Development of a Diagnostic System for Air Brakes in Trucks

Swaroop Darbha
Department of Mechanical Engineering
Texas A&M University
College Station TX-77843

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Outline

- Introduction to Air Brakes
- Main Issues for a diagnostic system for air brakes
- Experimental Setup at Texas A&M University
- Diagnostic Algorithms
  - Estimation of Stroke of Pushrod
  - Detection of Leaks

Introduction

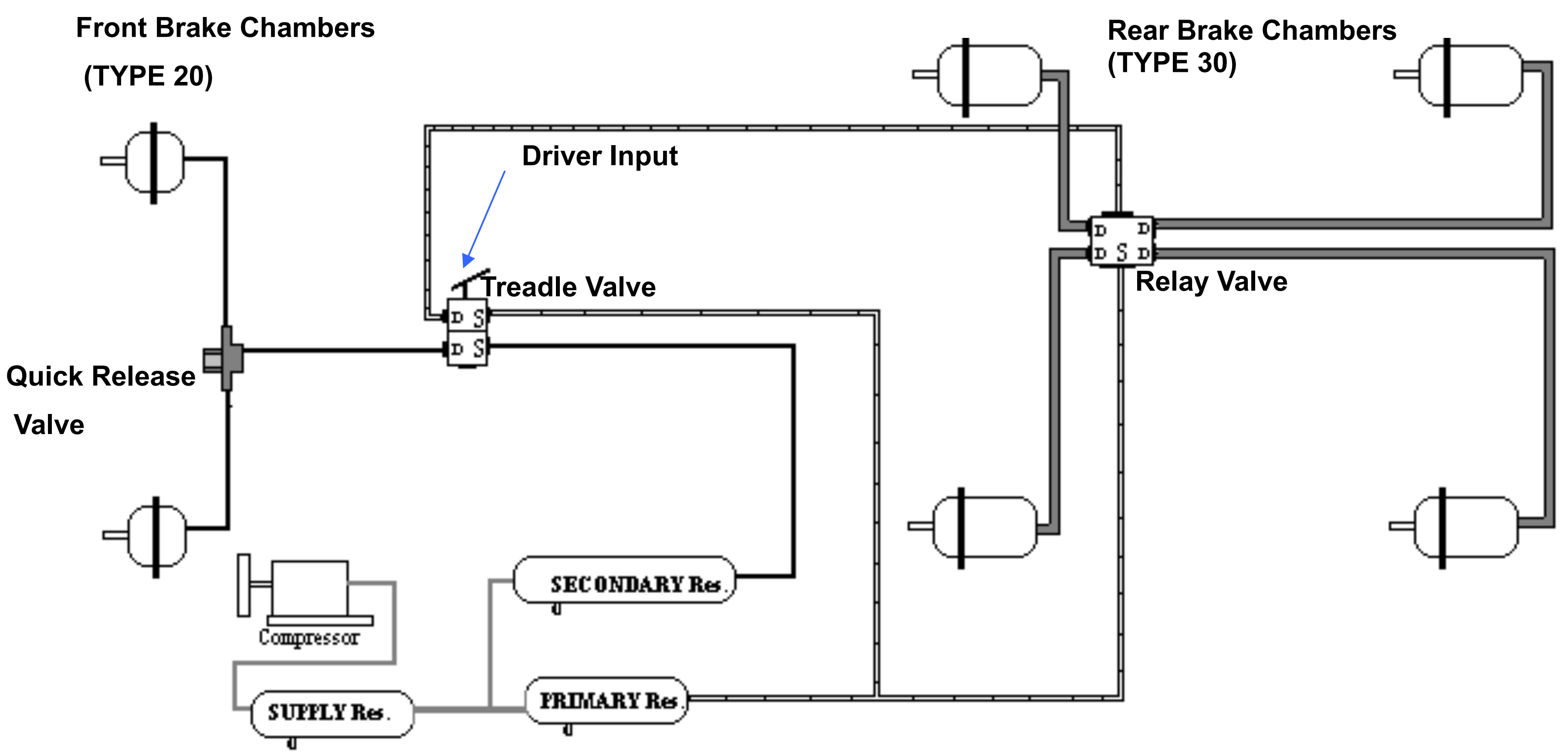
- **Commercial vehicles**
  - **Transport 23% of freight in the United States**

    (Source: US DoT – Bureau of Transportation Stat.)
  - **23.5 million children use school buses**

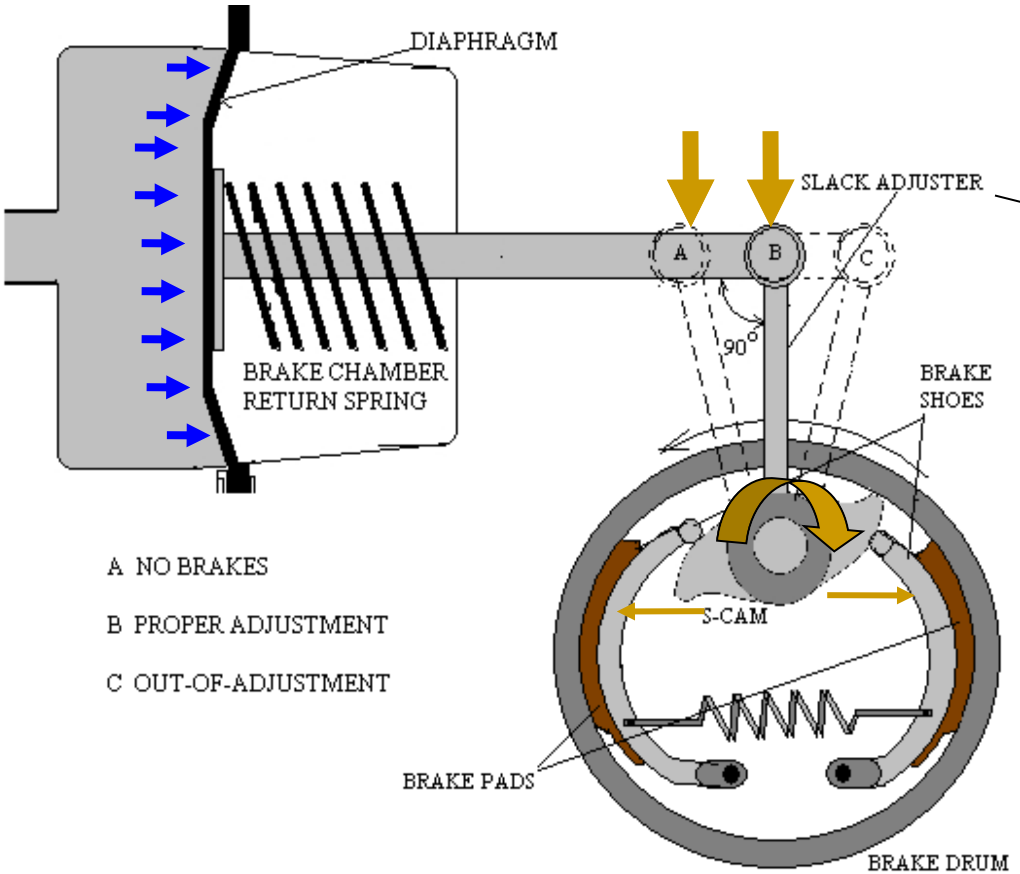
    (Source: US DoT – Bureau of Transportation Stat.)
  - **9 million HCVs reported in the US in 2006**

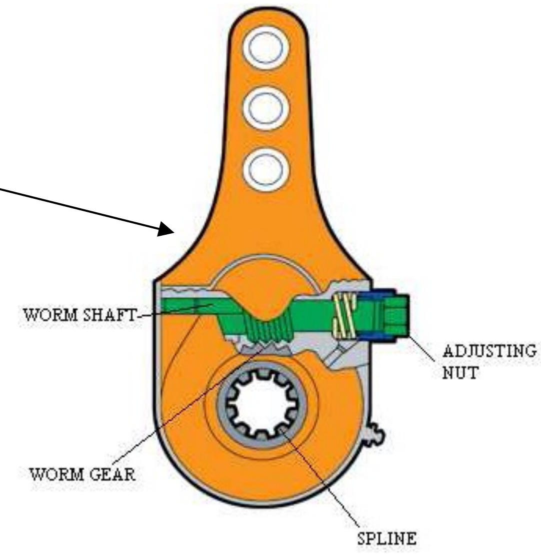
    (Source: US DoT – Bureau of Transportation Stat.)
  - **Heavy commercial vehicles (HCVs)**
    - **Gross vehicle weight rating > ~14,000 kg**
  - **HCVs require large braking forces**
    - **Use air brake system for braking**

Air Brake System

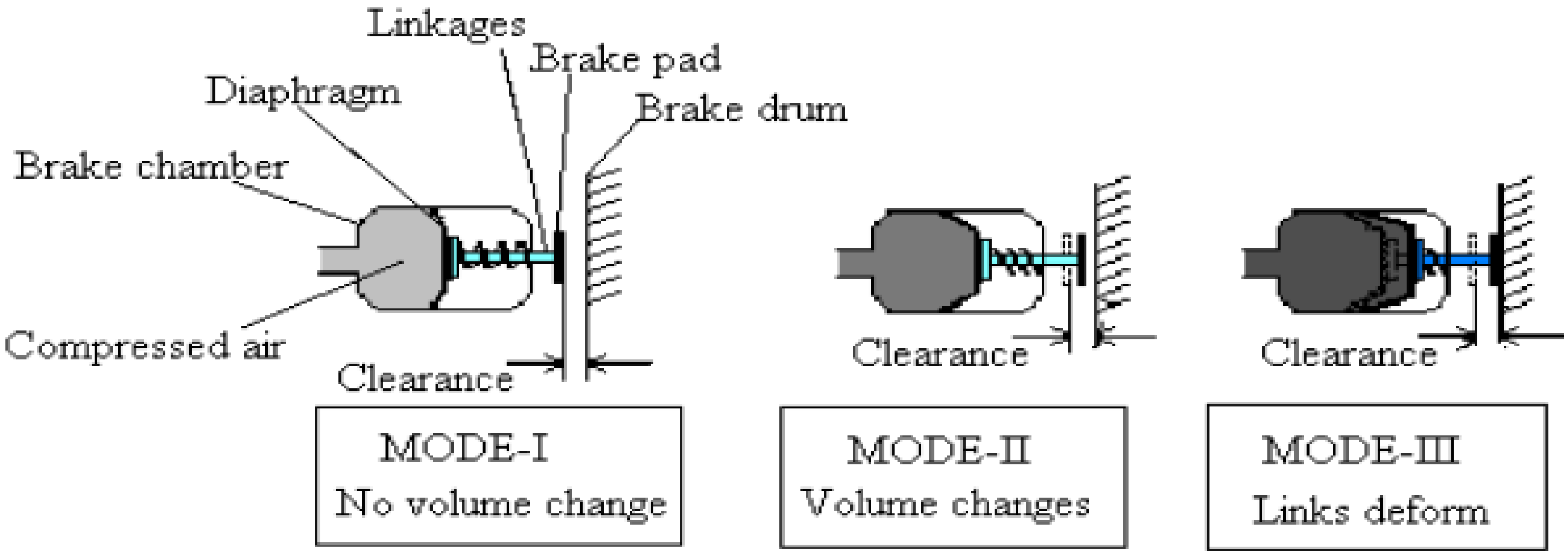


Mechanical Subsystem





Air Brake System a Hybrid System



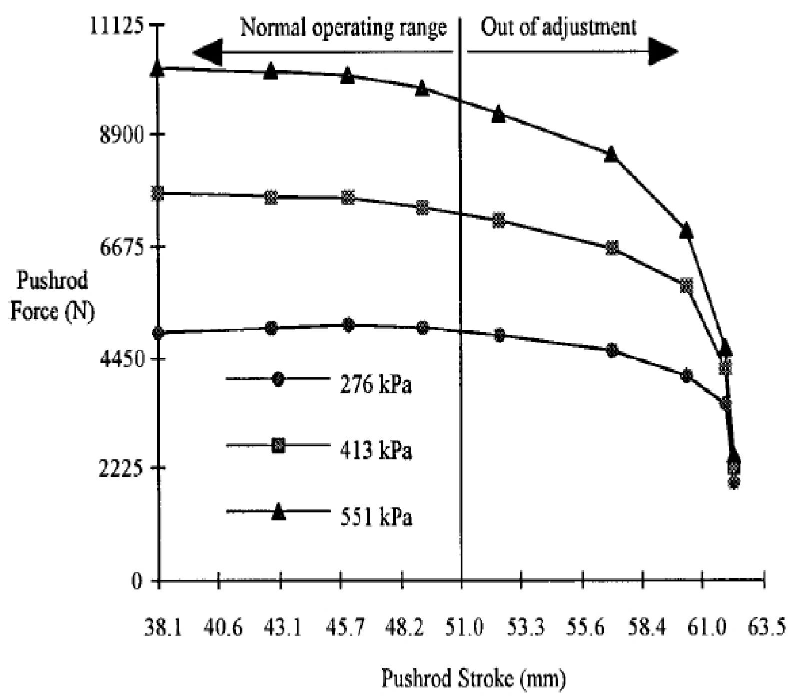
Main Issues for diagnostics of air brakes

- **Leakage of air**
  - **Affects the lag and maximum deceleration of the truck**
- **Pushrod stroke**
  - **Affects the volume available for air to expand → lag**
  - **Too much stroke → dead time in response**
  - **Stroke exceeds out-of-adjustment limit → braking force will be diminished**

Out-of-adjustment of Pushrod

- **Causes of out-of-adjustment:**
  - Thermal expansion of brake drum
  - Mechanical wear of brake pads
- **Effect:**
  - Kinematic misalignment
  - Loss of braking force
- **Out-of-adjustment:**
  - If extension exceeds predefined safe limit (FMVSS 121)

Pushrod force variation with stroke



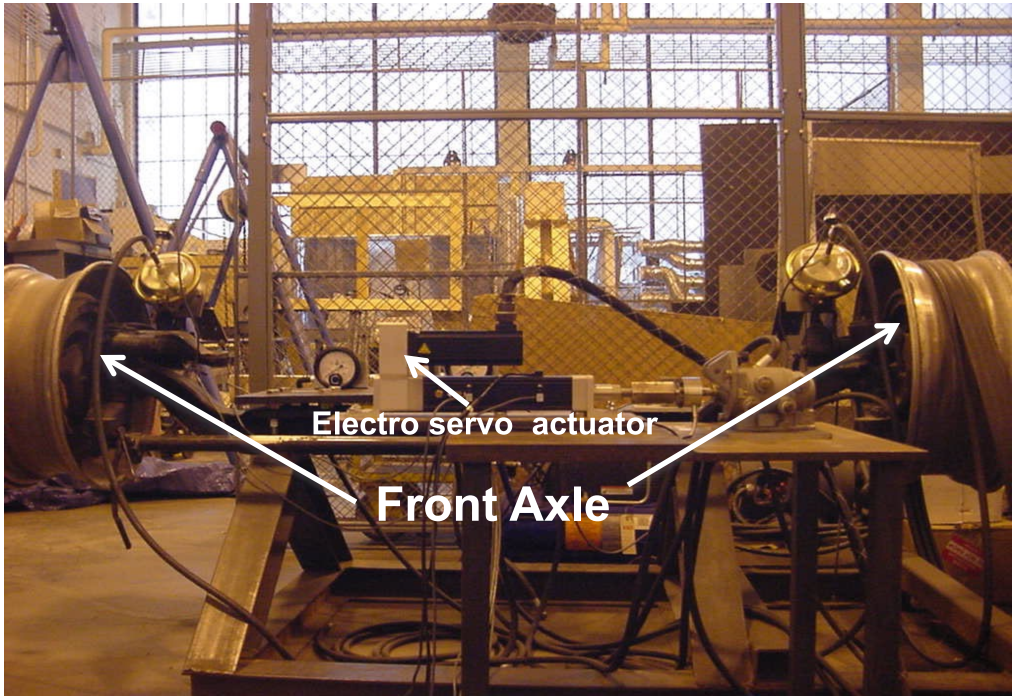
Existing Inspection Methods

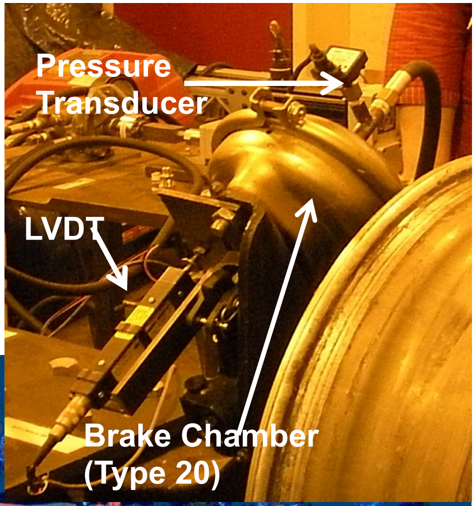
- **Manual Inspection (FMVSS 121)**
  - **Labor intensive**
  - **Take 20 min. of 40 min. inspection time**
- **Performance based inspection (FMCSR part 393)**
  - **Roller dynamometers, Flat bed testers etc.**
  - **Measure max. deceleration / braking force**
  - **Transients not measured**

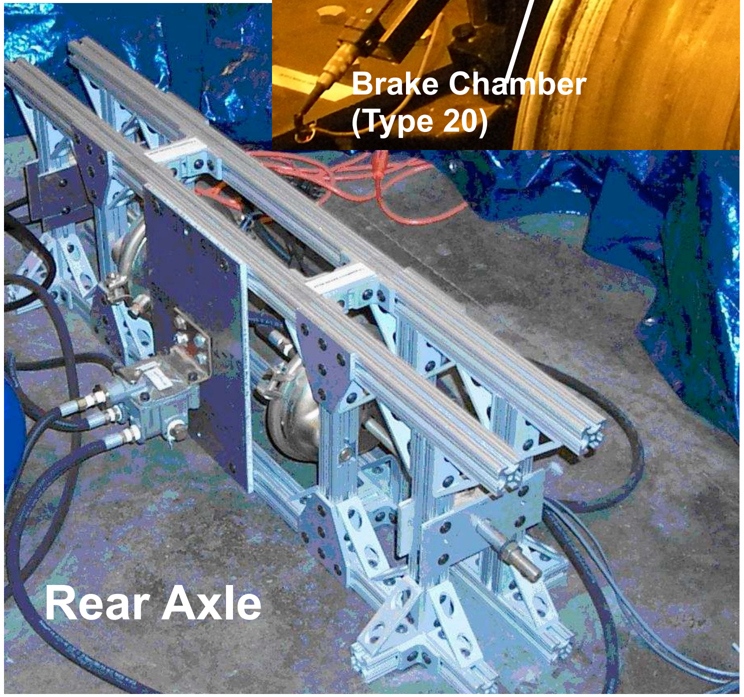
Outline

- Introduction to Air Brakes
- Main issues for the development of diagnostic systems for air brakes
- ***Experimental Setup at Texas A&M University***
- Basic idea for the estimation of Pushrod Stroke
- Conclusions

Experimental Setup



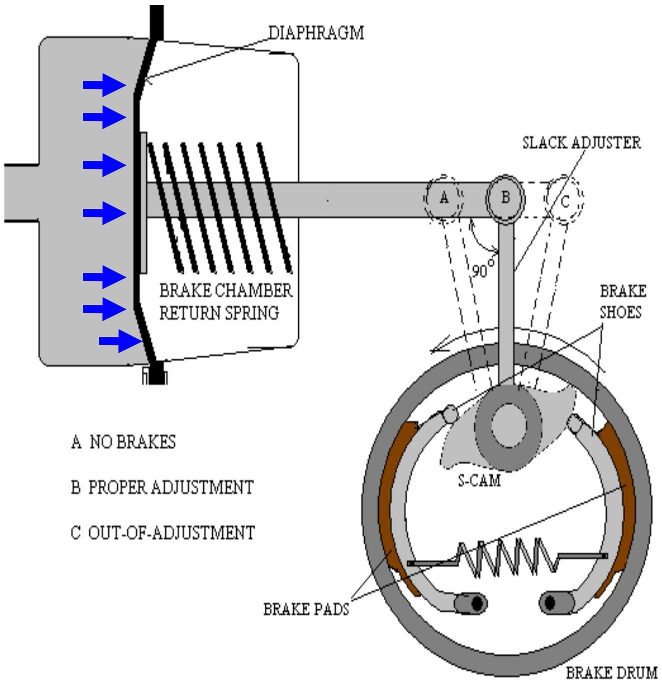




Outline

- Introduction to Air Brakes
- Main Issues for the diagnostics of air brakes
- Experimental Setup at Texas A&M University
- ***Basic Idea for the estimation scheme***
- Conclusions

Main Idea of Estimation



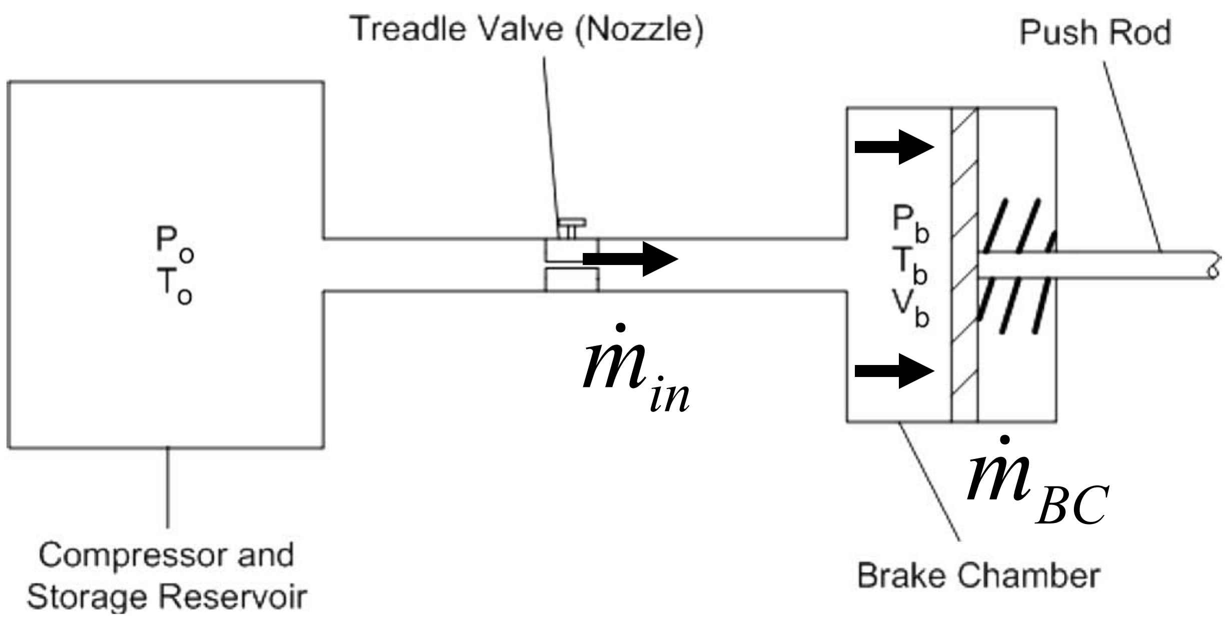
- **Measurements:** Pressure in the brake chamber when the brake pedal is fully applied.
- **Question:** What should the motion of the diaphragm be so that for the given mass flow rate of air entering the brake chamber, one would have the observed brake pressure?
- **Benefit:** Circumvents the hybrid nature of the problem and converts the problem to a standard nonlinear control problem
- **Method:** Once the motion of the diaphragm is known, one can estimate the stroke of the pushrod by numerical integration.

Mathematical Model of Air Brake

- **Assumptions**
  - **Lumped parameter approach**
  - **Air behaves as ideal gas → all locations**
  - **Treadle valve opening → a nozzle and varies.**
  - **Isothermal process**
  - **No frictional losses in hoses**
  - **Compressibility effects ignored in hoses**
  - **No leakage of air**

Mathematical Model of Air Brake

Pneumatic Subsystem



$$\dot{m}_{in} = \dot{m}_{BC}$$

Pressure Evolution Equation

- **Isothermal process** $\dot{m}_{BC} = \dfrac{\dot{P}_b V_b + P_b \dot{V}_b}{RT_b}$
- **"Full-brake" application & isothermal process**

$$\therefore \dot{m}_{in} = \underbrace{A_P}_{fixed} \underbrace{P_b \sqrt{2RT \log\left(\frac{P_{\sup}}{P_b}\right)}}_{u(P_b)}$$

- **Volume varies with pushrod motion**

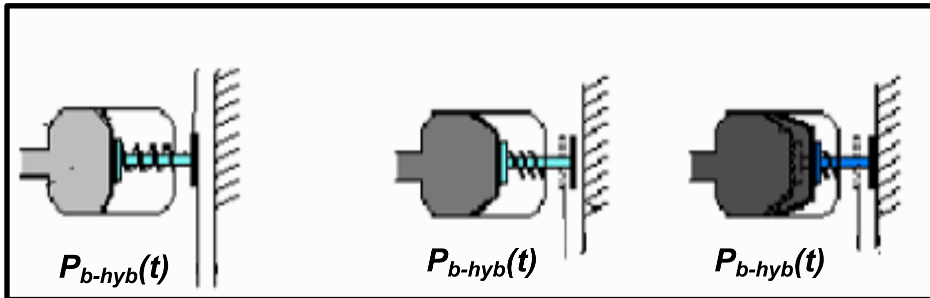
$V_b(t) = V_i + A_b z(t)$ **Z→ Pushrod displacement**

- **Balance of mass → $\dot{m}_{in} = \dot{m}_{BC}$ → evolution of pressure**

$$\dot{P}_b = \frac{A_P P_b \sqrt{2RT \log\left(\frac{P_{\sup}}{P_b}\right)} - A_b P_b \dot{z}}{V_i + A_b z}$$

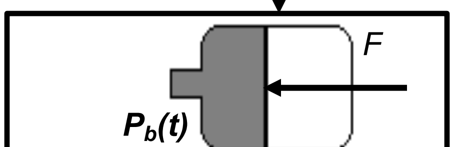
Estimation Scheme

$$\dot{P}_{b-hyb} = f_A(P_{b-hyb}, z) + f_B(P_{b-hyb}, z)\dot{z}$$



$$\dot{z} = \begin{cases} g_1(P_{b-hyb}, z, K_1, C_1) & z \leq z_{cl} \\ g_2(P_{b-hyb}, z, K_2, C_2) & z > z_{cl} \end{cases}$$

$$y_m = P_{b-hyb}$$



$$\dot{P}_b = f_A(P_b, z) + f_B(P_b, z)F$$

$$\dot{z} = F$$

- **Find *F* such that $P_b(t)$ exactly tracks $y_m(t)$**

Estimator for *z*

- **For exact tracking → *$P_b(t)$ =$y_m(t)$* →*F***

$$F = \frac{1}{f_B(y_m, z)}\left[\dot{y}_m - f_A(y_m, z)\right]$$

- **Estimator for *z(T)***

$$\dot{z} = \frac{1}{f_B(y_m, z)}\left[\dot{y}_m - f_A(y_m, z)\right]$$

$$z(0) = z_0$$

Estimation Scheme

- **Assume y_m is smooth and noise free**
- **Assume internal dynamics are stable**
- **Tracking error** $e = P_b - y_m$
- **Choose *F* such that**
  - **Exponential decay of tracking error**
- $$F = \frac{1}{f_B(P_b, z)}\left[\dot{y}_m - k_1(P_b - y_m) - f_A(P_b, z)\right]$$
- ***K_1*(>0) depends on desired rate of decay**

Governing Equations

$$\dot{P}_{b-hyb} = \underbrace{\frac{A_P P_{b-hyb}\sqrt{2RT\log\left(\frac{P_{\sup}}{P_{b-hyb}}\right)}}{V_i + A_b z}}_{f_A(P_{b-hyb},z)} + \underbrace{\left(\frac{-A_b P_{b-hyb}}{V_i + A_b z}\right)}_{f_B(P_{b-hyb},z)}\dot{z}$$

} Pneumatic subsystem

$$\dot{z} = \begin{cases} g_1(P_{b-hyb}, z) & z \le z_{cl} \\ g_2(P_{b-hyb}, z) & z > z_{cl} \end{cases}$$

} Mechanical subsystem

$$y_m = P_{b-hyb}$$

z_{cl} → *clearance*

y_m → *measured output*

Estimation of *z* with uncertainty in A_p

- **A_p varies with the type of valve (E-6, E-7, E-10)**
  - **Assume uncertainty in A_p**
- **The non hybrid system** $\dot{P}_b = \underbrace{A_p G_A(P_b, z)}_{f_A()} + f_B(P_b, z)F$

$$\dot{z} = F$$

- **Assume estimate of A_p known →** $\hat{A}_P$

$$F = \frac{1}{f_B(P_b, z)}\left[\dot{y}_m - k_1(P_b - y_m) - \hat{A}_p G_A(P_b, z)\right]$$

- **Since** $\hat{A}_P \neq A_P$ **→ error evolution** $\dot{e} + k_1 e = \tilde{A}_p G_A(P_b, z)$
  - $\tilde{A}_p = A_P - \hat{A}_P$

Estimation of *z* with uncertainty in A_p

- **Choose adaptation law for** $\hat{A}_P$

$$\dot{\hat{A}}_p = \Gamma (P_b - y_m) G_A (P_b, z)$$
$$\Gamma > 0$$

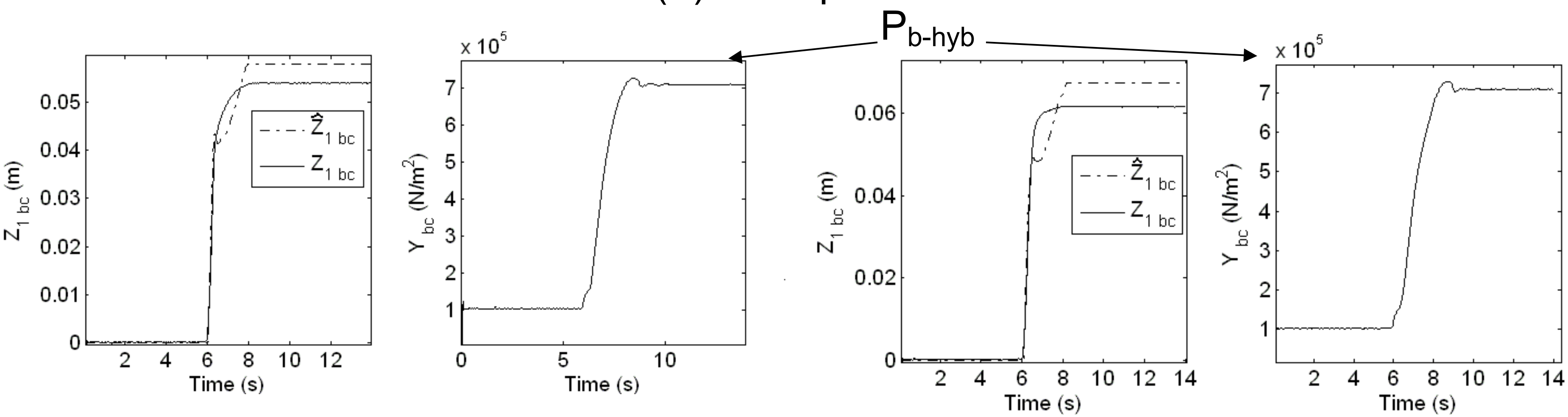
- **Can be shown →** $e \to 0$
- **Estimator**

$$\dot{z} = \frac{1}{f_B(P_b, z)} \left[\dot{y}_m - k_1 (P_b - y_m) - \hat{A}_p G_A (P_b, z) \right]$$
$$\dot{\hat{A}}_p = \Gamma (P_b - y_m) G_A (P_b, z)$$
$$A_p(0) = A_{po}$$
$$z(0) = 0$$

Experimental Corroboration

- **Data for “full-brake” application**
- **Different strokes simulated**
  - **Changing pad-drum clearance → slack adj. nut**

Estimate of z(T) for experimental data

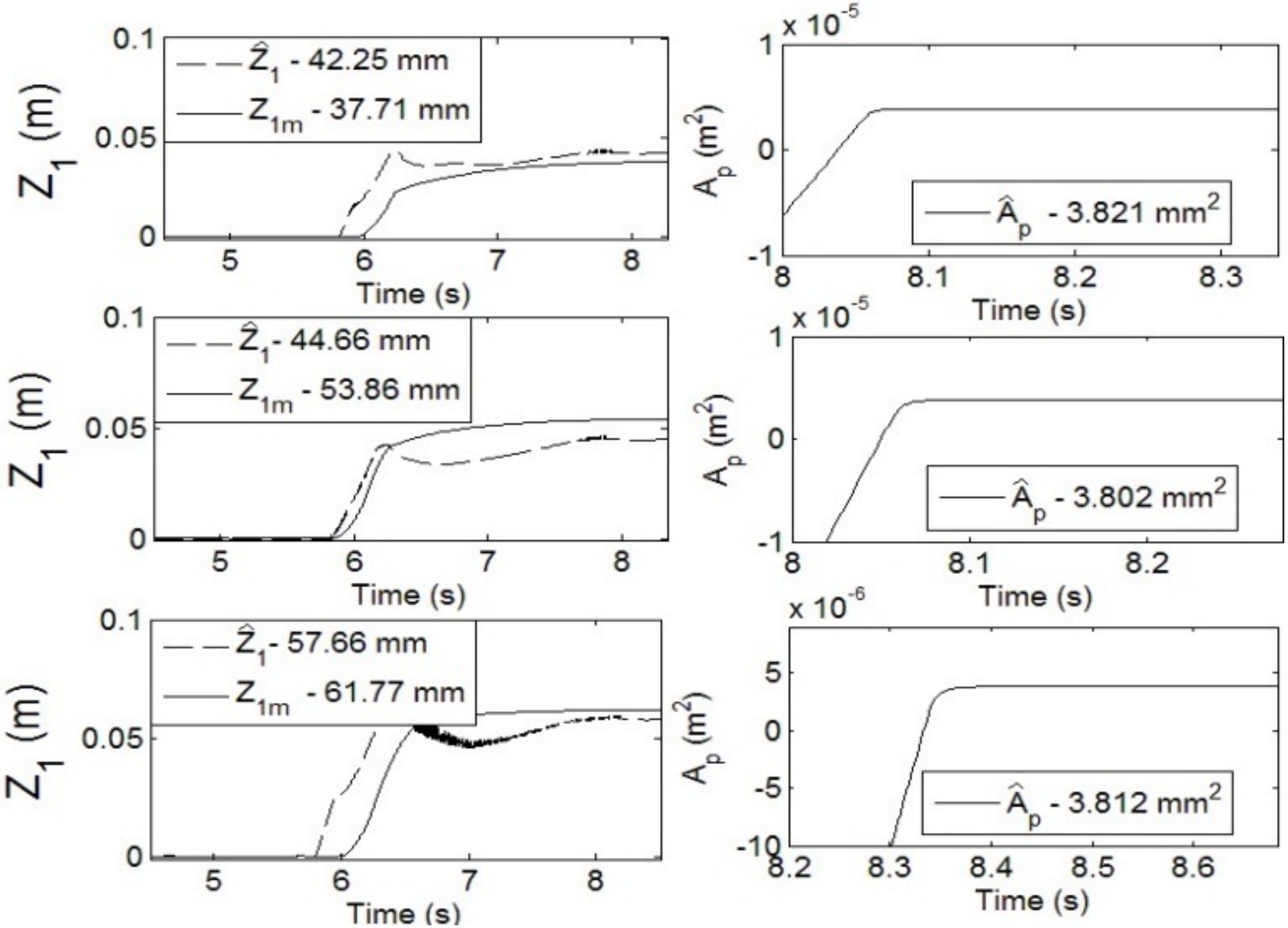


For z_{setup} (T)= *55 mm*

For z_{setup} (T)= *61 mm*

Experimental Corroboration

Estimate of z & A_p for experimental data



Conclusions

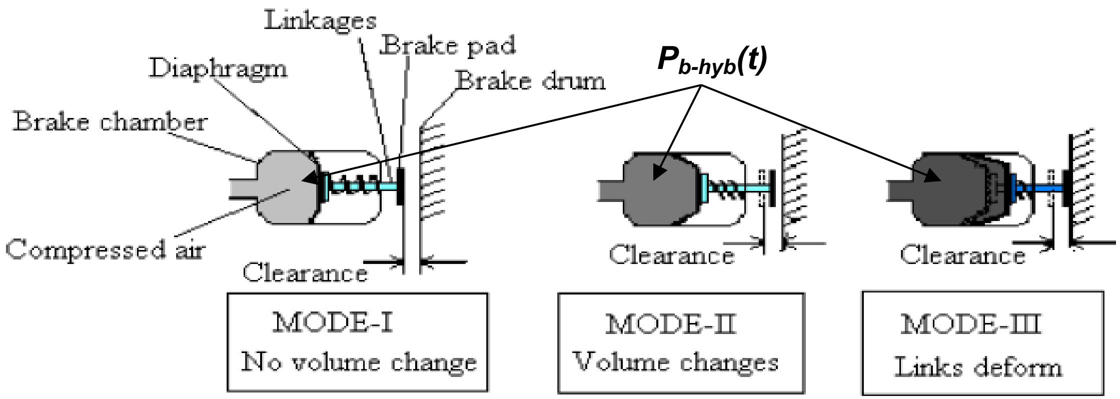
- **Model based estimation of pushrod stroke**
  - **Controller design problem for non hybrid system**
  - **Non hybrid system obtained**
    - **Disconnecting hybrid part**
  - **Parameter estimation**
    - **Integrating equations for internal dynamics**
- **Schemes corroborated with test setup data**

Thank you

Questions ?

Air Brake a Hybrid System

- **Mode dependent motion of pushrod**

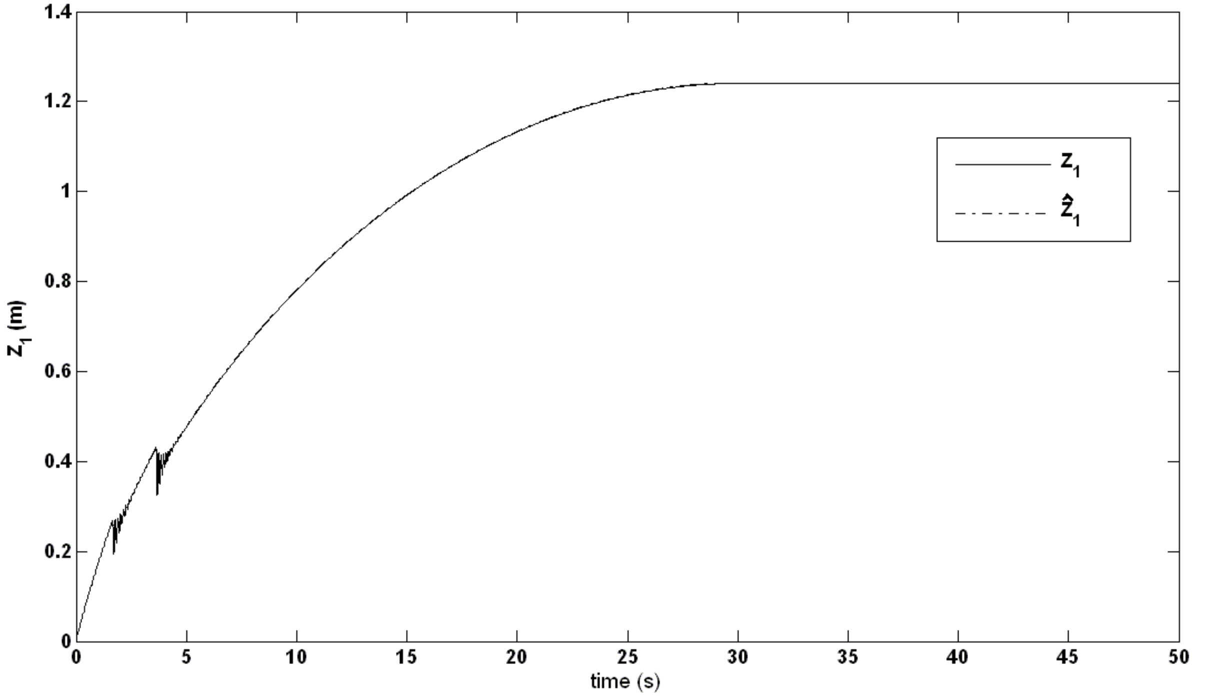


  - **Different governing equations in each mode**
  - **Air Brake System →a hybrid system**

Estimation in Hybrid Systems

- **Mode to mode transition parameters**
  - **Air brake system → *clearance* (z_{cl})**
- **Parameters of system in each mode**
  - **θ_i, i={1, 2}**

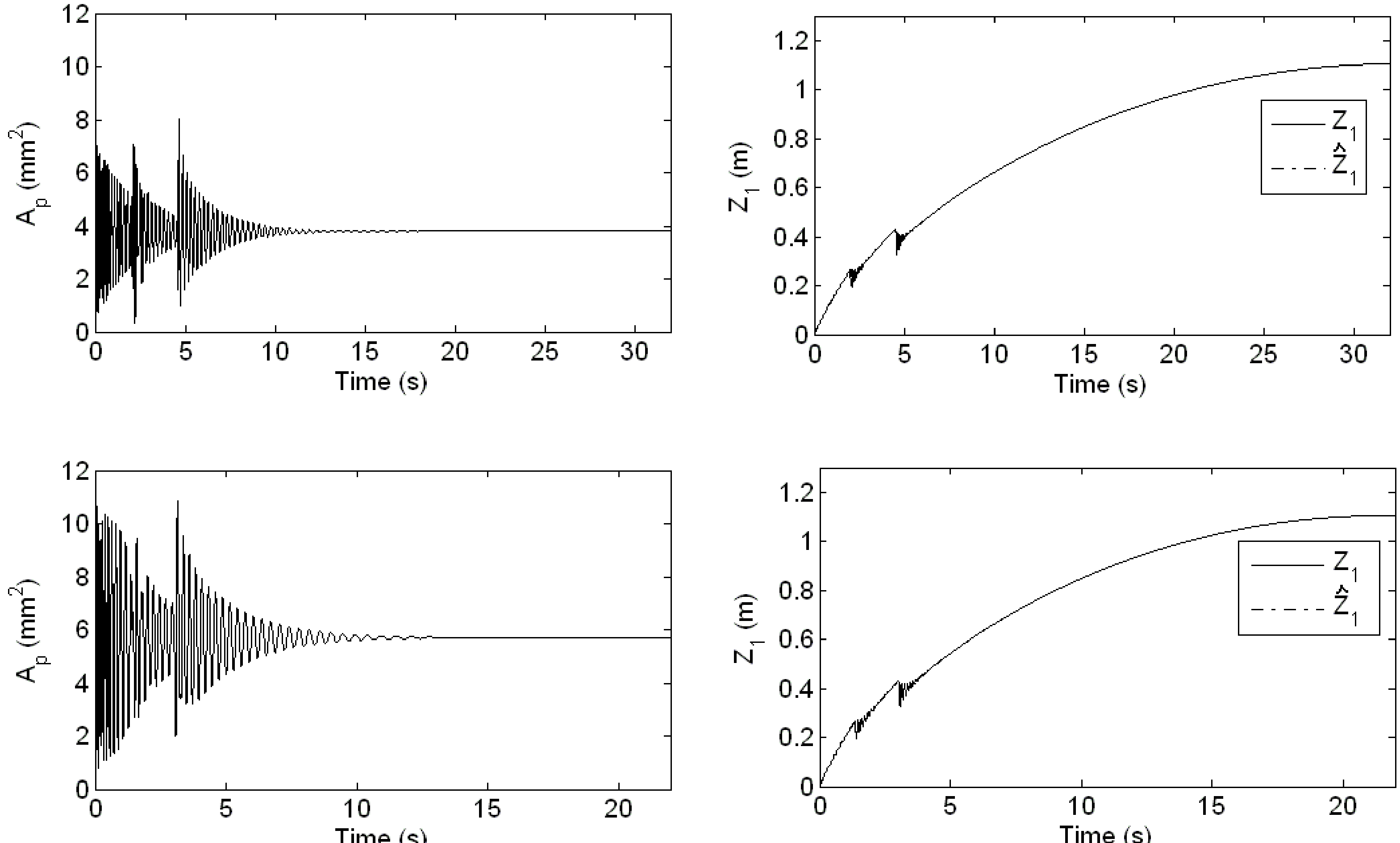
Simulation Results



Estimate of z for simulated output of air brake system

Simulation Results

Estimates of two different A_p for same supply pressure



Problem of Estimation

- **Mode to mode transition parameters *not known***
  - z_{cl} **not known**
- **Parameters of system in each mode *not known***
  - θ
- **Uncertainty in parameters (valve area)**
- ***Can one estimate the pushrod stroke in steady-state ?***

Faults Affecting Air Brake System

- **26% of the reported crashes caused by brake faults**
- **Prominent faults (39.9%)**
  - **Out-of-adjustment of pushrod**
  - **Leakage of compressed air**

Source: LTCCS 2008 FMCSA US DoT

Safety Devices On-board & Inspection

- **Out-of-adjustment of pushrod**
  - **Currently no on-board warning system**

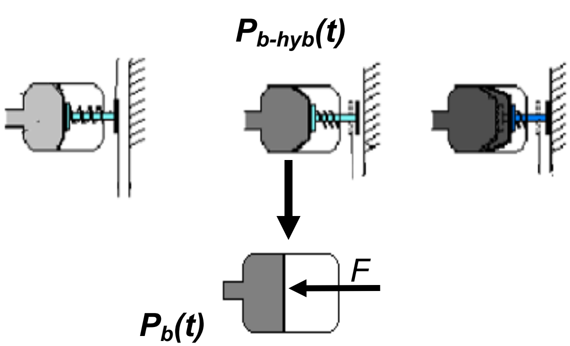
- **Inspection of Out-of-adjustment of pushrod**
  - **"Full-brake" application @ 90psi**
  - **Measure steady-state stroke of pushrod**
  - **Compare with FMVSS 121**

Practical Motivation

- Diagnostic algorithms facilitating automated inspection
  - To be implemented as
    - Hand-held device
    - On-board diagnostics
- Estimate steady-state stroke of pushrod
  - Uncertainty of area of opening of treadle valve (E-6, E-7, E-10)
- Experimental implementation of the scheme

Advances to the state-of-art in hybrid systems

- Sequential hybrid systems
- Develop a parameter estimation scheme
  - Parametric uncertainty



- Seems to generalize for mechanical hybrid systems
- Experimental implementation