III. Problem Solving

- Performance Measures
- Design Constraints and Challenge
- Problem Formulation
- Controller Design
- A Truck ABS Design Example
- Practical Optimization

Performance Measures

- Command Following
  - Bandwidth
  - Precision
- Disturbance Rejection
  - Internal Disturbance
  - External Disturbance
- Sensor Noise Sensitivity
  - Smoothness of control signals
- Robustness
  - Stability Margins
  - Performance Robustness

Design Constraints

- Actuator Saturation
- Bandwidth Bottleneck
  - Sensor Noise Modeling Accuracy
  - Dynamics Variations
- Digital Control Issues
  - Phase Lag: $-\omega T_s/2$
  - Finit resolution: 8,12,16 bits ADC
  - Anti-aliasing Filter bandwidth

The Challenge

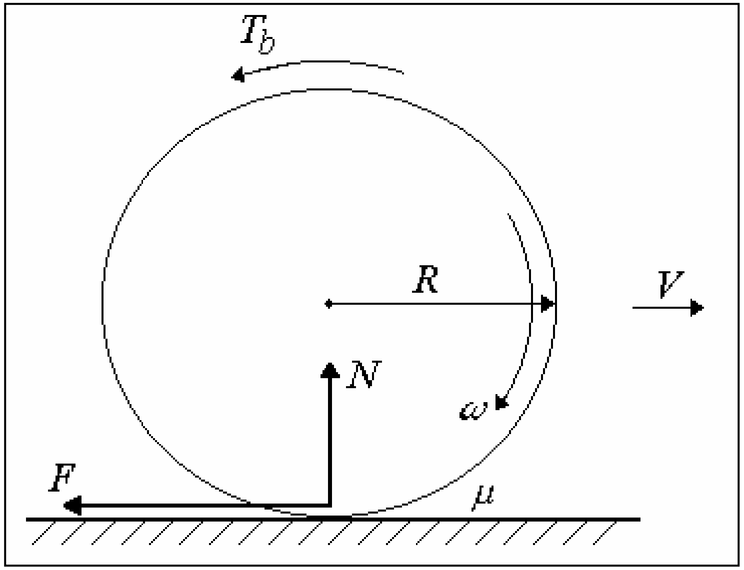
- Finding the best (optimal?) solution under the constraints of each application
- The limitations of existing optimal control methods
  - Mathematical Optimality
  - Practical Optimality
- The lack of science in control design makes it an art

Problem Formulation

- Control problem is not given but discovered
- Identify the “Control Part” in a system problem
  - Could be the most challenging/interesting part
  - See through the disguise
- Identify the input and output of the process
- Define design objectives

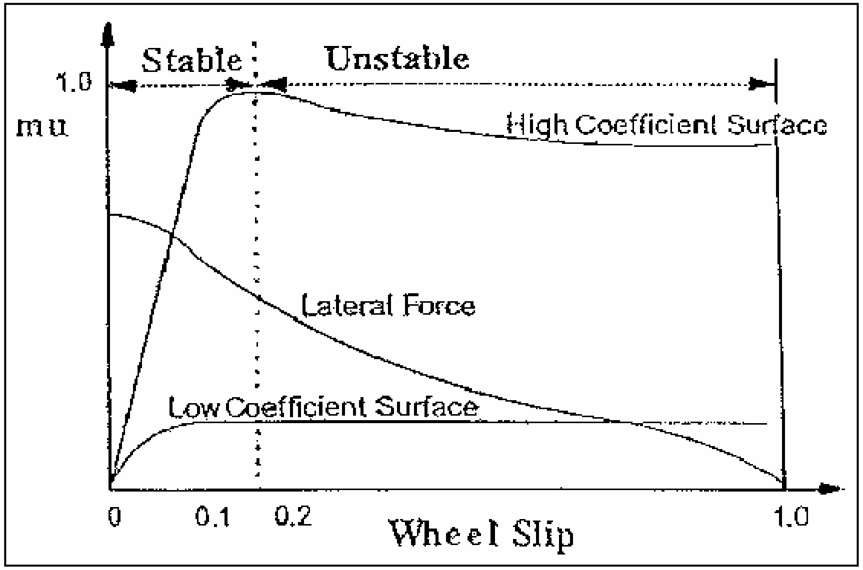
ABS Dynamics

Wheel Slip



$$\lambda = \frac{V - \omega R}{V}$$

μ-slip curve



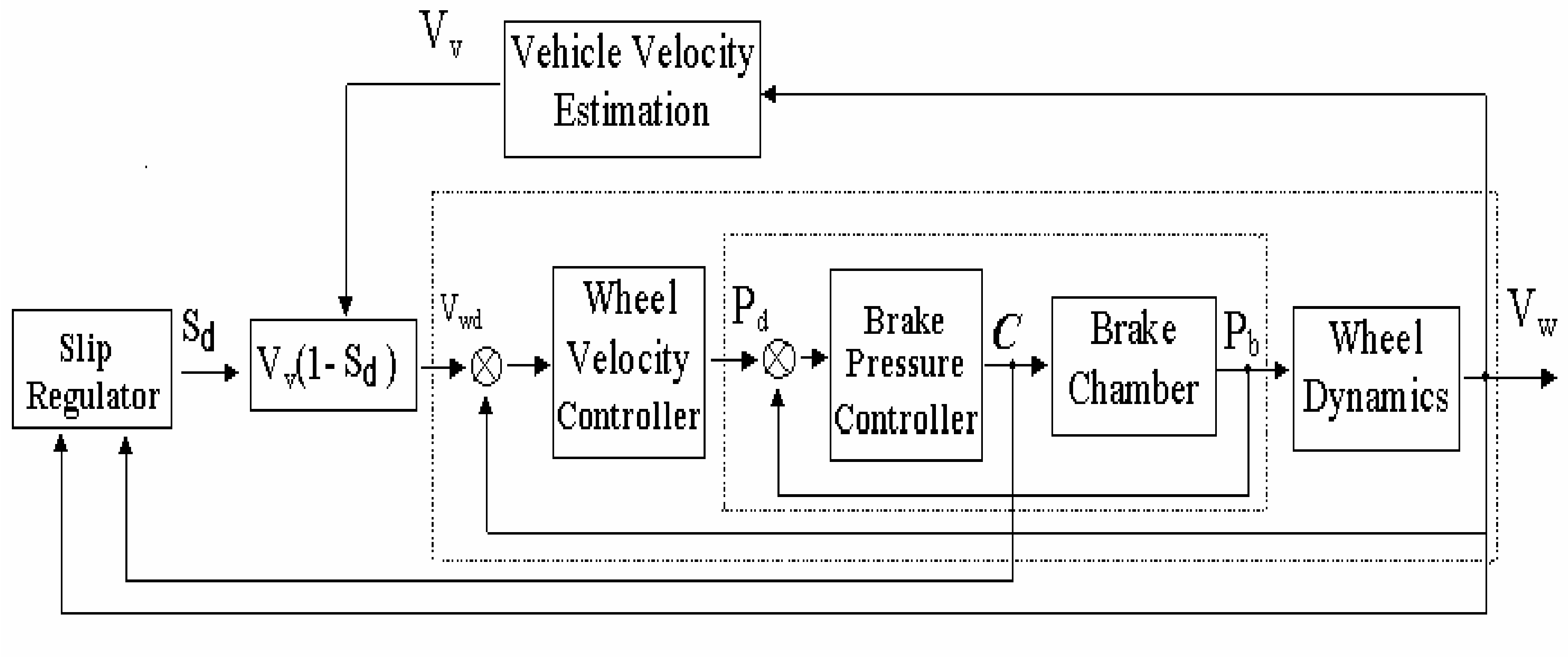
λ=0
Free-rolling

λ=1
Lockup

Previous Approach

- Measured signal: wheel speed
- Control action: turn valve on or off (charge or discharge brake chamber)
- Design objective: avoid wheel lock up
    - shorten stopping distance
    - Maintain lateral force
- Control Law
    - Sequential logic
    - Not treated as a “control” problem
    - Long state-flow programs

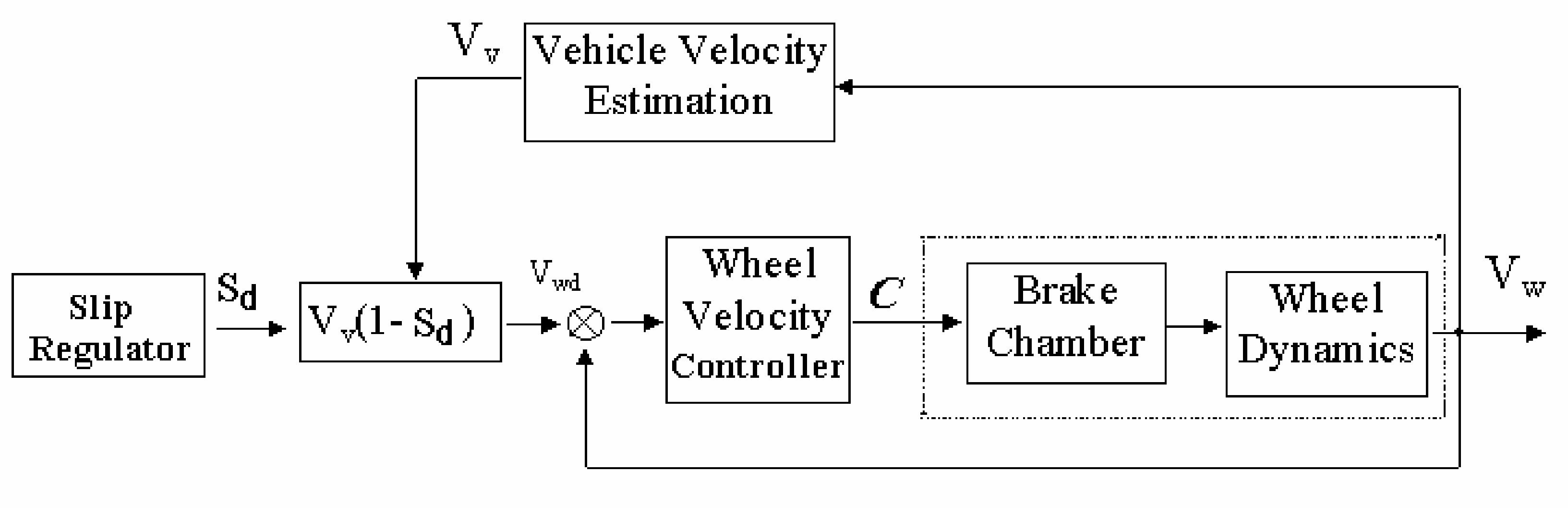
ABS Problem Formulation



Control Design

- Math and Simulation Model Set Up
- Select Control Strategy and Methods
- Controller Design
- Simulation
- Implementation

ABS Problem-Solving Example



- Vehicle Velocity Estimation
- Modeling
- Controller Design
- Simulation Verification

Vehicle Velocity Estimation

- Literature Review
- A Nonlinear Filter Method
- Off-line Testing Results
- Summary & Implementation Issues

Literature Review

- Kalman Filter
- Extended Kalman Filter
- Fuzzy Logic Estimation

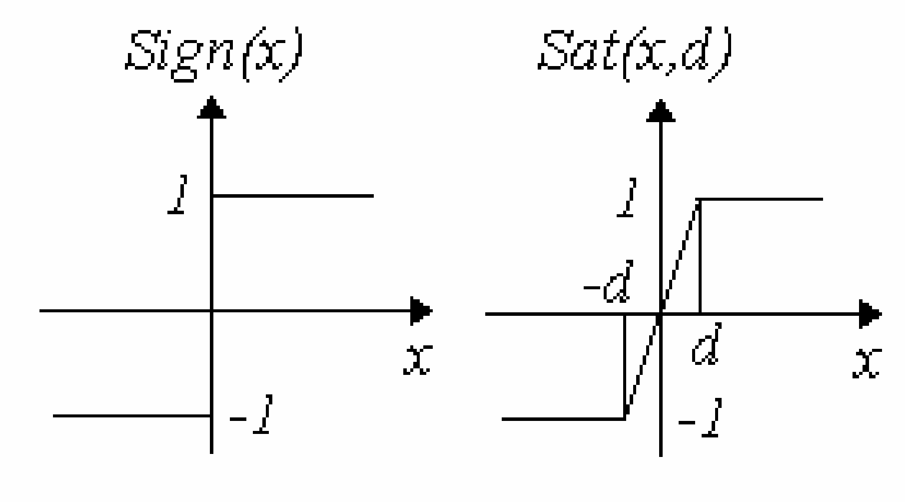
- Require More Sensors
- Not Ready for Application

A Nonlinear Filter Method

$$\dot{y}(t) = -R_g \cdot \mathrm{sign}(y(t) - x(t))$$

$$y(t=0) = y_0$$

$$f(x) = \mathrm{Sign}(x) = \begin{cases} 1, & \text{when } x > 0 \\ 0, & \text{when } x = 0 \\ -1, & \text{when } x < 0 \end{cases}$$



$$f(x) = \mathrm{Sat}(x,d) = \begin{cases} 1, & \text{when } x > d \\ -1, & \text{when } x < -d \\ x/d, & \text{else} \end{cases}$$

A Nonlinear Filter Method

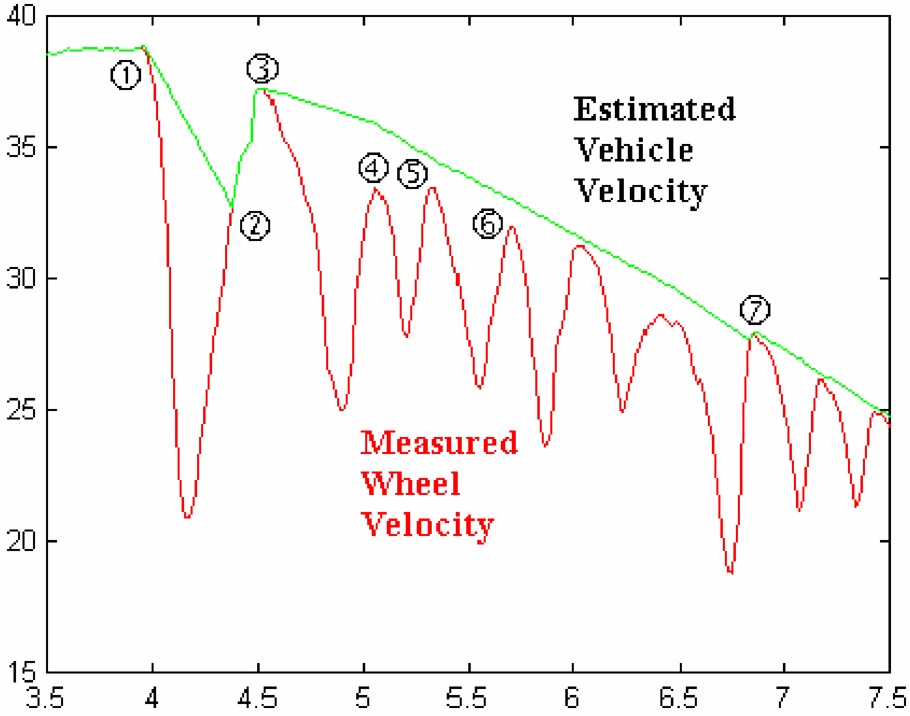
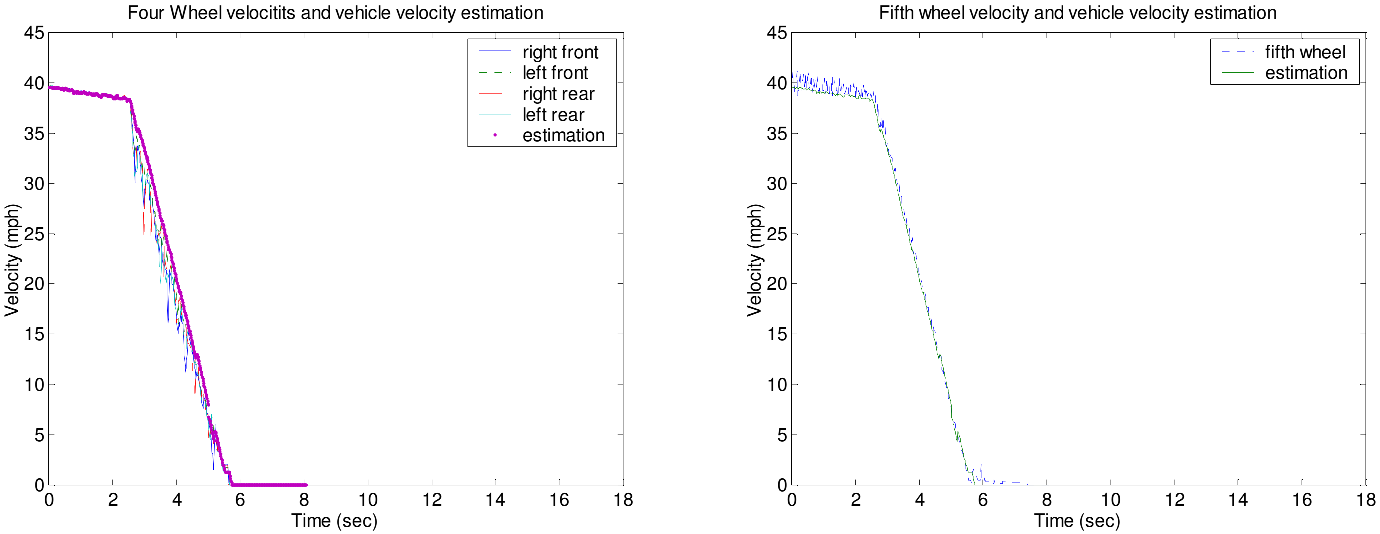


Illustration of the vehicle velocity estimation

■ Off-line Testing Results



Test # sbn075, high coefficient surface (dry asphalt)

Summary & Implementation Issues

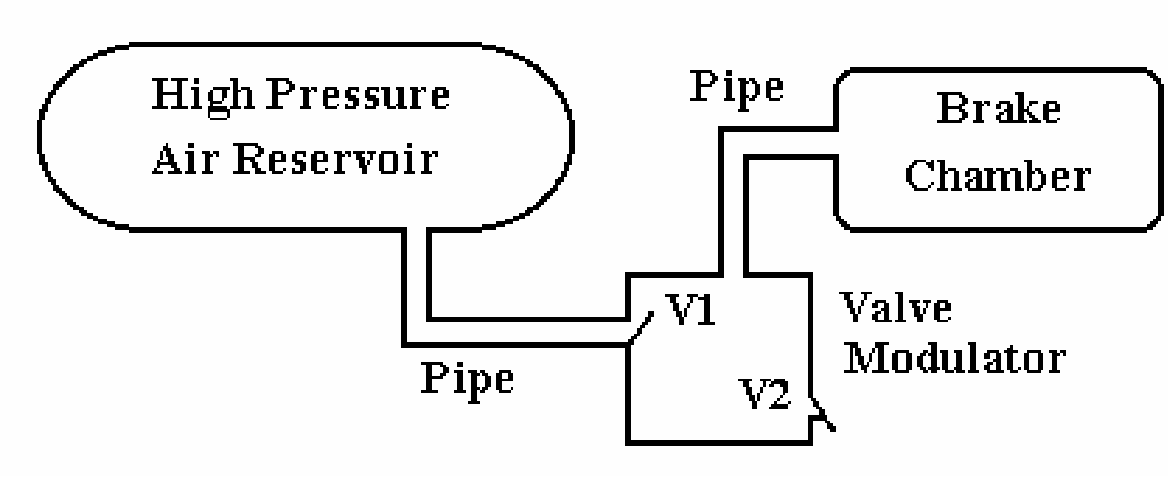
- ✓ Simple, Efficient & Practical
- ✓ Adaptive
- ✓ Accurate & Smooth Estimation

- Verify in Hardware
- Not Applicable to Smooth Wheel Velocity

ABS Modeling

- Brake Chamber Model
- Quarter Vehicle Model
- Model Verification
- Closed-loop Simulink Model

■ Brake Chamber Model



Simplified diagram of pneumatic
brake modulator/chamber system

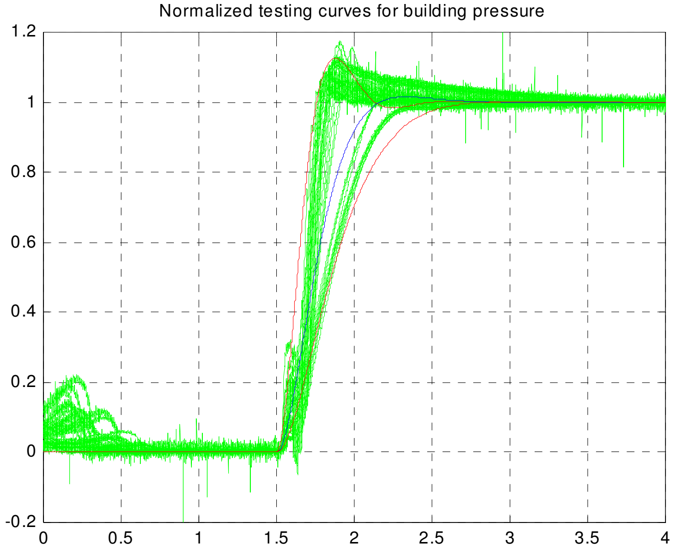
■ Brake Chamber Model

$$G_b(s) = \frac{P_c G_I}{s} \cdot \frac{1}{\tau^2 s^2 + 2\tau D s + 1}$$

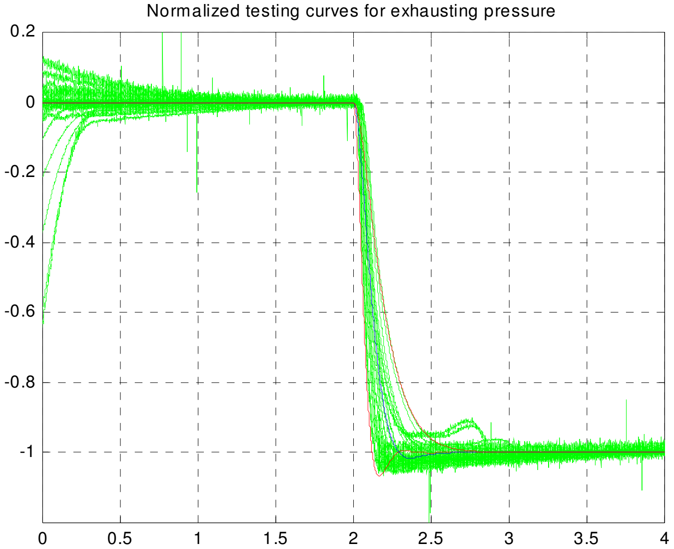
Building	τ	D			G_I
Fastest	0.1	0.55		Min	6.3
Slowest	0.22	0.9		Max	8.9
Nominal	0.16	0.8		Nominal	8.8

Exhausting	τ	D			G_I
Fastest	0.04	0.65		Min	10.7
Slowest	0.1	1		Max	13.2
Nominal	0.07	0.8		Nominal	12.5

■ Brake Chamber Model



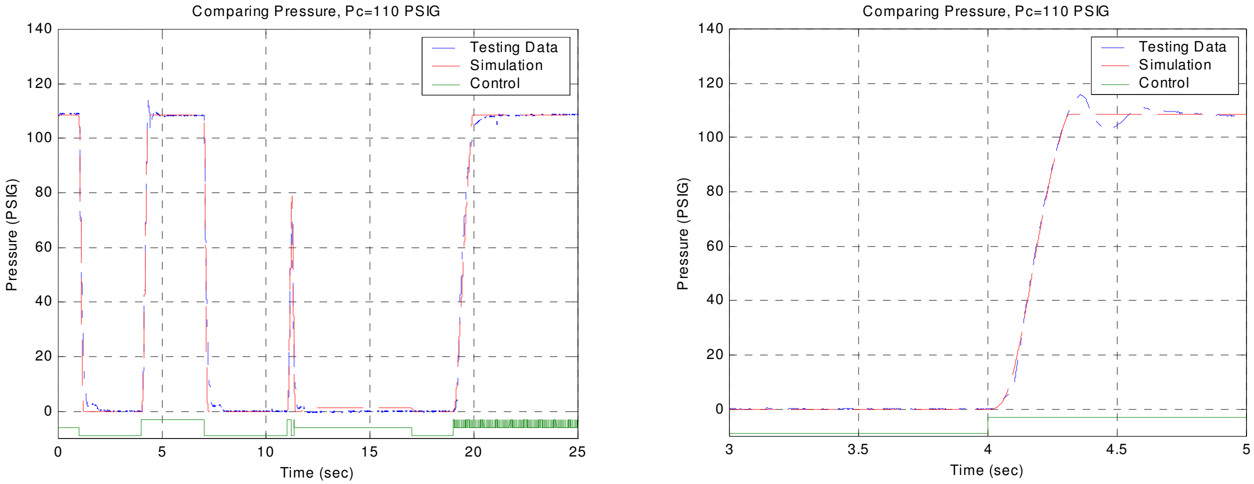
Building pressure (Normalized)



Exhausting pressure (Normalized)

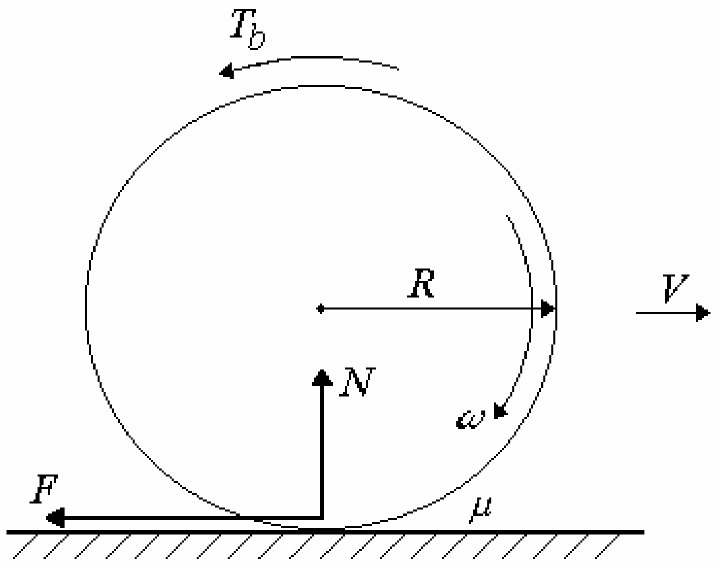
■ Brake Chamber Model Verification

Fully build, Fully exhaust, Turn around, Pulse build



Brake model verification at P_c=110 PSIG

Quarter Vehicle Model\



ω: Wheel angular velocity

F: Tire force

R: Wheel rolling radius

V: Vehicle forward velocity

T_b: Brake torque

N: Normal force on the tire

μ: Coefficient of friction

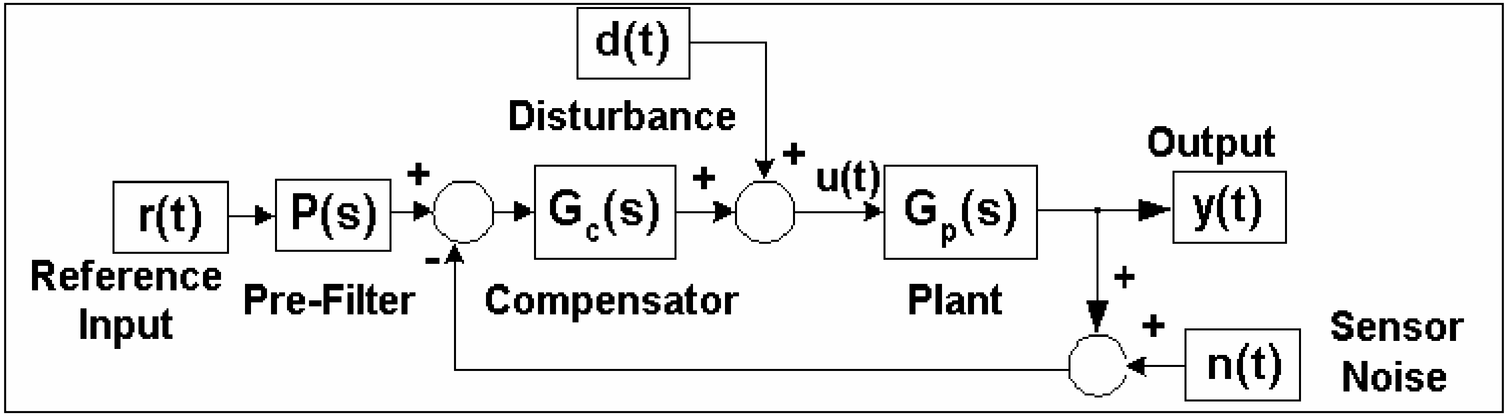
$$\frac{d\omega}{dt} = \frac{N\mu R - K_b P_b}{J}, \qquad \lambda = \frac{V - \omega R}{V}$$

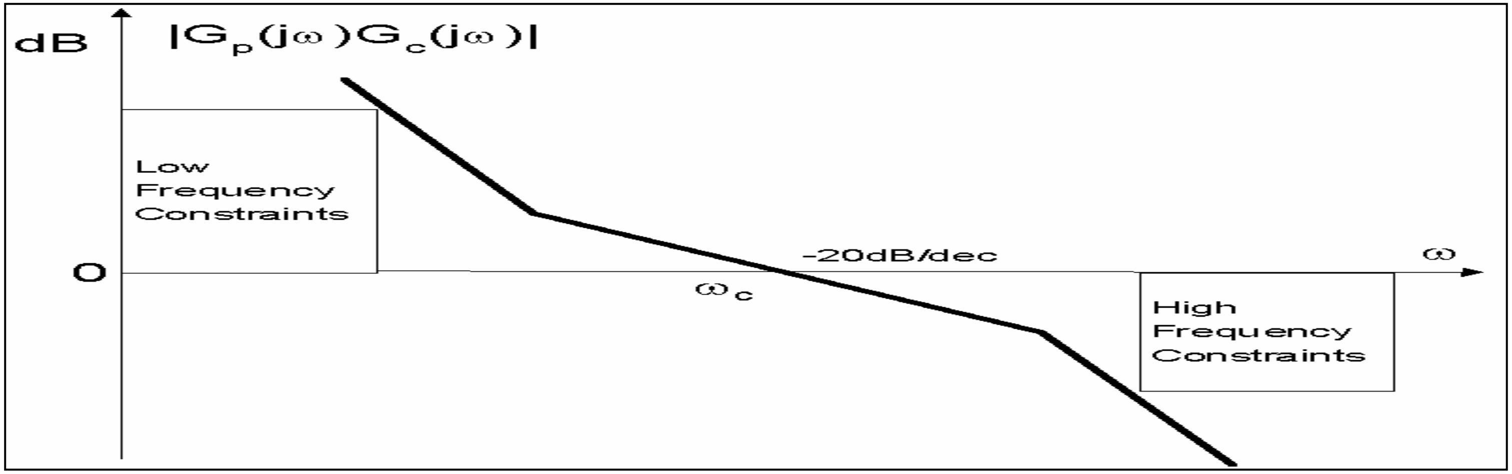
$$\frac{dV}{dt} = \frac{-F}{m} = \frac{-N\mu}{m} = \frac{-mg\mu}{m} = -\mu g$$

ABS Controller Design

- PID
- Loop-shaping
- Nonlinear PID (NPID)

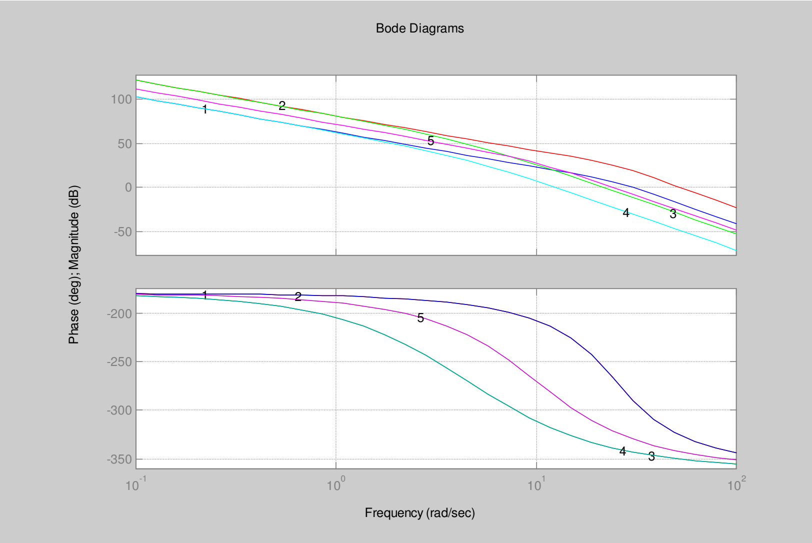
■ Loop-shaping Controller Design





Loop-shaping Controller Design

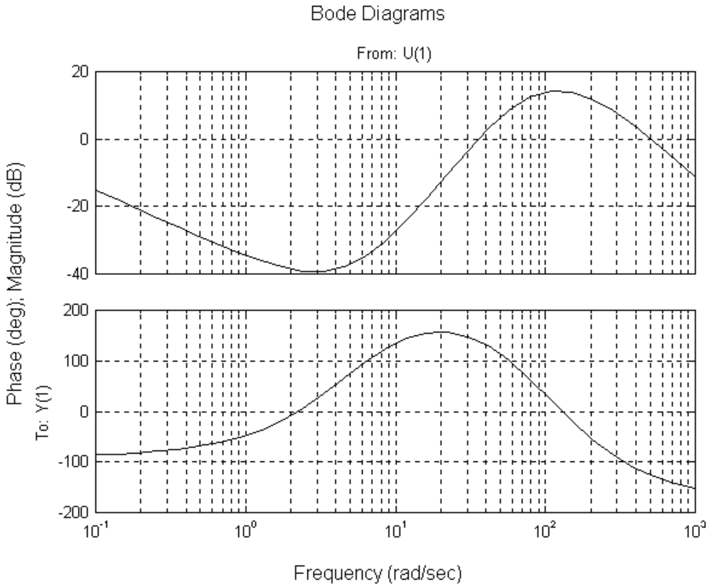
$$G_p(s) = \frac{P_c G_I K_b}{J}\,\frac{1}{s^2(\tau^2 s^2 + 2\tau D s + 1)}$$

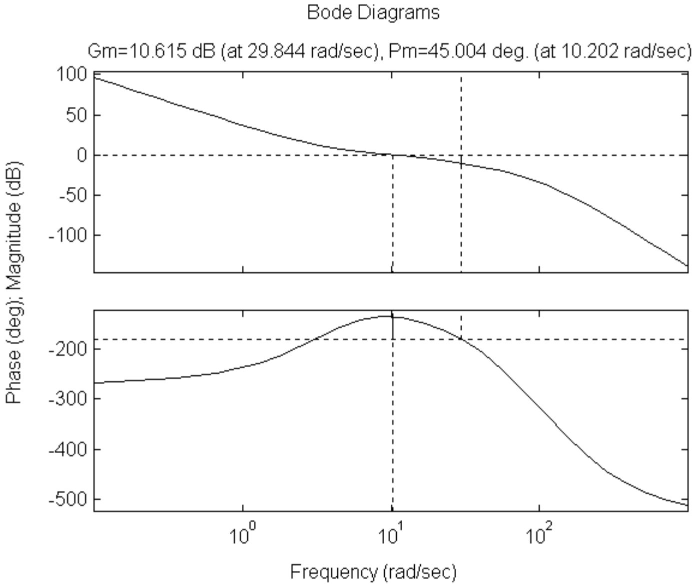


1. Pc=30, G_I=6.3, lowest gain, τ=0.04, D=0.55, fastest
2. Pc=120, G_I=13.2, highest gain, τ=0.04, D=0.55, fastest
3. Pc=120, G_I=13.2, highest gain, τ=0.22, D=1.0, slowest
4. Pc=30, G_I=6.3, lowest gain, τ=0.22, D=1.0, slowest
5. Pc=60, G_I=8.8, τ=0.1, D=0.8, Nominal

Loop-shaping Controller Design

$$G_{c2}(s) = \frac{1.5\times10^{5}(s+5)^{4}}{s(s+100)^{5}}$$





PID vs. NPID

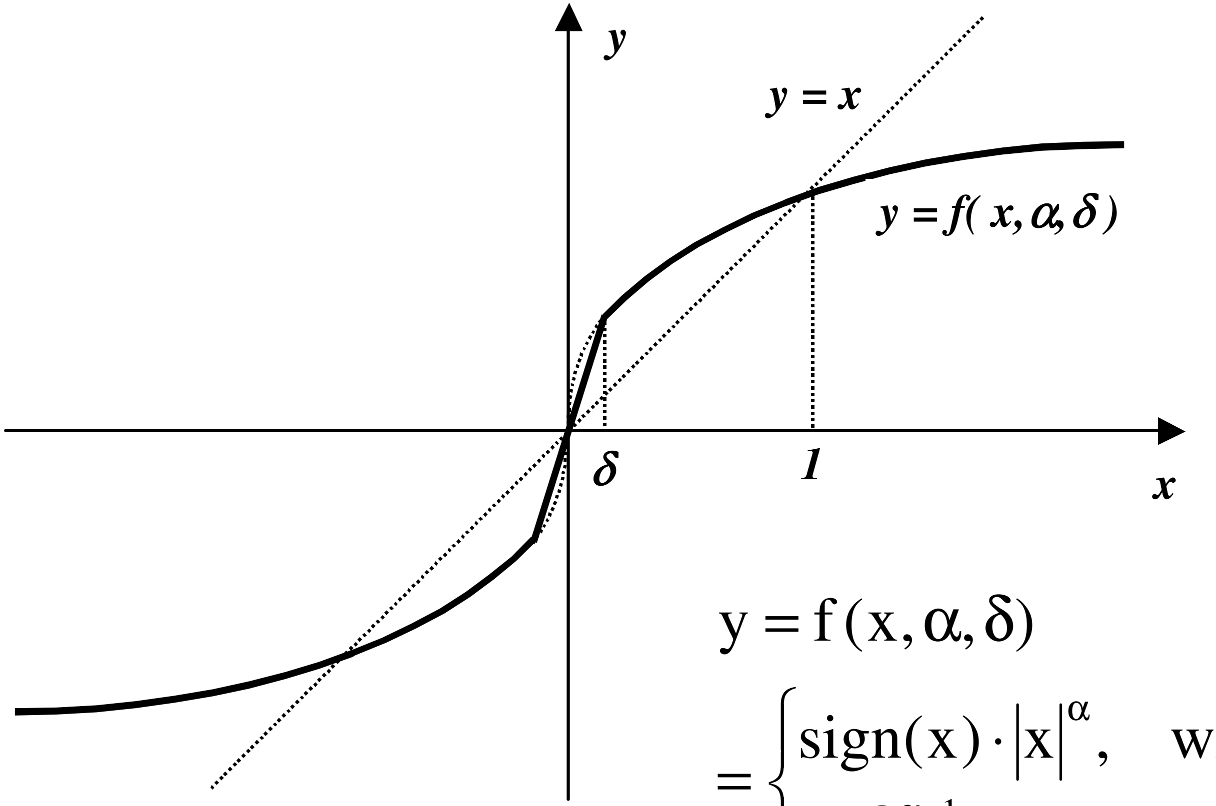
PID:

$$u = K_P\left(e + T_I \int e + T_D \dot{e}\right)$$

NPID:

$$u = K_{NP}\left[f(e, \alpha_P, \delta_P) + T_{NI}\, f\left(\int e, \alpha_I, \delta_I\right) + T_{ND}\, f(\dot{e}, \alpha_D, \delta_D)\right]$$

■ PID vs. NPID



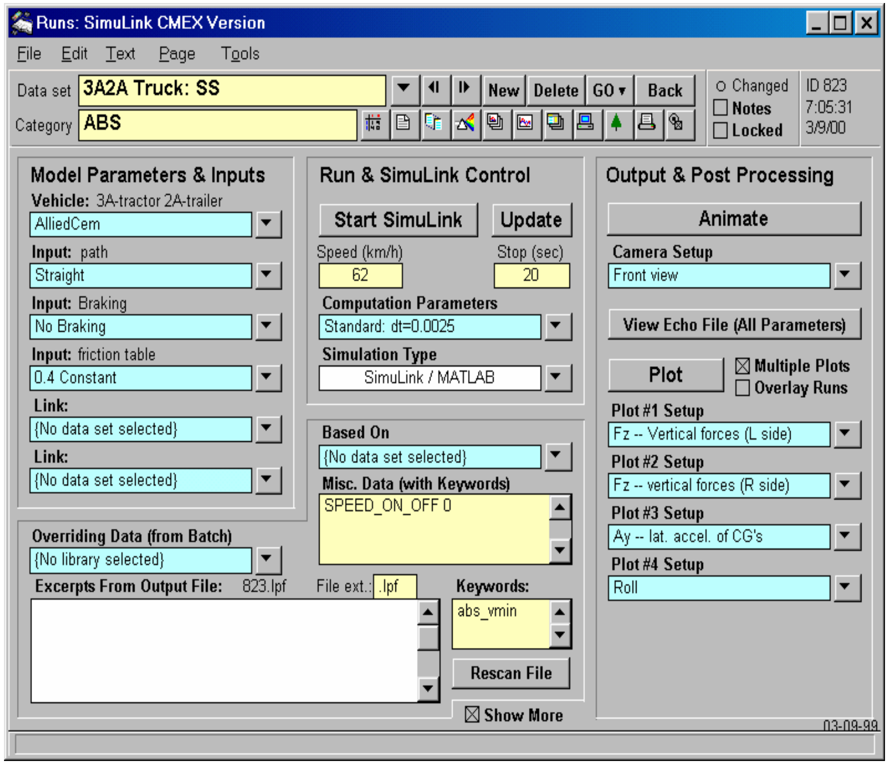
$$y = f(x, \alpha, \delta) = \begin{cases} \operatorname{sign}(x) \cdot |x|^{\alpha}, & \text{when } |x| > \delta \\ \delta^{\alpha-1} \cdot x, & \text{when } |x| \le \delta \end{cases}$$

TruckSim Simulation

- TruckSim Introduction
- Simulation Cases
- Basis for Comparison
- Simulation Results
- Comparison
- Conclusion

TruckSim

- Industrial Simulator
- Formerly by UMTRI
- Now by MSC
- Complete & Complex



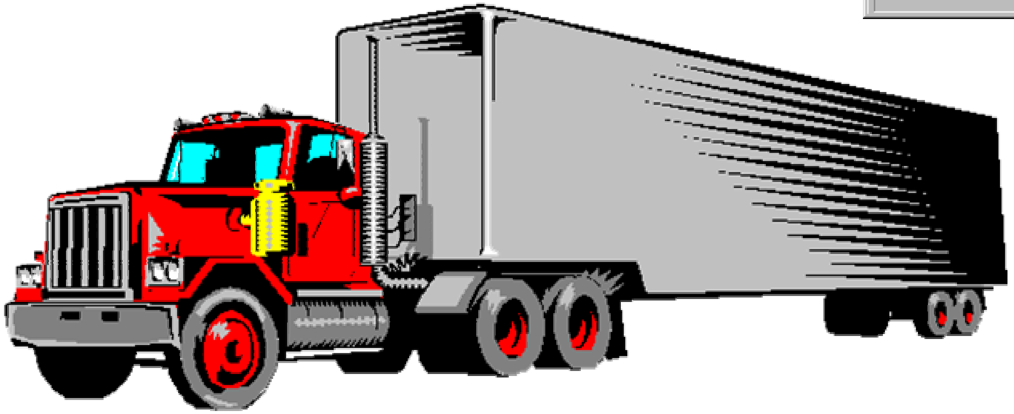
Data set: 3A2A Truck: SS
Category: ABS
○ Changed
☐ Notes
☐ Locked
ID 823
7:05:31
3/9/00

Model Parameters & Inputs
Vehicle: 3A-tractor 2A-trailer: AlliedCem
Input: path: Straight
Input: Braking: No Braking
Input: friction table: 0.4 Constant
Link: {No data set selected}
Link: {No data set selected}
Overriding Data (from Batch): {No library selected}
Excerpts From Output File: 823.lpf

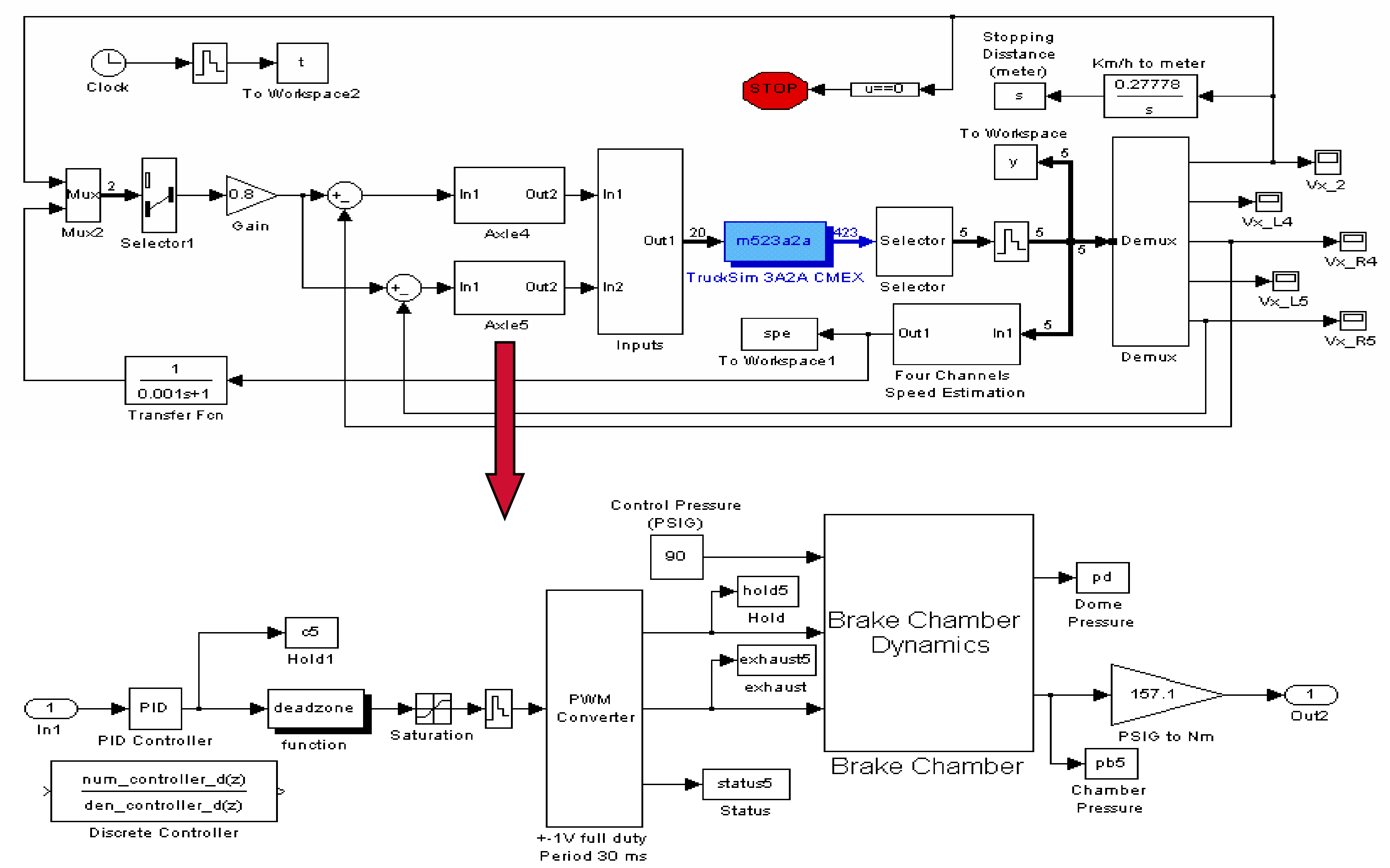
Run & SimuLink Control
Speed (km/h): 62
Stop (sec): 20
Computation Parameters: Standard: dt=0.0025
Simulation Type: SimuLink / MATLAB
Based On: {No data set selected}
Misc. Data (with Keywords): SPEED_ON_OFF 0
File ext.: .lpf
Keywords: abs_vmin
☒ Show More

Output & Post Processing
Camera Setup: Front view
☒ Multiple Plots
☐ Overlay Runs
Plot #1 Setup: Fz -- Vertical forces (L side)
Plot #2 Setup: Fz -- vertical forces (R side)
Plot #3 Setup: Ay -- lat. accel. of CG's
Plot #4 Setup: Roll

TruckSim interface

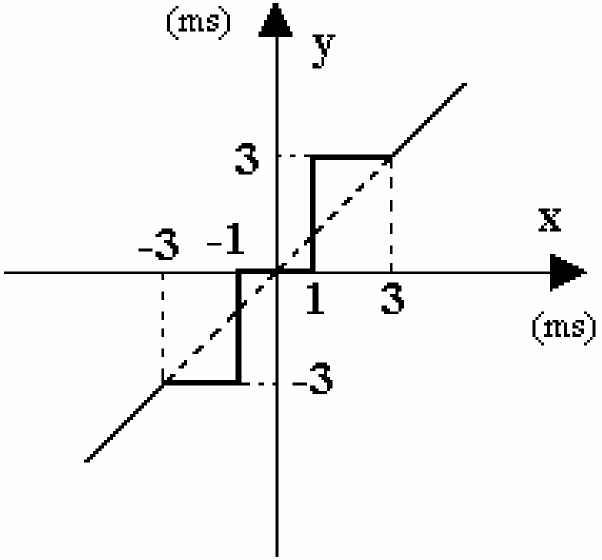


■ TruckSim Introduction



TruckSim Introduction

- Sampling Time 15ms
- Digitized Controller
- First Order Holder
- Saturation
- Valve Deadzone Compensation



■ Simulation Cases

S1): Nominal (P_c=90 PSIG, μ=0.7)

S2): Low μ surface (μ=0.4)

S3): High air supply pressure (P_c=120 PSIG)

S4): Low air supply pressure (P_c=60 PSIG)

S5): Fast brake response

S6): Slow brake response

■ Basis for Comparison

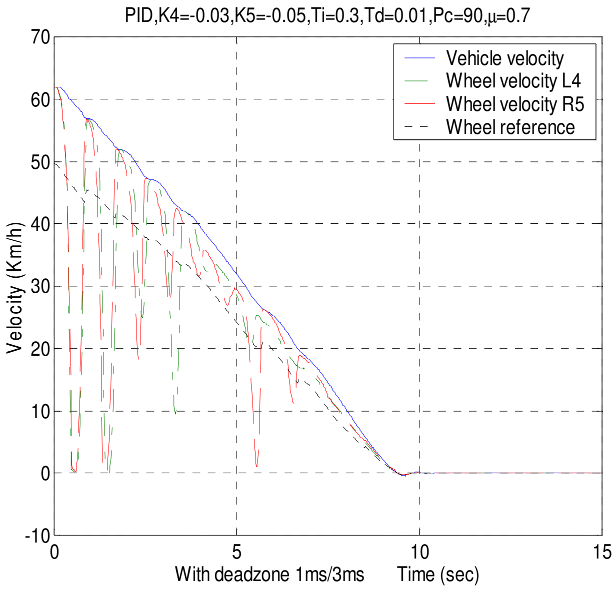
1: Stopping Distance

$$\mathrm{SD} = \int_{t_0}^{t_1} V_V \, dt$$

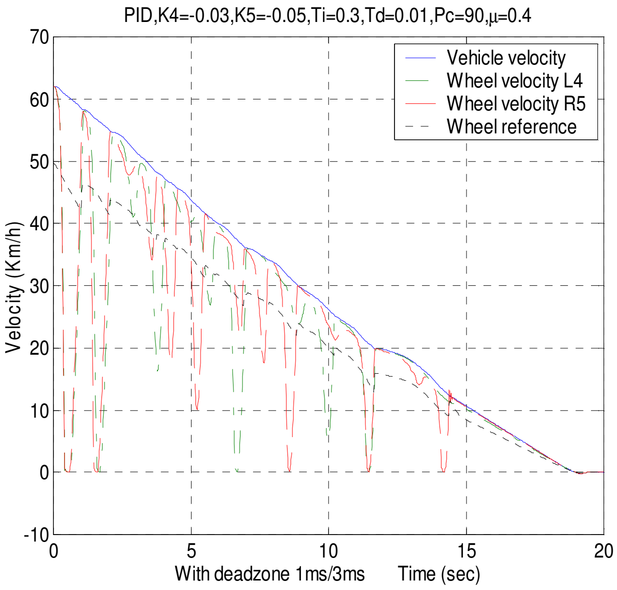
$$2: \quad \|e\|_2 = \sqrt{\sum_i e_i^2}$$

■ Simulation Results (PID)

K_{P4}=-0.03, K_{P5}=-0.05, T_{I4}=T_{I5}=0.3, T_{D4}=T_{D5}=0.01



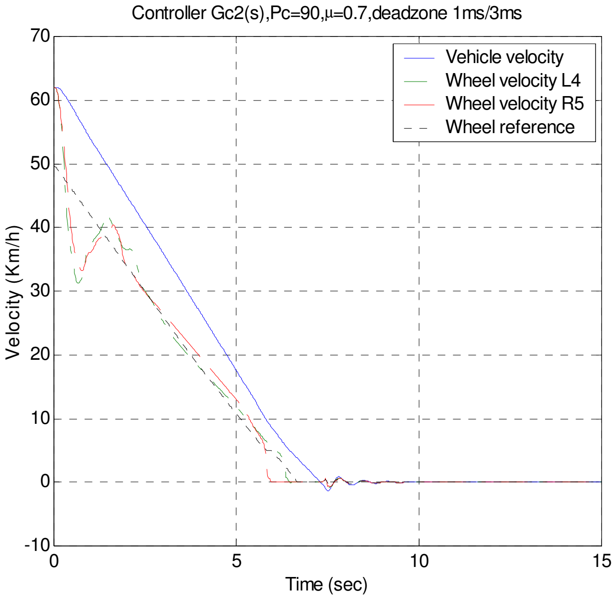
S1: Nominal



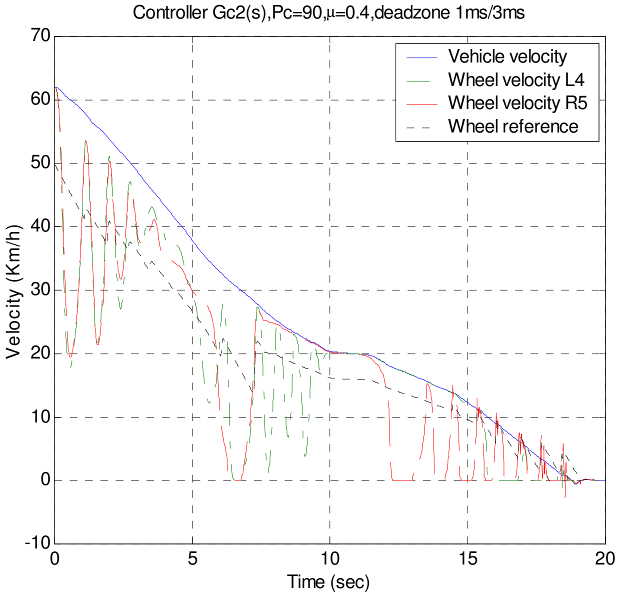
S2: Low μ

■ Simulation Results (Loop-shaping)

$$G_{d2}(z) = \frac{-0.59563 \times (z-0.9277)^4 (z+1)^2}{(z-1)(z-0.1429)^5}$$



S1: Nominal



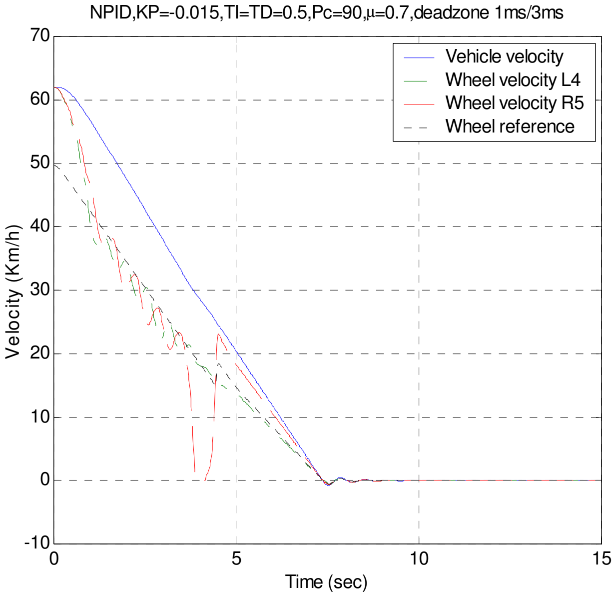
S2: Low μ

■ Simulation Results (NPID)

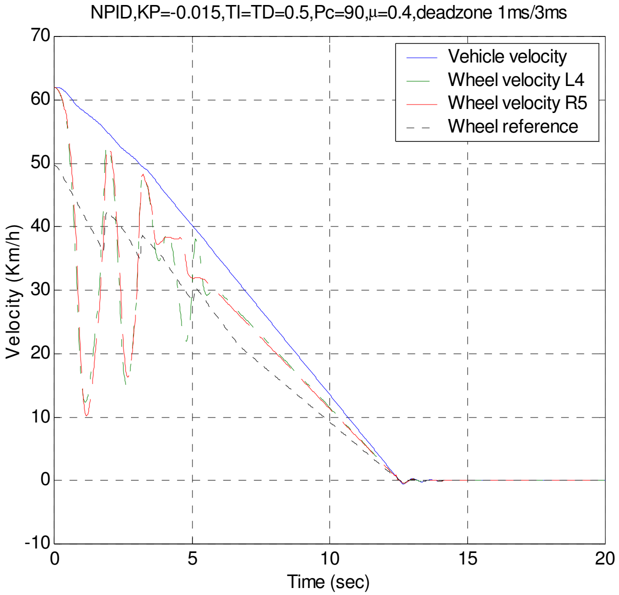
$$\alpha_P = \alpha_I = \alpha_D = \alpha = 0.5$$

$$\delta_P = \delta_I = \delta_D = \delta = 0.1$$

K_{NP}=-0.015,
T_{NI}=T_{ND}=0.5



S1: Nominal



S2: Low µ

Comparison

Stopping Distance

SD (Stopping distance)		PID	Loop-shaping	NPID
Nominal	S1	86.3	61.3^{Δ}	65.9^{*}
Low μ	S2	154.1	139.9	114.6^{Δ}
High air supply pressure	S3	91.0	63.4^{Δ}	66.4^{*}
Low air supply pressure	S4	83.3	62.5^{Δ}	66.7^{*}
Fast brake response	S5	78.5	80.4	64.3^{Δ}
Slow brake response	S6	94.7	67.6^{Δ}	70.8^{*}

$\|e\|_2$

NM (Wheel velocity error 2-norm)		PID	Loop-shaping	NPID
Nominal	S1	740.7	216.1^{Δ}	286.1^{*}
Low μ	S2	945.1	694.2^{*}	603.2^{Δ}
High air supply pressure	S3	770.4	360.2^{Δ}	394.5^{*}
Low air supply pressure	S4	631.7	241.8^{Δ}	256.8^{*}
Fast brake response	S5	594.6	492.7	229.3^{Δ}
Slow brake response	S6	818.6	518.2	377.0^{Δ}