Vehicle Primary Ride Dynamics
Part 2: Simulation and Test

Tim Drotar (TD)

About the author

Tim Drotar is currently a lead engineer in advanced vehicle dynamics at Stellantis. Previously, he spent 30 years at Ford Motor Company where he specialized in chassis systems and vehicle dynamics for passenger cars and light trucks. Tim is a member of SAE, SCCA and The Tire Society. He holds a B.S. in Mechanical Engineering from Lawrence Technological University and a M.S. in Mechanical Engineering from the University of Michigan-Dearborn.

Tim also teaches the following classes for SAE:

- Advanced Vehicle Dynamics for Passenger Cars and Light Trucks
  - https://www.sae.org/learn/content/c0415/
- Fundamentals of Steering Systems
  - https://www.sae.org/learn/content/c0716/

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Outline

- Learning Objectives
- References
- (Re-) Introduction to Primary Ride
- Physical Measurement of Primary Ride
- Simulation of Primary Ride
- Parameters Affecting Primary Ride Performance
- Maurice Olley and Guidelines for Primary Ride
- Summary

Learning Objectives

At the end of this presentation, you should be able to:

- Distinguish between primary and secondary ride
- Specify physical measurement of primary ride
- Calculate common primary ride metrics
- Identify chassis parameters that influence primary ride performance
- Quote the works of Maurice Olley
- Apply CAE to the evaluation of primary ride performance

References

These notes were created from several sources, including:

Mola, Simone. Chassis Design – ME421 Class notes. Flint MI: General Motors Institute, 1991.

Milliken, William and Milliken, Douglas, Chassis Design: Principles and Analysis. Warrendale, PA: Society of Automotive Engineers, 2002.

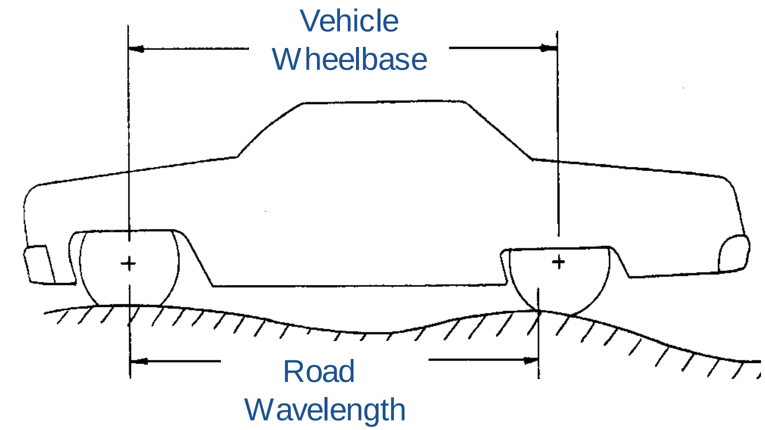
Gillespie, Thomas. Fundamentals of Vehicle Dynamics. Warrendale, PA: Society of Automotive Engineers, 1992.

Olley, Maurice. Independent Wheel Suspension – Its Whys and Wherefores. Detroit, MI: Society of Automotive Engineers, 1934

What is the ride attribute?

Characterize the vehicle body and occupant displacement, velocity and acceleration while driving on different road surfaces

Primary Ride pertains to the rigid body motion of the vehicle sprung mass. Motions considered to be primary ride are bounce, pitch and roll. The frequency range of interest is quite low (approx. 0-5 Hz) and the displacements are relatively large, on the order of *inches*.



Secondary Ride pertains to higher frequency and smaller amplitude displacement of the body and chassis. The frequency range of interest is approx. 5-100 Hz for tactile and above 500 Hz for audible. Displacements are relatively small, on the order of *millimeters*

Belgium Block Road – Ford Lommel Proving Grounds

Physical Measurement of Primary Ride

A vehicle dynamics engineer may use road and and/or lab testing to evaluate the primary ride behavior of a vehicle

<u>For on-road vehicle test</u>, the development engineer will use public or special “ride roads” to evaluate primary ride performance. These roads include sine wave of varying wavelength and amplitude, with left and right side in phase (for bounce/pitch) or out of phase (for roll).

Physical Measurement of Primary Ride

<u>In the lab</u>, a test fixture called a "Four Post Simulator" can be used to apply motions to the four tire contact patches according to a prescribed displacement - time schedule. The resulting response of the vehicle body is measured using the same instrumentation as was used in road testing. The addition of vertical accelerometers to the actuator platform allows for calculation of transmissibility between the road and body.

Figure 1. Utility Vehicle on 4-Post Machine

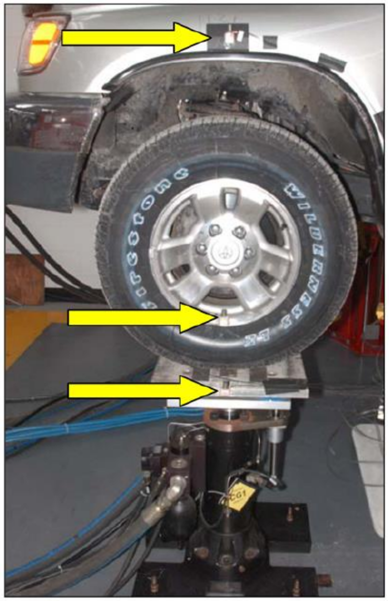


Figure 2. Placement of accelerometers

Duran, Amanda; Carr, Lee; Liebbe, Robert. **<u>Evaluation of Suspension Characteristics in Response to Cyclical Vertical Accelerations</u>**. SAE paper 2010-01-0106. Warrendale, PA: Society of Automotive Engineers, 2010.

https://youtu.be/8XsvGpjaUrw

Physical Measurement of Primary Ride

The same transducers as used in the four post simulator test will be used for the on road test.

- Front seat track rear inner vertical acceleration (bounce metrics)
- Roof longitudinal acceleration (pitch metrics)
- Roof lateral acceleration (roll metrics)
- Left front and rear fender vertical acceleration (front and rear bounce metrics)

Some Typical Primary Ride Metrics

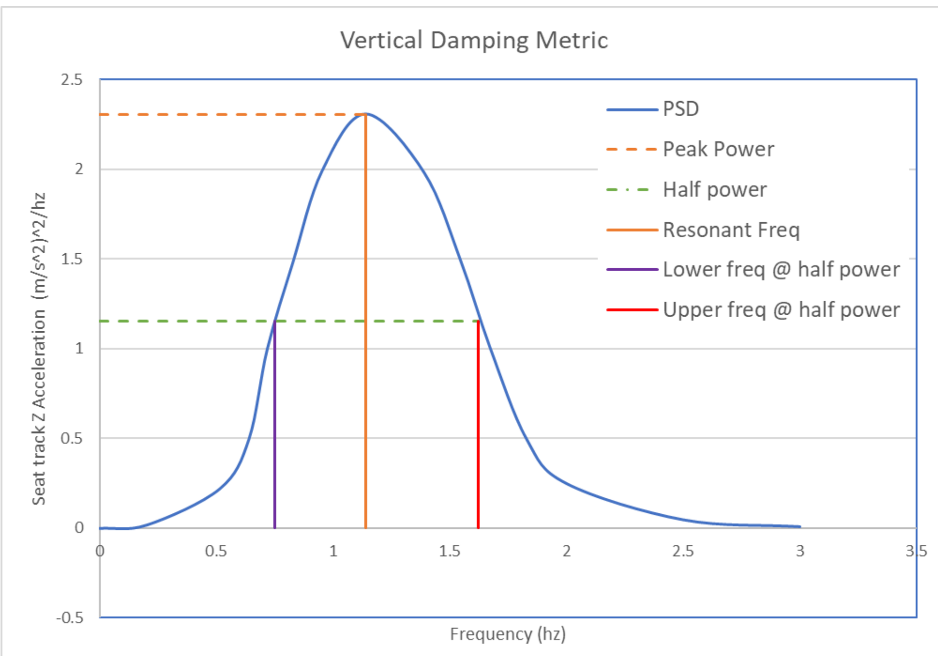
Primary Ride Damping

Metric: Half power bandwidth from PSD of vertical acceleration at the driver

$$Damping = \frac{f_u - f_l}{2f_p}$$

A Power Spectral Density (PSD) is:
- the measure of signal's power content versus frequency.
- typically used to characterize broadband random signals

Channels: Vertical acceleration from accelerometer on rear of driver inner seat track



Interpretation:
- The larger the number, the more damped the ride is perceived to be
- May be affected by front-rear balance since the measurement is taken at the drivers' seat rail
- Related to VDR metric for "Bounce Displacement"

Typical Values (Midsize SUV): 0.3-0.4

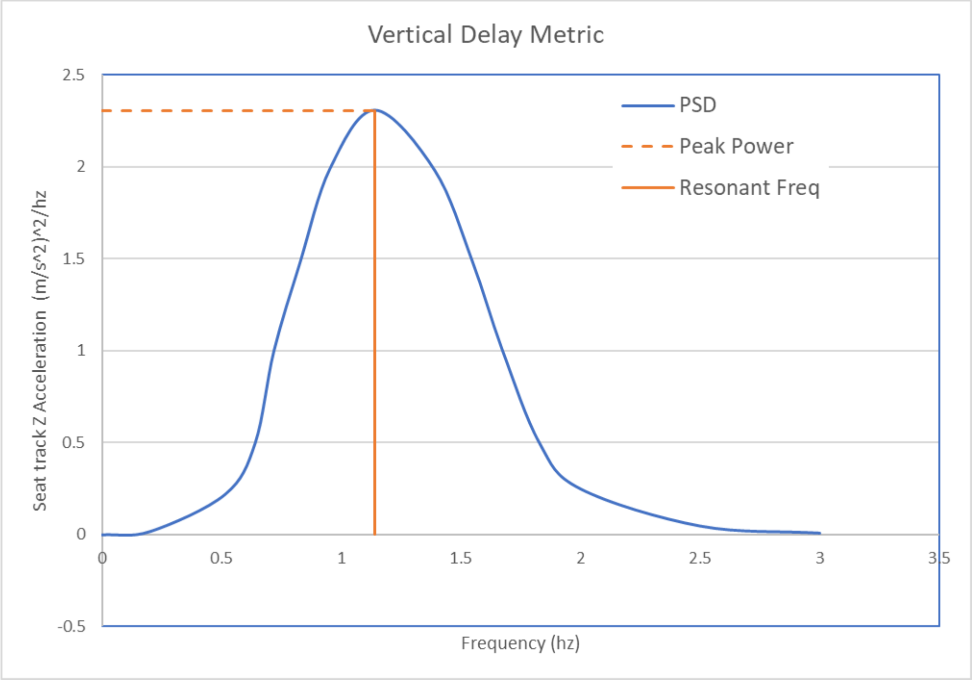
Reference:
Casiano, M. J. Extracting Damping Ratio From Dynamic Data and Numerical Solutions, NASA/TM 2016–218227, Huntsville AL., 2016

Primary Ride Delay

Metric: Frequency weighted peak amplitude of PSD of vertical acceleration at the driver

$$Delay = PSD_{peak} * \left(\frac{W}{f_p}\right)^2 \quad where\ W = correlation\ weighting\ factor$$

Channels: Vertical acceleration from accelerometer on rear of driver inner seat track



Interpretation:

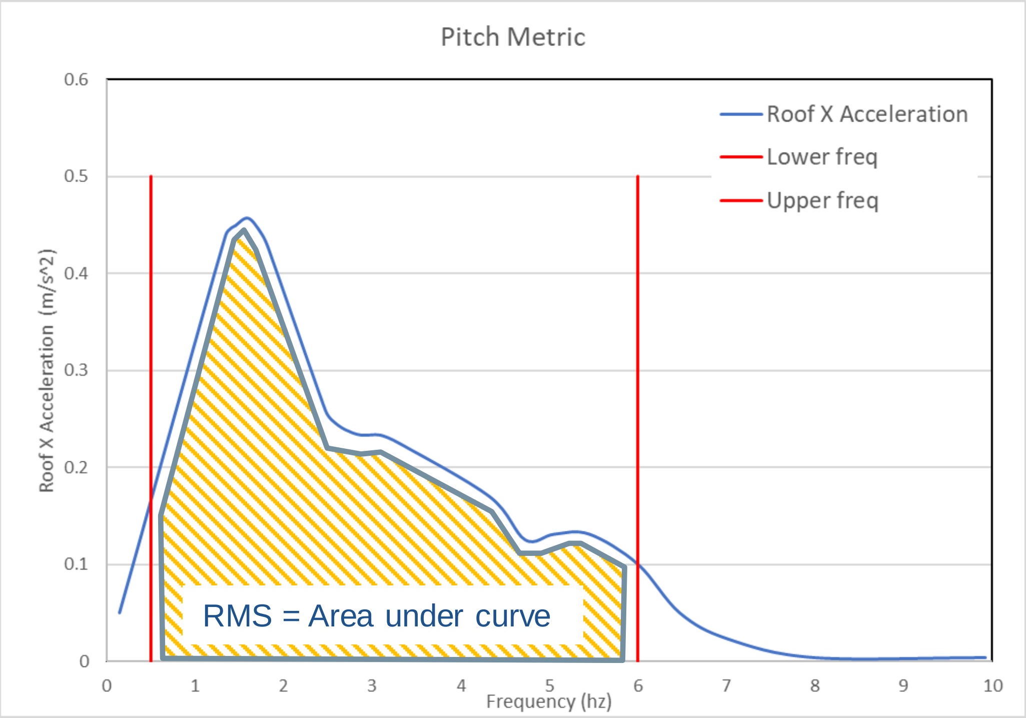
- The larger the number, the more delay is perceived.
- May be affected by front-rear balance since the measurement is taken at the drivers' seat rail
- Related to VDR metric “Float”

Typical Values (Mid-size SUV): 1-2

Pitch Control

Metric: Total RMS roof longitudinal acceleration

Channels: Longitudinal acceleration from roof mounted accelerometer



Interpretation:

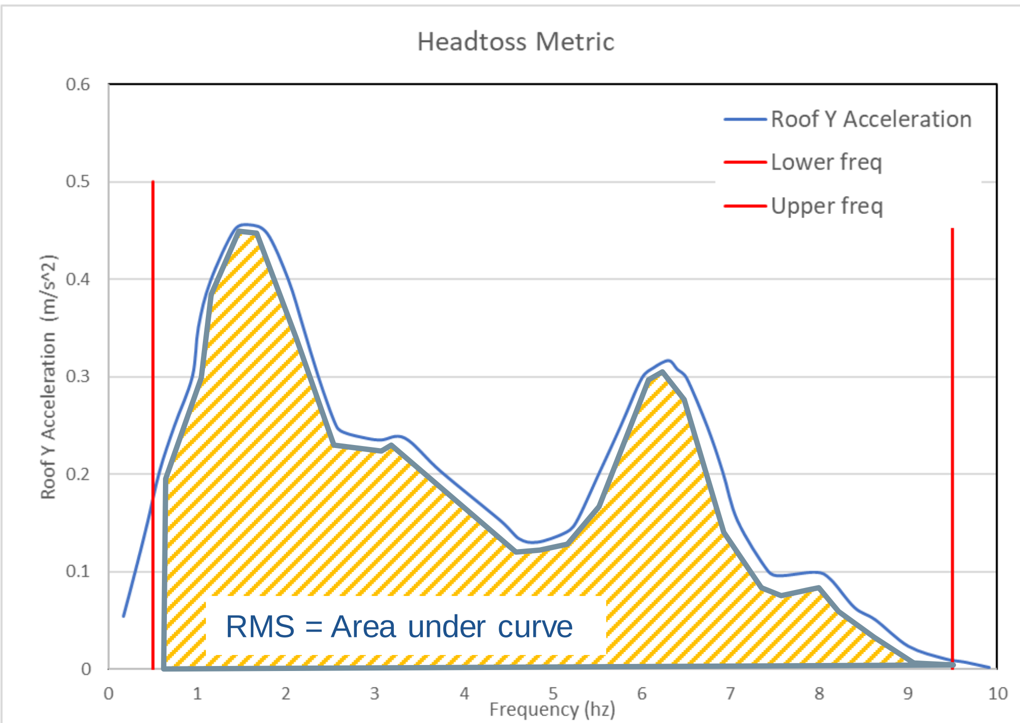
- The larger the number, the more pitch is perceived.
- Related to VDR metric "Pitch Balance"

Typical Values (Mid-size SUV): 0.7-0.9

Some Typical Primary Ride Metrics

<u>Headtoss</u>
Metric: Total RMS roof lateral acceleration

Channels: Lateral acceleration from roof mounted accelerometer



Interpretation:
- The larger the number, the more headtoss is perceived.
- Related to VDR metric "Headtoss"

Typical Values (Mid-size SUV): 1.0-1.3

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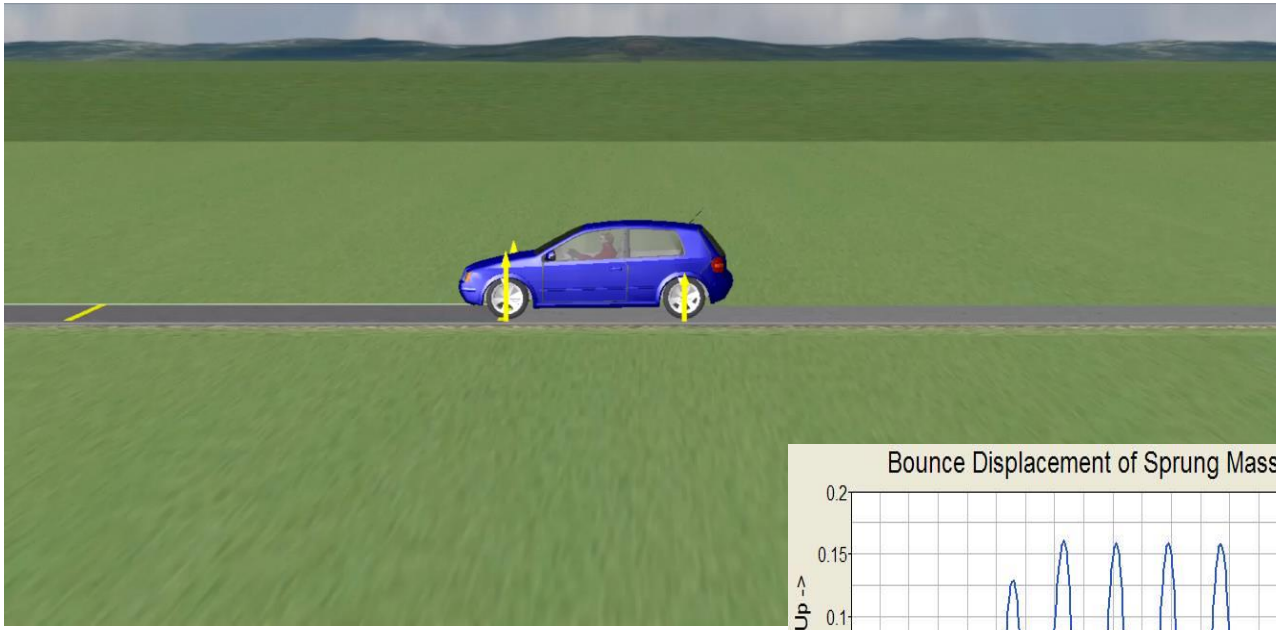
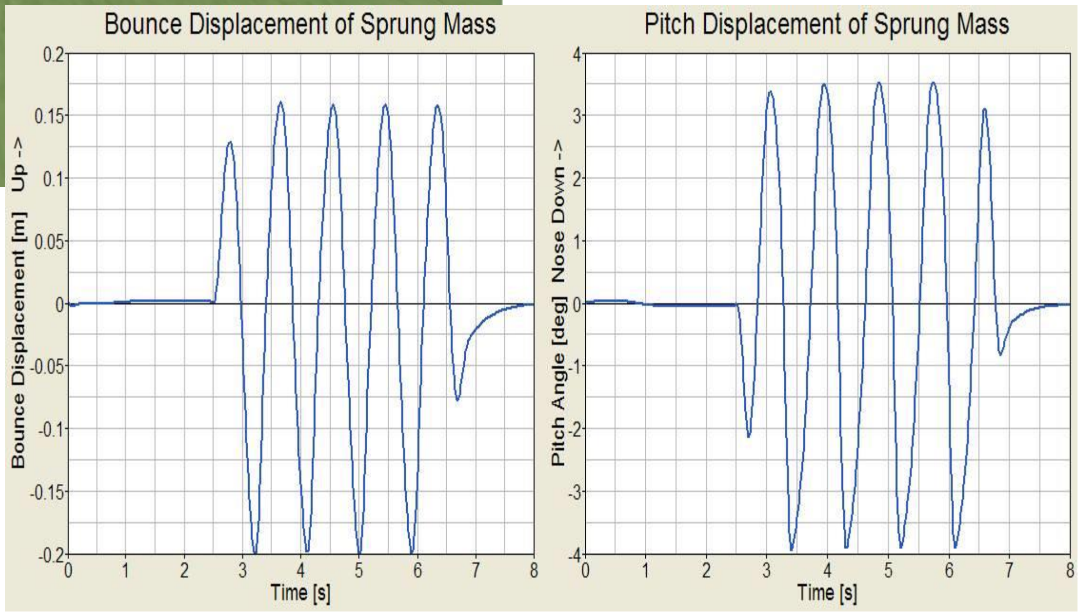
CarSim primary ride simulation of C-class hatchback



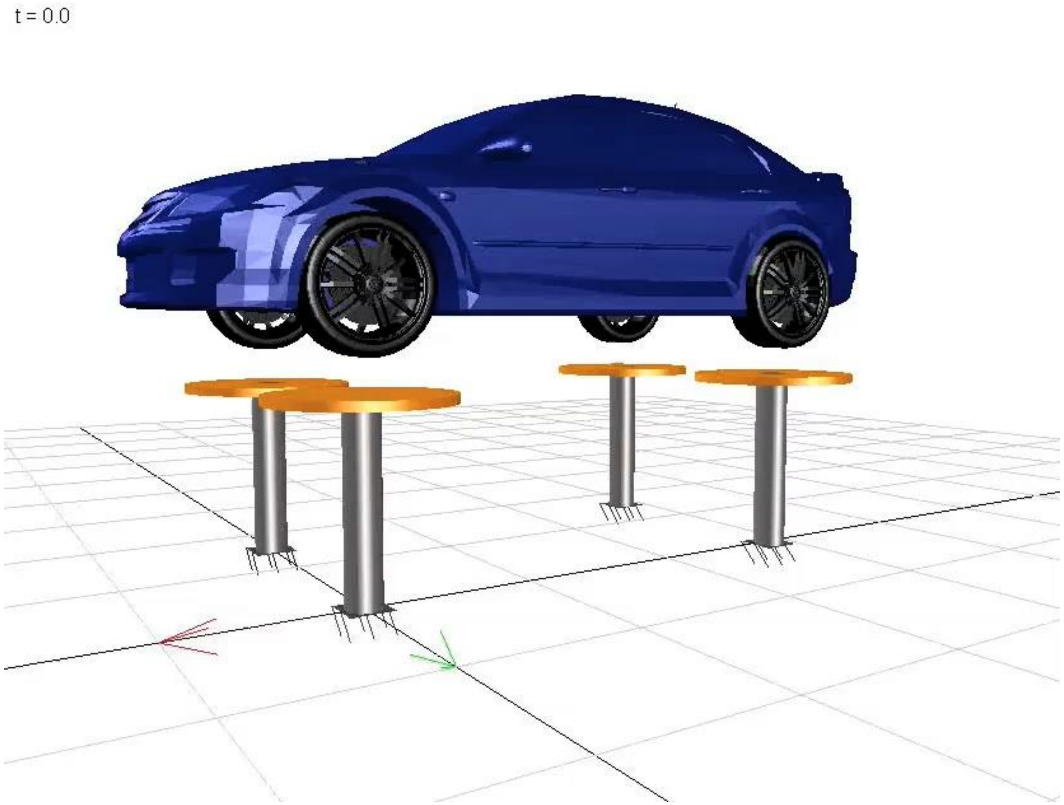
<- Simulation

Sprung mass response ->



Simulation of Primary Ride – 4 Post Test

4-post shaker simulation created in MapleSim



https://www.maplesoft.com/products/maplesim/modelgallery/detail.aspx?id=59

Parameters Affecting Primary Ride Performance

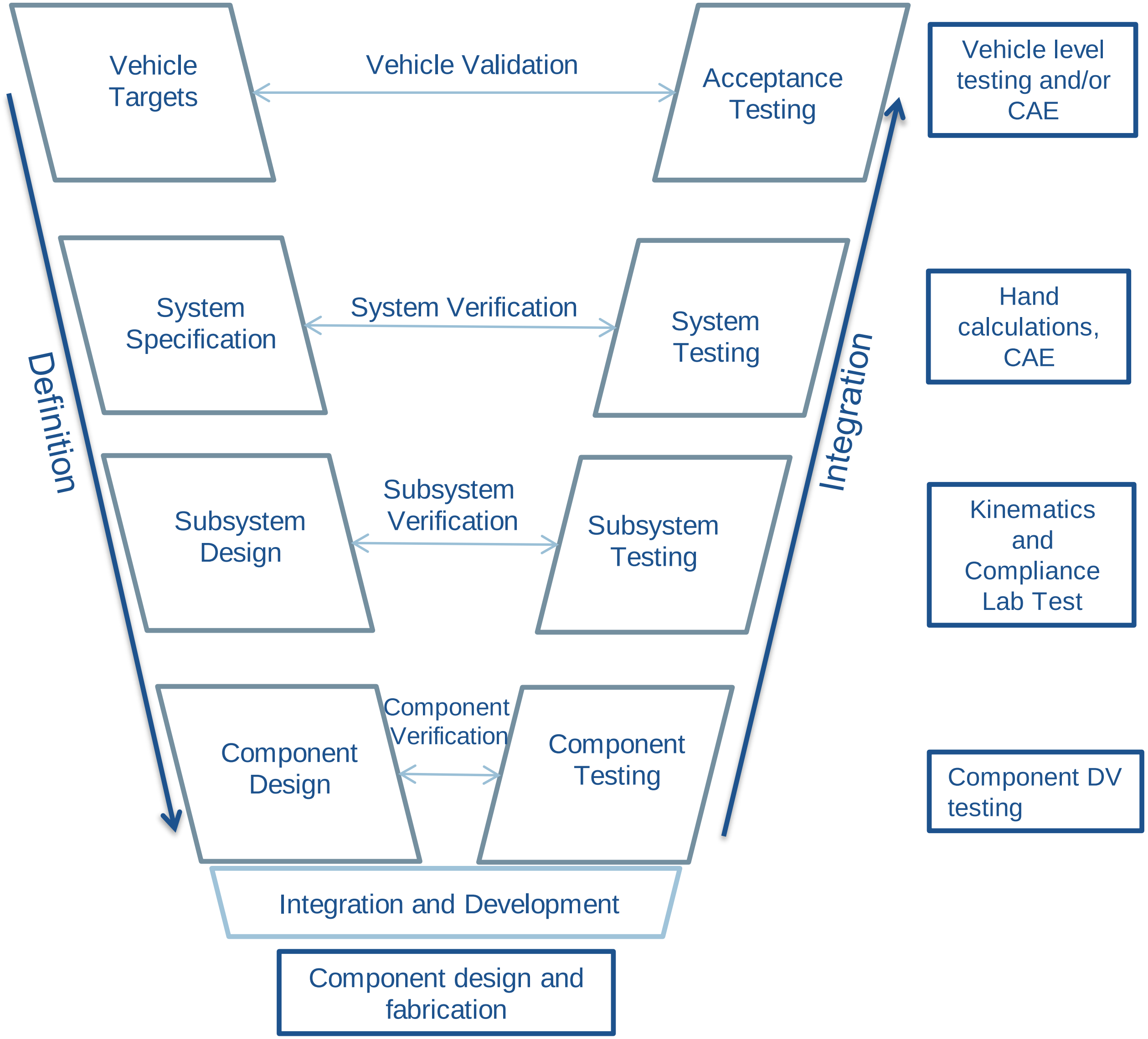
Vehicle Targets:
- Primary ride damping
- Primary ride delay
- Pitch Control
- Headtoss

Chassis System Targets:
- F/R ride nat. frequencies, ride freq.ratio
- Pitch/Bounce nat. frequency ratio
- Pitch/Bounce node locations
- Wheelhop nat. frequency
- …

Suspension Subsystem Targets:
- F/R ride rates
- F/R suspension rates
- F/R suspension parasitic rate
- F/R spring motion ratio
- F/R damping at the wheel
- F/R damper motion ratio
- …

Component Design Specifications
- Suspension hardpoints (xyz)
- Suspension spring stiffness
- Bushing torsional stiffness
- Damper friction
- Shock absorber F/V setting
- …

Constraints: Weight, weight distribution, roll/pitch inertia, wheelbase, unsprung mass



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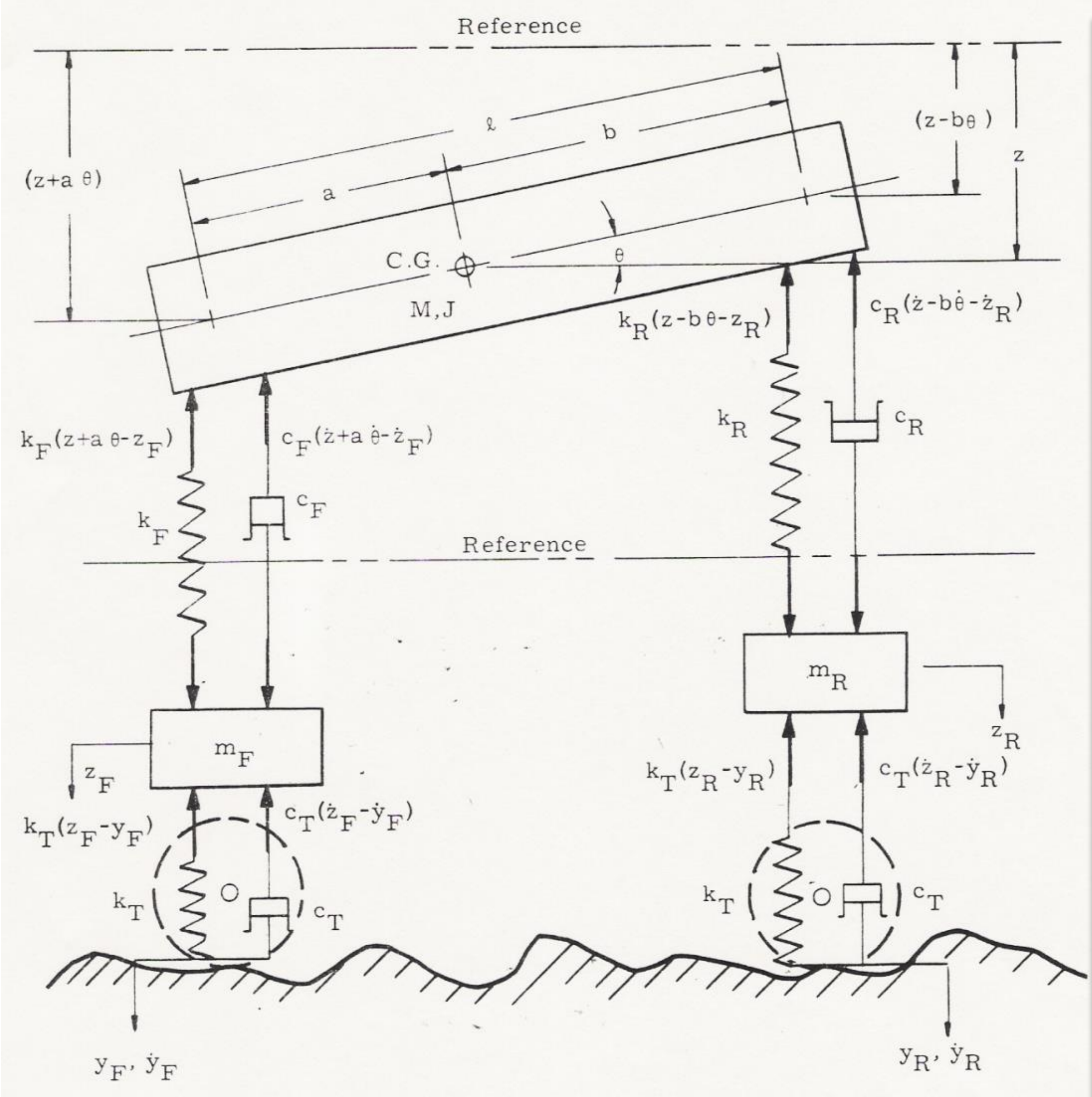
The 4-DOF Primary Ride Model



(1) The terms 'spring rate' and 'spring stiffness' are synonymous

M (kg) = Sprung mass

J (kg-m^2) = Sprung mass inertia

a, b (m) = Distance from sprung mass Cg to front, rear axle

l (m) = Wheelbase

θ (rad) = Pitch angle

z (m) = Vertical displacement of sprung mass

k_F, k_R (N/m) = 2x front, rear suspension rate[1] at the wheel

c_F, c_R (N-s/m) = 2x front, rear suspension damping at the wheel

m_F, m_R (kg) = Unsprung mass

z_F, z_R (m) = Vertical Displacement of unsprung mass

k_T (N/m) = 2x tire rate[1]

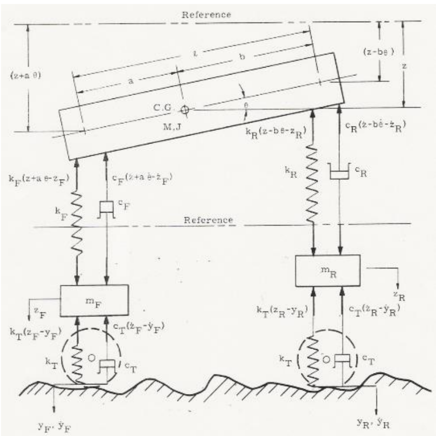
c_T (N-s/m) = 2x tire damping

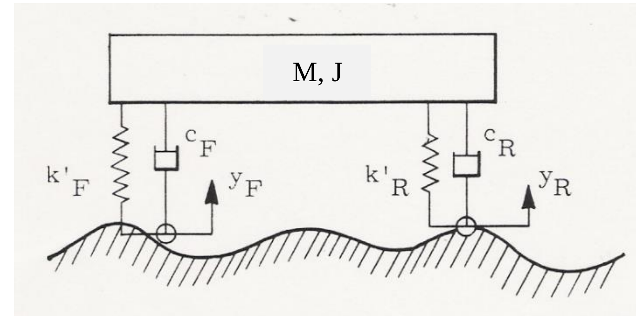
y_F, y_R (m) = Vertical road input displacement

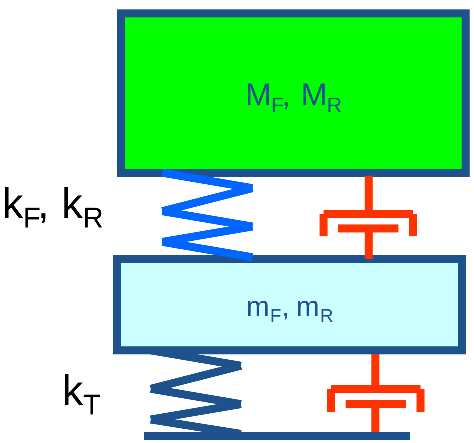
$\dot{y}_F, \dot{y}_R$ (m/s) = Vertical road input velocity

2-DOF Primary Ride Model

Taking the suspension rates[1] k_F, k_R in series with the tire rate, k_T, give us the ride rates, k'_F, k'_R







$$\frac{1}{k_F'} = \frac{1}{k_F} + \frac{1}{k_T}$$

$$k_F' = \frac{k_F k_T}{k_F + k_T}$$

$$k_R' = \frac{k_R k_T}{k_R + k_T}$$

M (kg) = Sprung mass

J (kg-m^2) = Sprung mass inertia

a, b (m) = Distance from sprung mass Cg to front, rear axle

l (m) = Wheelbase

θ (rad) = Pitch angle of sprung mass

z (m) = Vertical displacement of sprung mass

k'_F, k'_R (N/m) = 2x front, rear ride rate

c_F, c_R (N-s/m) = 2x front, rear suspension damping at the wheel

m_F, m_R (kg) = Unsprung mass

y_F, y_R (m) = Vertical road input displacement

(1) The terms 'spring rate' and 'spring stiffness' are synonymous

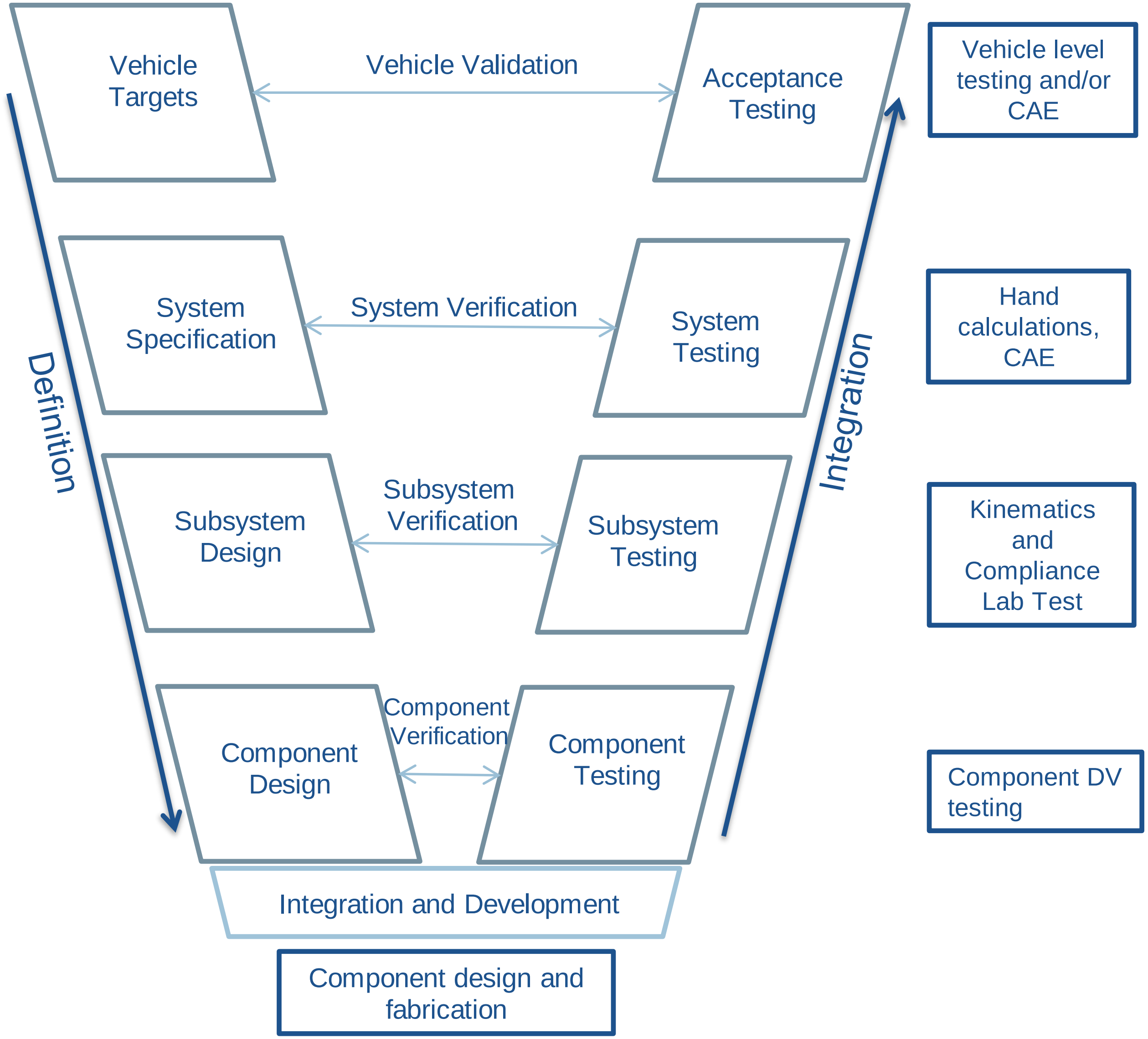
Parameters Affecting Primary Ride Performance

Vehicle Targets:
- Primary ride damping
- Primary ride delay
- Pitch Control
- Headtoss

Chassis System Targets:
- F/R ride nat. frequencies, ride freq.ratio
- Pitch/Bounce nat. frequency ratio
- Pitch/Bounce node locations
- Wheelhop nat. frequency
- …

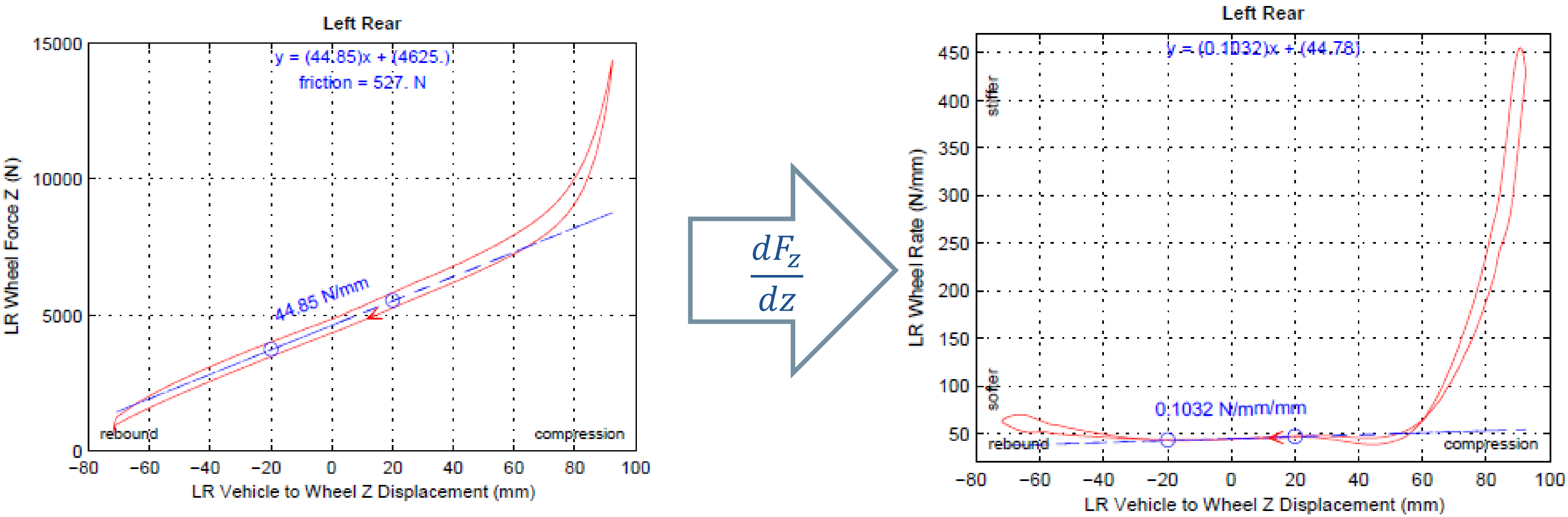
Suspension Subsystem Targets:
- F/R ride rates
- **F/R suspension rates**
- **F/R suspension parasitic rate**
- **F/R spring motion ratio**
- F/R critical damping at the wheel
- F/R damper motion ratio
- …

Component Design Specifications
- Suspension hardpoints (xyz)
- Suspension spring stiffness
- Bushing torsional stiffness
- Damper friction
- Shock absorber F/V setting
- …



Constraints: Weight, weight distribution, roll/pitch inertia, wheelbase, unsprung mass

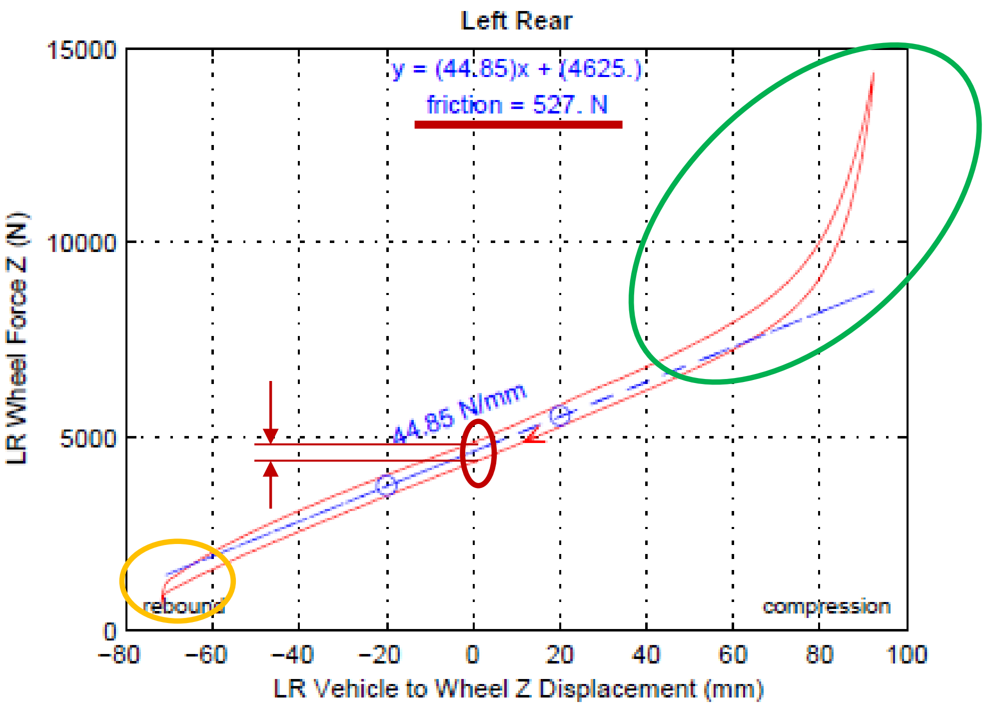
If we have vertical wheel force – vertical wheel displacement data from a kinematics and compliance (K&C) test (M3 SOP-2 shown), we can get the suspension rate (k_f or k_r) as a function of vertical wheel displacement



For this example the rear suspension linear rate is 44.85 N/mm

Parameters Affecting Suspension Rate

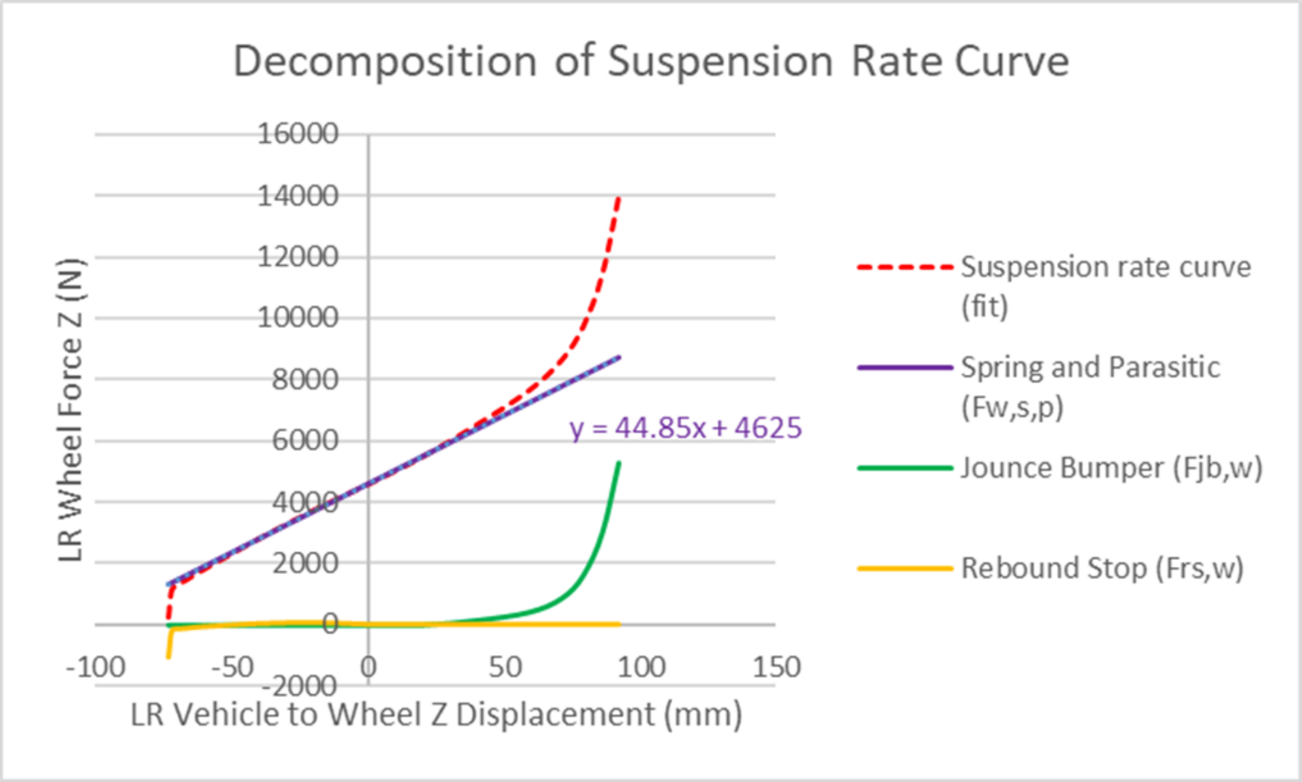
Examining the shape of the curve, we can identify some features



- Linear suspension rate (44.85 N/mm) due to:
  - Coil spring stiffness
  - Spring motion ratio (mm spring travel/mm vertical wheel travel
  - "Parasitic rate" – Suspension rate due to torsional stiffness of control arm bushings
- Nonlinear portion of curve in compression due to jounce bumper stiffness
- Discontinuity in rebound is where the rebound stop in the shock is engaged
- Hysteresis mainly due to friction (damper, ball joints)

We can use first principals to decompose the suspension rate curve into spring, bumper and parasitic contributors

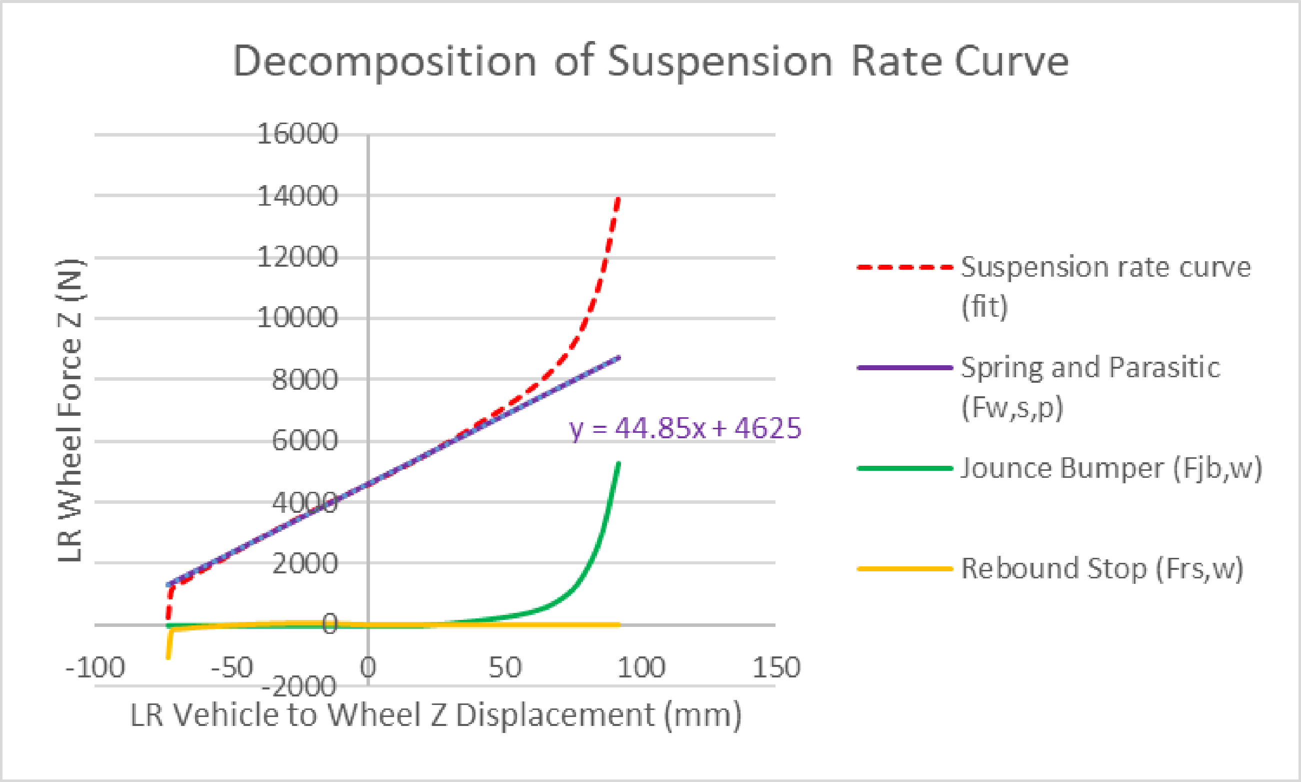
Decomposition of Suspension Rate Curve



$$F_w = F_{w,s,p} + F_{w,jb} + F_{w,rs}$$

F_w = Wheel force
$F_{w,s,p}$ = Wheel force due to spring and bushing parasitic rate
$F_{w,jb}$ = Wheel force due to jounce bumper
$F_{w,rs}$ = Wheel force due to rebound stop

Jounce Bumper and Rebound Stop Wheel Forces



$F_{w,jb} = F_w - F_{w,s,p}$ for Z > 0

$F_{w,rs} = F_w - F_{w,s,p}$ for Z < 0

F_w = Wheel force

$F_{w,s,p}$ = Wheel force due to spring and bushing parasitic rate

$F_{w,jb}$ = Wheel force due to jounce bumper

$F_{w,rs}$ = Wheel force due to rebound stop

$F_{w,f}$ = Wheel force due to suspension friction

Decomposition of Spring and Parasitic Rate Curve

Wheel force due to spring and bushing parasitic rate

$$F_{w,s,p} = F_{w,s} + F_{w,p}$$

Solving for parasitic force

$$F_{w,p} = F_{w,s,p} - F_{w,s}$$

But

$$F_{w,s} = \ (k_s * \ mr_s^2) * \ Z_w$$

k_s = Linear spring rate (N/mm)
mr_s = Spring motion ratio (spring disp / wheel Z disp)

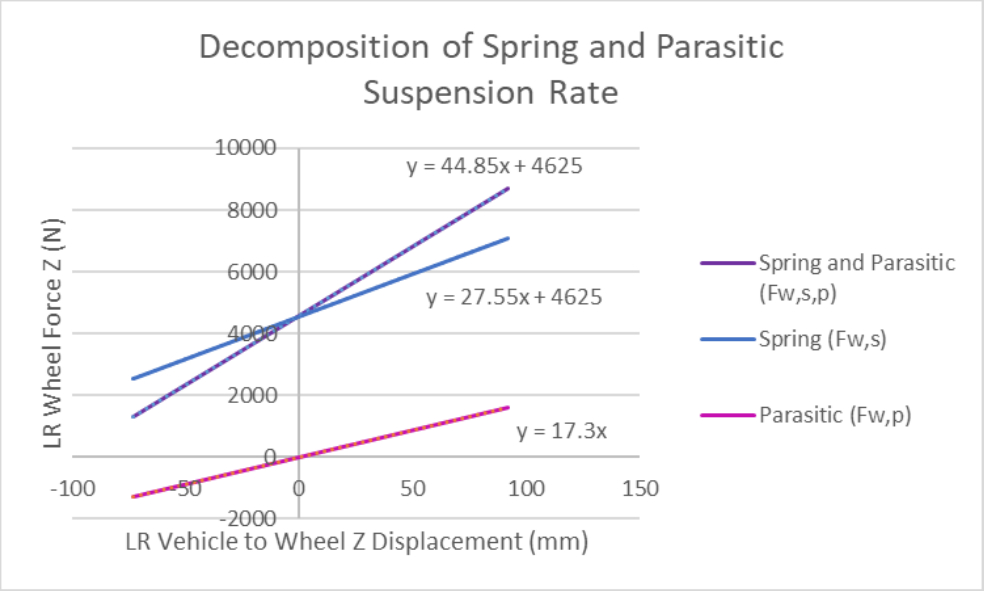
So

$$F_{w,p} = F_{w,s,p} \ - (k_s * \ mr_s{}^2 \ ) * Z_w$$

If we divide through by Z_w

$$\frac{F_{w,p}}{Z_w} = \frac{F_{w,s,p}}{Z_w} - (k_s * \ mr_s{}^2) \quad \text{or}$$

$$\boxed{K_{w,p} = K_{w,s,p} - (k_s * mr_s^2)}$$



M3 SOP-2 Rear

Input	Suspension rate	$K_{w,s,p}$	44.85	N/mm
	spring rate	K_s	73.8	N/mm
	spring motion ratio	mr_s	0.611	mm/mm
Calc	Suspension rate due to spring	$K_{w,s}$	27.55	N/mm
	Suspension parasitic rate	$K_{w,p}$	17.30	N/mm

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Parameters Affecting Primary Ride Performance

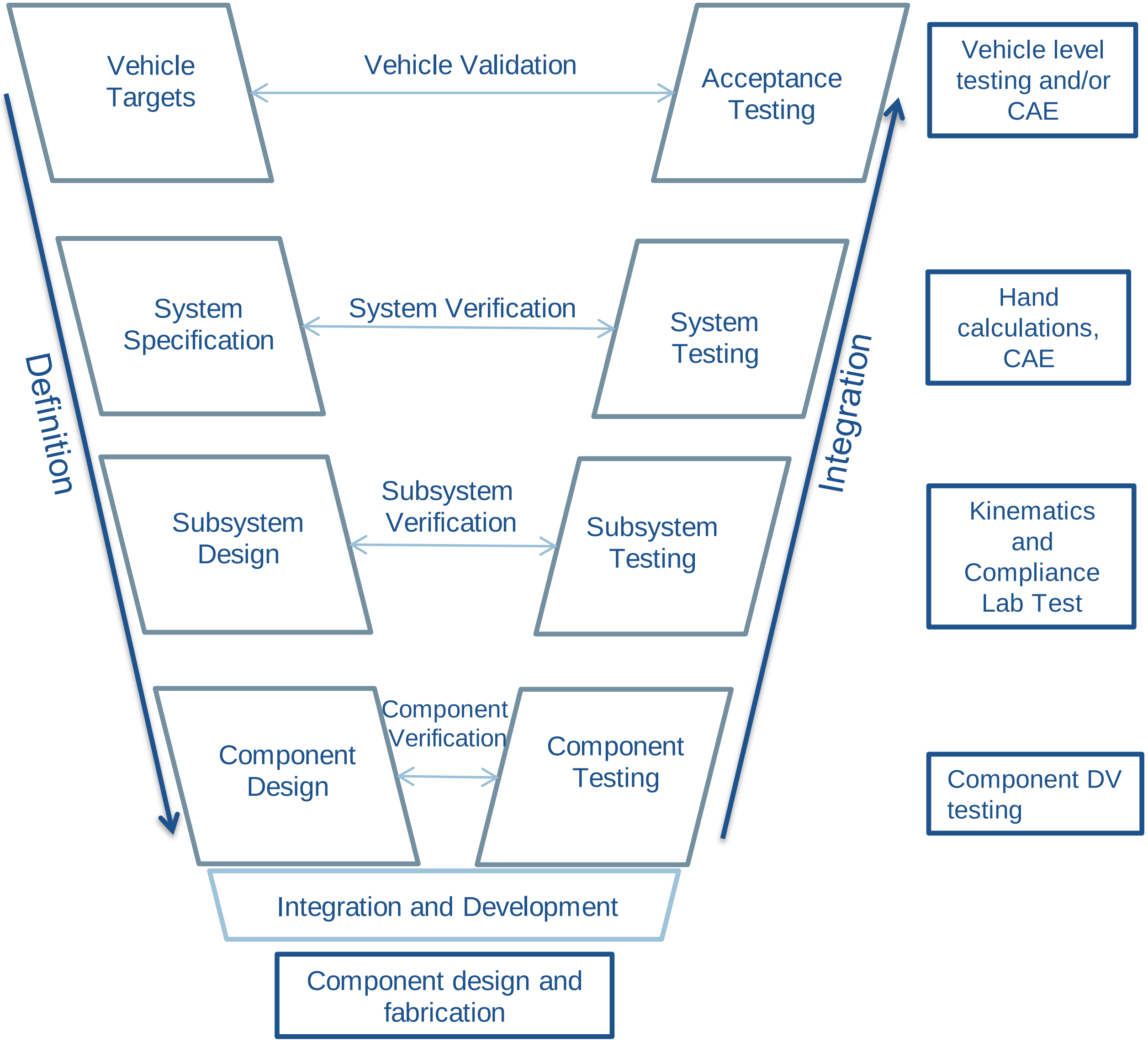
Vehicle Targets:
- Primary ride damping
- Primary ride delay
- Pitch Control
- Headtoss

Chassis System Targets:
- F/R ride nat. frequencies, ride freq.ratio
- Pitch/Bounce nat. frequency ratio
- Pitch/Bounce node locations
- Wheelhop nat. frequency
- …

Suspension Subsystem Targets:
- F/R ride rates
- F/R suspension rates
- F/R suspension parasitic rate
- F/R spring motion ratio
- **F/R critical damping at the wheel**
- **F/R damper motion ratio**
- …

Component Design Specifications
- Suspension hardpoints (xyz)
- Suspension spring stiffness
- Bushing torsional stiffness
- Damper friction
- Damper F/V tuning
- …

Constraints: Weight, weight distribution, roll/pitch inertia, wheelbase, unsprung mass



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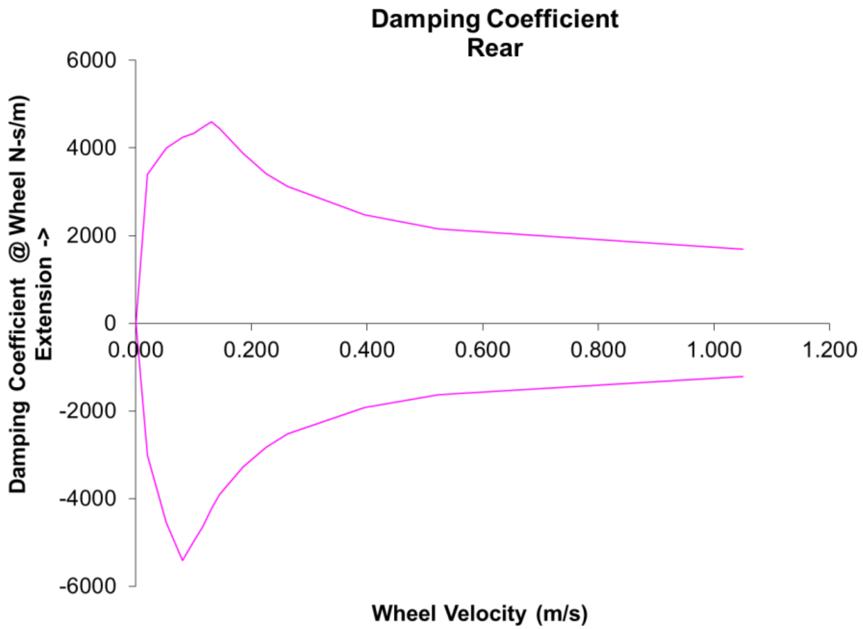
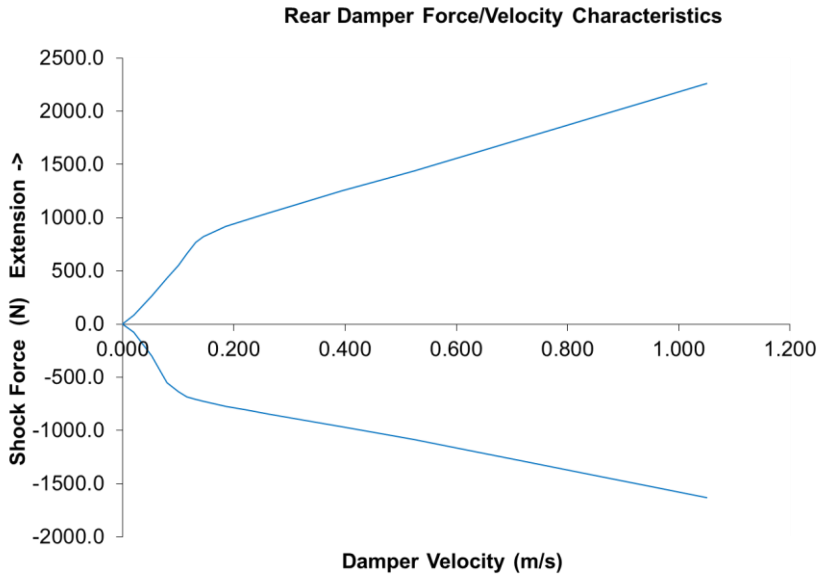
Relating Critical damping at the wheel to damper F/V





C_w , V_w

Parameter	Variable	Units	Equation
Damping coefficient	C_W	N-s/m	F/V
Damper motion ratio	mr_d	-	damper travel/vertical wheel travel

F_d , V_d

Olley Criteria for Good Primary Ride

Maurice Olley was a mechanical engineer with Rolls Royce and General Motors, whose career stretched from the late 1920's until the early 60's. In the 1930's, while Olley was a suspension engineer with Cadillac, he conducted extensive testing relating to primary ride balance.

According to Olley, there exists a relationship between front and rear wheel rates that provides desirable primary pitch and bounce characteristics, the so called **'flat ride',** in the absence of shock damping. Once this relationship is established, the development engineer needs to apply minimal shock damping to finely tune the primary ride.

This follows the general development principal that the best shock control for ride is the least shock control that will do the job.

Olley Criteria for Good Primary Ride

As a result of his research, Olley developed the following guidelines:

1. The front suspension must have a greater effective deflection than the rear. Typical front deflections should be at least 30% greater than the rear
    - This translates into having higher rear ride frequency than the front, and thus laid the groundwork for the commonly used “rule of thumb” that the rear-to-front **ride frequency ratio should be greater than 1**

$$f_{R,F} = \frac{1}{2\pi}\sqrt{\frac{k'_F}{m_F}}$$

Front Ride Natural Frequency (Hz)

$$f_{R,R} = \frac{1}{2\pi}\sqrt{\frac{k'_R}{m_R}}$$

Rear Ride Natural Frequency (Hz)

$$R_R = \frac{f_{R,r}}{f_{R,f}}$$

Ride Frequency Ratio (-)

Olley Criteria for Good Primary Ride

2. The ratio of pitch natural frequency to bounce natural frequency should be reasonably close together, with a maximum ratio of 1.2
    - If the pitch and bounce frequencies are far apart, the ride motion will consist of sharp, **<u>interference kicks</u>**, making comfort nearly impossible
    - Having equal pitch and bounce frequencies is unacceptable since the motion of the vehicle will have no discernable “pattern”.

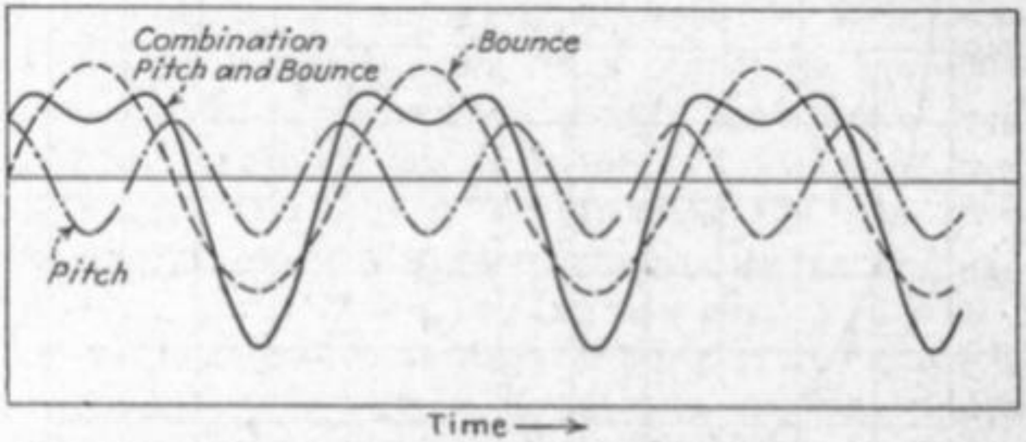


Fig. 6—Interference Kicks or “Heterodyning” of Ride in Car with Conventional Front Axle

In this example, $f_p / f_b \sim 1.5$

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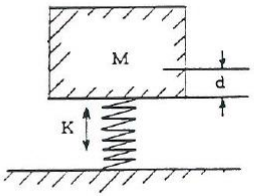
Olley Criteria for Good Primary Ride

3. Ride Frequencies should not be greater than 77 CPM (1.3hz), corresponding to an effective ride deflection of 6”
   - Olley observed that occupants complained of ‘jarring’ in tests where the ride frequencies were higher than 1.3hz
   - Olley used an ‘useful approximation’ relating ride frequency to suspension travel

Effective Suspension Deflection as a Function of Ride Frequency

Taken from "Notes on Suspension" By Maurice Olley, August 1961

It starts logically with a simple mass on a spring, the spring being assumed to have a constant rate.



If the spring has a rate k (lb/in), the natural frequency of the mass is $\omega(rad/s) = \sqrt{\frac{k}{m}}$

or frequency in cycles/sec, $f(cps) = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$

But m = W/g, so that $f(cps) = \frac{1}{2\pi}\sqrt{\frac{k * g}{W}} = 0.159\sqrt{\frac{g}{d}}$

where d = deflection of spring under weight, W

Effective Suspension Deflection as a Function of Ride Frequency

This can be expressed very simply. If d is in inches. G must be inches/sec^2. Then:

$$f(cps) = 0.159\sqrt{\frac{386.4}{d}} = \frac{3.126}{\sqrt{d}}$$

By multiplying denominator by $\frac{\sqrt{10}}{\sqrt{10}}$, this can also be written as

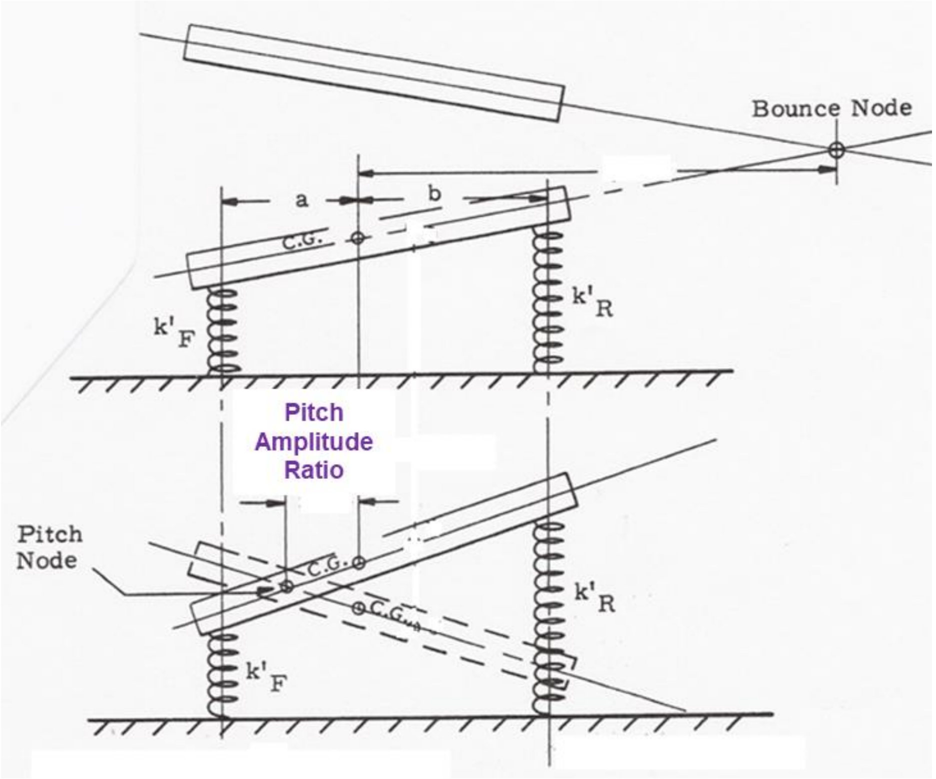
$$f(cps) = \frac{3.126}{3.16\sqrt{\frac{d}{10}}} \cong \sqrt{\frac{10}{d}}$$

So, for example, if the effective deflection is 6", the frequency is approximately

$$\sqrt{\frac{10}{6}} \cong 1.3cps = 1.3hz$$

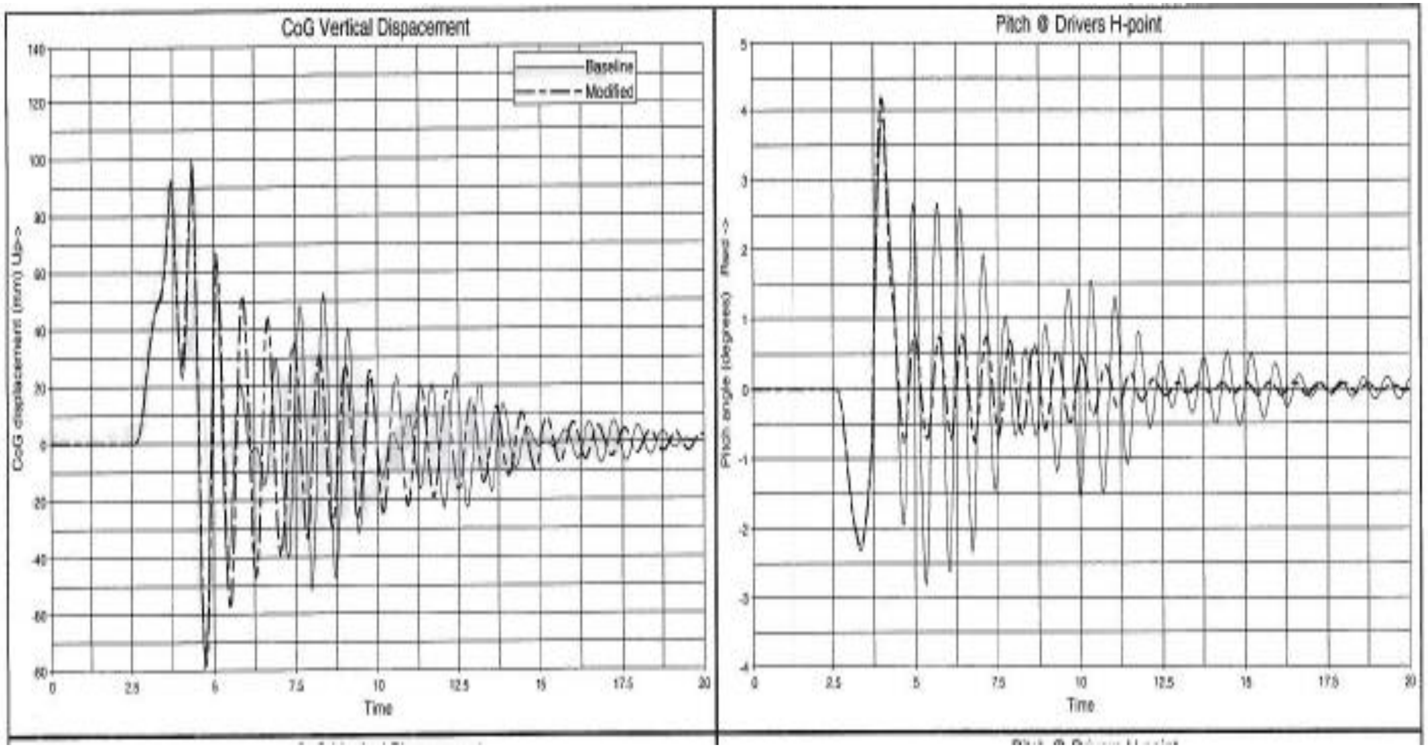
Olley Criteria for Good Primary Ride

5. It is desirable to have the pitch node close to the drivers H-point and the bounce node at infinity, fore or aft of the vehicle CoG
   - As was the case with the pitch and bounce frequencies, having the pitch and bounce nodes close to each other will produce oscillations with no discernable pattern, and hence, poor primary ride.



Simulation Example: Node Separation

ADAMS simulation of a vehicle traveling over a 5” amplitude sine wave of 1*wheelbase wavelength @ 20mph



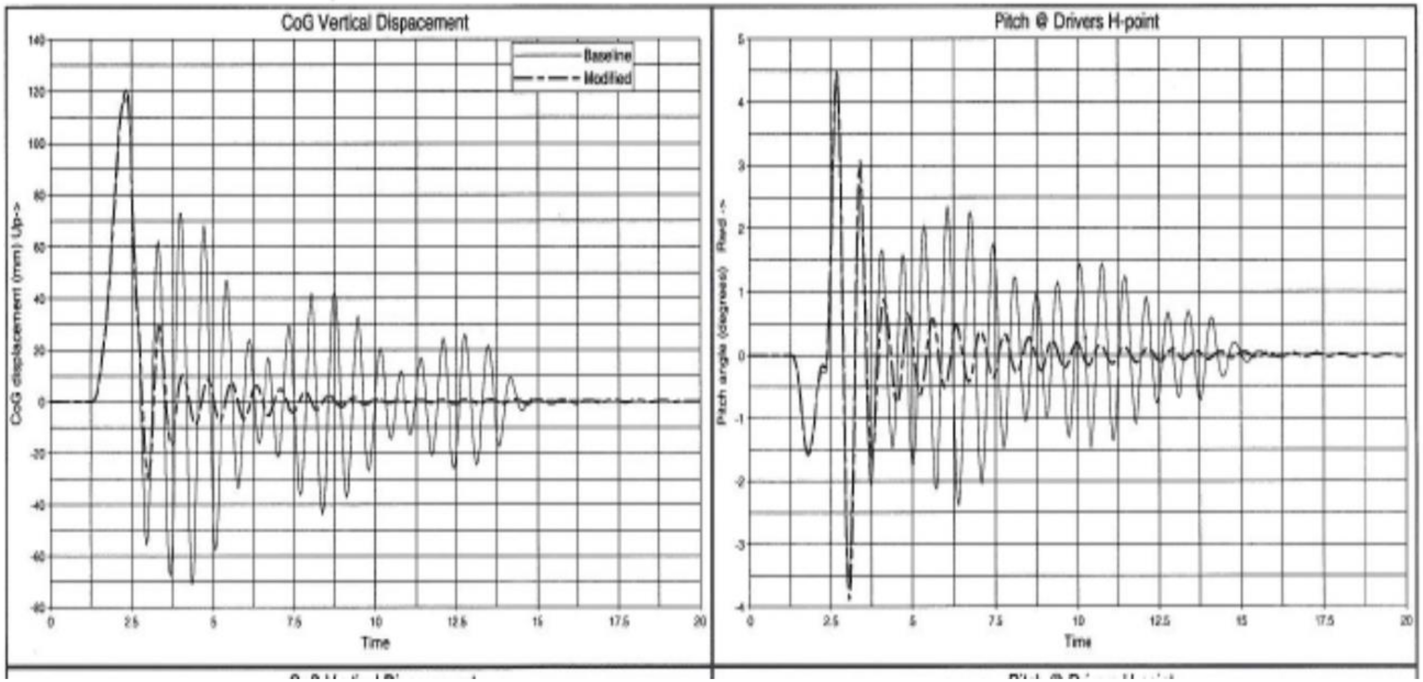
- Baseline: pitch and bounce nodes close together
- Modified: pitch and bounce nodes far apart
- Bounce excitation: road wavelength = wheelbase
- No suspension damping

Baseline
Modified

Notice that the modified vehicle has relatively little residual pitch response when excited by a bounce input, while the baseline vehicle exhibits a combination of bounce and pitch response

Simulation Example: Node Separation

ADAMS simulation of a vehicle traveling over a 5” amplitude sine wave of 2*wheelbase wavelength @ 20mph



- Baseline: pitch and bounce nodes close together
- Modified: pitch and bounce nodes far apart
- Pitch excitation: road wavelength = 2*wheelbase
- No suspension damping

Baseline
Modified

Notice that the modified vehicle has relatively little residual bounce response when excited by a pitch input, while the baseline vehicle exhibits a combination of bounce and pitch response

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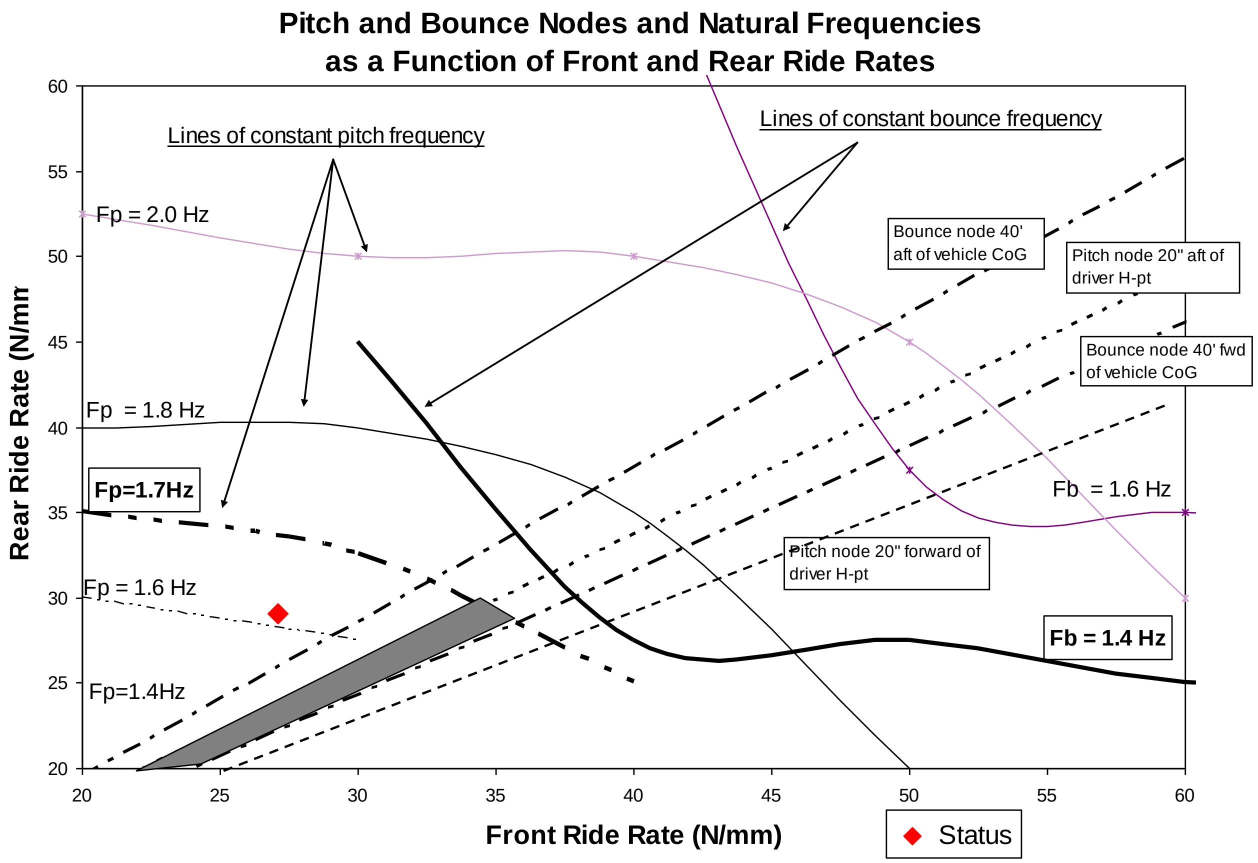
Olley Criteria for Good Primary Ride

Recall that Part 1, we presented a graph of pitch and bounce frequencies and nodes as a function of front and rear ride rates:



Applying Olley's criteria, we can define a design space where a combination of front and rear ride rate would separate the nodes and deliver "flat ride" in the absence of damping

Summary

- Primary ride pertains to the rigid body motion of the vehicle sprung mass.
- Secondary ride pertains to higher frequency and smaller amplitude displacement of the body and chassis.
- Accelerometers are commonly used to acquire data to measure the bounce, pitch and roll response of the vehicle
- RMS and PSD metrics can be used to objectively evaluate primary ride performance
- Suspension rate, tire rate and suspension damping are chassis parameters that affect primary ride performance
- First principals can be used to decompose suspension rate and damping into component specification
- In the 1930’s, Maurice Olley developed guidelines for good primary ride in the absence of damping that are still applicable today
- Simulation can be used to evaluate primary ride performance, duplicating lab or on-road testing