TERRAMECHANICS IMPACT OF THE WHEEL NORMAL REACTION ON MOBILITY AND STEERABILITY MARGINS

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OUTLINE:

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4. Boundaries on normal reaction
5. Dynamic normal reaction in two examples of suspension damping forces
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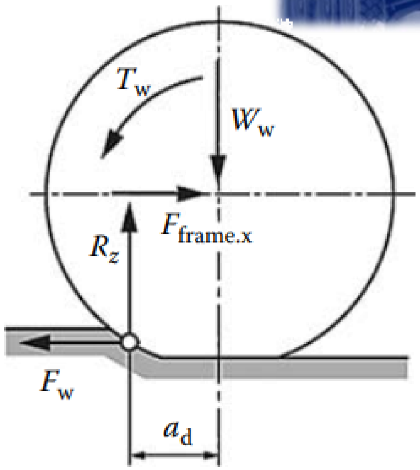
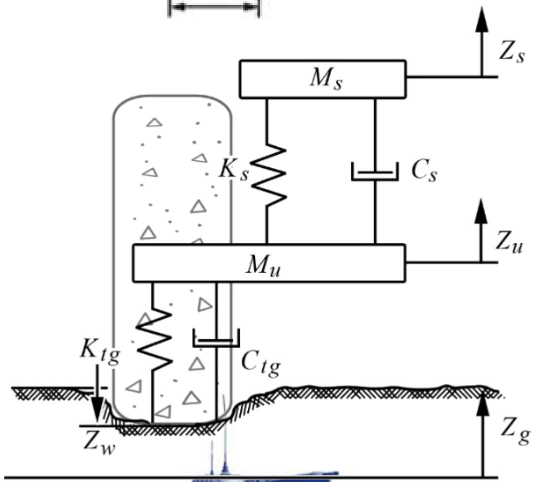
Motivation and Problem statement:

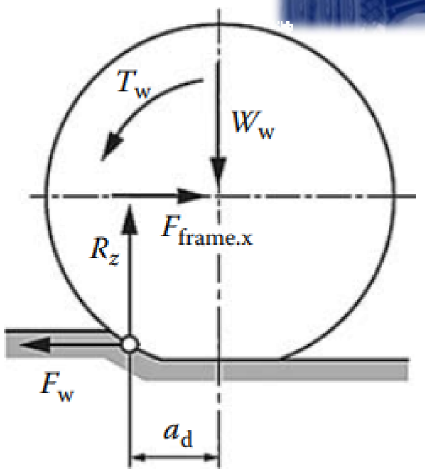
- Normal reaction force in the tire-soil patch is a continuously changing wheel parameter.
- When a vehicle moves over uneven ground, motion in the vehicle's sprung and unsprung masses produce dynamic shifts in the magnitude of the load transmitted to the ground.
- With the damping force controlled for better ride quality, tight constraining of the sprung mass motion may lead to significant dynamic changes of the normal load.

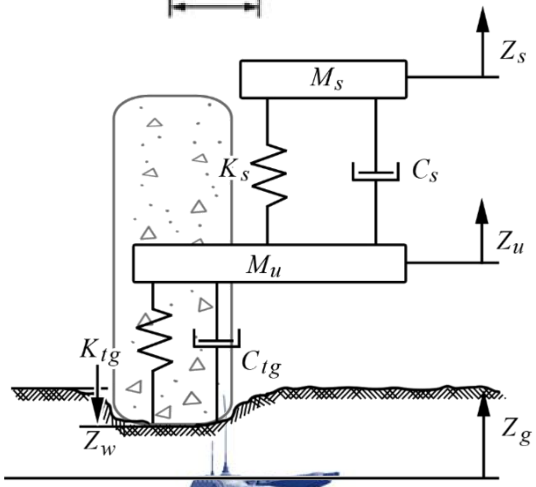




Approach:

1. Develop a method to model and simulate the normal reaction when limiting travel of the sprung mass.
2. A virtual sensor that measures the suspension travel is used to determine the normal reaction in real time.
3. Extreme values of the normal reaction are researched to establish boundaries for mobility and bearing capacity.





Quarter-car model of one-wheel module:

- Sprung Mass Acceleration:

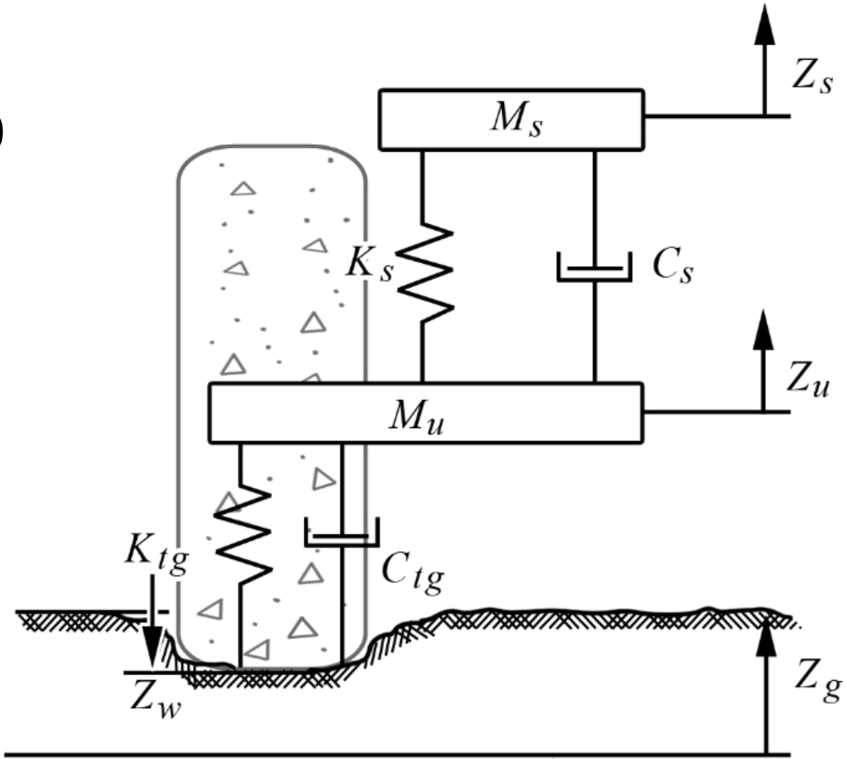
$$m_s \ddot{z}_s - K_s(z_u - z_s) - C_s(\dot{z}_u - \dot{z}_s) = 0$$

- Unsprung Mass Acceleration:

$$m_u \ddot{z}_u + K_s(z_u - z_s) - K_{tg}(z_g - z_u) + C_s(\dot{z}_u - \dot{z}_s) - C_{tg}(\dot{z}_g - \dot{z}_u) = 0$$

- Soil stiffness influence included as combined tire-soil stiffness, K_{tg}:

$$K_{tg} = \frac{K_t K_g}{K_t + K_g}$$

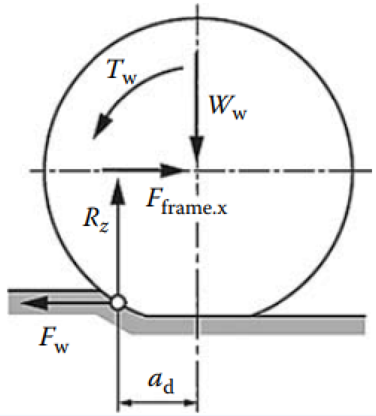


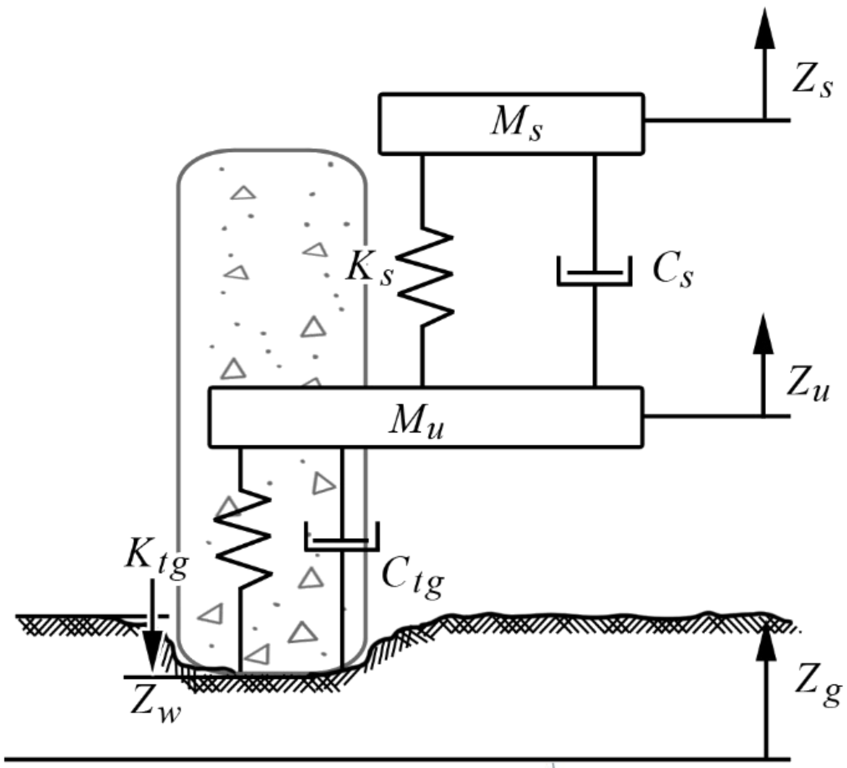
Dynamic Normal Reaction R_z:

$$R_z = R_{z\_s} + K_{tg}(z_u - z_g) + C_{tg}(\dot{z}_u - \dot{z}_g)$$

Static normal reaction R_{z_s} *becomes* R_{z_s} *under influence of relative travel* $z_u - z_g$ and velocity $\dot{z}_u - \dot{z}_g$

Driving mode wheel forces:





Dynamic Normal Reaction R_z:

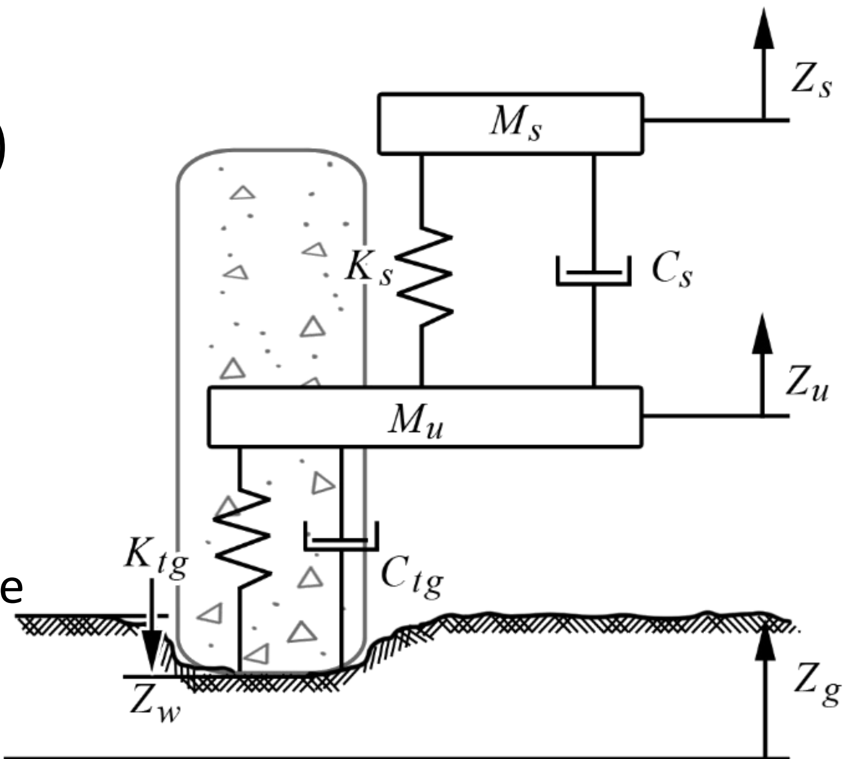
$$R_z = R_{z\_s} + K_{tg}(z_u - z_g) + C_{tg}(\dot{z}_u - \dot{z}_g)$$

Relative travel of sprung mass z_s and unsprung mass z_u:

$$L = (z_s - z_u)$$

Dynamic normal reaction in terms of relative travel of sprung and unsprung masses:

$$R_z = R_{z\_s} + m_u \ddot{L} + \left(\frac{m_u}{m_s} + 1\right)\left(C_s \dot{L} + K_s L\right)$$



Soil pressure-sinkage:

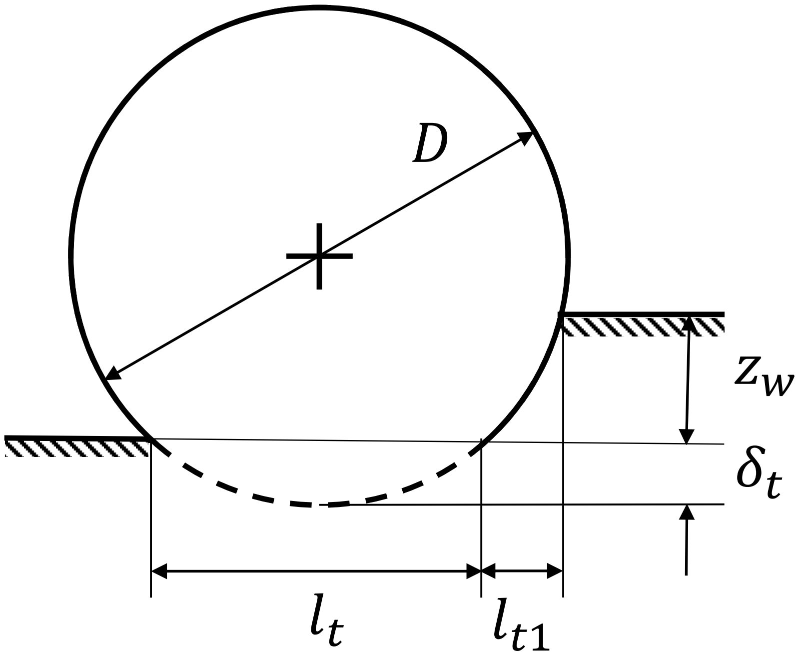
$$z_w = \left(\frac{p_{gr}}{\frac{k_c}{b} + k_\phi} \right)^{\frac{1}{n}}$$

z_w: sinkage

p_{gr}: ground pressure

b: contact width

k_c, k_ϕ, n: Bekker model soil parameters



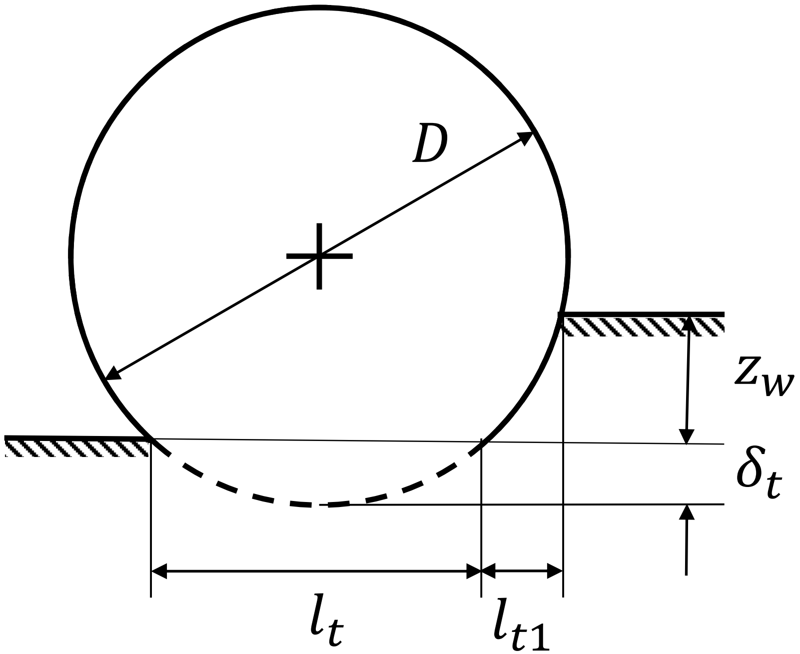
Iterative process for deflection δ_t of deformable tire: balance normal load R_z with soil reaction:

- $R_z = p_{gr} l_t b + W_{cu}$

  (W_{cu}: component of soil reaction on curved portion of contact length l_{t1})

- $W_{cu} = l_t \left(\frac{k_c}{b} + k_\phi\right) \sqrt{D} (z_w + \delta_t)^{n-1} \times \frac{\left[(3-n)(z_w+\delta_t)^{3/2} - (3-n)\delta_t^{\frac{3}{2}} - 3 z_w \sqrt{\delta_t}\right]}{3}$

- $l_t = 2\sqrt{D\delta_t - \delta_t^2}$



Boundaries on normal reaction:

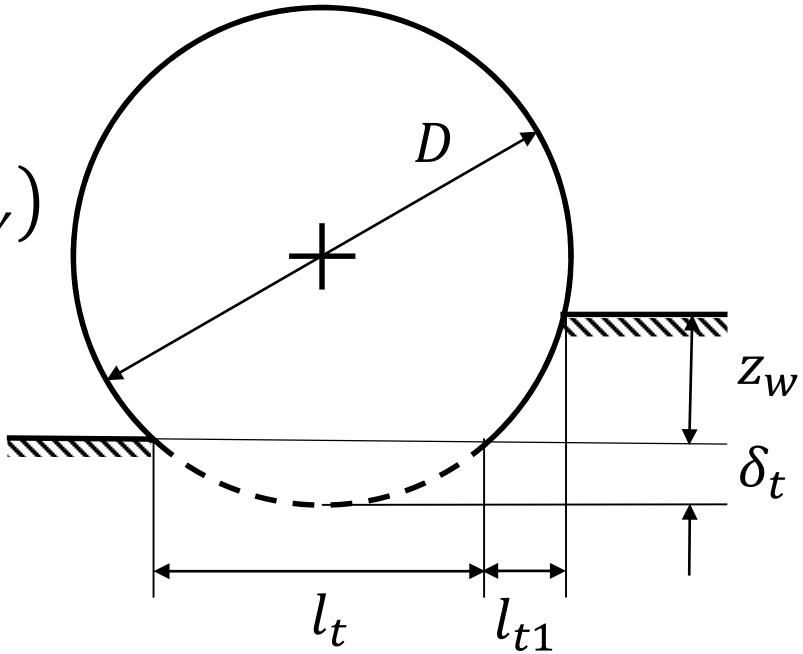
- Bearing capacity of soil W_s:

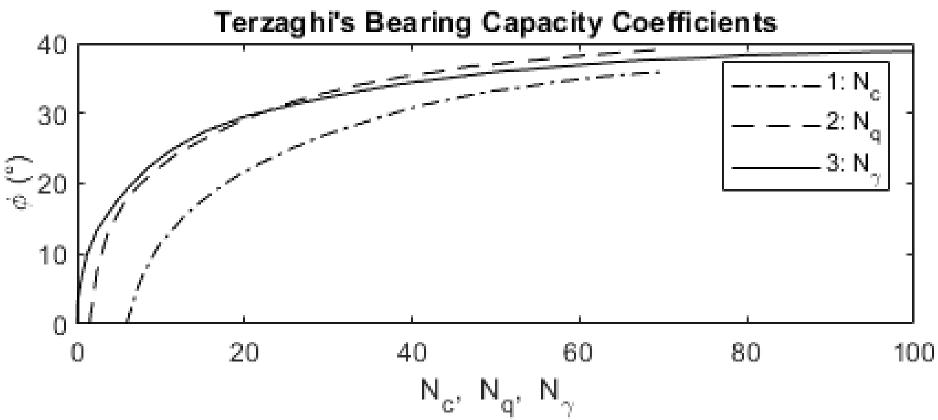
$$W_s = A\left(cN_c + \gamma z_w N_q + 0.5\gamma b N_\gamma\right)$$

A: contact area

c: soil cohesion

γ: unit weight of soil





N_c, N_q, N_γ: bearing capacity coefficients dependent on soil angle of internal friction ϕ

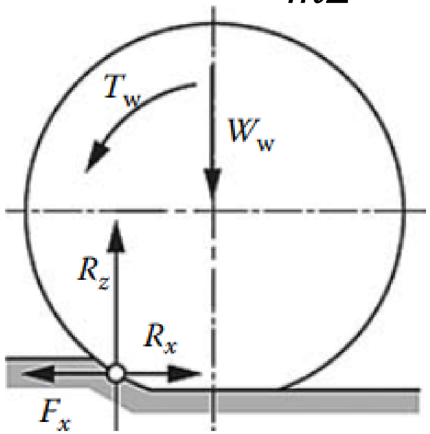
Boundaries on normal reaction:

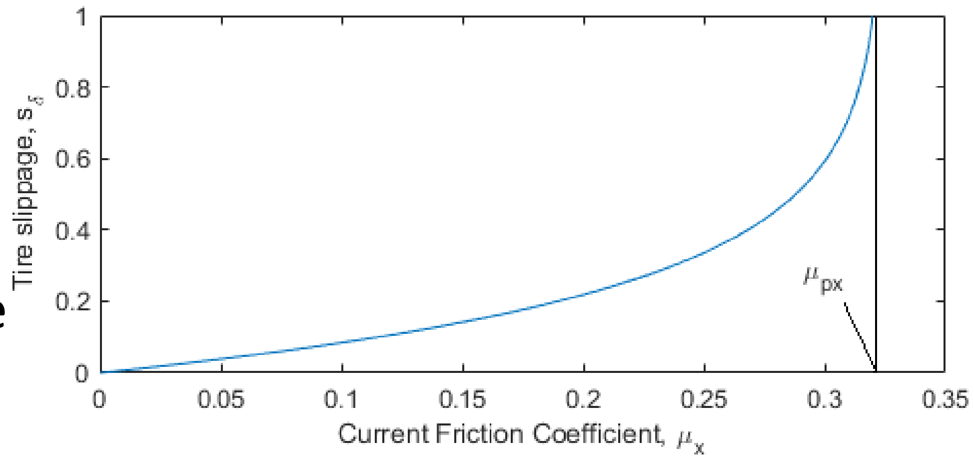
- Circumferential wheel force:

$$\mu_x = \frac{F_x}{R_z}$$

Circumferential force F_x must be able to match the corresponding motion resistance $R_{m\Sigma}$:

$$\mu_{px} R_z^{min} > R_{m\Sigma}$$

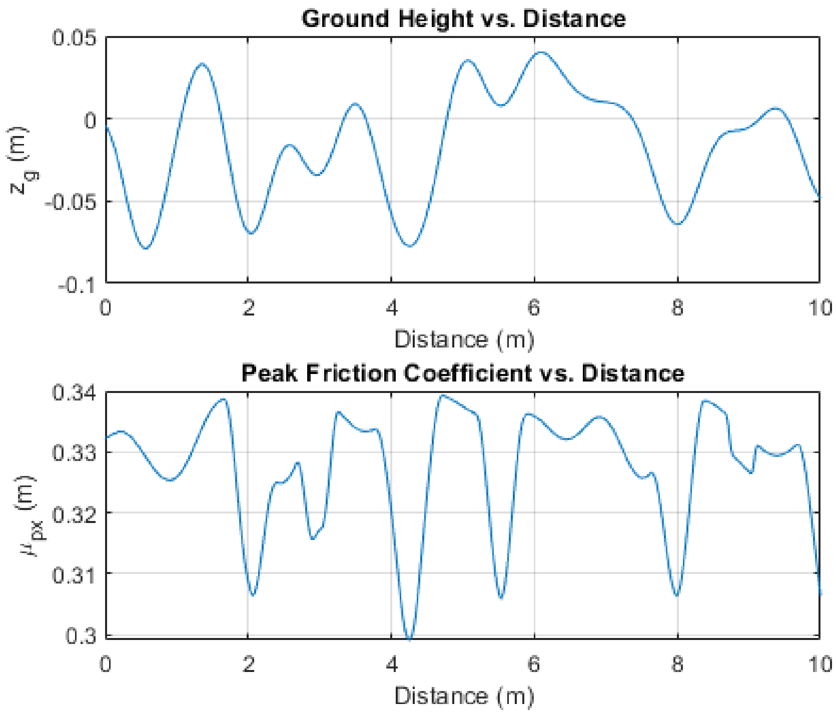




- As the current friction coefficient μ_x increases, the tire slippage increases exponentially.
- Maximum value of μ_x is limited by the peak friction coefficient μ_{px}, which μ_x approaches asymptotically.

Stochastic terrain simulation model:

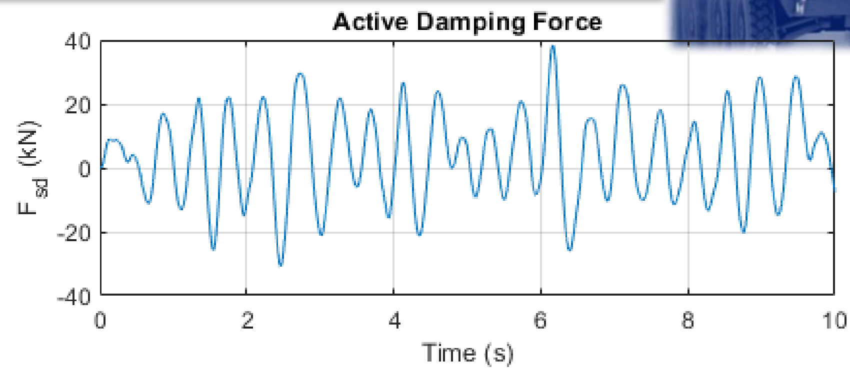
- Varying ground height profile z_g produces disturbances to motion of wheel module masses, affecting dynamic normal reaction
- Varying peak friction coefficient affects maximum circumferential force F_x

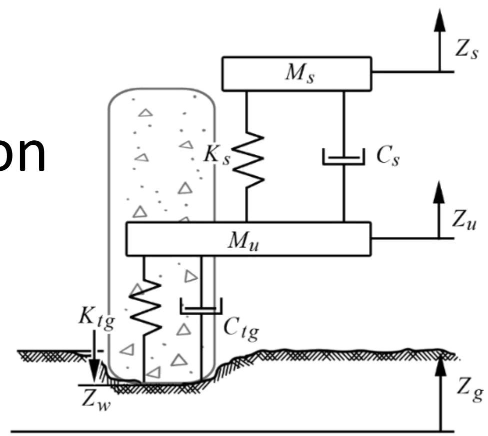


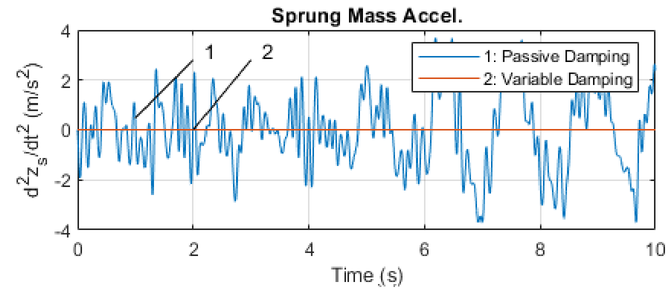
Comparison of two suspension damping cases:

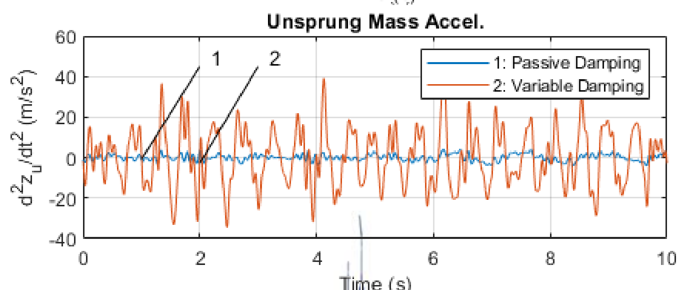
- Passive damping with damping constant C_s
- Active damper varying damping force to limit sprung mass acceleration
- Damping force F_{sd} determined through inverse dynamics:

$$F_{sd} = m_s \ddot{z}_s - K_s(z_u - z_s)$$



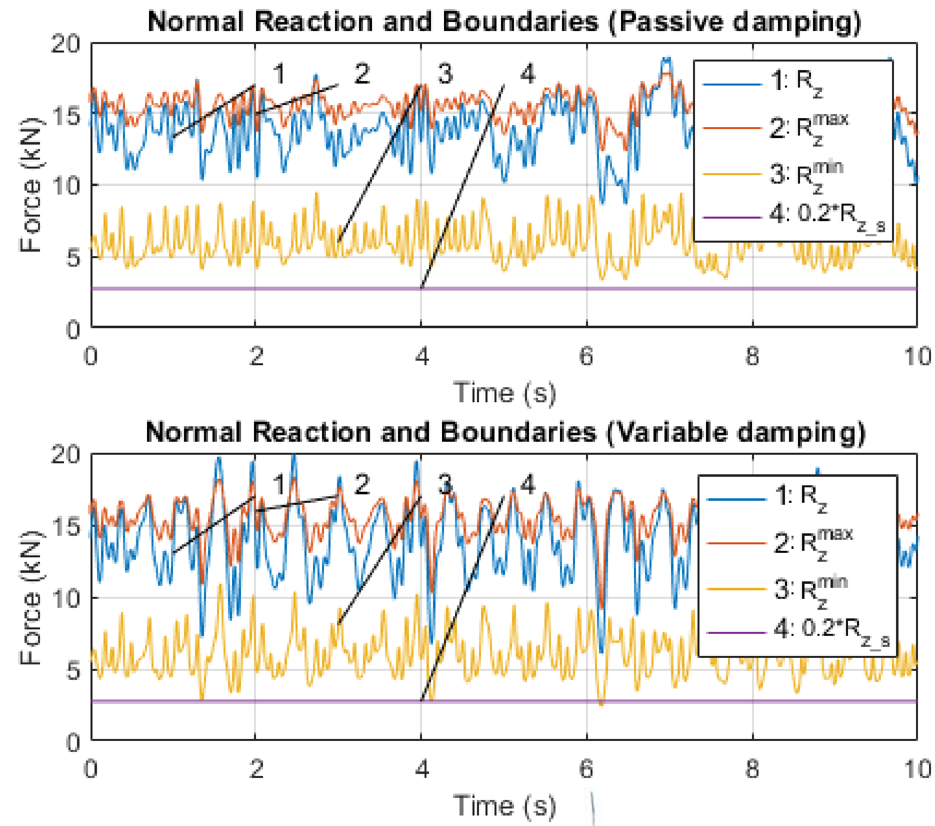






Dynamic normal reaction and boundaries for both damping examples:

1. Dynamic R_z
2. Upper limit R_z^{max} based on bearing capacity: $R_z^{max} < W_s$
3. Lower limit based on minimum for required circumferential force: $\mu_{px} R_z^{min} > R_{m\Sigma}$
4. Lower limit based on steerability: $R_z^{min} > 0.2 R_{z\_s}$



Conclusions/summary:

- Method to determine boundaries of wheel normal reaction
- Dynamic normal reaction can be obtained from relative travel of sprung and unsprung masses
- When the sprung mass is held steady, the dynamic changes in the normal reaction are increased.
- Goals of stabilizing the sprung mass, avoiding exceeding the soil bearing capacity, and maintaining sufficient normal reaction for mobility and steerability must be kept in balance.

- Q&A