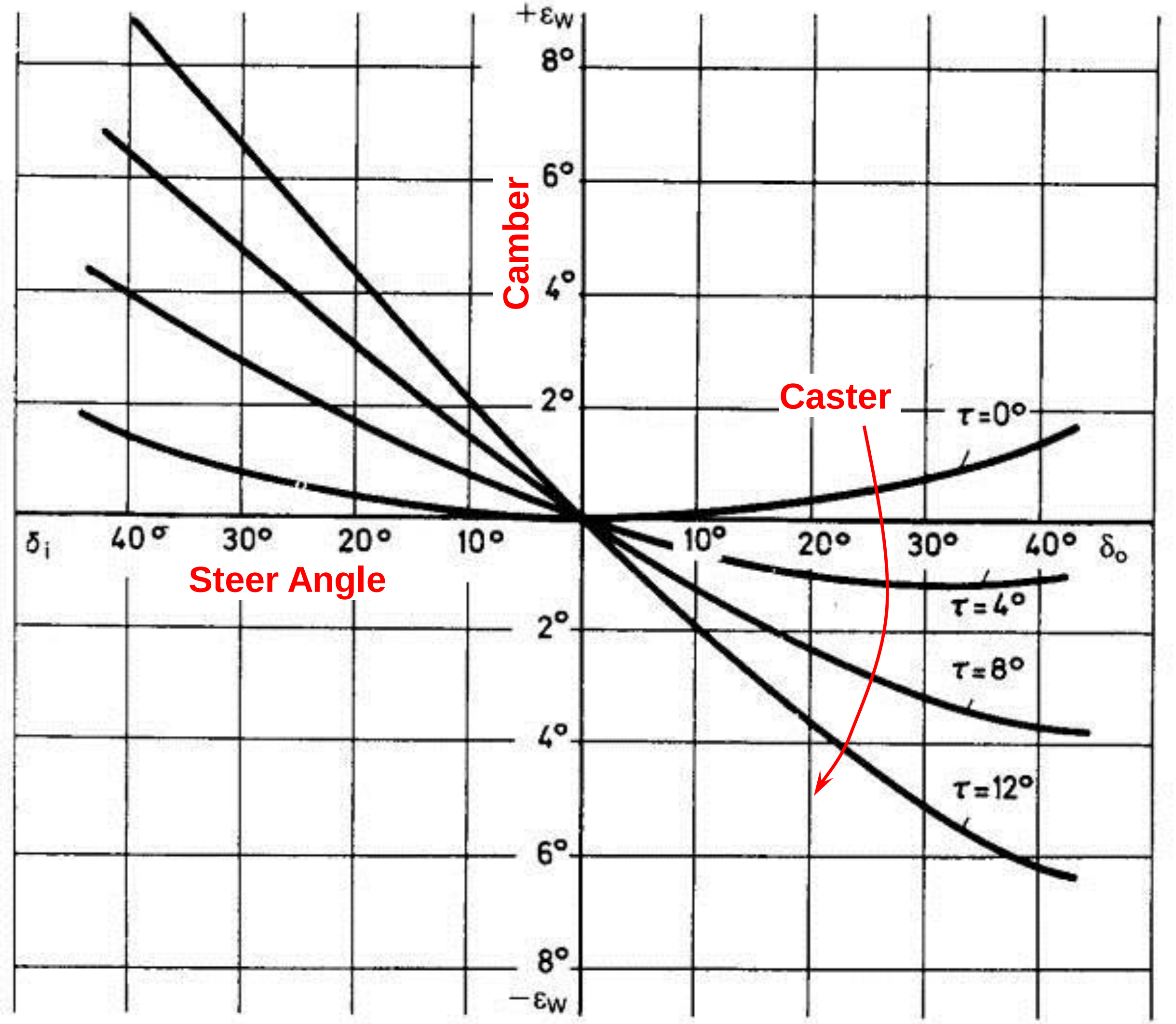



**Fig. 3.102** Camber angle $\epsilon_{W,o}$ and $\epsilon_{W,i}$, as a function of the steering angle $\delta_a$ (outside of bend) and $\delta_i$ (inside of bend). The influence of the various caster angles $\tau$ can be clearly seen. Given was: $\sigma_0 = 6°$ and $\epsilon_{W,0} = 0°$

From The Automotive Chassis: Engineering Principles, J. Reimpell & H. Stoll, SAE 1996

# Front Suspension: Other Steering Considerations

- Caster and Caster Trail establish how forces build in the steering.
  - Caster gives effort as a function of steering wheel angle (Lotus Engineering).
  - Caster Trail gives effort as a function of lateral acceleration (Lotus Engineering).
  - Spindle offset allows picking caster trail independent of caster.

# Rear Suspension Rear View

- Start with tire/wheel/hub/brake rotor/brake caliper package.
  - pick ball joint (outer bushing) location
  - pick rear view instant center length and height.
  - pick control arm length.
  - pick steering tie rod length and orientation.
  - pick spring/damper location.

# RSRV: wheel/hub/brake package

- Ball joint location establishes:
  - Scrub radius: Scrub radius determines the sign and magnitude of of the forces in the steering that result from braking.
  - Spindle length: Spindle length determines the magnitude of the steer forces  that result from hitting a bump and from drive forces. Spindle length is a result of the choice of ball joint (outer bushing) location and the choice of scrub radius.

# RSRV: wheel/hub/brake package

- Rear view instant center length and height establishes:
  - Instantaneous camber change
  - Roll center height

# RSRV: wheel/hub/brake package

- The upper control arm length compared to the lower control arm length establishes:
  - Roll center movement relative to the body (vertical and lateral) in both ride and roll.
  - Camber change at higher wheel deflections.

# RSRV: wheel/hub/brake package

- Some independent rear suspensions have a link that acts like a front suspension steering tie rod. On these suspensions, steering tie rod length and orientation (angle) determines the shape (straight, concave in, concave out) and slope of the ride steer curve.

# RSRV: wheel/hub/brake package

- The spring location on a SLA suspension determines:
  - the magnitude of the force transmitted to the body when a bump is hit (the force to the body is higher than the force to the wheel)
  - the relationship between spring rate and wheel rate (spring rate will be higher than wheel rate)
  - how much spring force induces bushing loads
- An offset spring on a strut can reduce ride friction by counteracting strut bending.

# Rear Suspension Side View

- Picking outer ball joint/bushing location establishes:
  - Caster
  - Negative caster can be used to get lateral force understeer

# Rear Suspension Side View

- Picking side view instant center location establishes:
  - anti-lift (braking)
  - anti-squat (rear wheel vehicle acceleration)

# Rear Suspension Side View

- Anti-lift (braking):
  - Instant center above ground and forward of tire/ground or below ground and aft of tire/ground.
  - Brake hop if distance from wheel center to instant center is too short.

# Rear Suspension Side View

- Anti-squat (rear wheel vehicle acceleration)
- “Cars are like primates. They need to squat to go.”—Carroll Smith
  - – independent
    - wheel center must move aft in jounce
    - instant center above and forward of wheel center or below and aft of wheel center
    - increases effective spring rate when accelerating.
  - – beam
    - instant center above ground and forward of tire/ground or below ground and aft of tire/ground.

# Rear Suspension

- Scrub radius:
  - small negative insures toe-in on braking
- Spindle length:
  - small values help maintain small acceleration steer values

# Rear Suspension

- Camber change:
  - at least the same as the front is desired
  - tire wear is a concern with high values
  - leveling allows higher values

# Rear Suspension

- Roll Center Height:
  - independent
    - avoid rear heights that are much higher than the front, slight roll axis inclination forward is preferred
  - beam axle
    - heights are higher than on independent suspensions no jacking from roll center height with symmetric lateral restraint

# Rear Suspension

- Roll center movement:
  - independent:
    - do not make the rear 1 to 1 if the front is not
  - beam
    - no lateral movement
    - vertical movement most likely not 1 to 1

# Rear Suspension

- Ride steer / roll steer:
  - independent
    - small toe in in jounce preferred
    - consider toe in in both jounce and rebound
      - gives toe in with roll and with load
      - toe in on braking when the rear rises
  - beam
    - increasing roll understeer with load desired
    - 10 percent roll understeer loaded is enough
    - roll oversteer at light load hurts directional stability

# Rear Suspension

- Anti-lift:
  - independent
    - instant center to wheel center at least 1.5 times track (short lengths compromise other geometry) to avoid brake hop

# Dampers- A Really Quick Look

- Purpose of Dampers
- Damper Types and Valving
- Performance Testing
- Development of Dampers

# Introduction

Primary function: dampen the sprung and unsprung motions of the vehicle, through the dissipation of energy.

Can also function as a relative displacement limiter between the body and the wheel, in either compression or extension.  Or as a structural member, strut.

Simple model: force proportional to velocity.

$$\text{Force} = kx + c\dot{x}$$

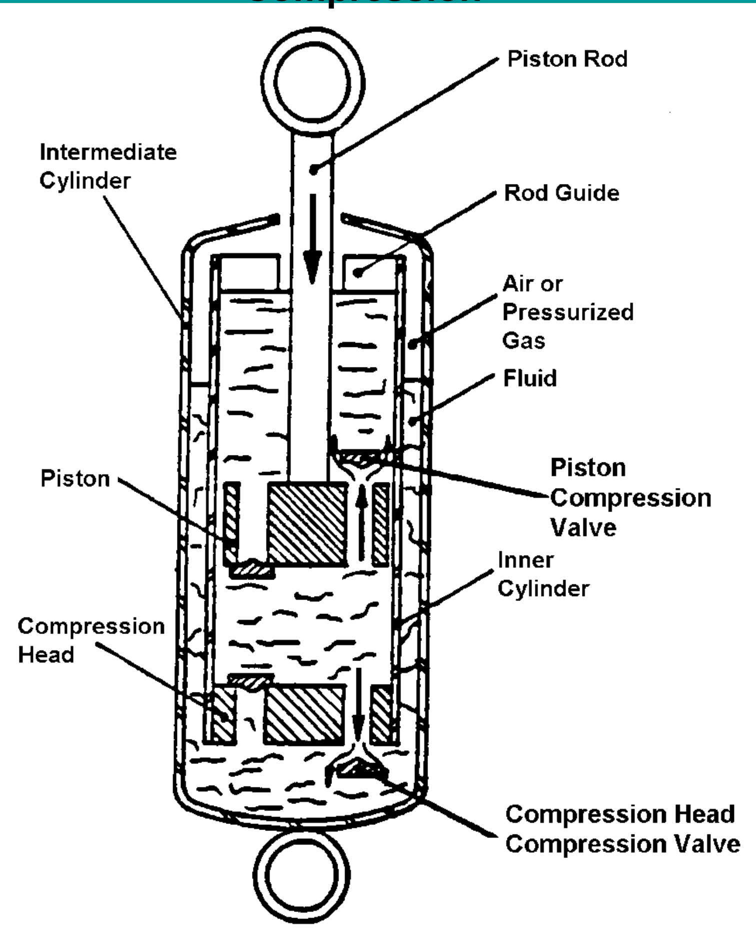
Real World:

- The multi-speed valving characteristics of the damper (low, mid and high relative piston velocity) permit flexibility in tuning the damper.
- Different valving circuits in compression (jounce) and extension (rebound) of the damper permits further flexibility.
- Also generates forces that are a function of position, acceleration and temperature.

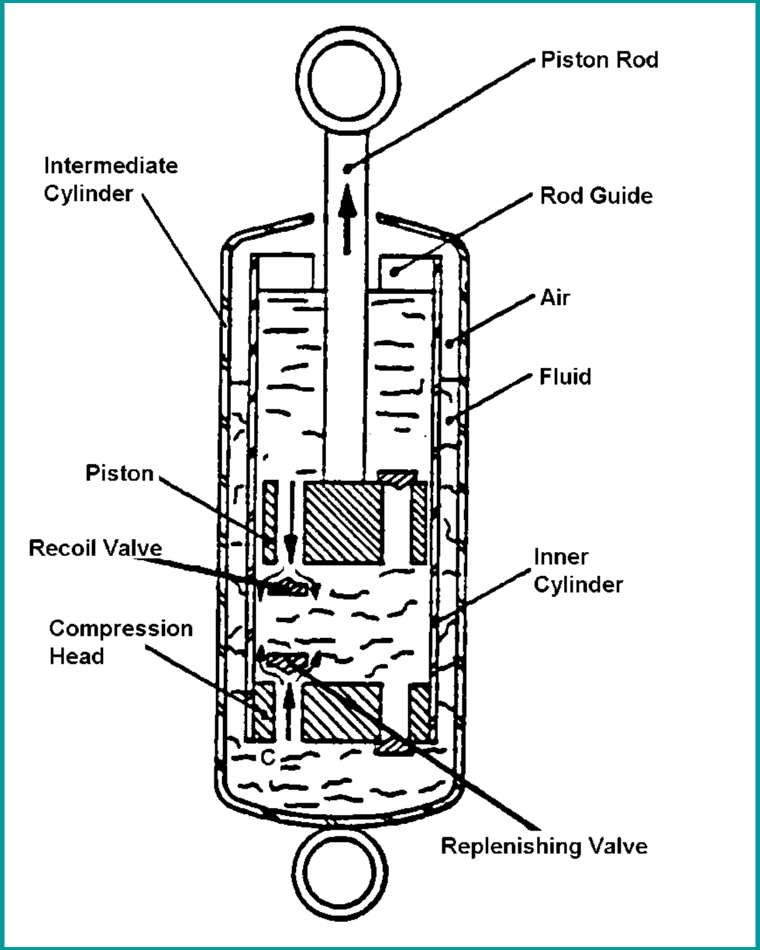
$$\text{Force} = kx + c_1 x + c_2 \dot{x} + c_3 \ddot{x} + c_4 T$$

# Twin Tube Damper

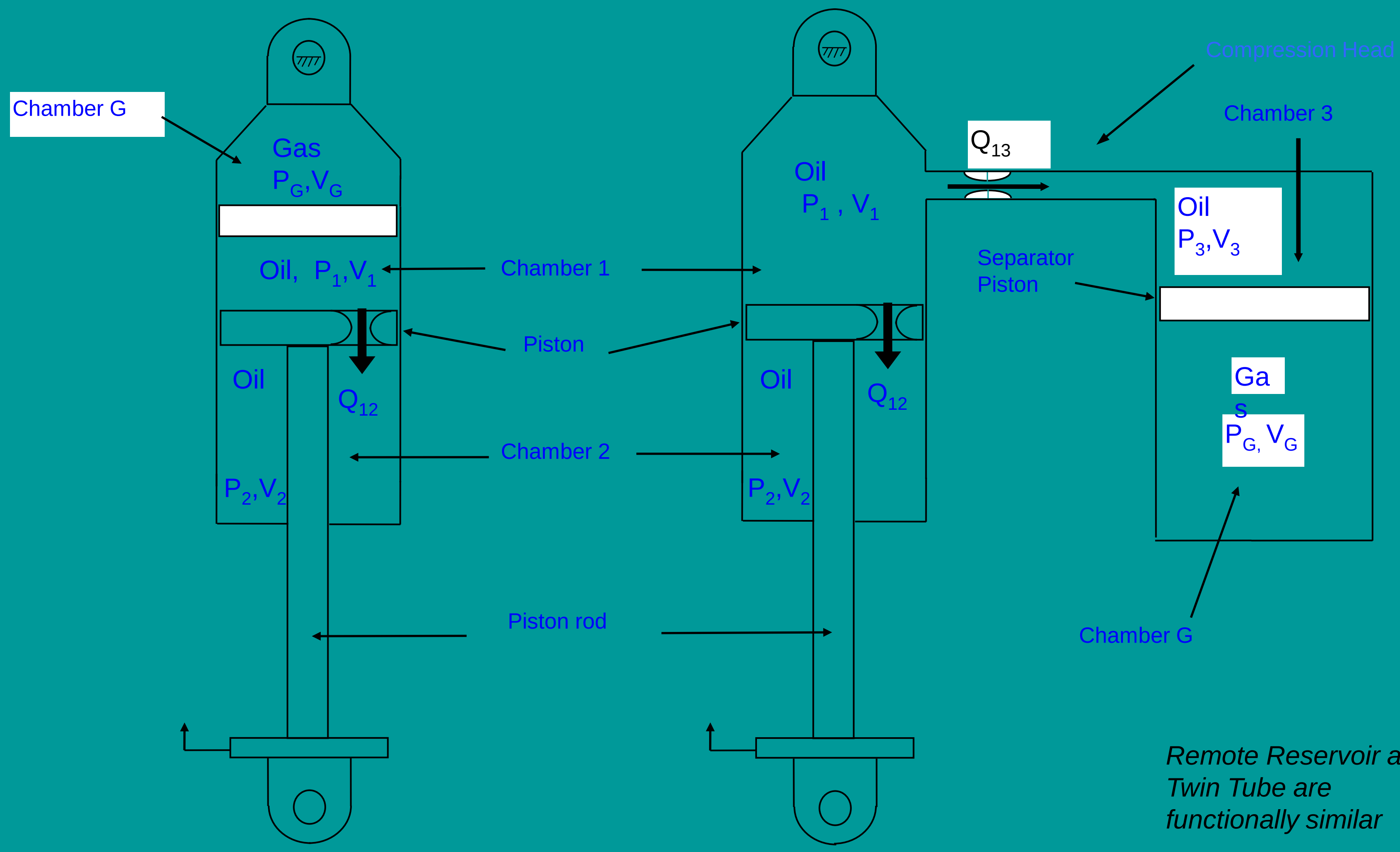
Compression




Rebound



# Monotube Damper Schematics

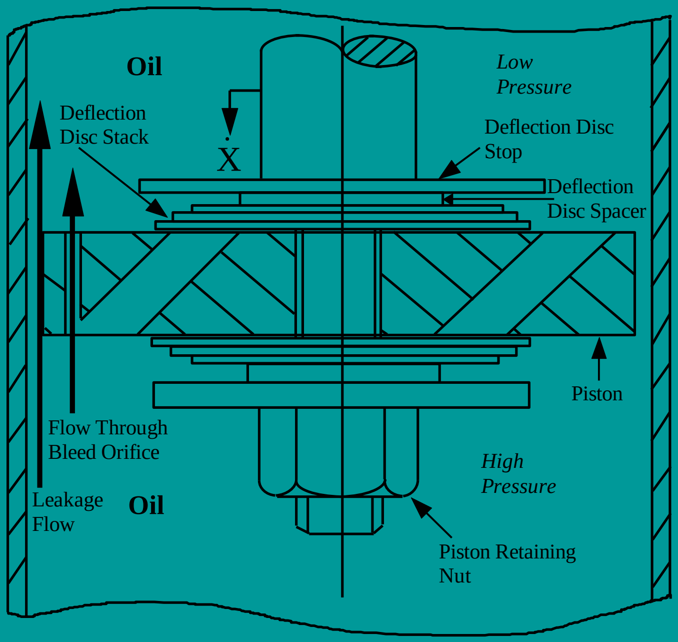



*Remote Reservoir and Twin Tube are functionally similar*

a) Monotube (b) Remote Reservoir

Schematics of monotube and remote reservoir dampers.

# Monotube Low Speed Damping Force




**Schematic of low speed compression valve flow.**

At low speeds, total DAMPER force might be influenced more by friction and gas spring, then damping.

**Low speed flow is normally controlled by an orifice.**

**Types of orifices:**

**•Hole in piston (with or without one way valve)**

**•Notch in disc**

**•Coin land**

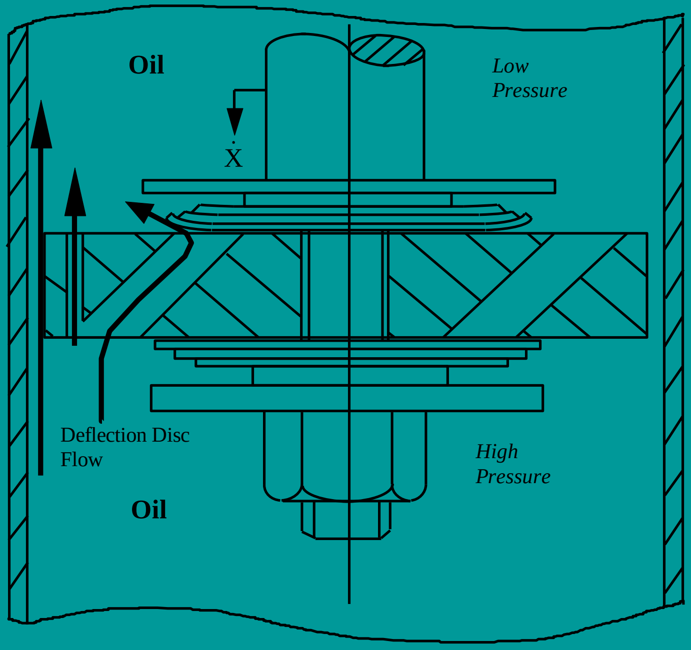
**For turbulent flow:**

$$\Delta P = \left( \frac{Q}{C_d \cdot A_{eff}} \right)^2 \cdot \frac{\rho}{2}$$

**As flow rate Q is equal to relative velocity of the piston times the area of the piston in compression (piston area – rod area in rebound):**

**Orifice damping force is proportional to the square of the piston speed.**

# Monotube Mid Speed Damping Force




Schematic of mid speed compression valve flow.

Mid speed flow is normally controlled by an flow compensating device.

Types of flow compensating devices:

•Deflection Discs ( typically stacked)

•Blow off valve (helical spring)

Preloaded on the valve determines the cracking pressure, and hence the force at which they come into play.  Define the knee in FV curve.

Preload:

•Disc, shape of piston, often expressed in degree.

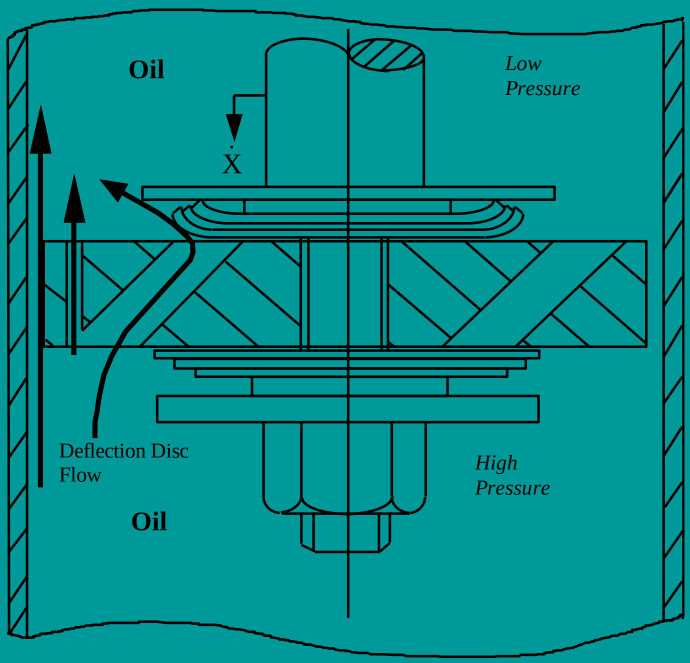
•Disc, spring to preload (sometimes found in adjustable race dampers)

•Spring, amount of initial deflection.

•Torque variation on jam nut can often vary preload. Undesired for production damper,

With flow compensation pressure drop and force are proportional to velocity.

# Monotube High Speed Damping Force




**Schematic of high speed compression valve flow.**

**High speed flow is controlled by restrictions in effective flow area. i.e. effectively orifice flow.**

**Flow restrictions, typically which ever has smaller effective area:**

**•Limit of disc or blow off valve travel.**

**•Orifice size through piston.**

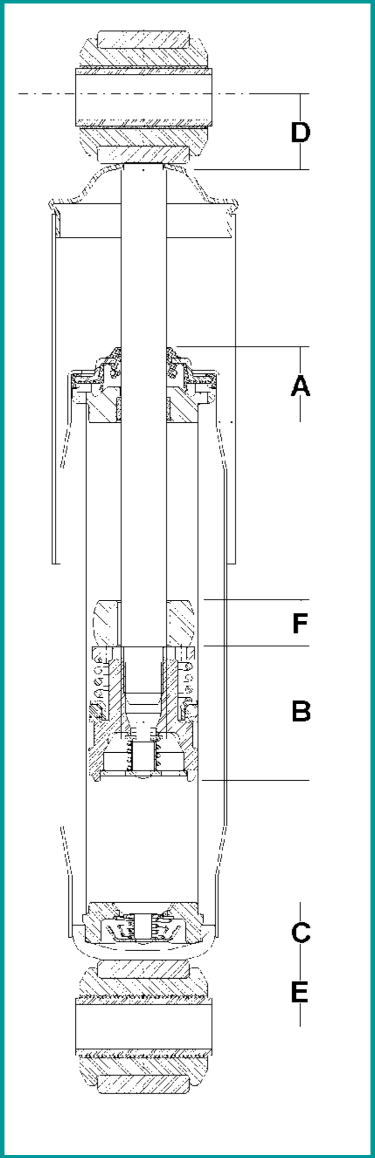
**As per low speed damping, pressure drop and force are proportional to velocity squared.**

**Rebound damping and pressure drops across compression heads (foot valves) are similar to those discussed here.**

# Dead Length

**Dead Length = A + B + C + D + E + F**

**Max Travel = (Extended Length – Dead Length) /2**



# Performance Measurement

**Computer Controlled Servo Hydraulic Shock Dyno**

**Various wave forms can be used to test, sinusoidal, step, triangular, track measurements, etc.**

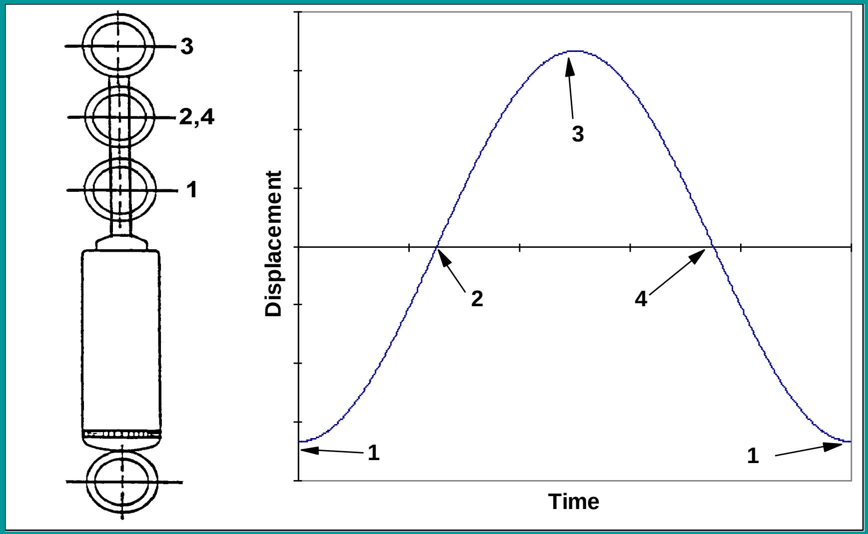
**Data captured for further manipulation.**

**Easy to vary input freq. and amplitude.**

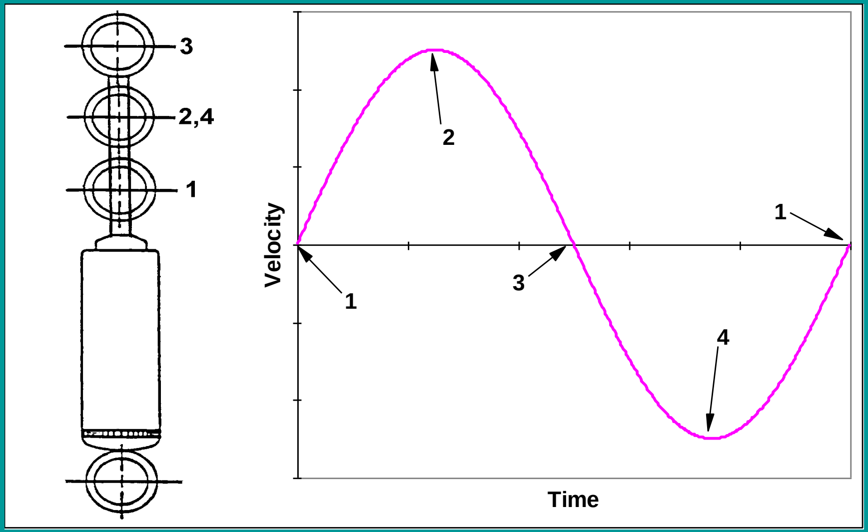
**Offers potential to perform low speed friction and gas spring check, which are removed from the damper forces, to produce damping charts.**

**Need to know which algorithms are used.**

# Sinusoidal Input




Sine Wave Displacement Input




Corresponding Velocity Input

Sinusoid, most Common Input form for Shock Testing

Displacement = X sin ($\omega$t)

Velocity = V = X $\omega$ cos ($\omega$ t)

Where w = 2 * $\pi$ * Freq.

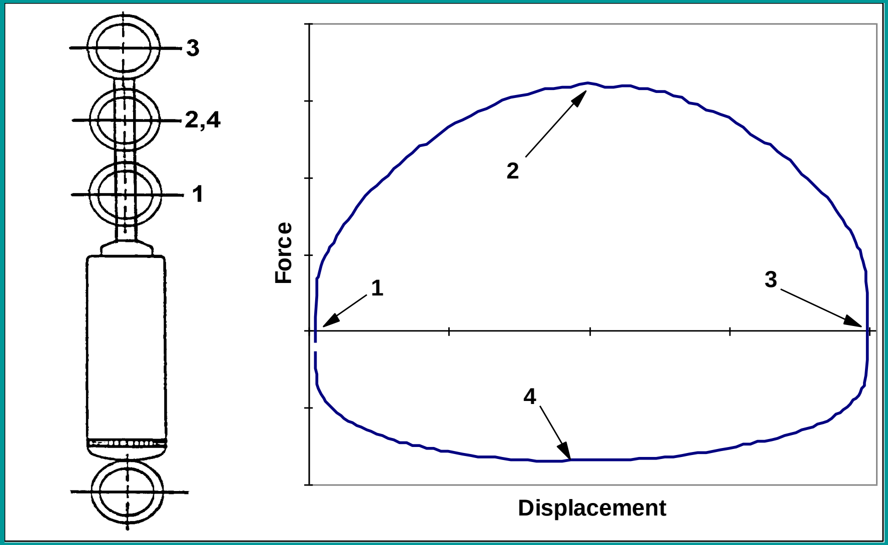
Peak Velocity = X * $\omega$

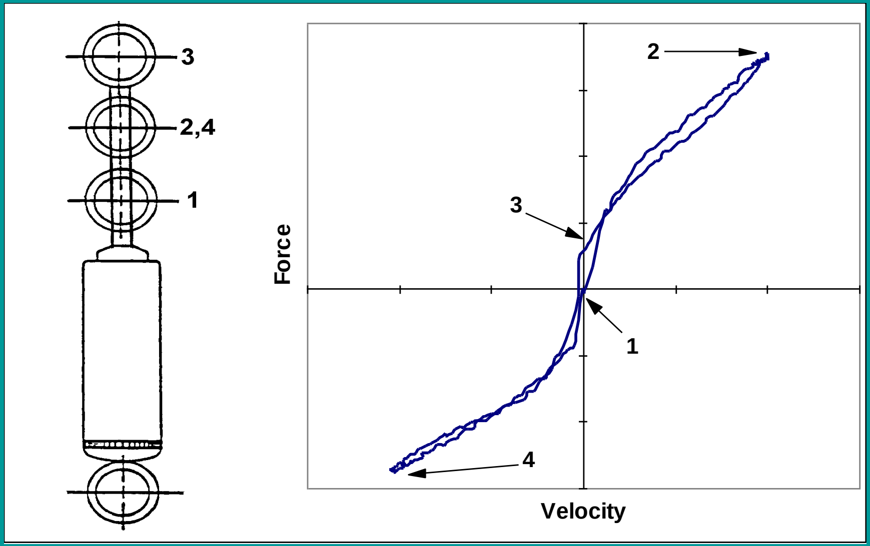
Typically test at a given stroke and vary frequency.

Suspension normally respondes at forcing freq. and natural frequencies.

So should we test at bounce and wheel hop freq.?

# Test Outputs

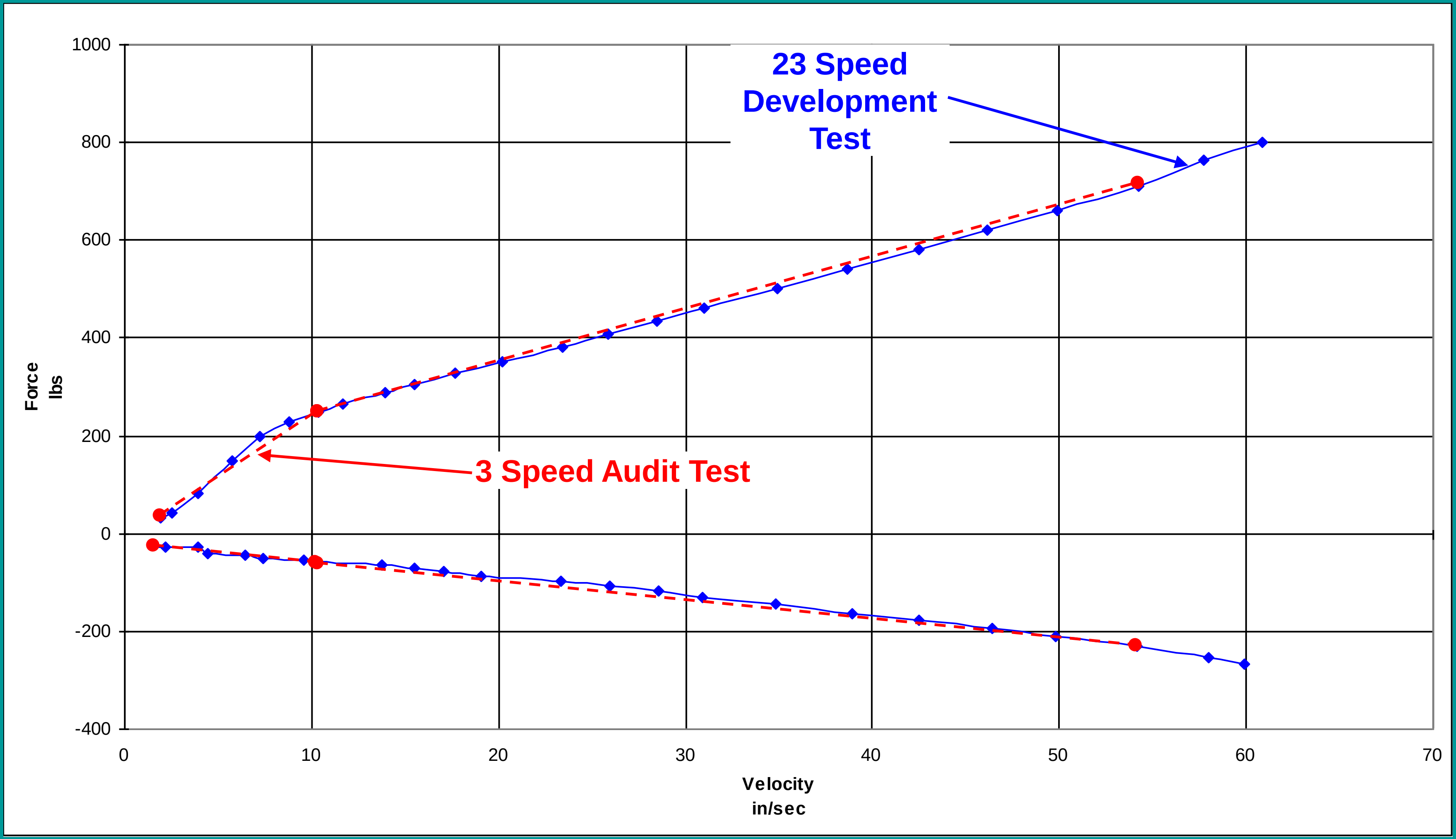



**Force-Displacement Plot**

**Force-Velocity Plot**

# Peak Force - Peak Velocity Plot




**Typical Peak Force - Peak Velocity Plot**

# Monotube vs. Twin Tube

**Advantages / Disadvantages of Twin Tube and Monotube Shock Absorbers**

| | **Twin Tube** | **Monotube** |
|---|---|---|
| Cost | Less | More |
| Weight | More | Less |
| Packaging | Less dead length. Minor external damage OK. Must be mounted upright. | Longer dead length. Minor external damage can cause failure. Can be mounted in any position |
| Rod Reaction Force | Low | High |
| Sealing Requirements | Moderate | High |
| Fade Performance | Moderate | Better |

Twin tube has greater sensitivity to compressibility and hence acceleration.