Anti-Lock Braking Systems (ABS) Concepts, Modeling and Simulation

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Overview and ABS background

- Feedback control of a single-braking wheel to avoid lock-up (slip regulation)
- Anti-lock brake system (ABS) modeling and simulation

- Concept dates back to early 1900s, and first patent went to Bosch in 1936.
- Concept is now well established.

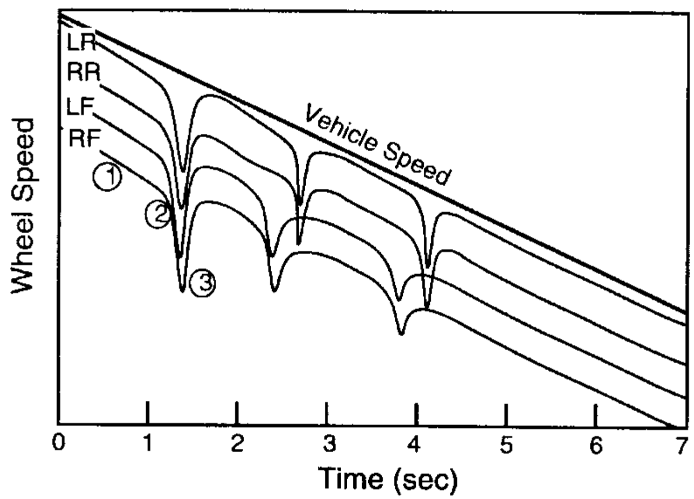


Fig. 3.10 Wheel speed cycling during ABS operation.

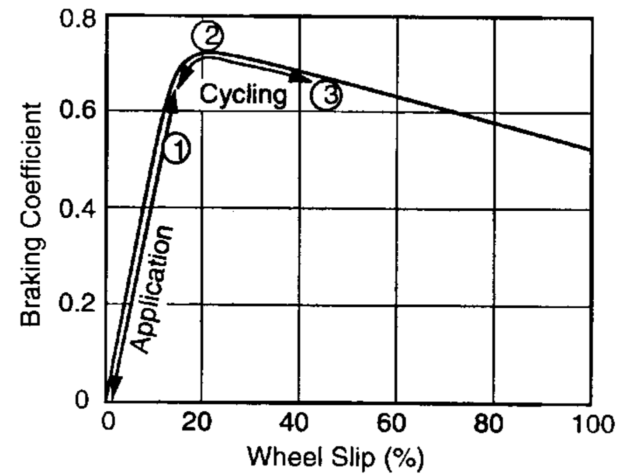


Fig 3.11 ABS operation to stay at the peak braking coefficient.

Figures from Gillespie (1992)

Example ABS operation
Heavy Vehicle with Pneumatic Brakes (Wong, 1993)

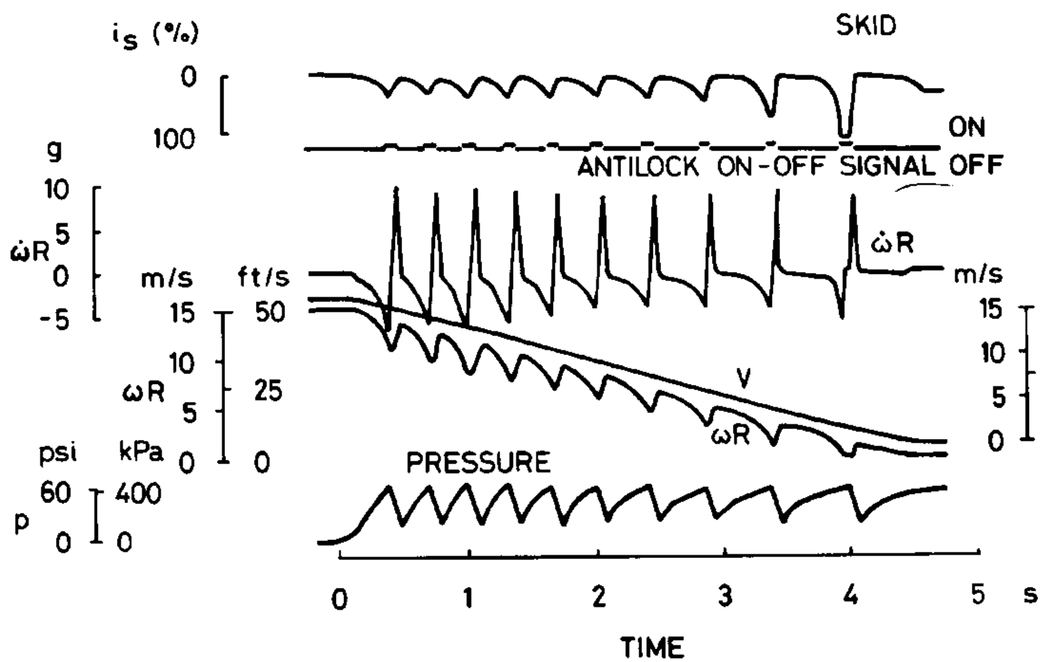


Fig. 3.57 Operating characteristics of an antilock system for heavy commercial vehicles with pneumatic braking systems.

This figure shows results for a heavy vehicle braking on wet pavement.

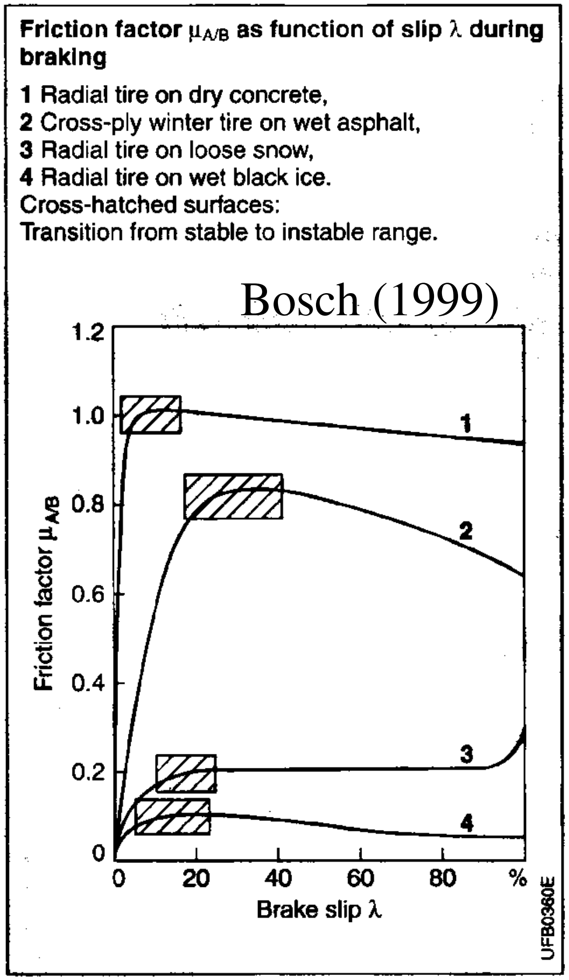
The cycle of reducing and restoring pressure can be repeated from 5 to 16 times per second.

The ABS operation is usually deactivated once the vehicle slows to about 2 or 3 mph.

Anti-lock braking systems

- **Monitor** operating conditions and **modify** the applied braking torque by modulating the brake pressure.
- The systems try to keep tires operating within a desired range of "skid", and by preventing wheel lock-up during braking they can help retain steerability and stability
- Anti-lock braking systems are closed loop control systems **within** the braking system.

Desired range of slip or skid



Trying to control slip in a 'desirable range' is complicated by changing road conditions.

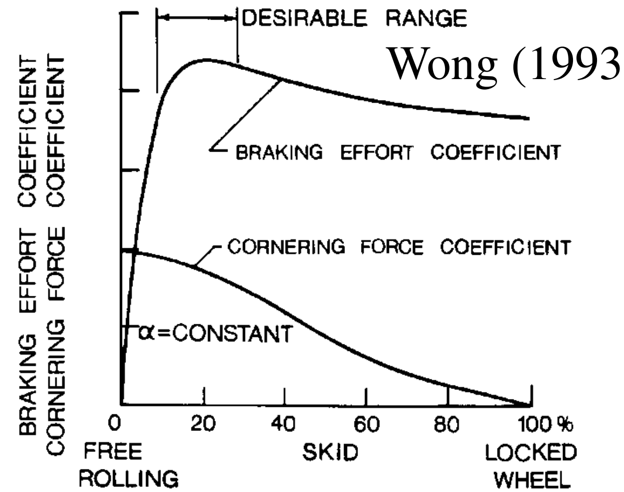


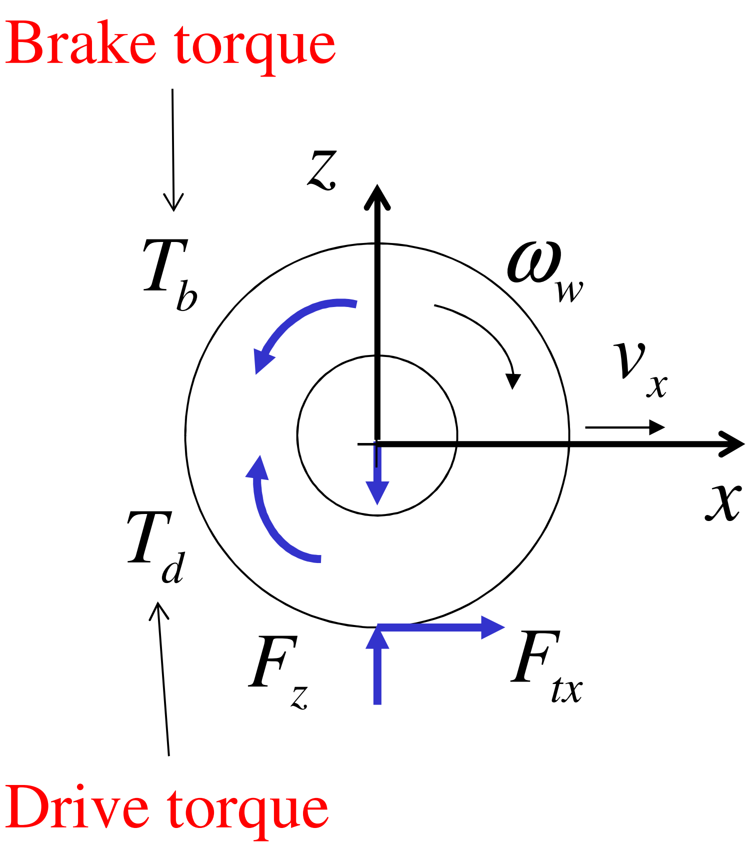
Fig. 3.54 Effect of skid on cornering force coefficient of a tire.

Coefficient of friction μ_{HF} between tire and road surface

Vehicle speed km/h	Tire condition	Dry road surface μ_{HF}	Wet road surface (water-depth 0.2 mm) μ_{HF}	Heavy rain (water-depth 1 mm) μ_{HF}	Puddles (water-depth 2 mm) μ_{HF}	Surface ice (black ice) μ_{HF}
50	new	0.85	0.65	0.55	0.5	0.1 and lower
	worn out	1	0.5	0.4	0.25	
90	new	0.8	0.6	0.3	0.05	
	worn out	0.95	0.2	0.1	0.0	
130	new	0.75	0.55	0.2	0	
	worn out	0.9	0.2	0.1	0	

Dynamics of a braking tire

Rotational dynamics of a wheel in traction or braking,



$$I_w \dot{\omega}_w = T_d - T_{loss} - T_t - T_b$$
$$= T_d - T_{loss} - r \cdot F_{tx} - \underbrace{T_b}_{\text{Brake application}}$$

$$\dot{p}_x = m_v \dot{v}_x = F_{tx} - \sum \text{Road loads}$$

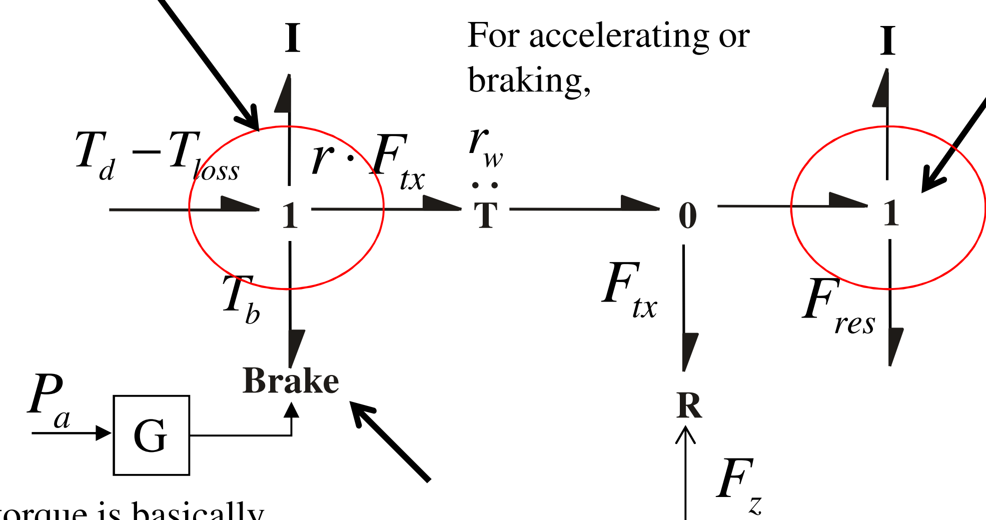
Control problem: longitudinal motion control by using F_{tx} via modulation of T_b

Generally must consider vertical loads and the pitch equation (for load transfer).

Model equations and bond graph for traction/braking

$$
\begin{aligned}
I_w \dot{\omega}_w &= T_d - T_{loss} - T_t - T_b \\
&= T_d - T_{loss} - r \cdot F_{tx} - \underbrace{T_b}_{\text{Brake application}}
\end{aligned}
$$

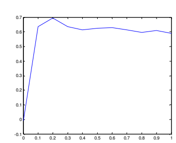
$$\dot{p}_x = m_v \dot{v}_x = F_{tx} - \sum \text{Road loads}$$



Model for brake torque is basically,

$$T_b = \mu_b \cdot N \cdot \mathrm{sgn}(\omega_w)$$

The normal force is controlled by applied pressure, say by hydraulic system, and may have some form of feedback control slip regulastion (ABS)

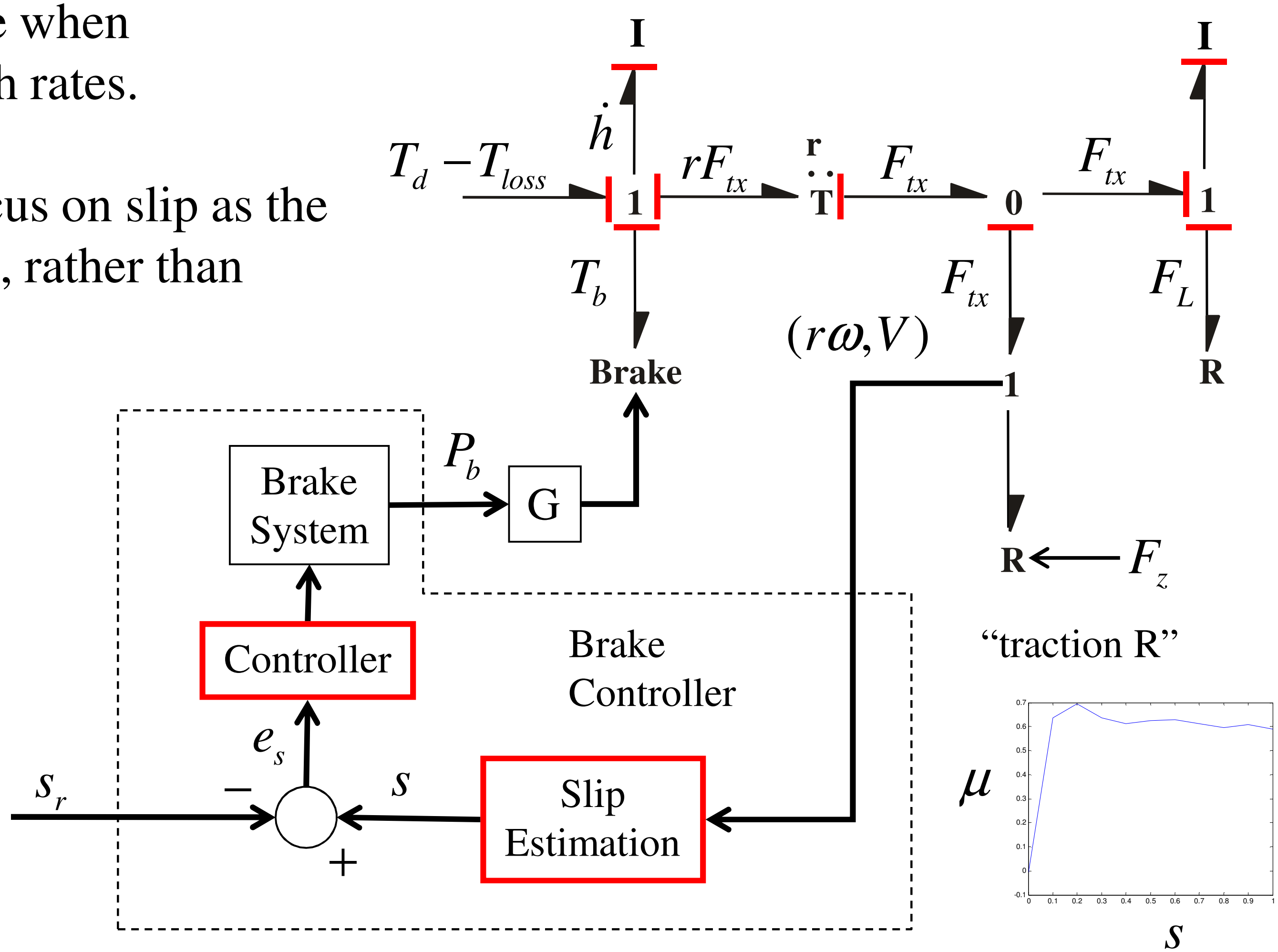


Remember this traction R requires tire-road friction

Controlling slip during braking

Slip is unavoidable when decelerating at high rates.

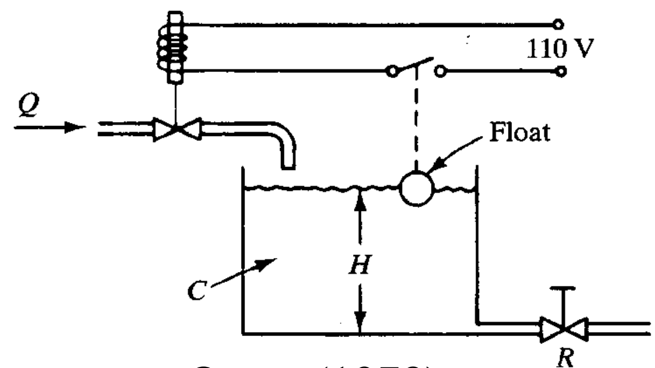
The controllers focus on slip as the controlled variable, rather than vehicle speed.



Reference input

Relation to two-position or on-off controllers

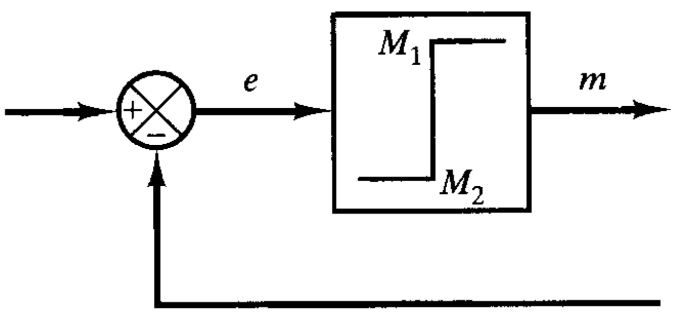
In a two-position control system, the actuating element can take on only two positions, and often this is either on or off. This is a very common and inexpensive way to control systems. For example, a level controller can be built this way, as shown below.



Ogata (1978)

A simple two-position controller could follow the basic rule,

$$m(t) = \begin{cases} M_1 & e(t) > 0 \\ M_2 & e(t) < 0 \end{cases}$$

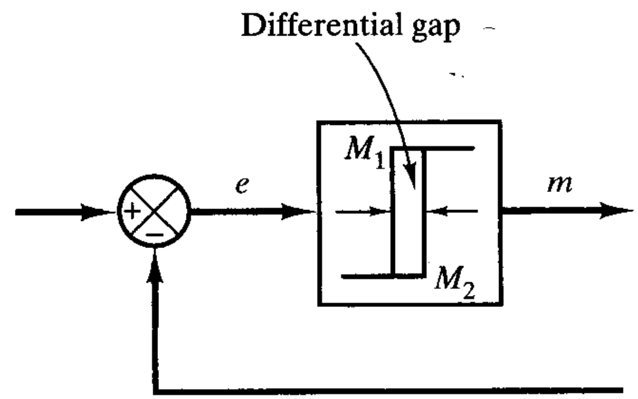


(a) Ogata (1978)

While the controller is in a given position, the system may behave linearly, however on-off controllers are classified as nonlinear because they are not amenable to classical linear control design methods.

On-off controller issues

Sometimes there may be some **hysteresis** in an on-off controller. The range that the error signal must go through before actuating either way is called the **differential gap**.



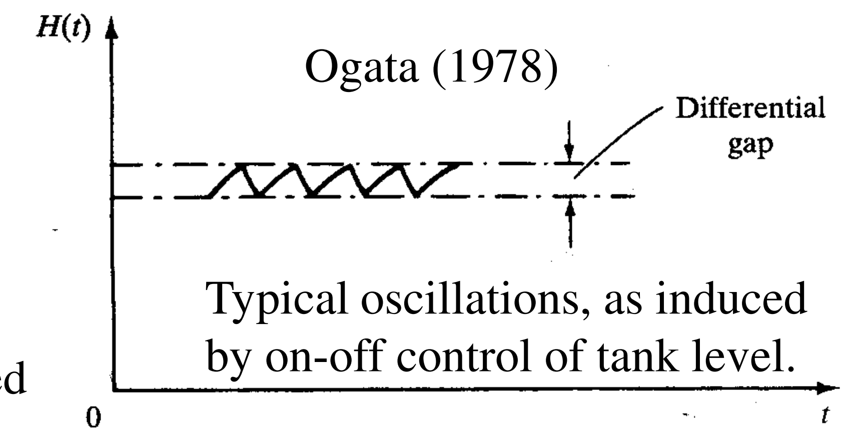
The hysteresis may be unintentional (caused by friction or gap in the mechanism), or it may be designed into the control action.

Example: on/off in steering of wall-follower

One reason to purposefully include hysteresis in an on-off controller is to 'slow down' the switching between the two-states.

Switching too often can lead to reduced life in the control actuating element. A differential gap, however, will cause the output to have some oscillations, the amplitude of which can be reduced by decreasing the gap.

Ogata (1978)



Typical oscillations, as induced by on-off control of tank level.

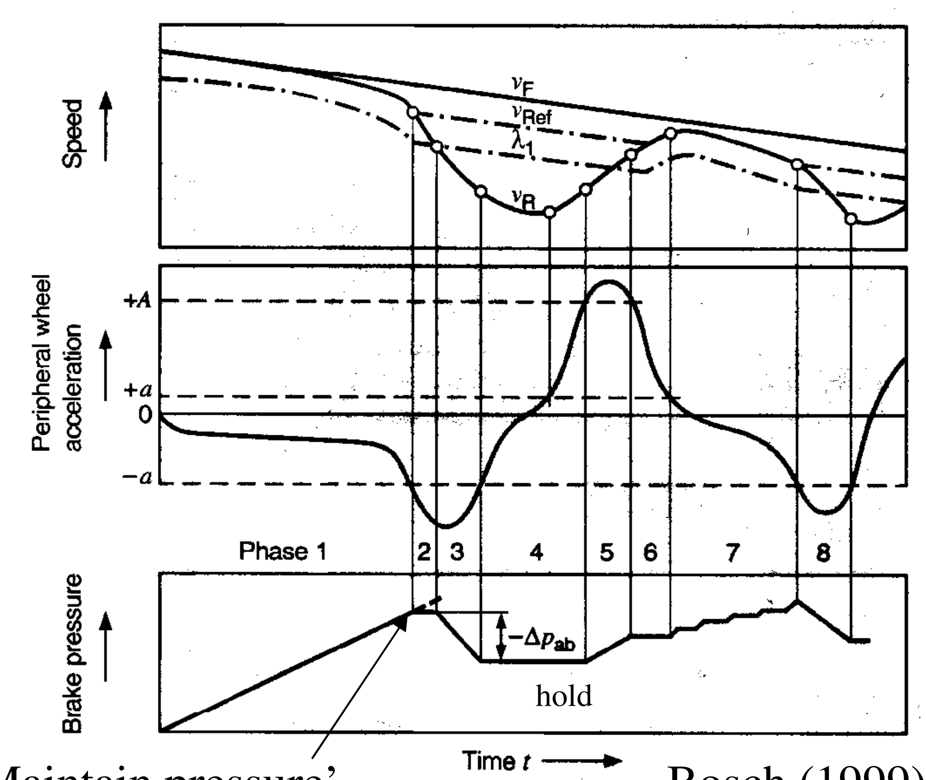
Typical ABS control cycle (from Bosch)

Not your 'basic' on-off control!

- This figure shows cycling on a high traction surface.
- Monitoring 'peripheral acceleration'.
- The reference speed is used to determine the slip switching threshold.
- Pressure is dropped as long as peripheral acceleration is below threshold.
- Increases in acceleration will lead to pressure build-up, but there are 'gaps' where system waits.

Braking control for high braking-force coefficients

v_F Vehicle speed, v_{Ref} Reference speed, v_R Peripheral wheel speed, λ_1 Slip switching threshold, $+A$,$+a$ Thresholds of peripheral wheel acceleration, $-a$ Threshold of peripheral wheel deceleration, $-\Delta p_{ab}$ Brake-pressure decrease.



'Maintain pressure'

Bosch (1999)

Modeling an ABS system

- Vehicle dynamics and base brake system
- Wheel speed sensors
- Hydraulic modulator and valves
- Control Module (all logic, diagnostics)
- Other: pedal travel and switch, accelerometers, accumulator and electric priming

We have a basic one-wheel model, 'ideal' wheel and vehicle speed sensing.
Now we need to turn brake pressure on and off…

Studying implementation in simulation

1. What's the simplest ABS model you can build that gives realistic results? Likely need some minimal hydraulics. We find that having a <u>pure on/off</u> gives unrealistic effects.
2. Do you need to include hydraulics? I think the true nature of ABS requires inherent dynamics that arise from the hydraulic components.
3. What is the simplest model that includes some 'hydraulics'? Need to at least model the pressure build-up. The lag due to the lines can actually be removed.
4. Do you need to implement a differential gap? Probably not. I think the hydraulics adds the a delay effect that leads to a more realistic model.

Simple on/off, no hydraulics (no differential gap)

Is it sufficient to represent an ABS controlled braking system with just on/off control?

This sets the pressure on and off.

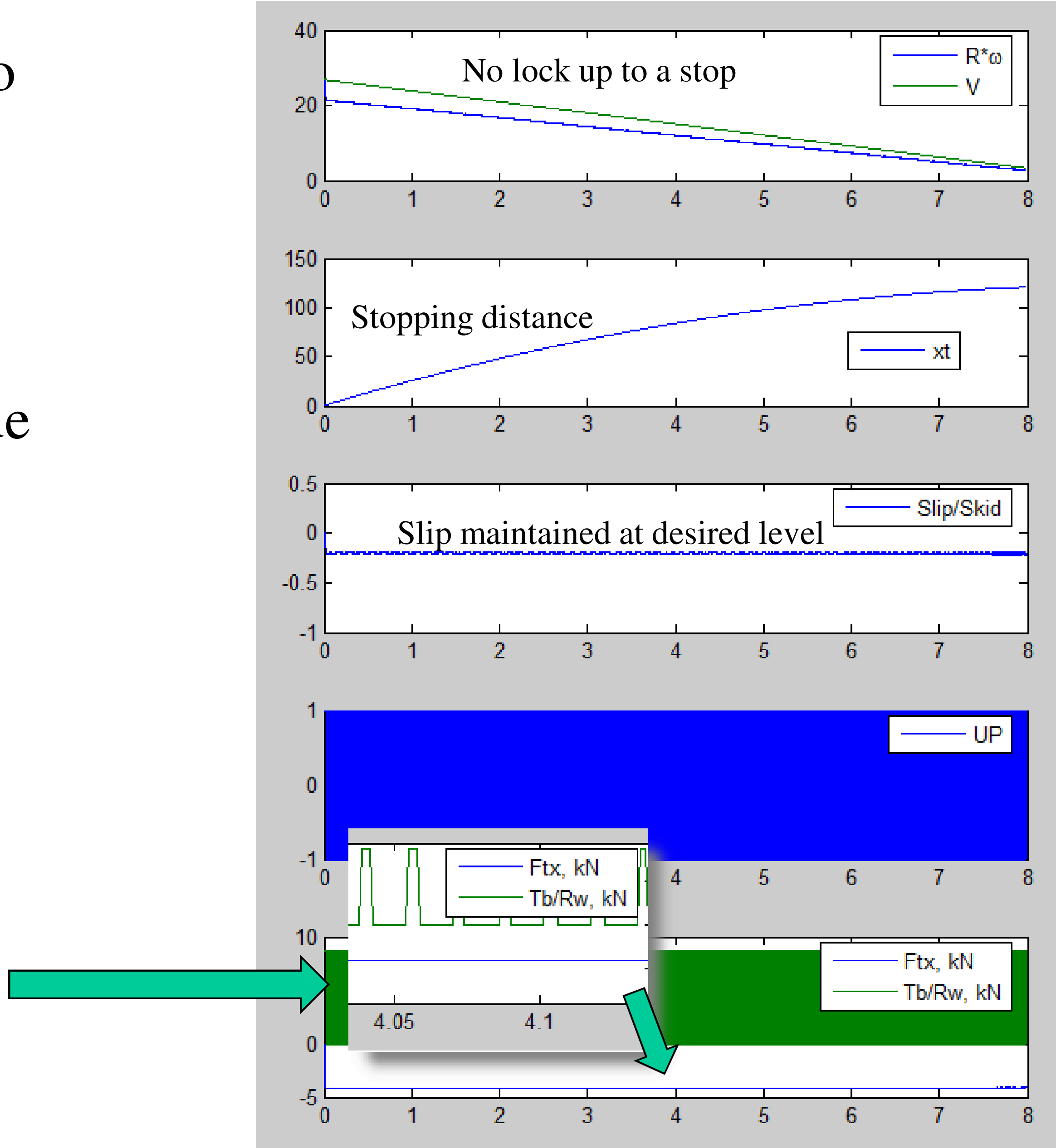
```
% determine slip state
s1 = (Rw*omega-V)/max(Rw*omega,V);
mu_ex = 0.7; % for extrapolation, keep mu at nominal value
mu1 = sign(s1)*interp1(slip,mu,abs(s1),'linear',mu_ex);
Ftx = +mu1*mv*g/Nw;
Tt=Rw*Ftx;

% Feedback for ABS
% slip_ref is the specified slip reference value

% Note, routine above gives + or - slip.
slip_error = slip_ref - abs(s1);

% Control: if slip is less than the reference value, increase pressure
% if slip is greater than reference value, decrease pressure

UP = sign(slip_error);
Kf = 6.895e5; % this is 100 psi expressed in Pa
% ideal pressure on/off
Pb = Kf*0.5*(UP+1);
% Assume same pressure goes to all Nw tires
Tb=G*abs(Pb);

% Net torque on one wheel
T = Td - Tb*sign(omega) - Tt;
```

So simple on/off works to control the slip at the reference level, keeping wheel from locking up.

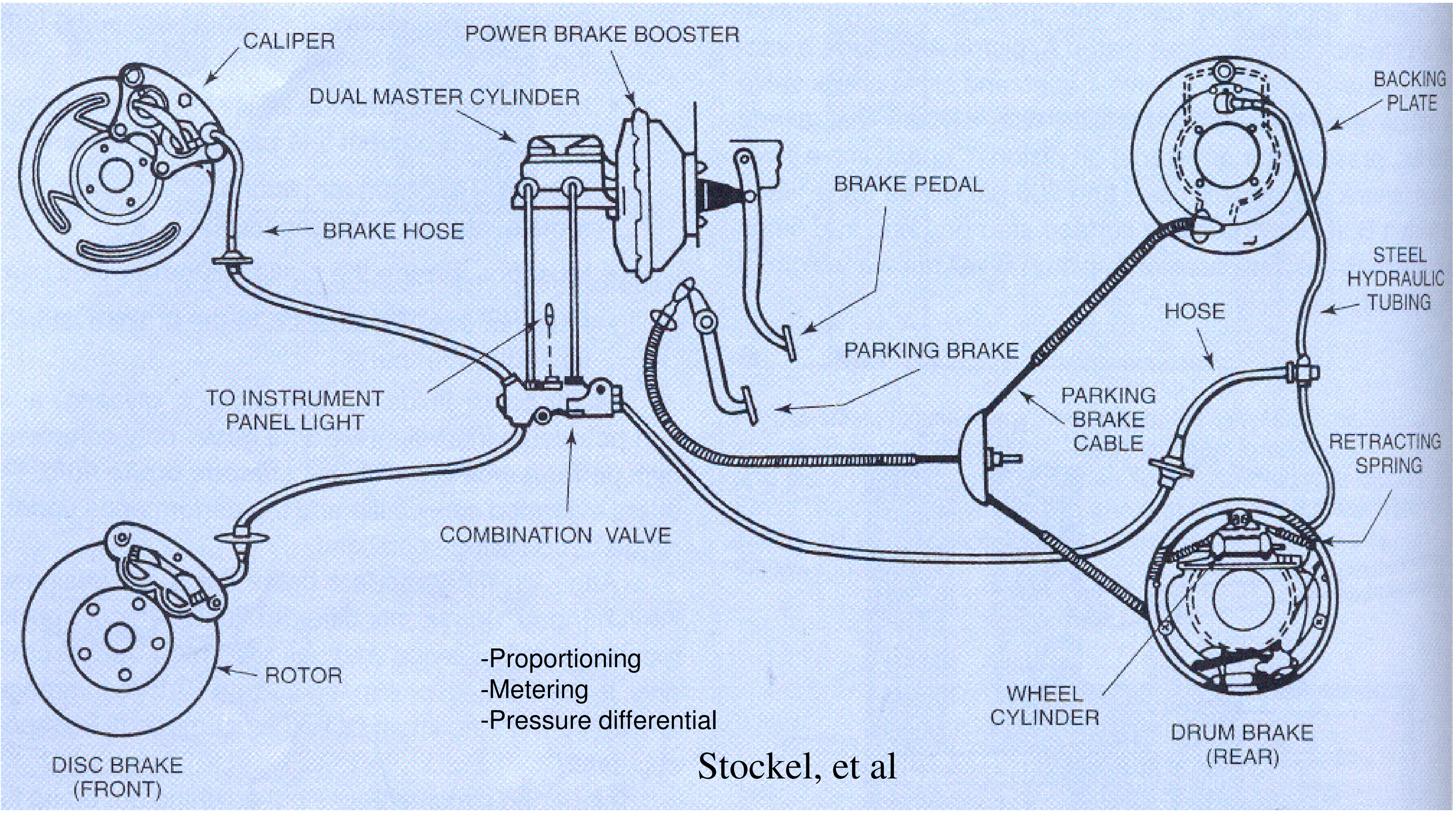
However, the brake torque is turned on and off at a very high rate.

This is not realistic or practical.

The green graph shows the high frequency brake torque pulsing.

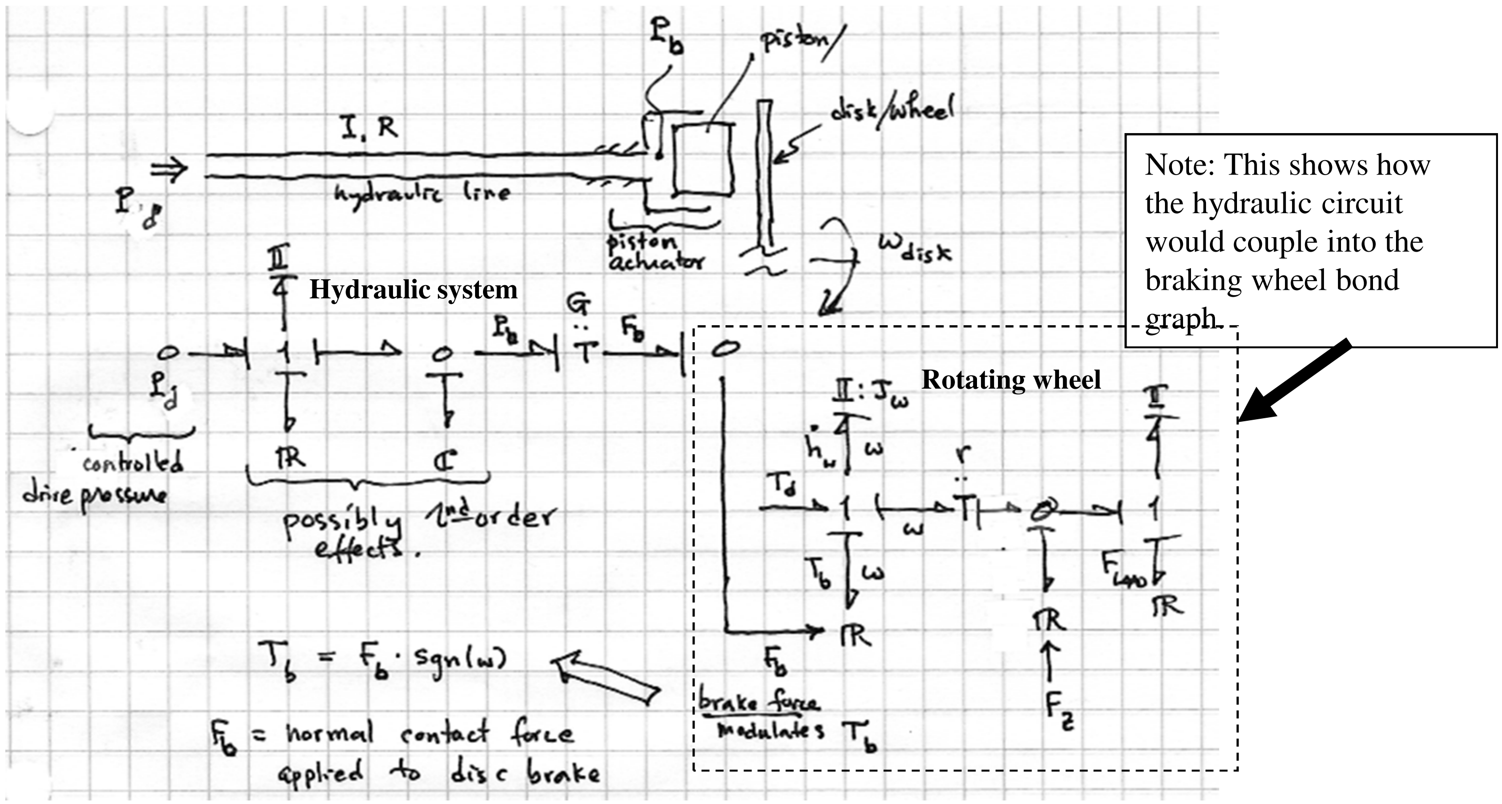


Basic brake actuation system, showing hydraulic lines, etc.



Model of a simple hydraulic line and pressure build-up

We don't really have many details, so let's construct a simple hydraulic line. Assume there is an input pressure commanded by your controller, P_d. This pressure would travel through a hydraulic line having some inertia, *I*, some resistance, *R*, terminated by a piston actuator, where pressure might build up to P_b. This pressure would induce a normal force, F_b, on disc brake caliper. This is illustrated below:

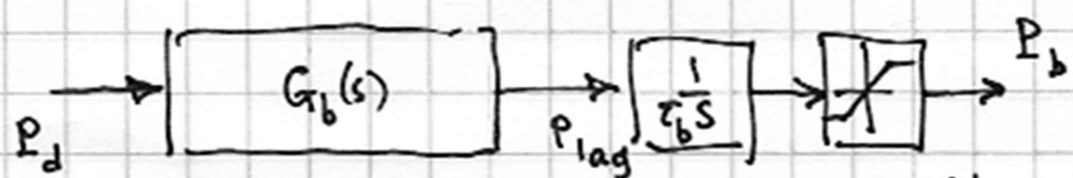


NOTE: $P_b \rightarrow F_b \rightarrow T_b$

Integrating into a system model

We'll model the line with a 'hydraulic lag', so the pressure at the end of that line would then build up through an integrator (this is like a hydraulic capacitor). It is good practice to include a saturation to limit the pressure output, P_b, to some maximum value. This P_b pressure sets the disc brake force.

In a block diagram form, we can show the progression as follows.



Also, let pressure build up:

$$P_b = \frac{1}{\tau_b s} \cdot P_{lag}$$

but it saturates at $P_{b\,max}$

$$G_b(s) = \frac{K_{lag}}{\tau_{lag} s + 1}.$$

$$\frac{P_{lag}}{P_b} = \frac{K_{lag}}{\tau_{lag} s + 1}.$$

But we want to write code, so we convert the transfer functions shown into ODEs.

Deriving the hydraulic model equations

Begin with the hydraulic line, and convert the transfer function to time-domain ODE:

$$\frac{P_{lag}}{P_d} = \frac{K_{lag}}{\tau_{lag} s + 1} \Rightarrow P_{lag}\left(\tau_{lag} s + 1\right) = K_{lag} P_d$$

$$\tau_{lag} s P_{lag} + P_{lag} = K_{lag} P_d$$

$$\Rightarrow \tau_{lag} \dot{P}_{lag} + P_{lag} = K_{lag} P_d$$

$$\text{or: } \dot{P}_{lag} = \frac{1}{\tau_{lag}}\left(-P_{lag} + K_{lag} P_d\right)$$

Here is one more ODE to add to your model. This is the ODE for P_{lag}. P_d is the pressure at the entrance to the line.

Now, this pressure at the end of the line feeds into the brake actuator cylinder, which is being modeled as a simple 'capacitor', and the pressure is given by,

$$P_b = \frac{1}{\tau_b s} P_{lag} \Rightarrow \tau_b s P_b = P_{lag}$$

$$\text{or: } \dot{P}_b = \frac{1}{\tau_b} P_{lag}$$

Another ODE. This is the ODE for P_b. P_{lag} is found from the other ODE above.

Once you have P_b, you can compute the brake torque: $T_b = G \cdot \text{abs}(P_b)$

Deriving the hydraulic model equations (cont.)

The last piece is setting the 'drive pressure' at the inlet.

We're scaling this value by K_{lag} in this model, so we'll let Pd be the output from the sign function, i.e.,

$$P_d = \text{sign}(\text{slip\_error}) = UP = \begin{cases} +1, \text{slip\_error} > 0 \\ 0, \text{slip\_error} = 0 \\ -1, \text{slip\_error} > 0 \end{cases}$$

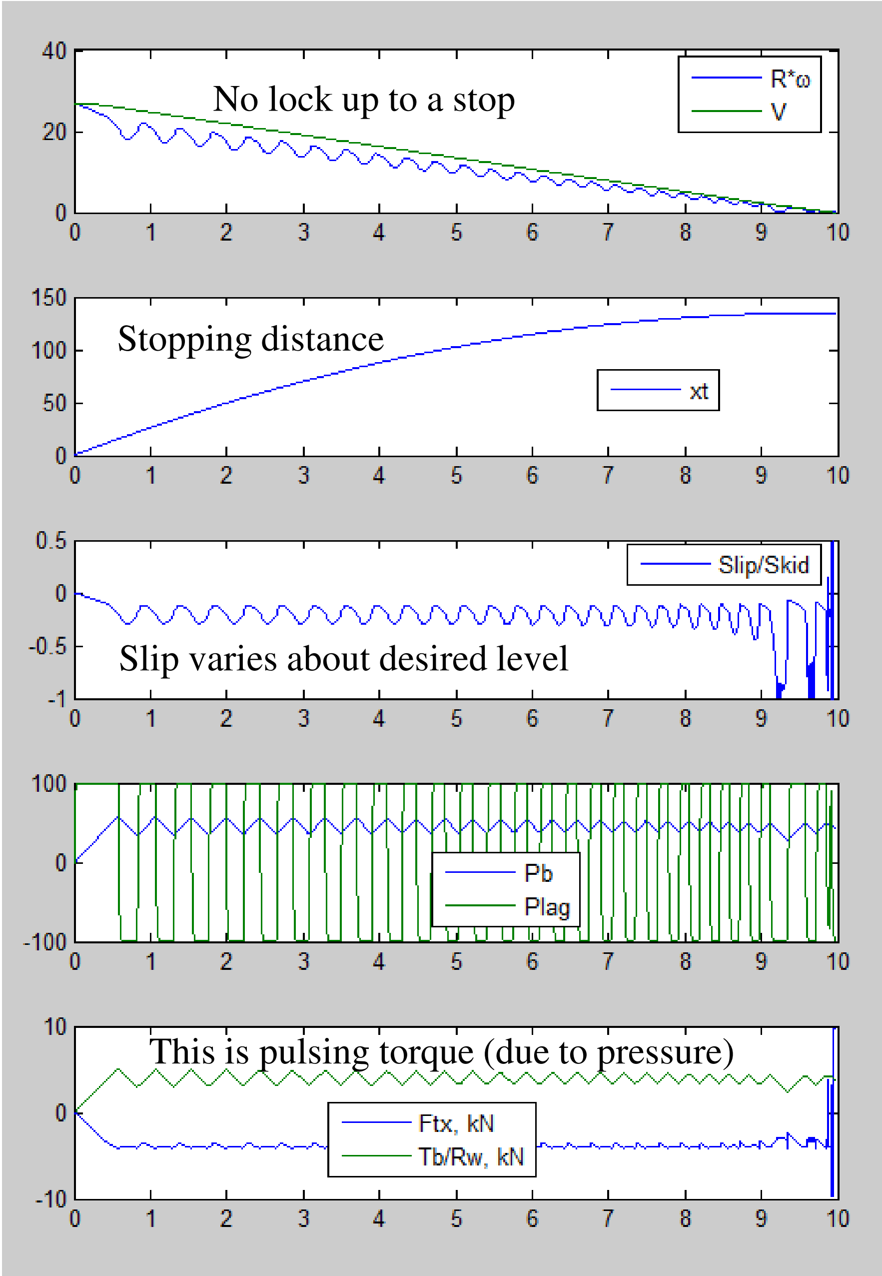
Here is one way to code this model:

```
slip_error = slip_ref - abs(s1);

UP = sign(slip_error);

Klag = 6.895e5; % this is 100 psi expressed in Pa

Plagdot = (-Plag + Klag*UP)/tau_lag; % lag

% if Pb exceeds Pbmax, saturate
if (Pb>Pbmax | Pb<0),
   Pbdot = 0;
else
   Pbdot = Plag/tau_b;
end

% Assume same pressure goes to all Nw tires
Tb=G*abs(Pb);

% This is the net torque on one wheel
T = Td - Tb*sign(omega) - Tt;
```

Here is a result from using the ABS simulation with hydraulics.

The brake torque varies in a pulsing manner as expected.

This is more realistic and practical.



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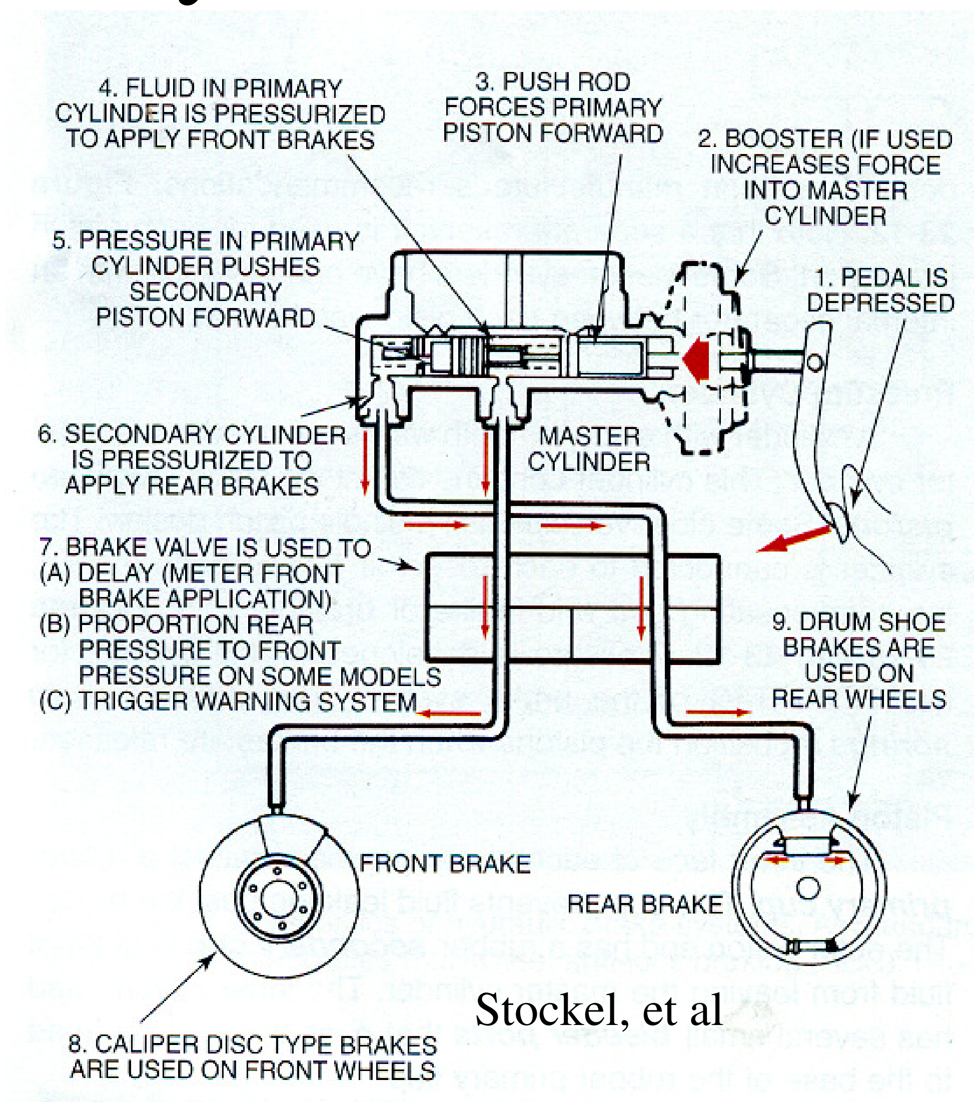
Appendix

Braking systems, hydraulics

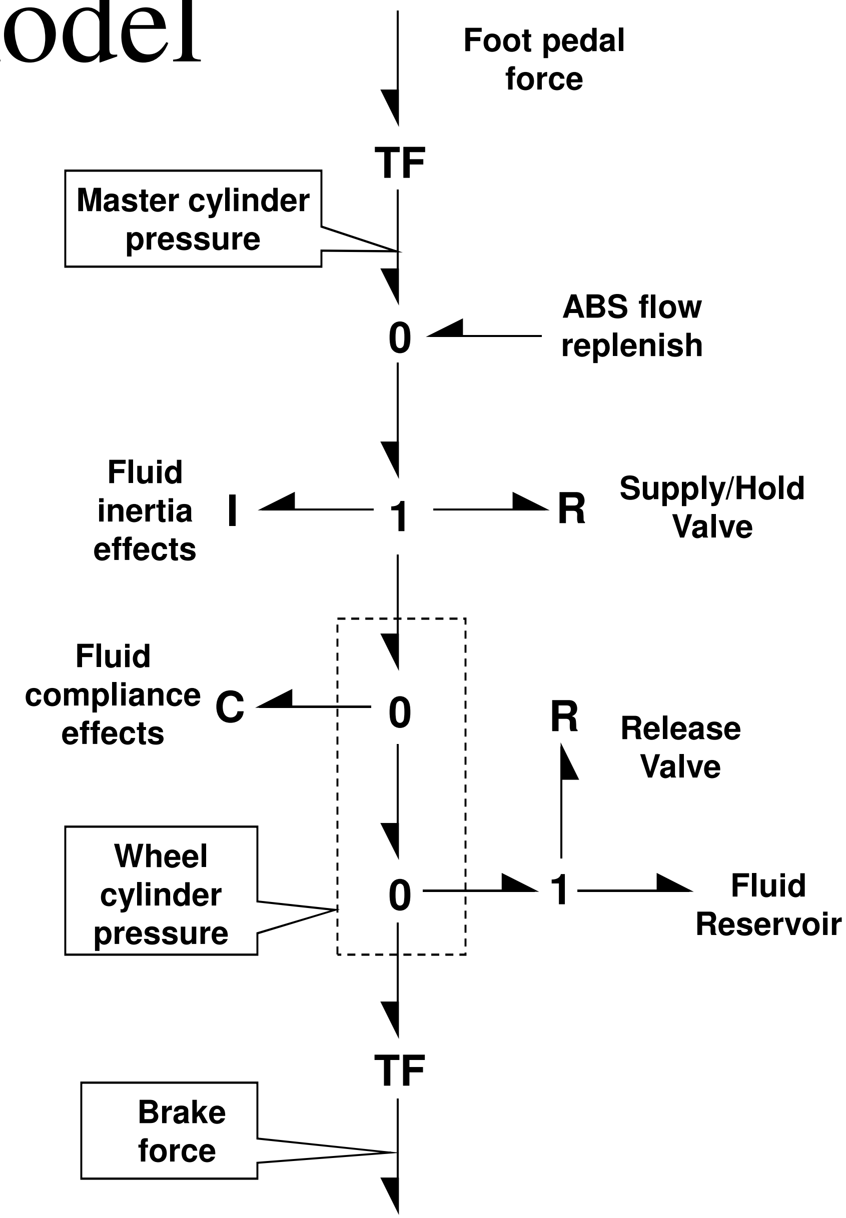
Scaled-vehicle braking experiments

Matlab/Simulink ABS simulation

Hydraulic circuit model



Stockel, et al

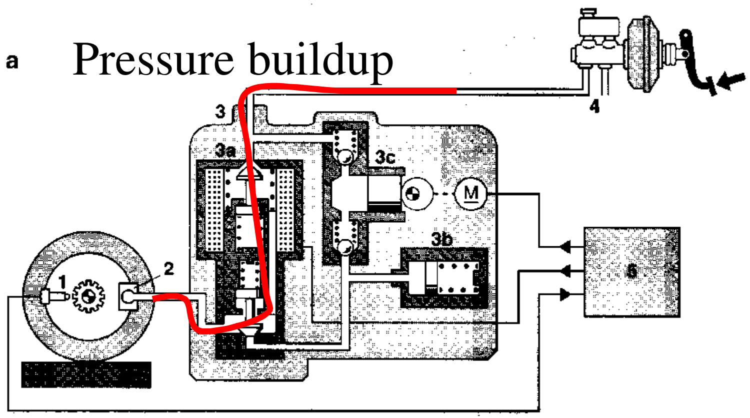


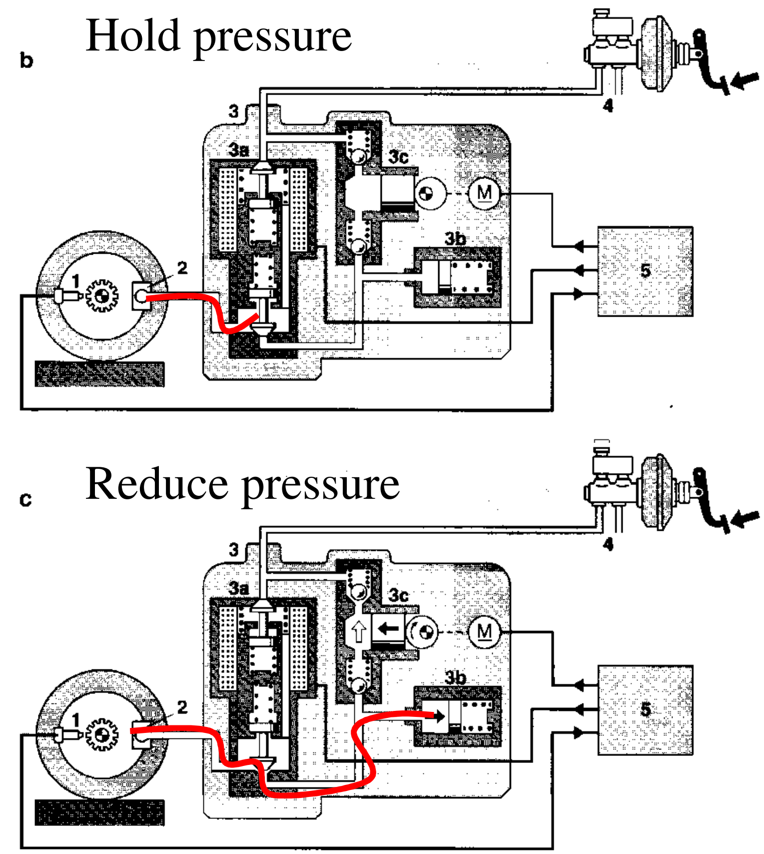
Brake-pressure modulation

Brake-pressure modulation

a Pressure buildup, **b** Hold pressure, **c** Reduce pressure.
1 Wheel-speed sensor, **2** Wheel-brake cylinder, **3** Hydraulic pressure modulator, **3a** Solenoid valve,
3b Accumulator, **3c** Return pump, **4** Brake master cylinder, **5** ECU.
—— "Dead" line, —— Current-carrying line.

Bosch (1999)

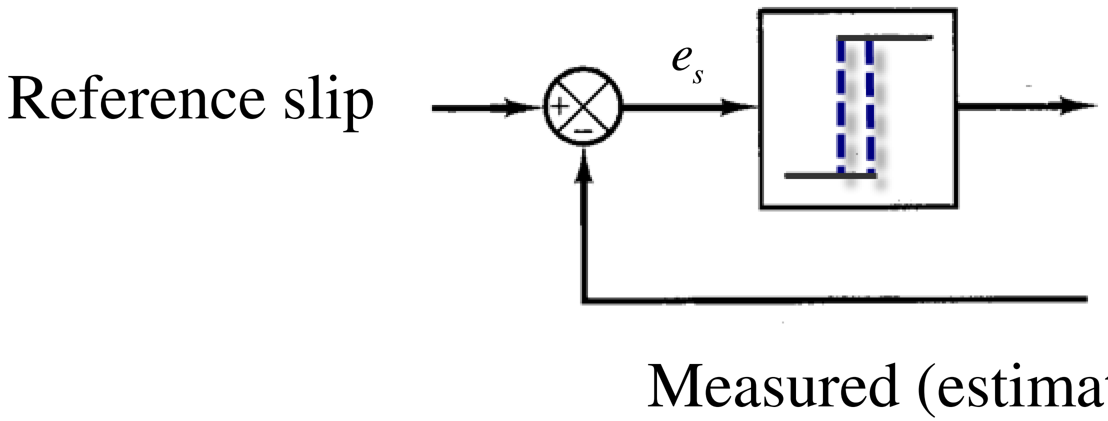




- Pressure decrease at appropriate wheel
- Pressure hold
- Pressure increase

On-off control of a pressure modulator

Can use a simple two-position controller, maybe with some gap.



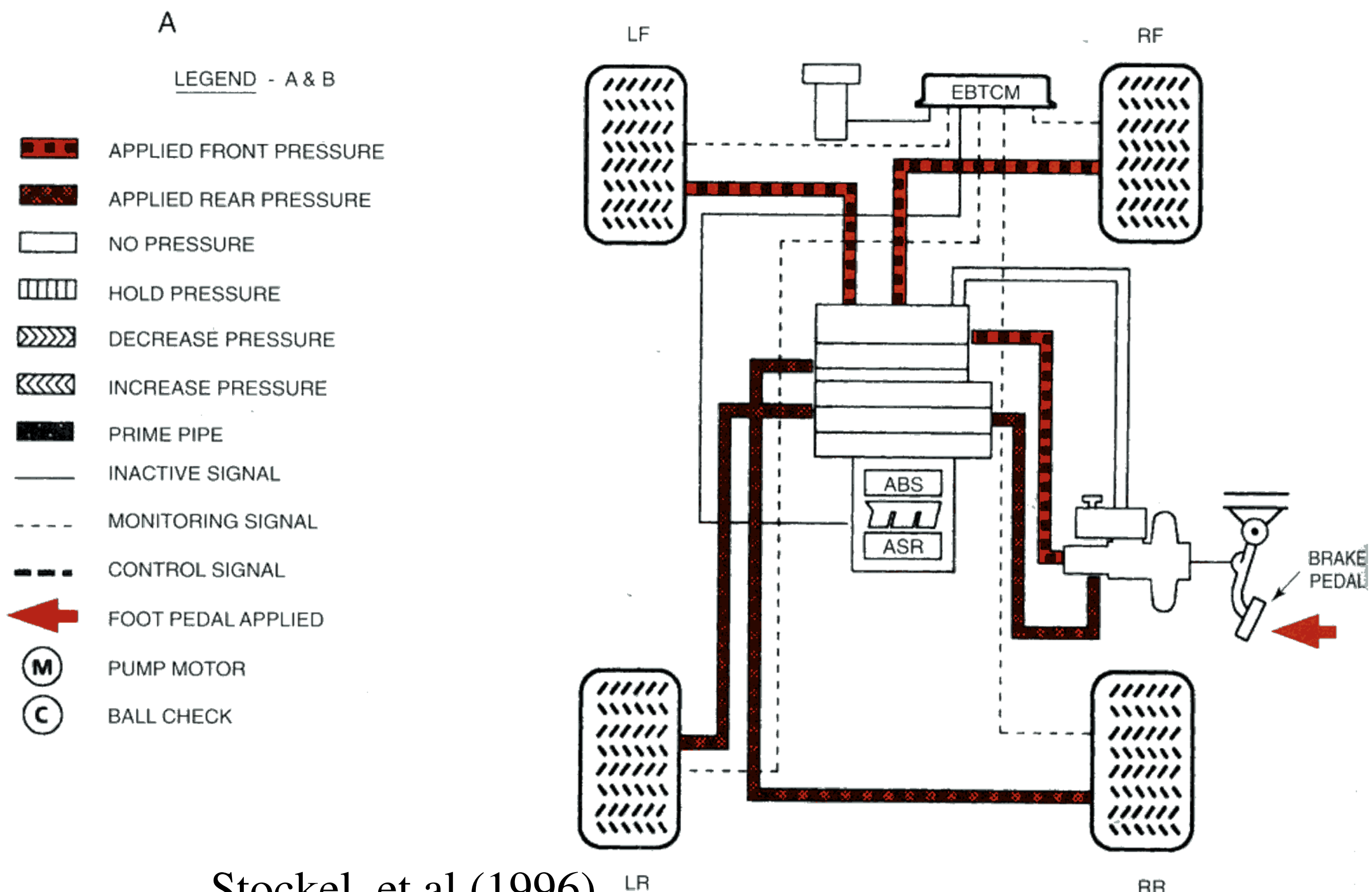
$$u_p(t) = \begin{cases} u_1 & e_s > 0 \\ u_2 & e_s < 0 \end{cases}$$

We might just model this as, $u_p(t) = \mathrm{sgn}(e_s)$

This means the command would be to increase pressure (+1) if the error was positive, or you need to increase slip (skid), or decrease pressure (-1) if the error is negative, indicating that the slip (skid) is larger than you want it to be.

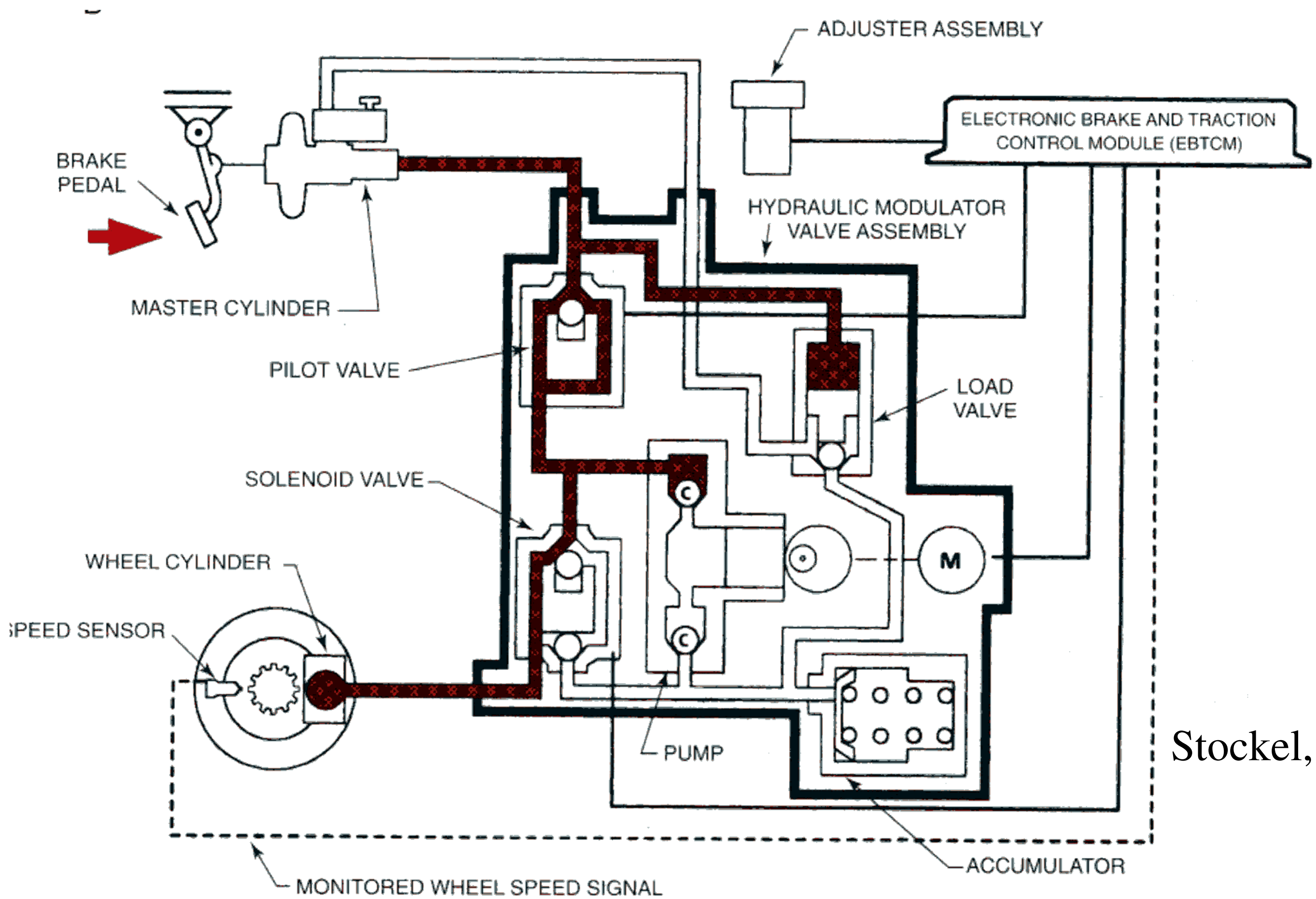
Example: Four wheel ABS

non-locking mode



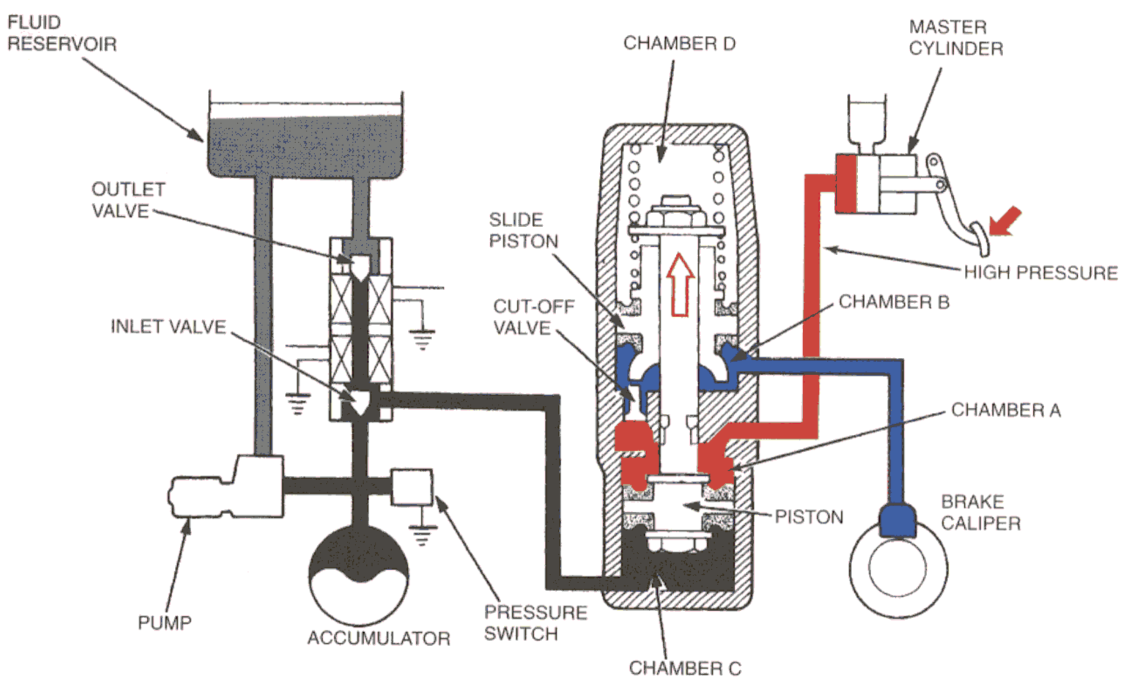
Stockel, et al (1996)

Example: Detail of Valve Flows



Stockel, et al (1996)

Example: Basic ABS Actuation



Stockel, et al (1996)

When lockup is detected:

•ABS operates solenoid valve and outlet valve is closed, inlet valve opened

•High pressure sent to chamber C, and the piston is pushed up so cut-off valve is closed.

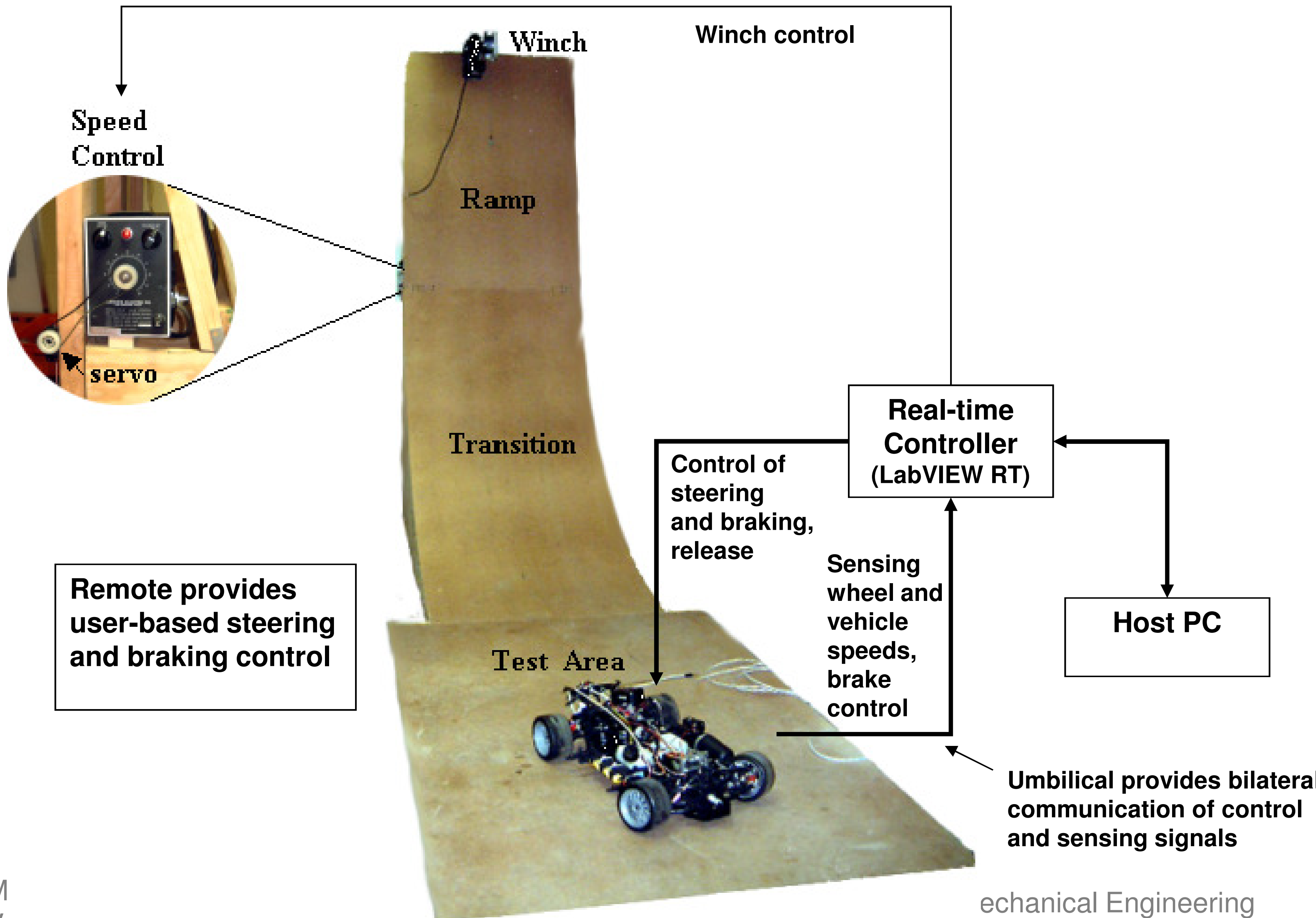
•With cut-off closed, supply from master cylinder to brake is closed.

•At the same time, the pressure in chamber B decreases.

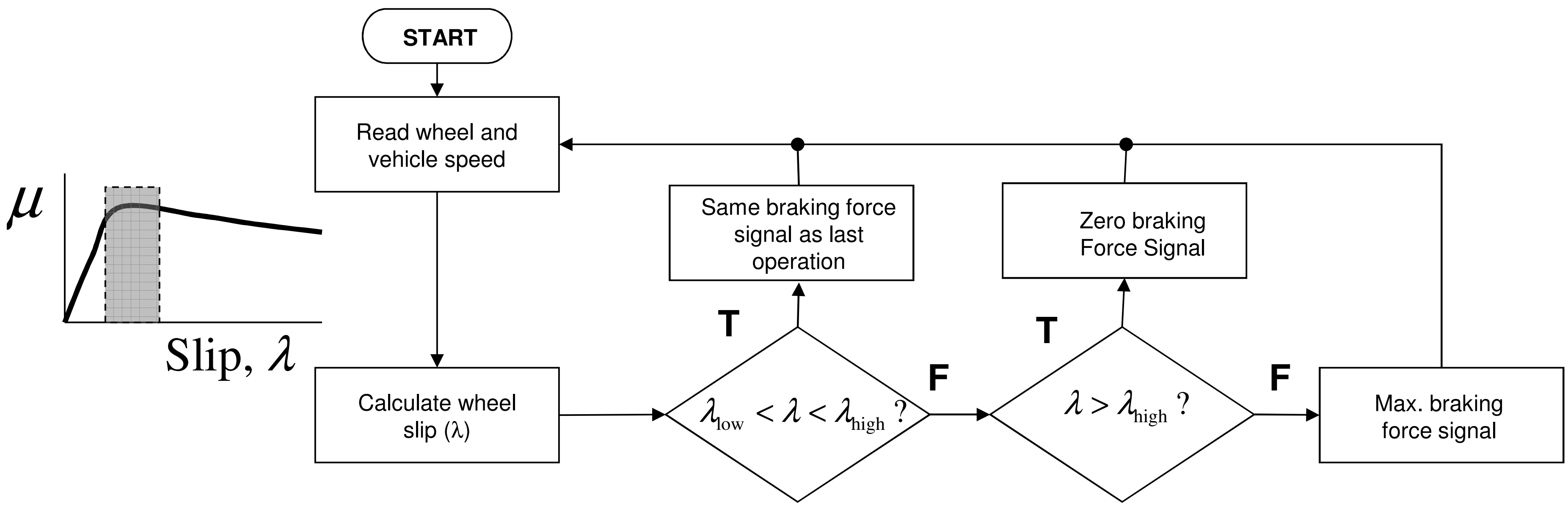
•If inlet/outlet valves both closed, pressure can be held constant.

•This process can be cycled.

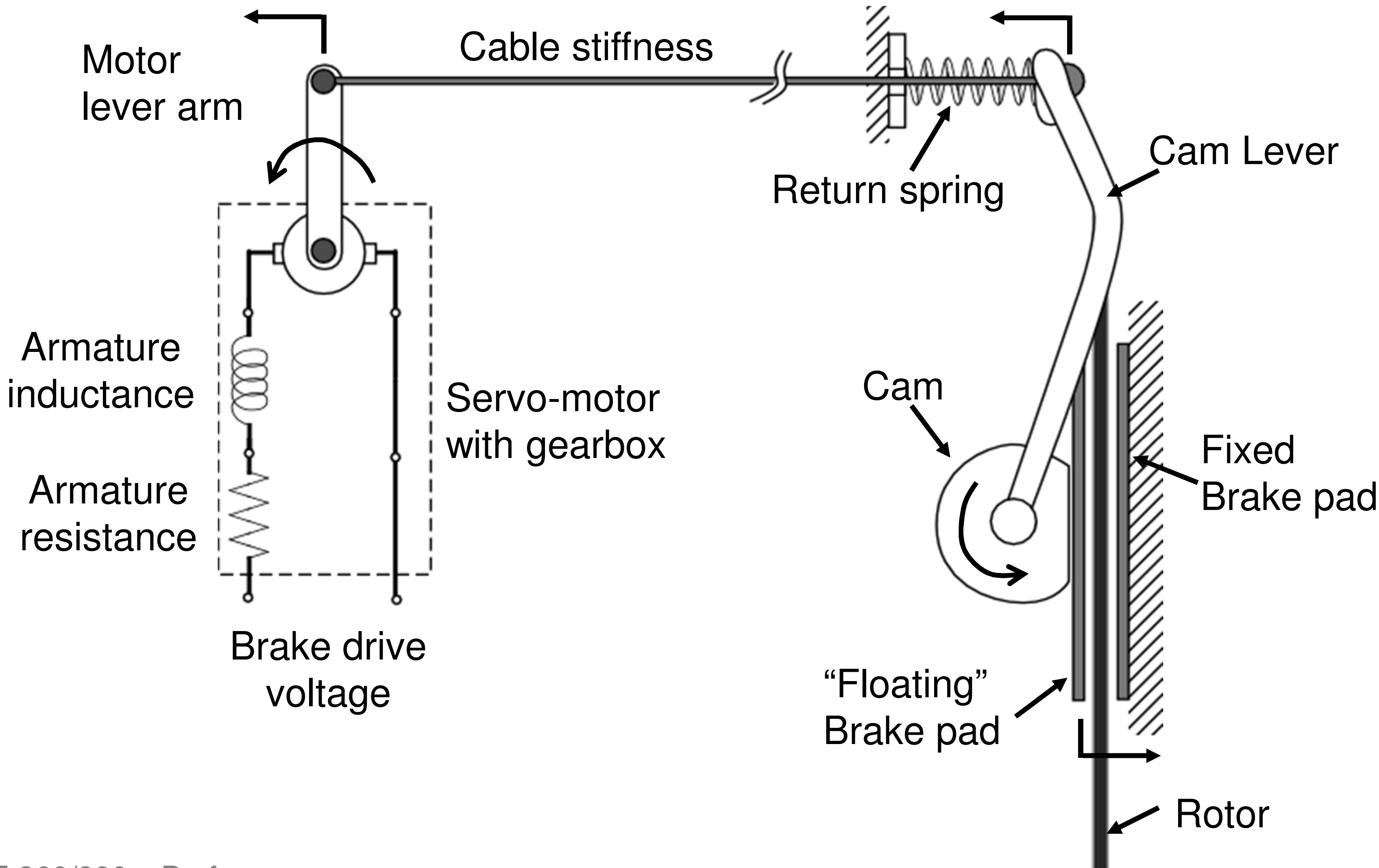
rampvehicle.png

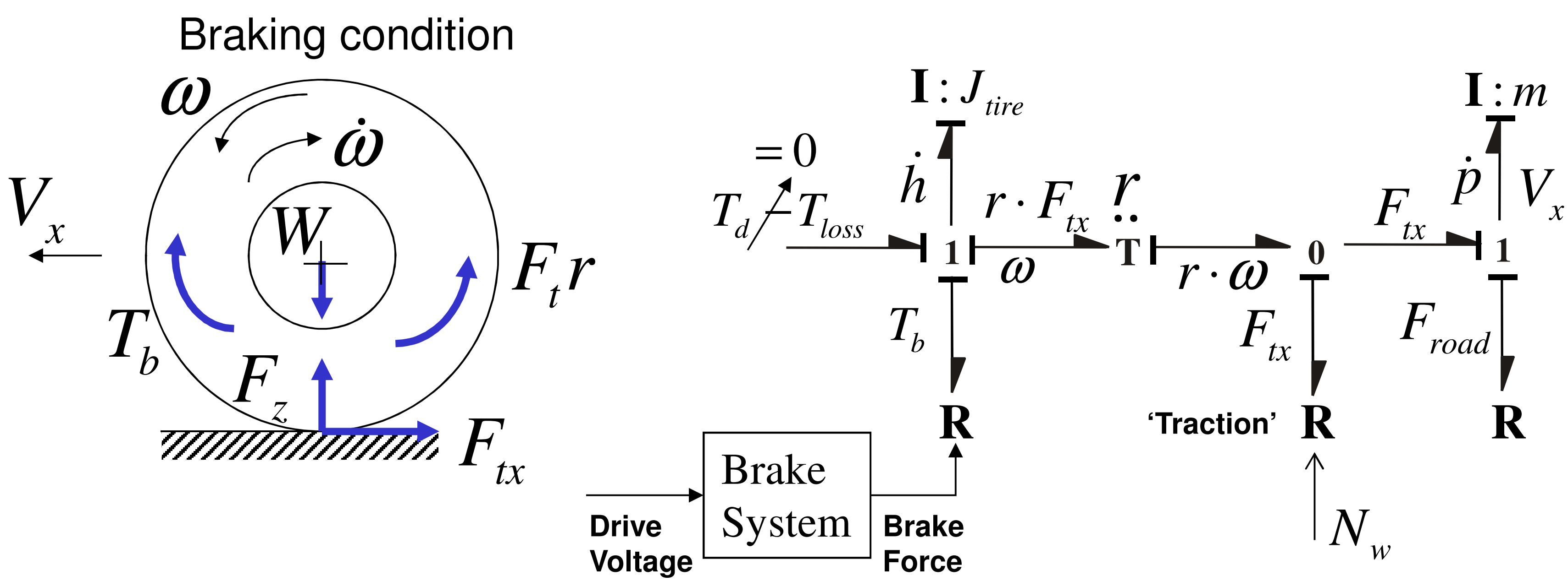


abs_logic_1a.png



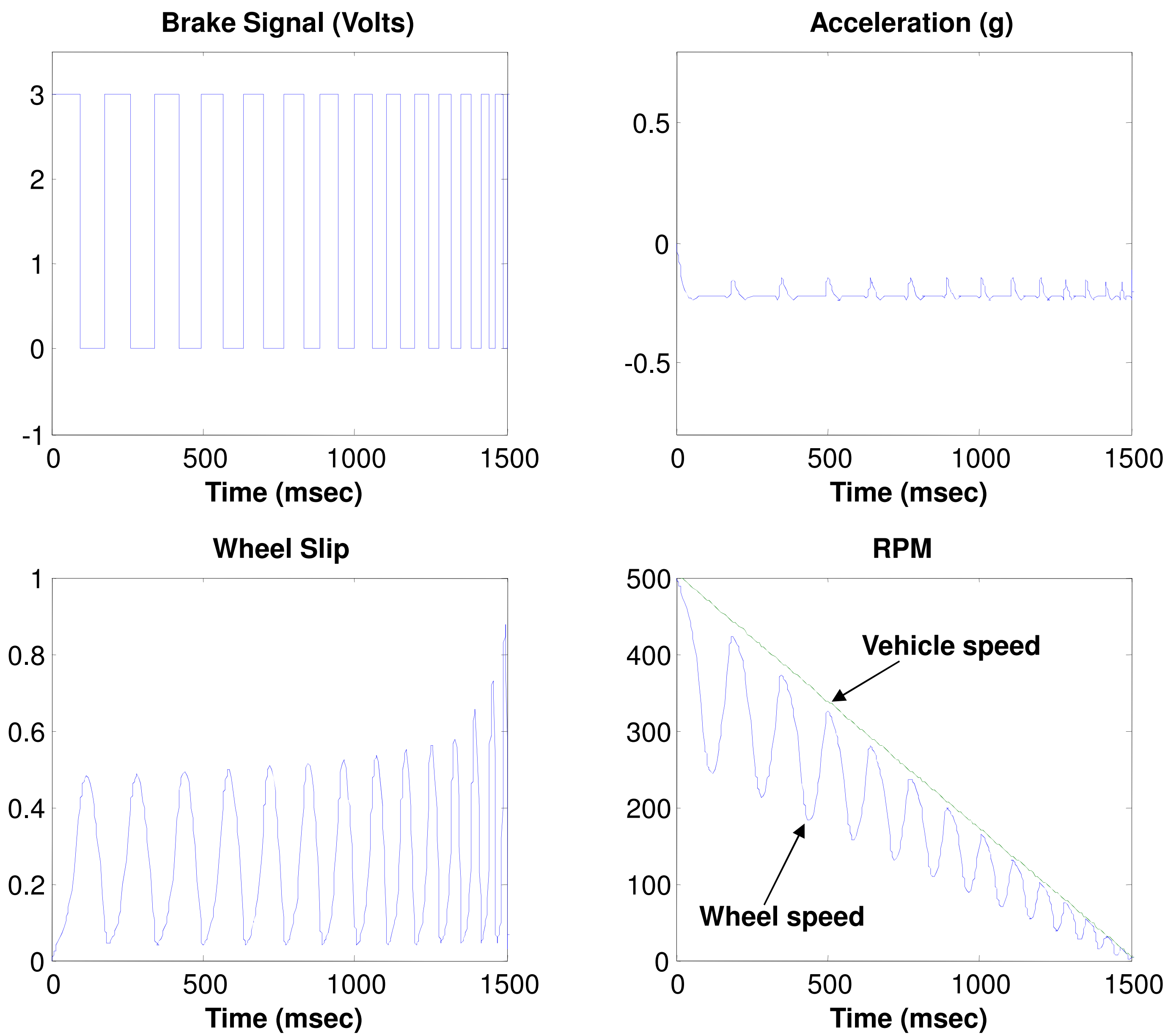
brakesystem.png



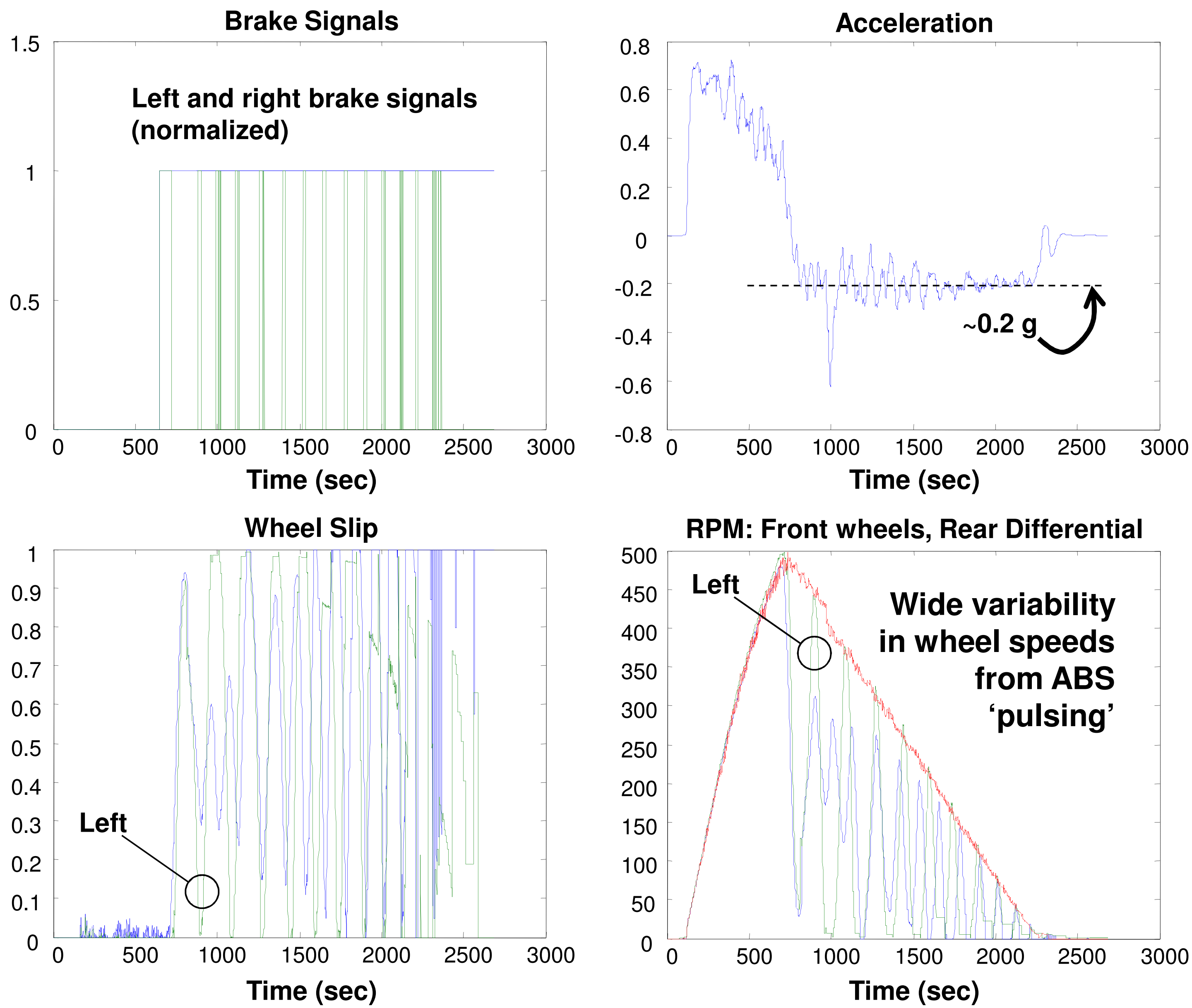


Braking condition
ω
$\dot{\omega}$
V_x
W
$F_t r$
T_b
F_z
F_{tx}
$I : J_{tire}$
$= 0$
$T_d - T_{loss}$
$\dot{h}$
$r \cdot F_{tx}$
r
1
ω
T
$r \cdot \omega$
0
F_{tx}
1
$I : m$
$\dot{p}$
V_x
T_b
F_{tx}
F_{road}
R
'Traction'
R
R
Brake System
Drive Voltage
Brake Force
N_w

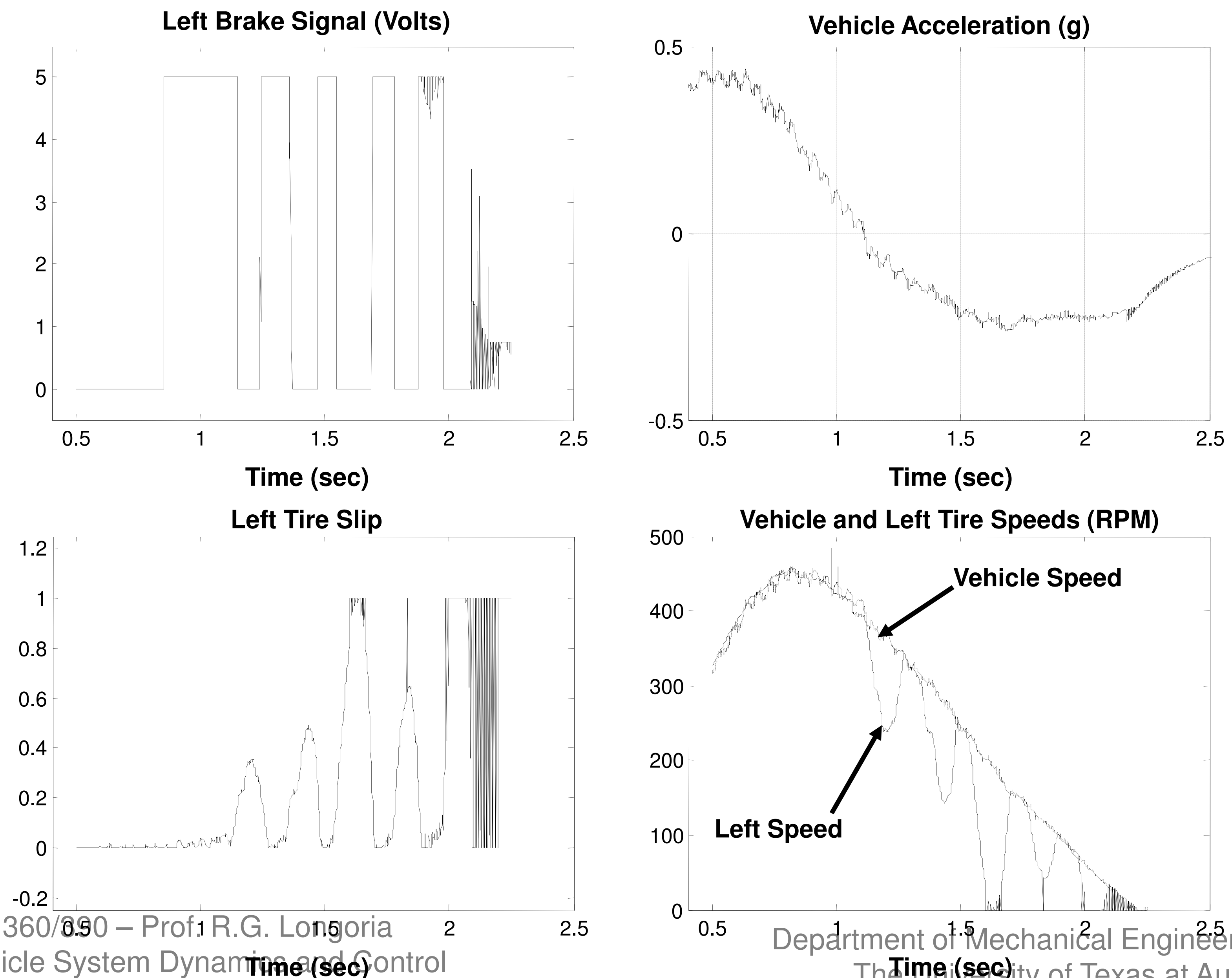
sim_abson_2.png



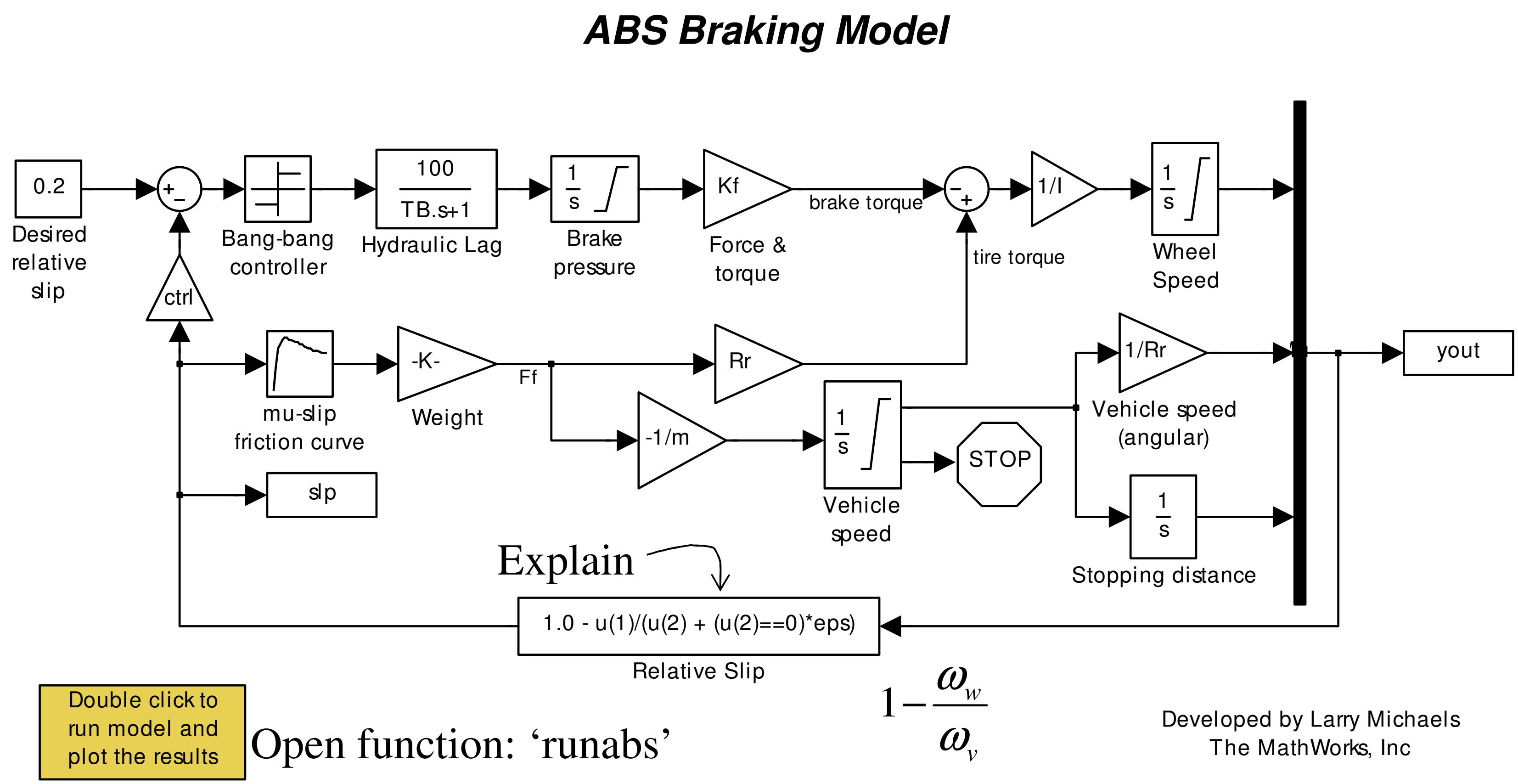
test_abson_041302.png



test_abson_sm.png



Example provided in Matlab/Simulink: ABS simulation



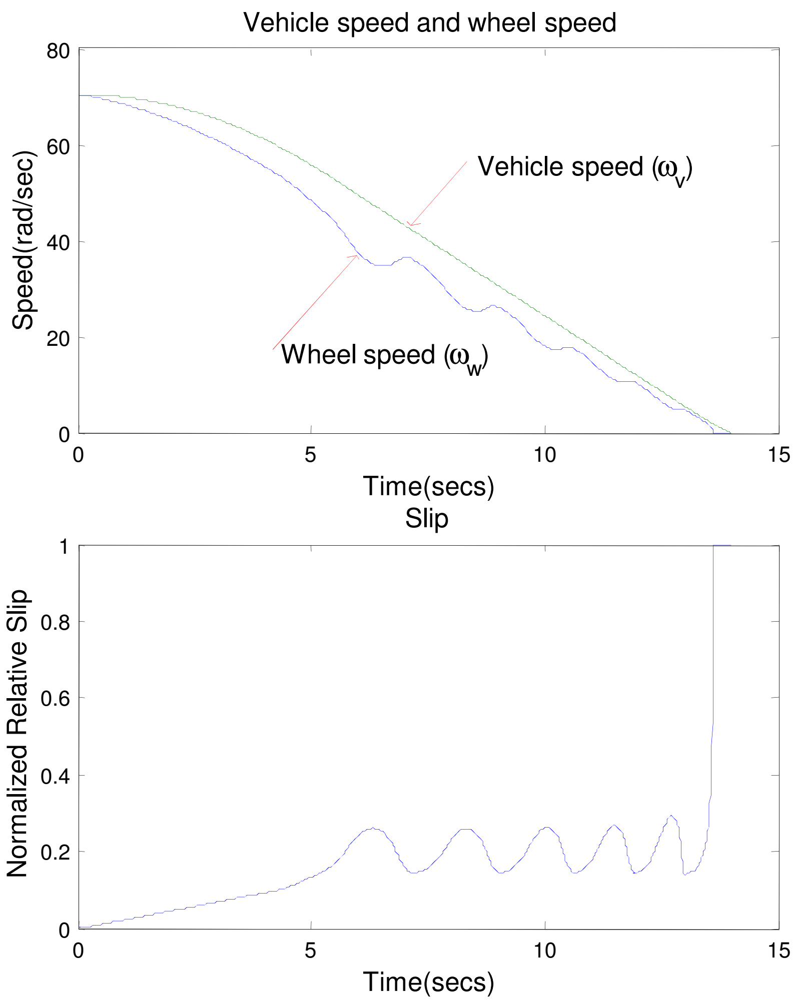
Explain

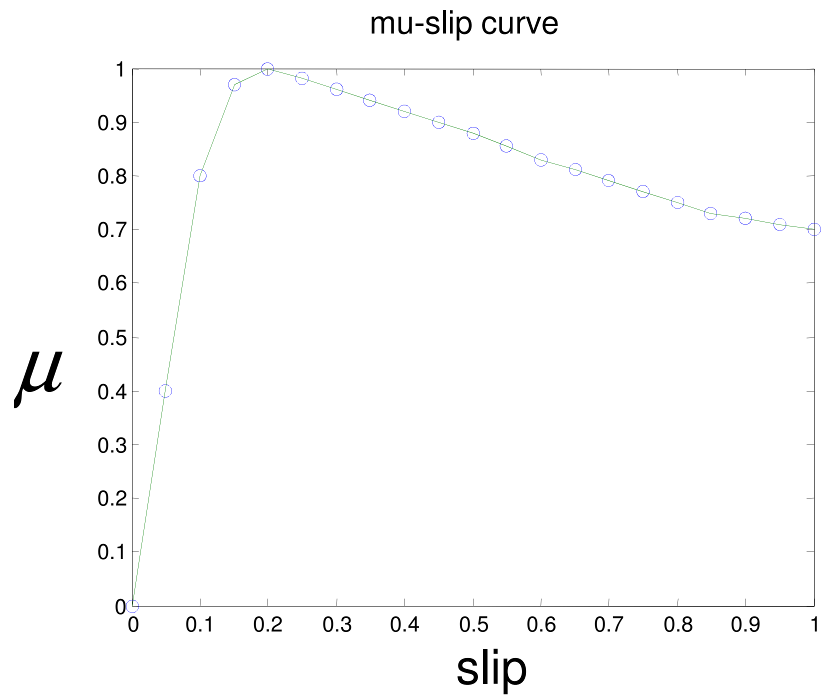
$$1-\frac{\omega_w}{\omega_v}$$

Open function: 'runabs'

PreLoadFcn = 'absdata' (in a Simulink model, you set this using set_param( ) on MATLAB command line.

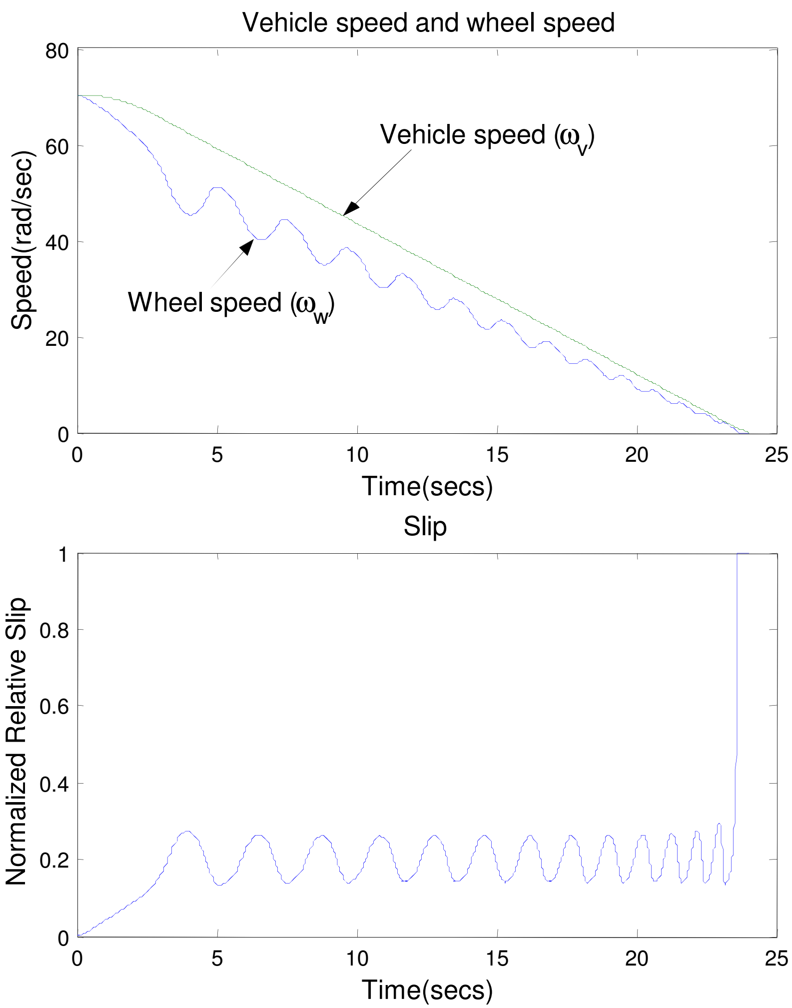
ABS simulation results



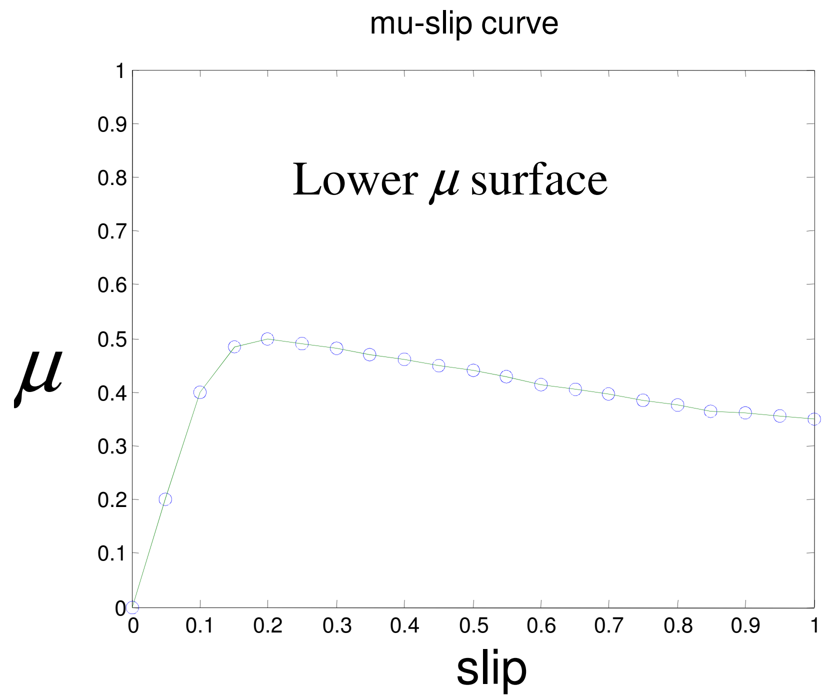


Note: refer to stopping distance plot!

ABS simulation results



Cut the peak friction in half



ABS simulation results

Use the simulation model to examine 3 different cases, with the last one the lower m case with no ABS.

This demonstrates the basic advantage of ABS.