# Hybrid Controller Schemes for Anti-lock Braking Systems in Road Vehicles

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# How the ABS Works

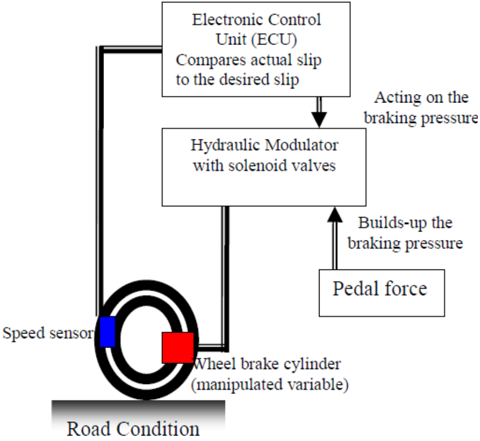


Figure: Schematic Representation of ABS

# Current ABS Control Scheme Cont.

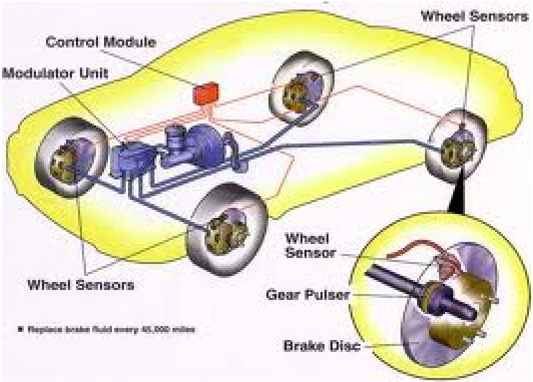


Figure: ABS Architecture (http://protoncar.wordpress.com)

# Current ABS Control Scheme Cont.


Figure: Hydraulic Modulator(http://auto.howstuffworks.com)

# The Short-Comings of Current ABS Scheme

- Current ABS is based on complicated logic rules executed by means of a computer that switches on and off solenoid valves to ensure the right pressures are delivered to the wheels while avoiding slippage,
  - the *on-off* operation of the solenoid valves, introduces a chattering effect and hence degrade the performance of the ABS,

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  - the *on-off* operation of the solenoid valves, introduces a chattering effect and hence degrade the performance of the ABS,
  - it also creates the problem of instability in the controller,
  - The slip tends to oscillate around the peak friction point introducing further noise to the ABS.
- Several road testing is required to get the system tuned in a trial-and-error fashion.

# The Control Problem

- Braking model has significant non-linearities.
- Varying road conditions introduce uncertainties.
- Road surfaces have significant noise roughness, which needs to be attenuated.
- Suspension system can disturb ABS unpredictably if poorly designed and could lead to extremely short braking time.

**ABS Controller must handle all these CHALLENGES simultaneously!**

# ABS Controllers Proposed in the Literature

- Proportional + Integral + Derivative (PID) Control (Chikhi et al, 2005; Yoo, 2006).
- Gain Scheduling Approach (Solyom, 2002).
- Optimal Control: LQR, LQG, LQG/LTR (Jiang, et al, 2009; Kayancan et al 2009; ), Varying (LPV).
- Artificial Intelligent Control (Poursamad, 2009; Precup et al, 2010).
- Hybrid Systems, e.g., Sliding Mode & Neural Network, PID & Fuzzy Logic (Assadian, 2001; Johansen et at, 2001)

# ABS Controller Design Aims

- Controller must improve braking system real-time performance parameters.
- Braking time (distance) must be minimal.
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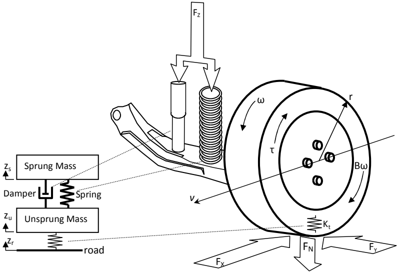
- Controller must improve braking system real-time performance parameters.
- Braking time (distance) must be minimal.
- Braking pressure must be minimised.
- The following performance criteria are used to evaluate the effectiveness of the controller
  - stopping distance $\leq 50m$ from initial speed of $80km/h$ $(22.23m/s)$
  - the integral squared error [ISE] of the slip $\int_{0}^{t_f} (\lambda - \lambda_d)^2 dt$,
  - the integral squared control input $\int_{0}^{t_f} {T_b}^2 dt$

# The Proposed Controller Solutions

- Due to the non-linear nature of the model, linear controllers will not be sufficient; therefore, the following solutions have been proposed:
  - Feedback linearization (FBL) with pole placement,
  - Hybrid combination of FBL and *Proportional-Integral-Derivative* (PID) controller
  - Neural network-based feedback linearization (NNFBL)
  - Hybrid combination of NNFBL and PID

# Physical Model

- For this work, the quarter car model is adopted.
- $v(t)$ is the forward longitudinal velocity.
- $\omega$ is wheel angular velocity.
- $F_z$ is the normal force component applied on the wheel during braking.
- $F_x$ is the tractive force due to the friction between the road and tyre.
- $T_b$ is the effective braking torque.
- $B$ is the viscous friction coefficient of the wheel bearings.
- It is assumed that the weight is equally distributed on the four wheels of the vehicle.
- It is also assumed that all the four wheels contribute equally to the car's total braking force.



# Mathematical Model

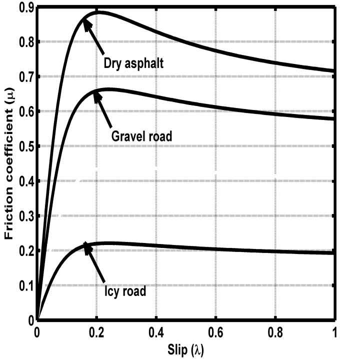
The dynamic equations of motion for the vehicle during braking are derived from Newton's laws:

$$\begin{aligned} \dot{\omega} &= \frac{1}{J}\left[r\mu(\lambda)F_z - B\omega - T_b(sign(\omega))\right] \\ \dot{v}_x &= -\frac{1}{m}\left[\mu_x(\lambda_x)F_z + C{v_x}^2\right] \\ \dot{T}_b &= \frac{1}{\tau}(-T_b + k_bP_b) \end{aligned} \tag{1}$$

# Friction Curve $\mu - \lambda$

- Our system's output $\lambda$ is a critical parameter on which the available maximal friction coefficient depends as shown in figure
- Typical plots for different road terrains are shown.
- Simplified equation of slip is given by:

$$\lambda = \frac{v - r\omega}{v} \qquad (2)$$



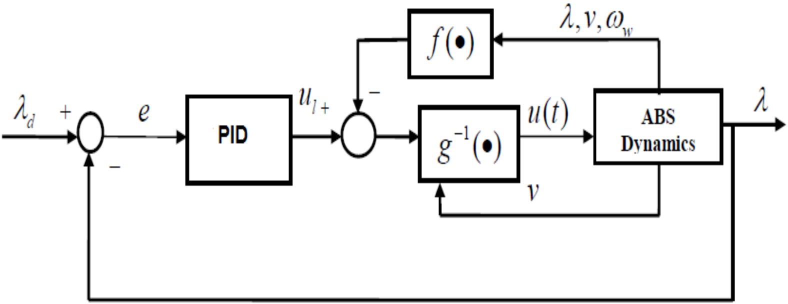
# Proposed Hybrid Solution

- The first proposed solution is a hybrid FBL with PID
- the PID structure used is given as:

$$U(s) = \left[ K_p \left( \frac{T_i s + 1}{T_i s} \frac{T_d s + 1}{\alpha T_d s + 1} \right) \right] E(s) \tag{3}$$

- where:
  - $U(s)$ is the plant input signal,
  - $K_P$ is the proportional gain,
  - $T_D$ is the derivative time constant,
  - $T_I$ is the integral time constant and
  - $\alpha$ is the lag factor in the derivative component of the PID controller.

# Proposed Hybrid Structure Block Diagram



# Proposed Neural Network-Based Solution

Two steps are involved in the indirect adaptive controller design, using neural networks: system identification and controller design.

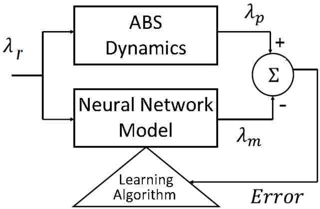



Figure: System identification of ABS dynamics for NNFBL control

# Proposed Neural Network-Based Solution

Multi-layerd-perceptron (MLP) neural network is used for training the NN, made-up of

- input layer,
- output layer and
- one hidden layer

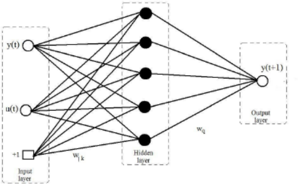
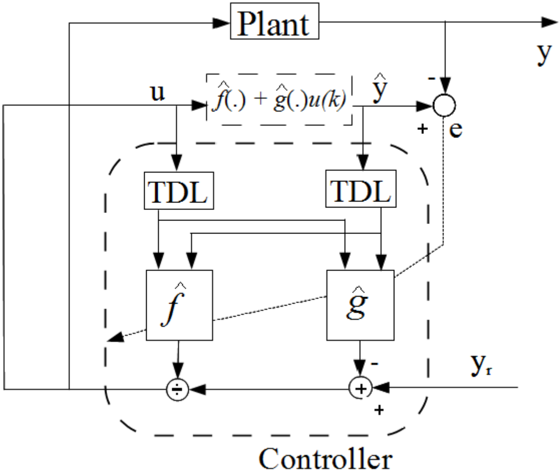



Figure: System identification of ABS dynamics for NNFBL control

# Parameters for the Neural Network Model

| Parameters | Values |
|---|---|
| Number of layers | 2 |
| Number of hidden layer neurons | 3 |
| Number of past outputs | 2 |
| Number of past inputs | 2 |
| Total number of samples | 25000 |
| Number of iterations | 500 |
| Training algorithm | Levenberg-Marquardt |
| Sampling time | 0.0001 sec |
| Maximum plant input | 1500 $N/m^2$ |
| Minimum plant input | 0 |
| Maximum plant output | 0.18 |
| Minimum plant output | 0 |

# Neural Network Controller Block Diagram



# Quarter-Car Model Parameters used for Simulations

- Simulations were conducted using the following system parameters:

| Parameters | Parameters | Parameters |
|---|---|---|
| B = 0.08 kgm$^2$/s | $C_x$ = 0.856 kg/m | J = 1.6 kgm$^2$ |
| $K_b$ = 0.8 | M = 395 kg | r = 0.3 m |
| $\tau$ = 0.03 s | $\lambda_d$ = 0.18 | g = 9.81 m/s$^2$ |

# FBL vs FBLPID Vehicle and Wheel Deceleration $\mu = 0.85$

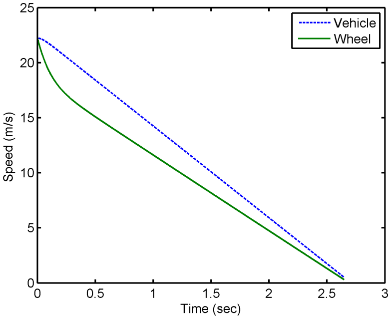



Figure: FBL Controller

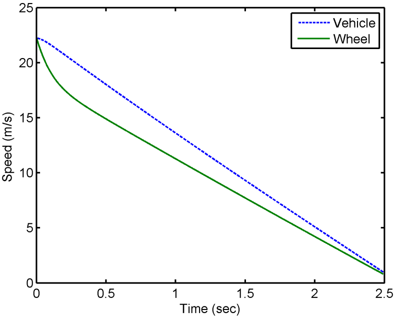



Figure: Hybrid Controller (FBLPID)

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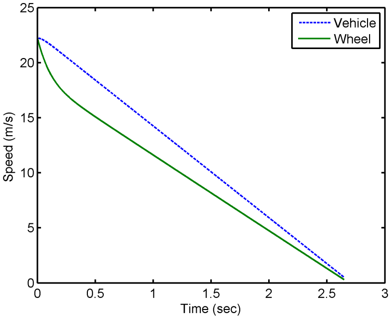


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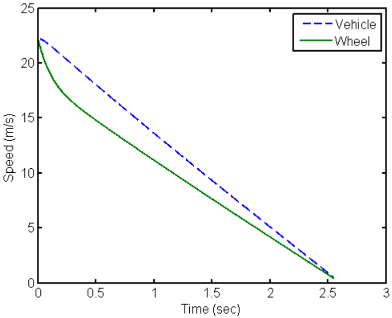



Figure: NN-Based Controller

# FBL vs FBLPID Vehicle and Wheel Deceleration $\mu = 0.2$

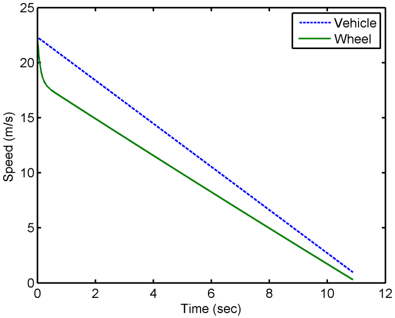
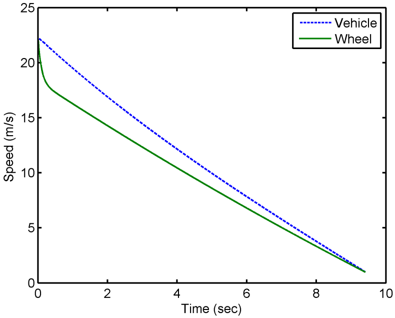



Figure: FBL Controller

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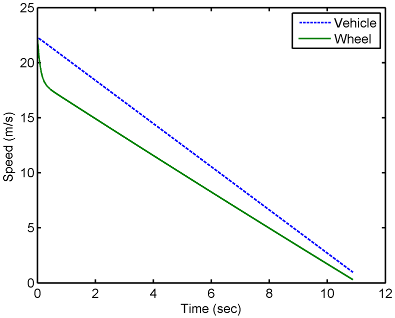



Figure: FBL Controller

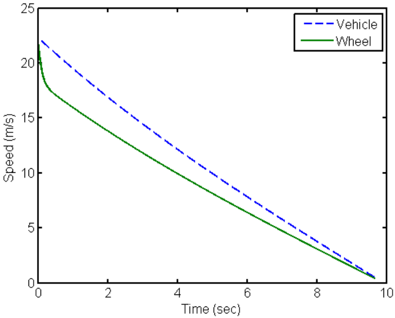
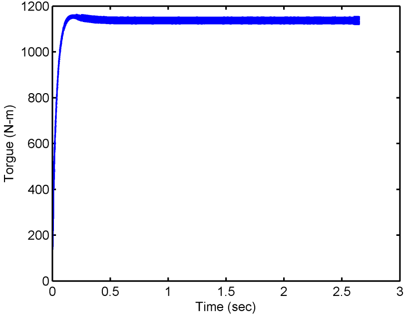



Figure: NN-Based Controller

# Braking Torque $\mu = 0.85$

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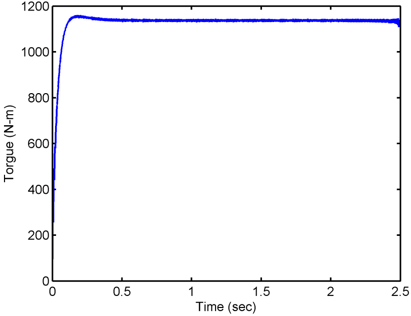


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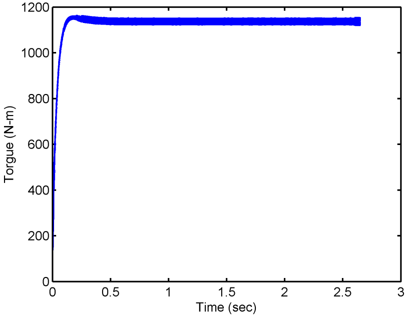


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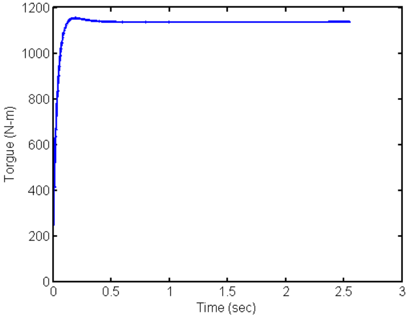


Figure: NN-Based Controller

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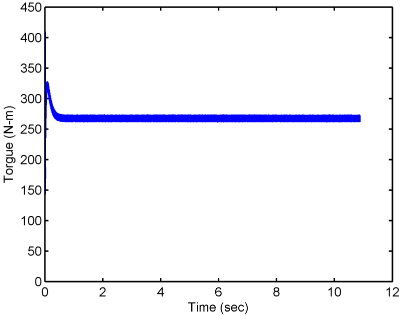


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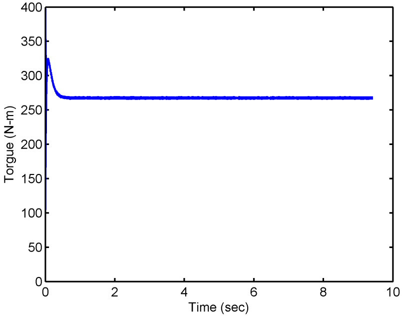


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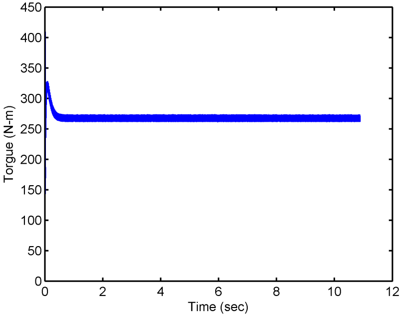


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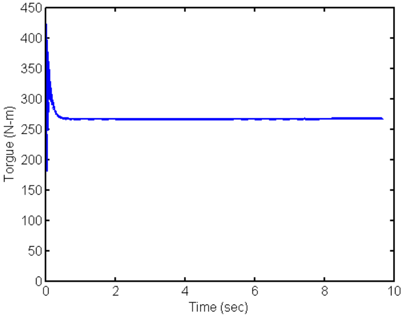


Figure: NN-Based Controller

# Summary of Simulation Results for $\mu = 0.85$

Table: Simulation results for $\mu = 0.85$ road condition

| Performance parameters | Specs | FBL | FBLPID | NNFBL |
|---|---|---|---|---|
| $\int_0^{t_f} (\lambda - \lambda_d)^2 dt (10^{-6})$ | min | 65.990 | 0.2113 | 1.704 |
| $\int_0^{t_f} {T_b}^2 dt (Nm)^2 (10^5)$ | min | 2.411 | 2.083 | 4.161 |
| $\int_0^{t_f} v dt (m)$ | $\leq 50$ | 31 | 29 | 29 |

# Summary of Simulation Results for $\mu = 0.2$

Table: Simulation results for $\mu = 0.2$ road condition

| Performance parameters | Specs | FBL | FBLPID | NNFBL |
|---|---|---|---|---|
| $\int_0^{t_f} (\lambda - \lambda_d)^2 dt (10^{-6})$ | min | 1.412 | 4.148 | 0.439 |
| $\int_0^{t_f} {T_b}^2 dt (Nm)^2 (10^5)$ | min | 0.645 | 0.481 | 0.922 |
| $\int_0^{t_f} v dt (m)$ | $\leq 50$ | 127 | 103 | 103 |

# Contributions

- Hybrid system of PID with FBL
- Linearization of non-linear equations using the FBL method does not necessarily require the traditional application of Pole placement.
- The proposed hybrid controller is superior to FBL in reducing the chattering effect
- Neural network-based controllers are feasible in the near future
- Proposed solutions are more robust than the current controllers

# Current Research - Green Hydrogen

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**Production** → **Transportation and Storage** → **Utilization**

**Production**

Green Hydrogen
Wind Biomass
Solar Hydro

Grey/Blue Hydrogen
NG Petroleum
Coal

↓

Carbon capture

**Transportation and Storage**

Gaseous Hydrogen

Liquid Hydrogen

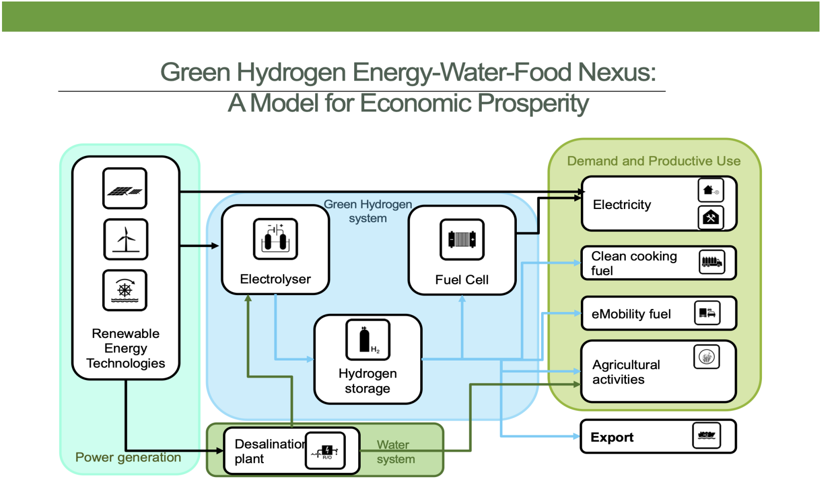
Material-based $H_2$

Ammonia

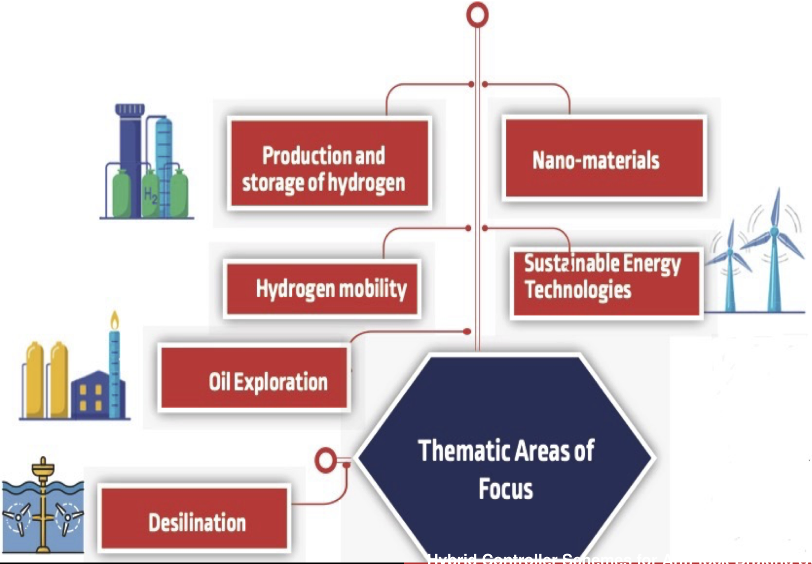
**Utilization**

End-users
Fuel cell vehicles
Power generation
Heating/Cooling
Steel production
Refining
Industrial feedstock

# Current Research - Green Hydrogen



# Current Research - Green Hydrogen



Thank you for your attention

QUESTIONS?