Iterative Learning Control of Antilock Braking of Electric and Hybrid Vehicles

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Outline

- *Introduction - Overview of HEV*
- *Part I – Iterative Learning Control*
- *Part II – Antilock Braking*
  - *Vehicle Model*
  - *Slip Ratio Model*
  - *The Learning Process*
  - *Required Braking torque*
- *Simulation Examples*
- *To Probe Further*

What is HEV

- HEV – Stands for Hybrid Electric Vehicle
- An HEV is a vehicle which involves multiple sources of propulsions
  - An EV is an electric vehicle, battery (or ultra capacitor, fly wheels) operated only. Sole propulsion by electric motor
  - A fuel cell vehicle is a series hybrid vehicle
  - A traditional vehicle has sole propulsion by ICE or diesel engine
- Therefore, HEV is essentially different from traditional vehicle

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Types of HEV

- Parallel HEV: multiple propulsion sources combined
- Series HEV: sole propulsion by electric motor, but the electric energy comes from another on board energy source, such as ICE
- Fuel Cell Vehicle (FCEV), use fuel cell as energy source, it is a series HEV

Why HEV ?

To Overcome the Disadvantage of Pure EV and Conventional Vehicles

Key Drawbacks of EVs

- *High Initial Cost*
  - *Many times that of conventional vehicles*
- *Short Driving Range*
  - *Less miles during each recharge*

  - *People need a vehicle not only for commuting (city driving), but also for pleasure (long distance highway driving)*
- *Recharging takes much longer time than refueling gasoline.*

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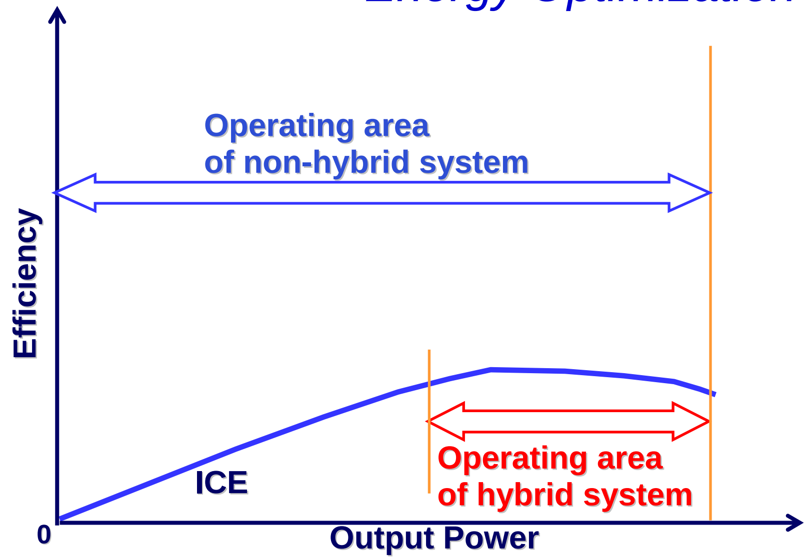
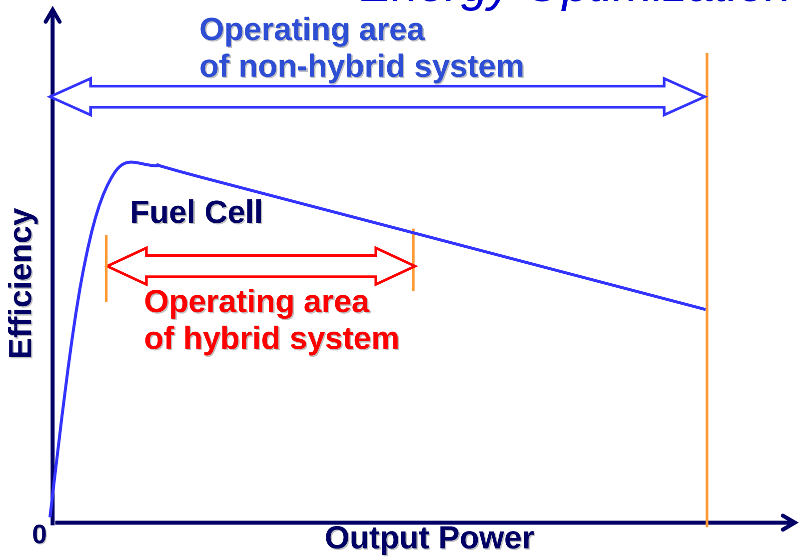
Key Advantage of HEV

- Optimize the fuel economy
  - Optimize the operating point of ICE
  - Stop the ICE if not needed
  - Recover the kinetic energy at braking
  - Reduce the sizes of ICE
- Reduce emissions
  - Minimize the emissions when ICE is in operation
  - Stop the ICE when it’s not needed
  - Reduced size of ICE means less emissions
- FCEV does not have emission

Energy Optimization



Energy Optimization



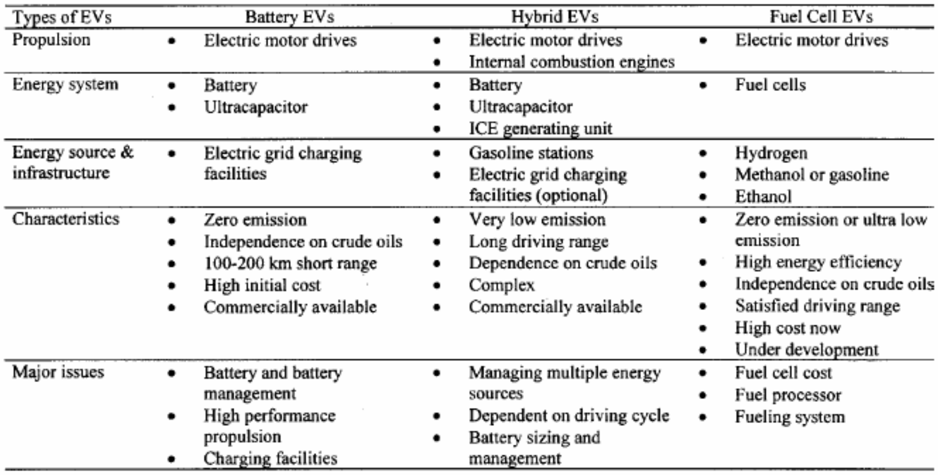
Performance

- ***Quiet Operation***
  - *There is no noise at low speed because ICE is stopped*
  - *Quiet motor, motor is stopped when vehicle comes to a stop*
- ***Reduced maintenance because ICE operation is optimized, which means***
  - *Less tune ups, longer life cycle of ICE*
  - *Less spark-plug changes*
  - *Less oil change*
  - *Less fuel filters, antifreeze, radiator flushes or water pumps*
  - *Less exhaust repairs or muffler changes*

History of Electric Vehicles

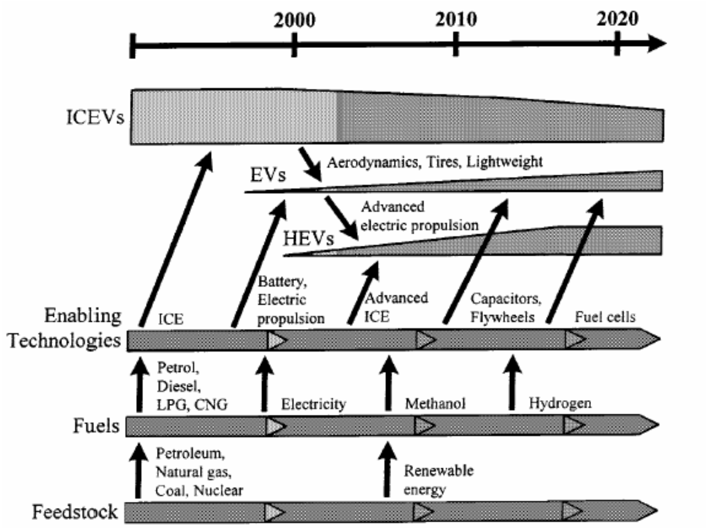
- EVs were invented in the 19^{th} century
- Vanished since 1930 due to range, price, and reliability
- Resumed in 1976 because oil crisis
- Has been very active over the world
- Have introduced different types of HEVs
- Have commercialized vehicles

A Comparison of EV, HEV and FCEV



Types of EVs	Battery EVs	Hybrid EVs	Fuel Cell EVs
Propulsion	• Electric motor drives	• Electric motor drives • Internal combustion engines	• Electric motor drives
Energy system	• Battery • Ultracapacitor	• Battery • Ultracapacitor • ICE generating unit	• Fuel cells
Energy source & infrastructure	• Electric grid charging facilities	• Gasoline stations • Electric grid charging facilities (optional)	• Hydrogen • Methanol or gasoline • Ethanol
Characteristics	• Zero emission • Independence on crude oils • 100-200 km short range • High initial cost • Commercially available	• Very low emission • Long driving range • Dependence on crude oils • Complex • Commercially available	• Zero emission or ultra low emission • High energy efficiency • Independence on crude oils • Satisfied driving range • High cost now • Under development
Major issues	• Battery and battery management • High performance propulsion • Charging facilities	• Managing multiple energy sources • Dependent on driving cycle • Battery sizing and management	• Fuel cell cost • Fuel processor • Fueling system

Development Trends



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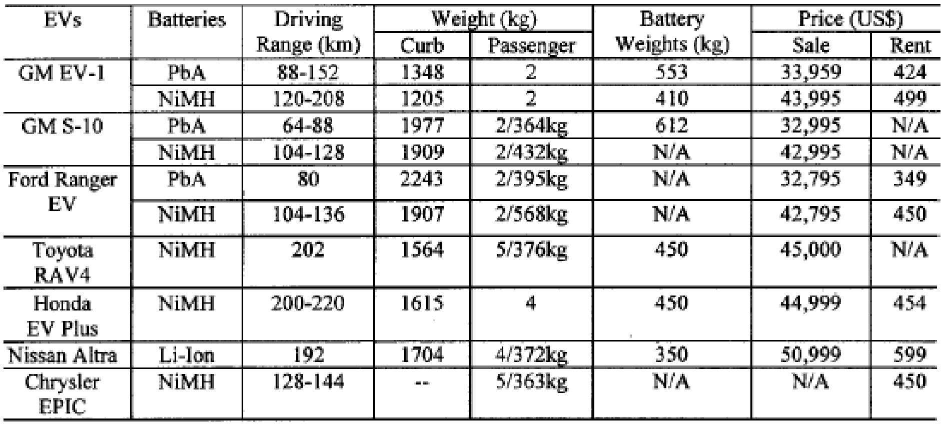
Key Data of Current EVs



EVs	Batteries	Driving Range (km)	Weight (kg)		Battery Weights (kg)	Price (US$)	
			Curb	Passenger		Sale	Rent
GM EV-1	PbA	88-152	1348	2	553	33,959	424
	NiMH	120-208	1205	2	410	43,995	499
GM S-10	PbA	64-88	1977	2/364kg	612	32,995	N/A
	NiMH	104-128	1909	2/432kg	N/A	42,995	N/A
Ford Ranger EV	PbA	80	2243	2/395kg	N/A	32,795	349
	NiMH	104-136	1907	2/568kg	N/A	42,795	450
Toyota RAV4	NiMH	202	1564	5/376kg	450	45,000	N/A
Honda EV Plus	NiMH	200-220	1615	4	450	44,999	454
Nissan Altra	Li-Ion	192	1704	4/372kg	350	50,999	599
Chrysler EPIC	NiMH	128-144	--	5/363kg	N/A	N/A	450

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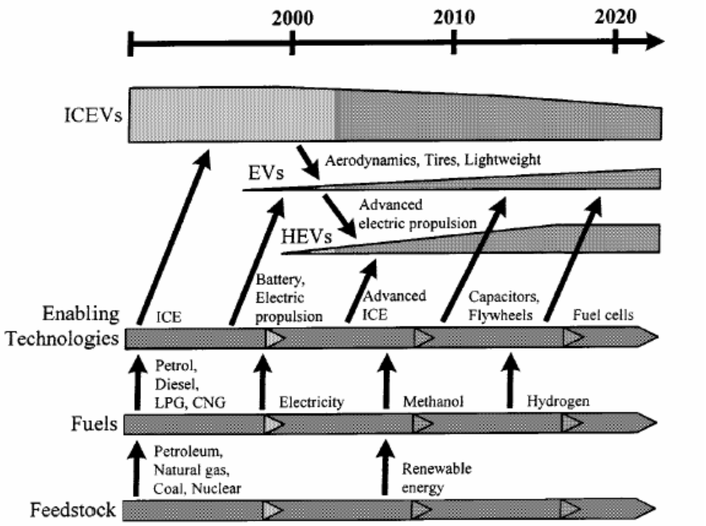
Development Trends



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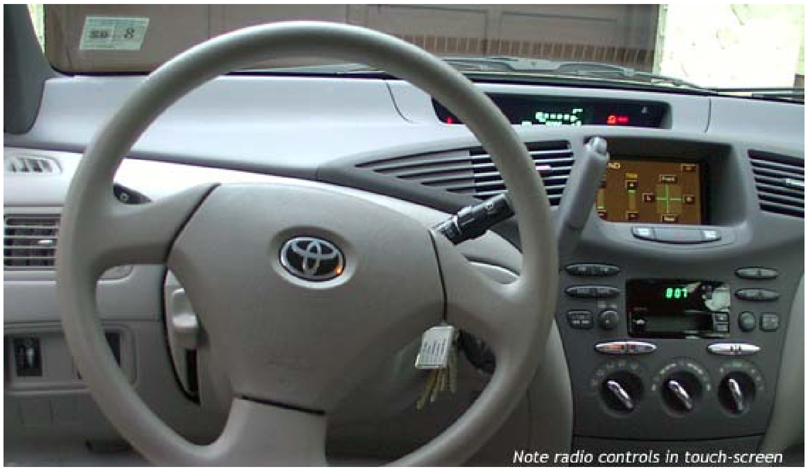
Overview of the Toyota Prius

Toyota Prius (1997)

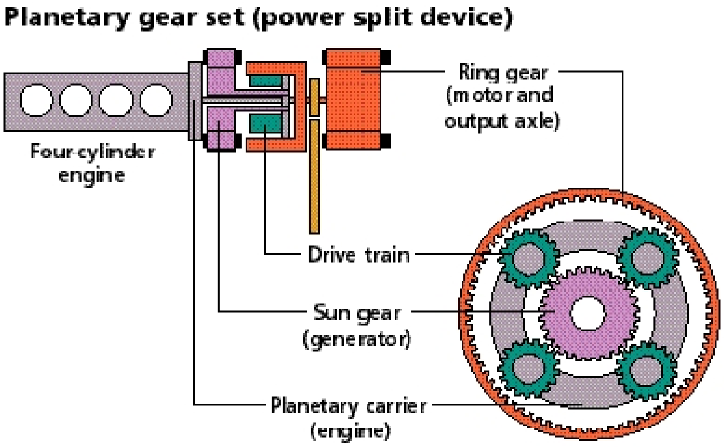
The 2003 Prius Model

Inside



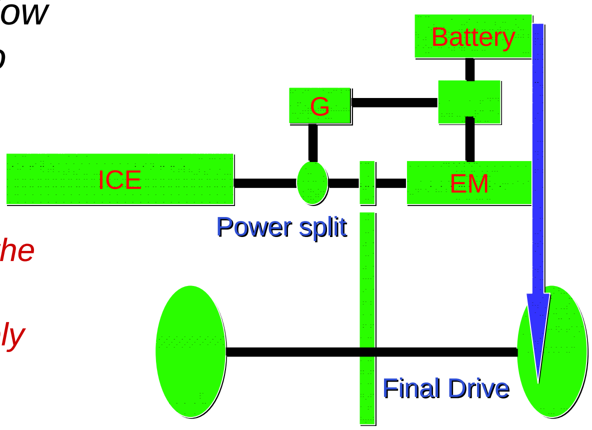
Trunk Space

Planetary Gear



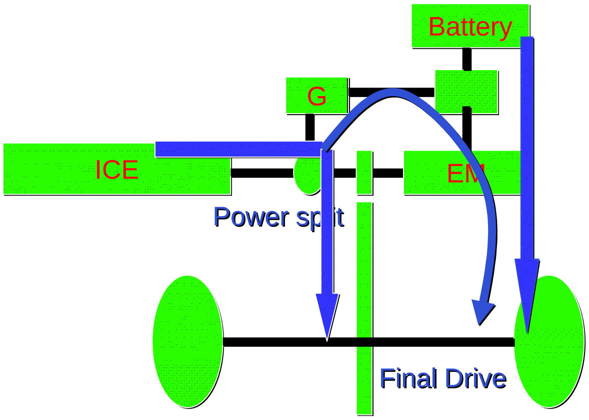
Power Flow

- *Starting and low speeds (up to 20mph)*
  - *ICE off*
  - *Motor drive the vehicle*
  - *Battery supply the needed power*



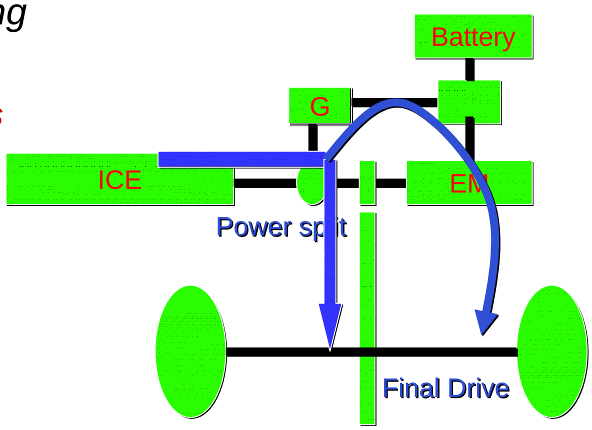
Power Flow

- *Sudden Acceleration*



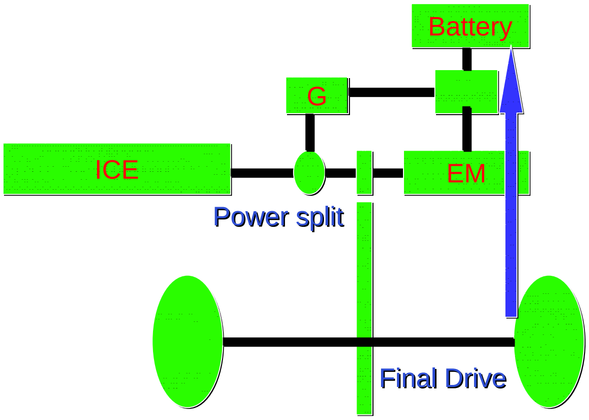
Power Flow

- *Normal Driving*
  - *ICE power is split*



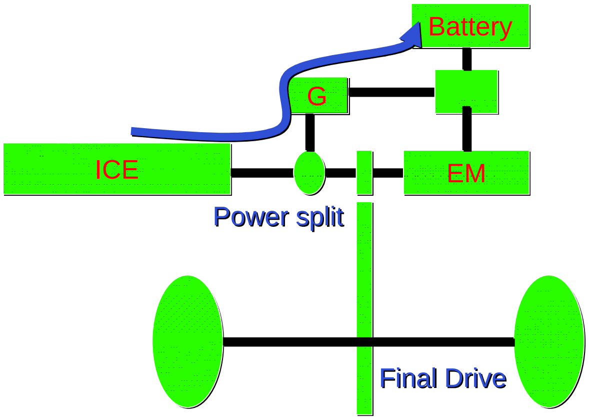
Power Flow

- *Braking*
  - *ICE is off*



Power Flow

- *Stationary Charging*



Specifications

- *Gas engine:*
  - *Inline 4-cylinder DOHC, Displacement: 1,497 cc,*
    Compression Ratio: 13.0:1
    Peak Horsepower: 70 hp at 4,500 rpm
    Peak Torque: 82 lb.-ft. at 4,200 rpm
    Fuel Tank Capacity: 11.9 Gal.
- *ELECTRIC MOTOR –*
  - *Permanent Magnet, Capacity: 6.5 amperes, Peak Torque: 258 lb./ft. (350.0 Nm) 0-400 rpm, maximum power of 33 kW (44 horsepower) from 1,040-5,600 rpm, and maximum torque of 350 N-m (258 lb./ft.) from 0-400 rpm.*

Specifications

- ELECTRIC GENERATOR –
  - Permanent Magnet, Capacity: 15kW, peak efficiency 84%, 33kg, max current 300A
- BATTERY PACK
  - Peak Horsepower: 25 kW (34 hp)
    Nominal Voltage: 274 volts

Specifications – Cont.

- EXTERIOR DIMENSIONS
  - Length: 169.6 in.
  - Width: 66.7 in.
  - Height: 57.6 in.
  - Wheelbase: 100.4 in.
  - Weight 2,765 lb.
  - Seating Capacity: 5

Specifications – Cont.

- INTERIOR DIMENSIONS
  - Headroom (front/rear): 38.8 / 37.1 in.
  - Legroom (front/rear): 41.2 / 35.4 in.
  - Shoulder room (front/rear): 52.8 / 52.2 in.
  - Hip room (front/rear): 50.7 / 51.9 in.
  - Passenger volume: 88.6 cu. ft.
  - Cargo volume: 11.8 cu. ft.
  - Total interior volume: 100.4 cu. ft.
  - EPA class: Compact

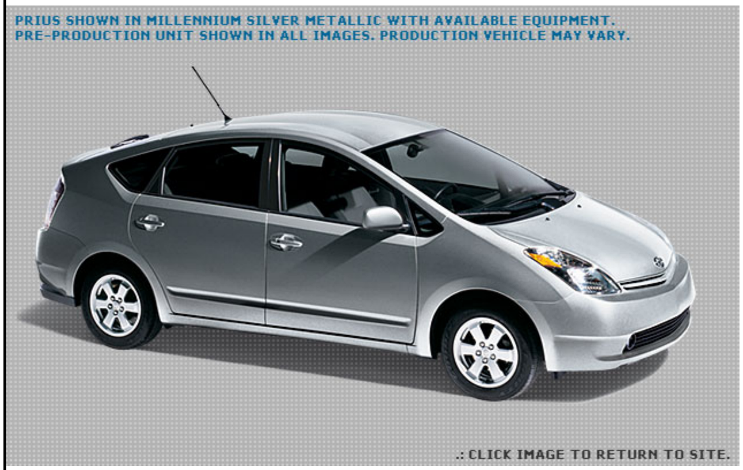
Specifications – Cont.

- Transmission: Electrically Controlled CVT
- Braking: Front ventilated disc/Rear drum (Hydraulic, with Power Assist)
  with Integrated Regenerative Brake System
- Steering: Rack and Pinion
  Suspension (front/rear): MacPherson strut / Torsion beam

Range/MPG/Emission

- *Range:*
  - *– **11.9** gallon tank allows **+500 miles** between refills*
- *MPG:52*
  - *– City (EPA rating)*
  - *– **45** Highway (EPA rating)*
- *Emission: SULEV (Super Ultra Low Emission Vehicle)*
  - ***– 90% less NO x (Nitrogen Oxide)***
  - ***– 50% less CO 2 (Carbon Dioxide)***

The 2004 Prius Model



Over 11,000 vehicles has been sold, with initial estimation of 3000 vehicles

MSRP: $19,995

The 2004 Prius Model

- Range:
  - **15** gallon tank allows **+500 miles** between refills
- MPG:60
  - City (EPA rating)
  - **51** Highway (EPA rating)
- Emission: SULEV (Super Ultra Low Emission Vehicle)

The future

- A few new models coming out
- Toyota is planning to manufacture and market its hybrid vehicle in the US and China
- To increase annually to 300,000 per year to 2006

Introduction

- *HEV offers remarkable fuel savings and emission reduction*
  - *Toyota Prius: 60 MPG city driving*
  - *Toyota Corolla: 30 MPG*
- *Past studies was focused on modeling of HEV*
- *The multiple sources of power in HEV offers great ease and flexibility to achieve advanced control and additional driving performance*

Introduction – Continued

- *Advanced features of modern vehicles include antilock braking system (ABS) and traction control (TC)*
- *ABS and TC may not be effective due to the nonlinear characteristics and unknown environmental parameters.*
- *Advanced control algorithms, such as fuzzy control and neural network have been used to achieve antilock braking for conventional vehicles*

Introduction – continued

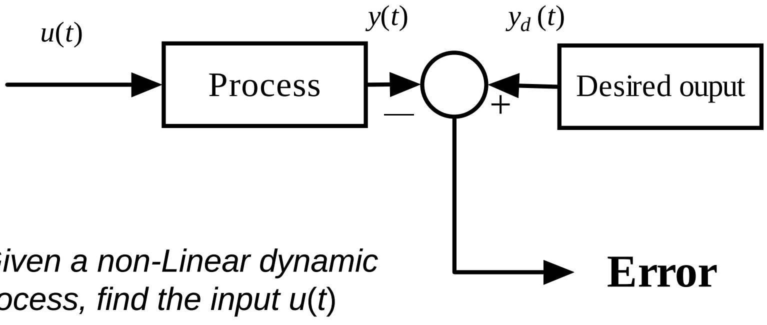
- *In addition to the primary function of propulsion, the electric motor can also be used effectively as the braking device*
  - *fast torque response characteristics*
  - *capability of regeneration.*
  - *The fast torque response provides the possibility to improve the vehicle antilock braking performance through the control of motor torque, without conventional ABS*

Part I: Iterative learning Control

What is ILC

- *Iterative learning control (ILC)*
  - *Proven to be effective for controls related to nonlinear dynamic systems*
  - *In this study, ILC was proposed to control the antilock braking of EV and HEV, using the electric motor to provide the required braking torque.*

Iterative Learning Control



•Given a non-Linear dynamic process, find the input u(t) function so that the output of the system y(t) closely follows the desired output $y_d(t)$

Example I

$$\dot{x}_1(t) = (\sin x_1 + 2\sin x_2)\frac{1}{1+t} + 3t \cdot u(t)$$

$$\dot{x}_2(t) = 0.3\sin x_1 + \frac{\sin x_2}{1+t} \cdot u(t)$$

$$y(t) = \sin x_1 + 0.5\sin x_2 + 0.5 \cdot u(t)$$

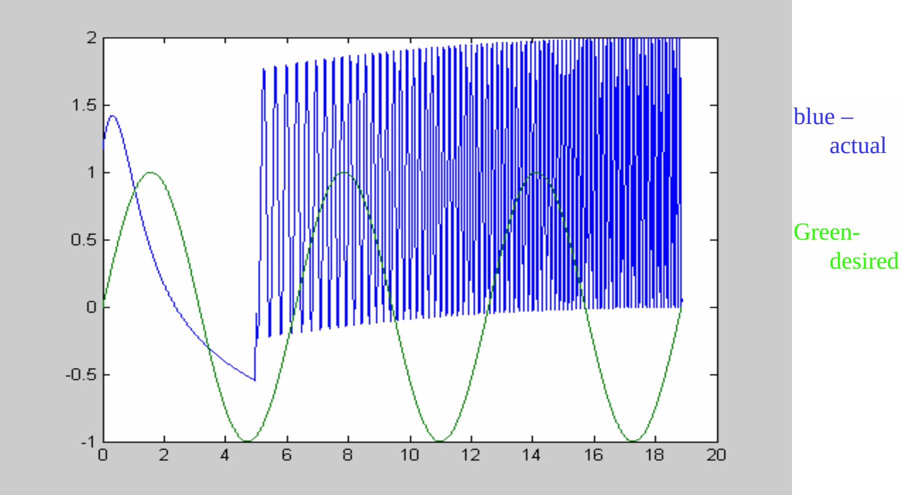
$$x_1(t) = 0.9$$

$$x_2(t) = 0.9$$

Desire that y(t) follows sin(t)

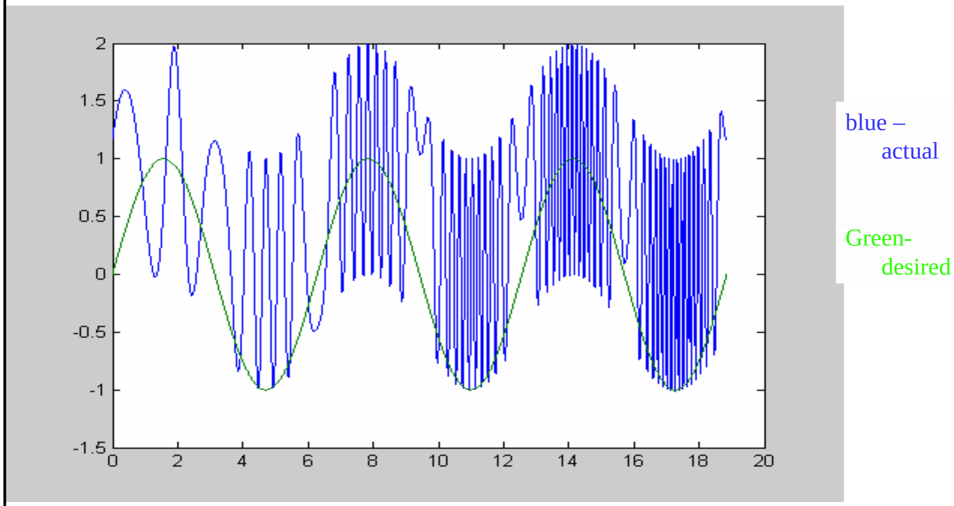
Ex.1 Continued

- *If we choose u(t) as a step function, then the output is as follows:*

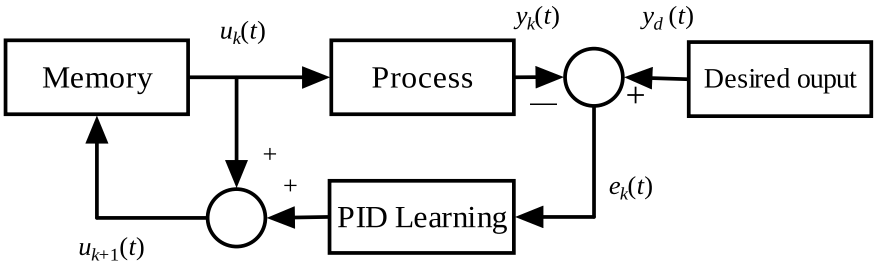


Ex.1 Continued

- *If we choose u(t) as a sine function, then the output is as follows:*

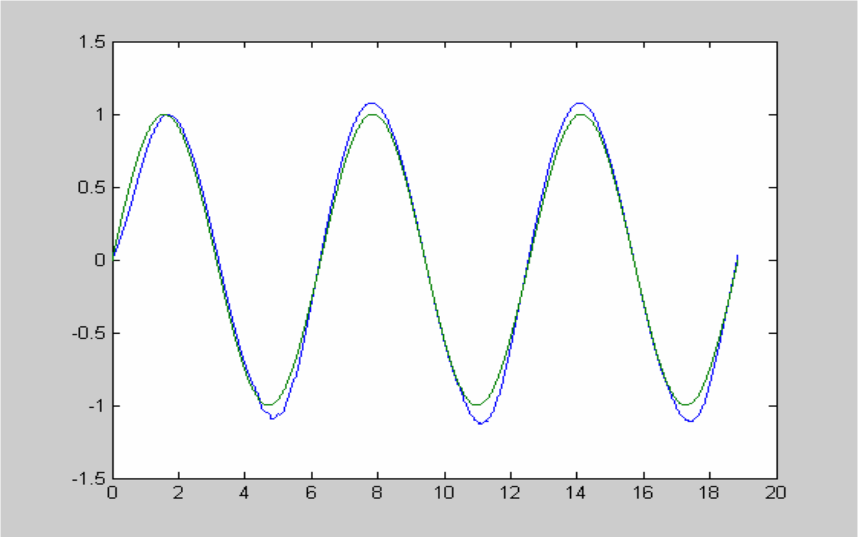


Using ILC

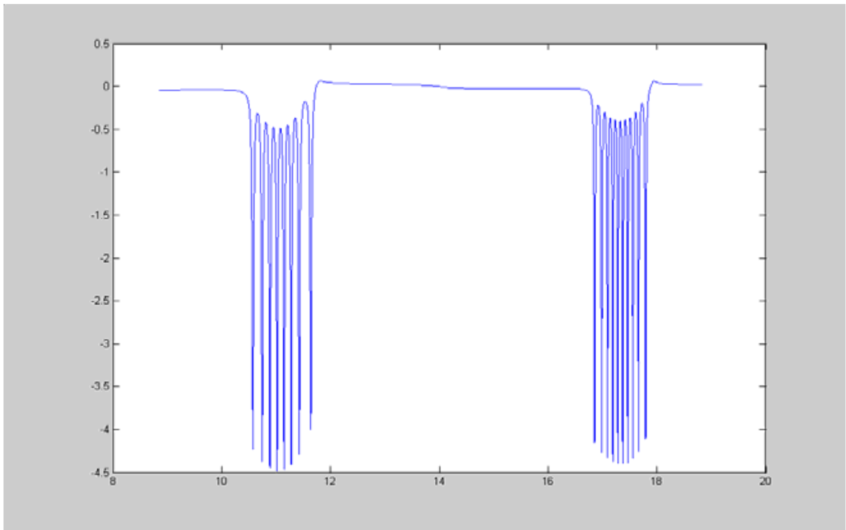


$$u_{k+1}(t) = u_k(t) + \Gamma \frac{de_{k+1}(t)}{dt} + \Gamma_p e_{k+1}(t)$$

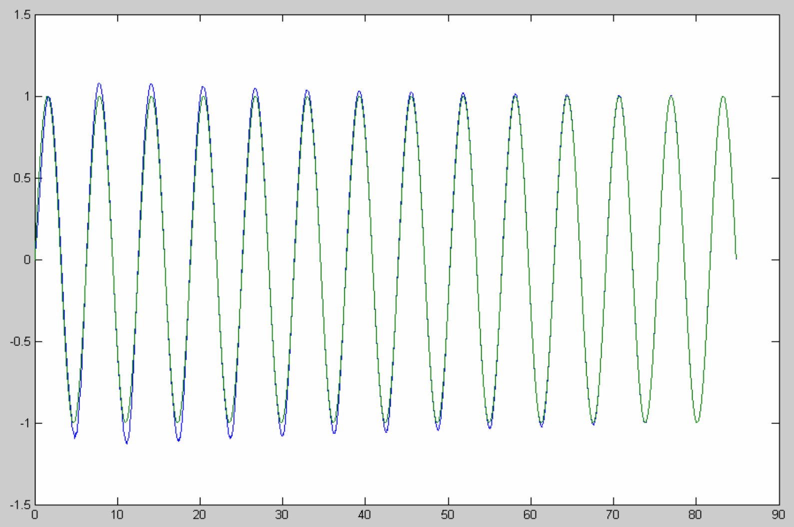
The output



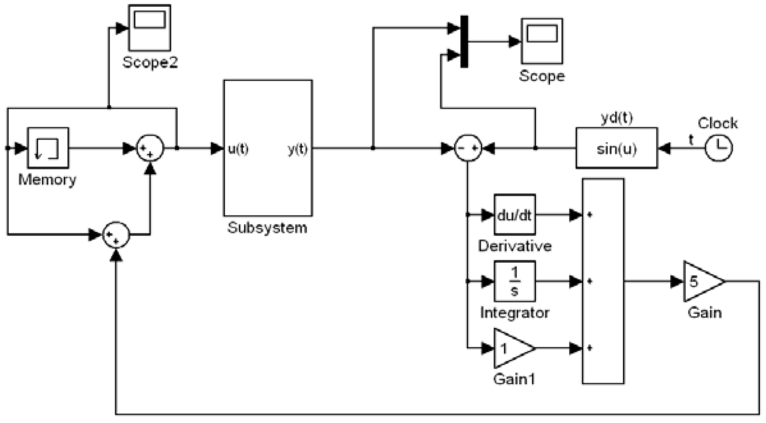
The Input u(t)



After 3 steps of learning



The Model of Ex.1



The leaning process

- u(t+1) is based on u(t)
- $u_{k+1}(t)$ is based on $u_k(t)$
- There have to be an optimum learning ratio
- There have to be a convergence problem
  - – Refer to references in “probe further” section

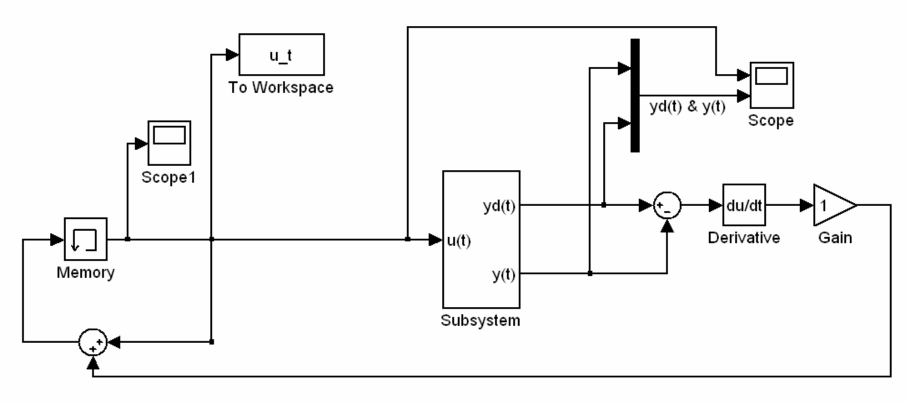
Example II

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -2-5t & -3-2t \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u(t)$$

$$y(t) = x_2(t)$$

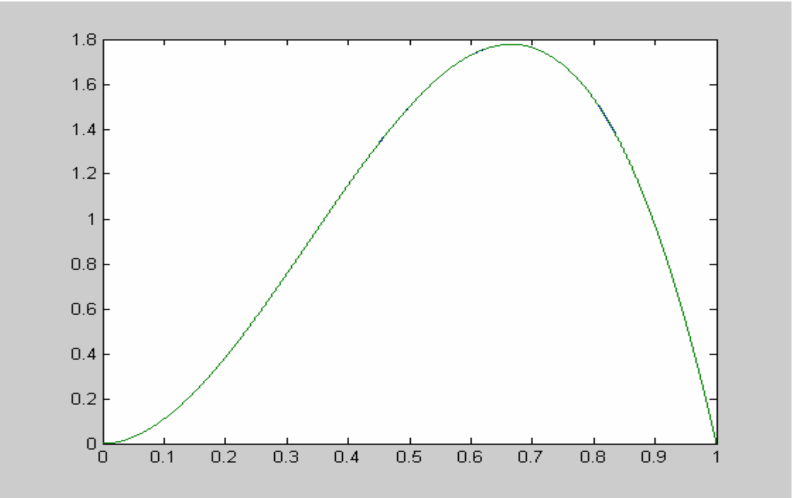
$$y_d(t) = 12t^2(1-t)$$

The model



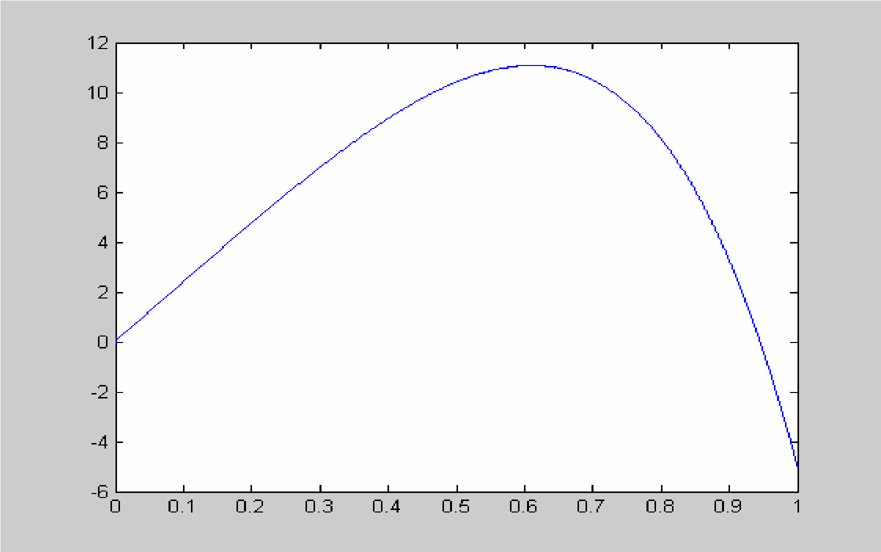
After Learning

The desired $y_d(t)$ and actual output $y(t)$



After Learning

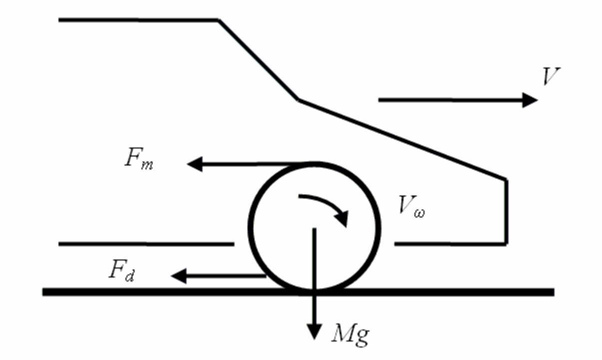
the input u(t)



Break – Demonstration of the two examples

Part II: Antilock Braking

Vehicle Model



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

$$M\frac{dV}{dt} = -F_d(\lambda)$$

$$F_d(\lambda) = \mu(\lambda)Mg$$

$$J_\omega \frac{d\omega}{dt} = -T_m + rF_d(\lambda)$$

Vehicle Model

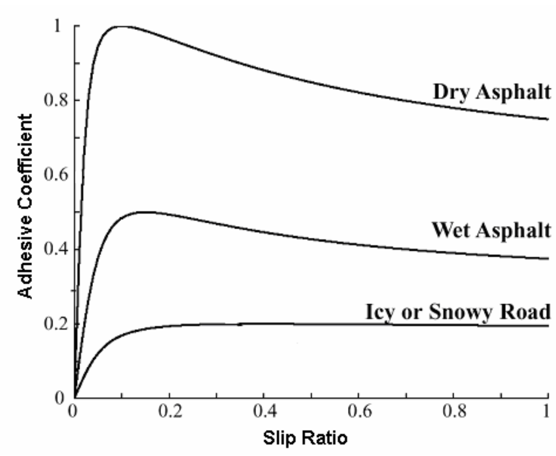
$$\lambda = \frac{V_\omega - V}{V}$$

$$M\frac{dV}{dt} = -F_d(\lambda)$$

$$J_\omega \frac{d\omega}{dt} = -T_m + rF_d(\lambda)$$

- *Slip ratio – control variable*
- *Slip ratio is a function of vehicle speed and wheel speed*
- *Vehicle speed is a function of braking force Fd*
- *Wheel speed is a function of braking torque Tm and braking force Fd*
- *Fd is unknown, but related to slip ratio*

Typical Adhesive Coefficient



- *For almost all road conditions, braking force reaches maximum around 0.15-0.20 slip ratio.*
- *We need to control the braking torque so that slip ratio is maintain at optimum, therefore, maximum braking effect can be achieved.*

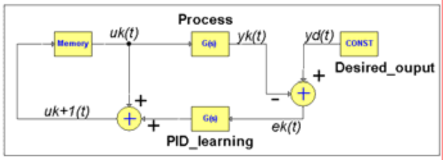
Slip Ratio Model

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

$$\dot{\lambda} = -\frac{1}{V}\dot{V}_\omega + \frac{V_\omega}{V^2}\dot{V}$$

$$= -(1+\lambda)\frac{\dot{V}}{V} + \frac{1}{V}\dot{V}_\omega$$

- *We need to develop the state space equations of the vehicle system so that we can apply an algorithm*
- *Output-slip ratio*
- *Input-motor torque*
- *Example is shown to derive the slip ratio model*



State Space Function

- *Let* $\begin{cases} x_1(t) = \lambda \\ x_2(t) = V \end{cases}$

$$\dot{V} = -g\mu(\lambda)$$

- *Then*

$$\begin{cases} \dot{x}_1(t) = (1 + x_1(t))\dfrac{g\mu(x_1)}{x_2(t)} + \dfrac{r^2 Mg\mu(x_1)}{x_2(t)J_\omega} - \dfrac{r}{x_2(t)J_\omega}T_m(t) \\ \dot{x}_2(t) = -g\mu(x_1) \end{cases}$$

State Space Function

- *Define motor torque as a function of vehicle speed*

$$T_m(t) = x_2(t)u(t)$$

- *Then*

$$\begin{cases} \dot{x}_1(t) = (1 + x_1(t))\dfrac{g\mu(x_1)}{x_2(t)} + \dfrac{r^2 Mg\mu(x_1)}{x_2(t)J_\omega} - \dfrac{r}{J_\omega}u(t) \\ \dot{x}_2(t) = -g\mu(x_1) \end{cases}$$

The Output

- *The output is defined as the slip ratio*

$$Y(t) = [1,0]\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}$$

State Space Function

$$\begin{cases} \dot{X}(t) = f(X(t),t) + B(X(t),t)u(t) \\ Y(t) = C(t)X(t) \end{cases}$$

$$X(t) = [x_1(t), x_2(t)]^T$$

$$\begin{cases} x_1(t) = \lambda(t) \\ x_2(t) = V(t) \end{cases}$$

Where

$$f(X(t),t) = \begin{bmatrix} (1 + x_1(t))\dfrac{g\mu(x_1)}{x_2(t)} + \dfrac{r^2 Mg\mu(x_1)}{x_2(t)J_\omega} \\ \\ -g\mu(x_1) \end{bmatrix}$$

$$B(X(t),t) = \left[-\frac{r}{J_\omega}, 0 \right]^T$$

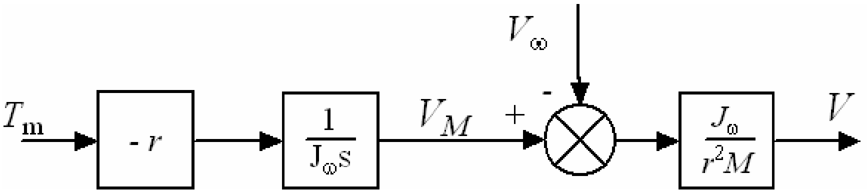
$$C(t) = [1,0]$$

$$\begin{cases} \dot{X}(t) = f(X(t),t) + B(X(t),t)u(t) \\ Y(t) = C(t)X(t) \end{cases}$$

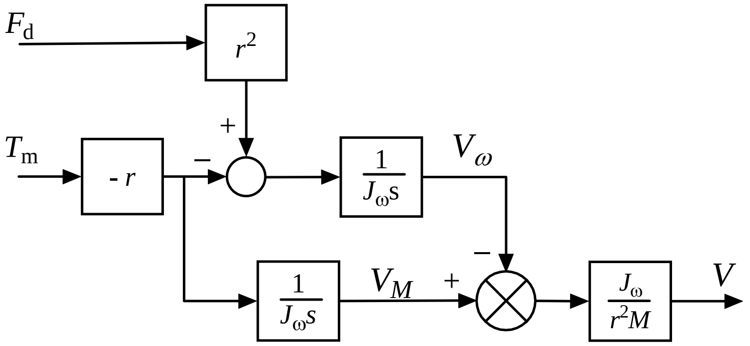
Vehicle Speed Observer

- The state space function involves vehicle speed, which is difficult measure.
- We therefore build a speed observer based on two inputs,

Vehicle Speed Observer



Actual Speed of the Vehicle



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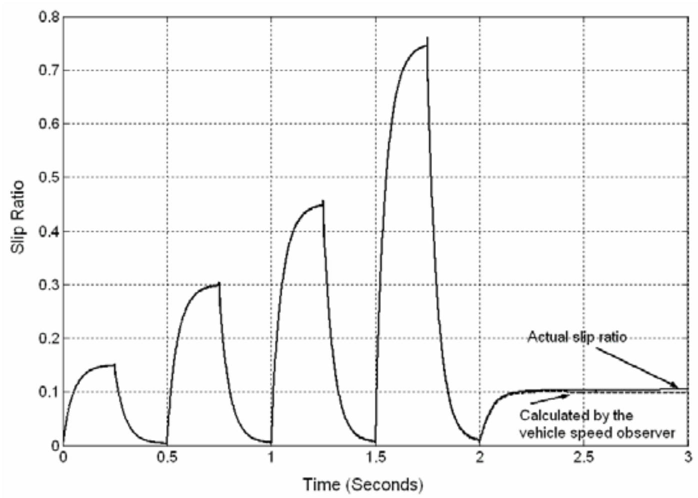
Vehicle Speed Observer

Comparison between observed and calculated



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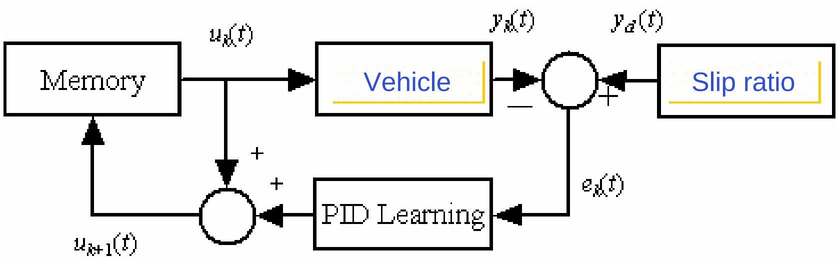
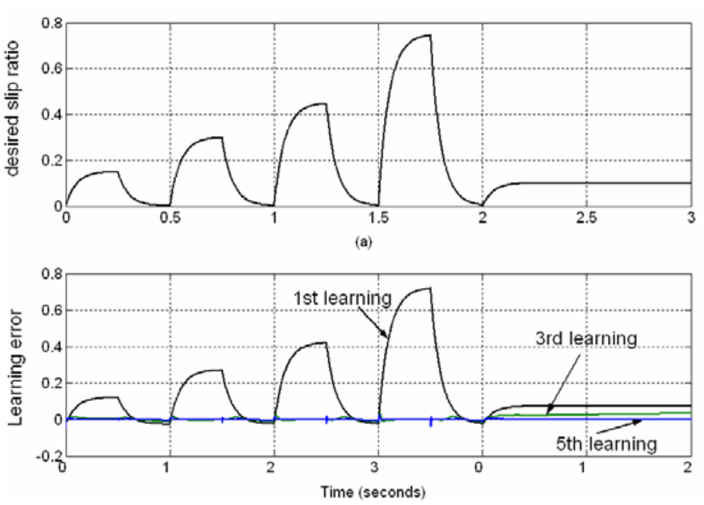
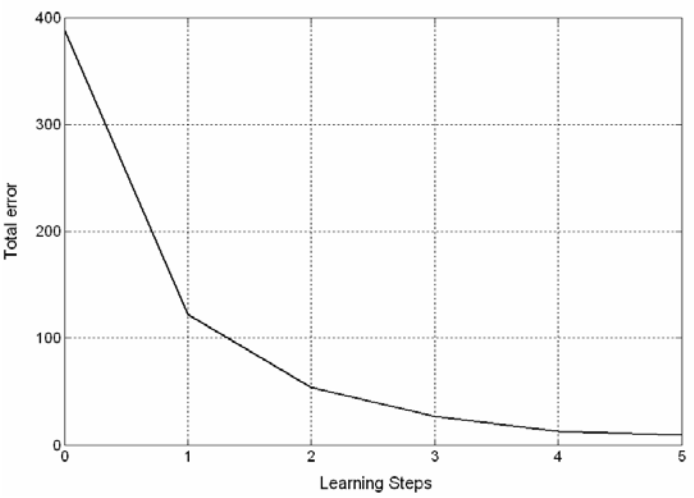
ILC for Motor Needed Torque



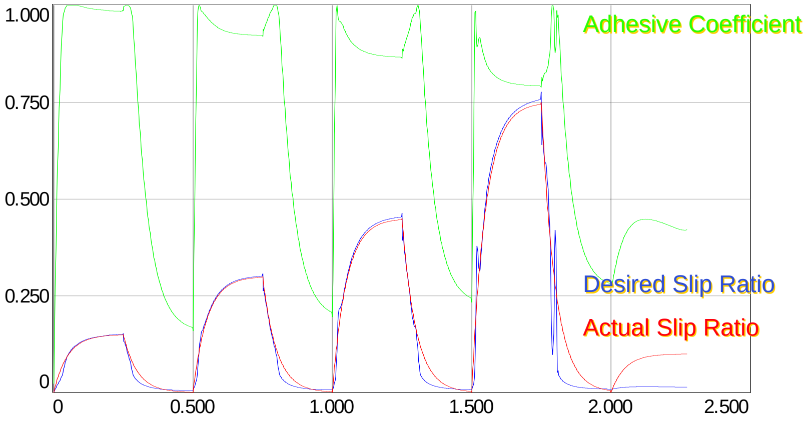
The Learning Process



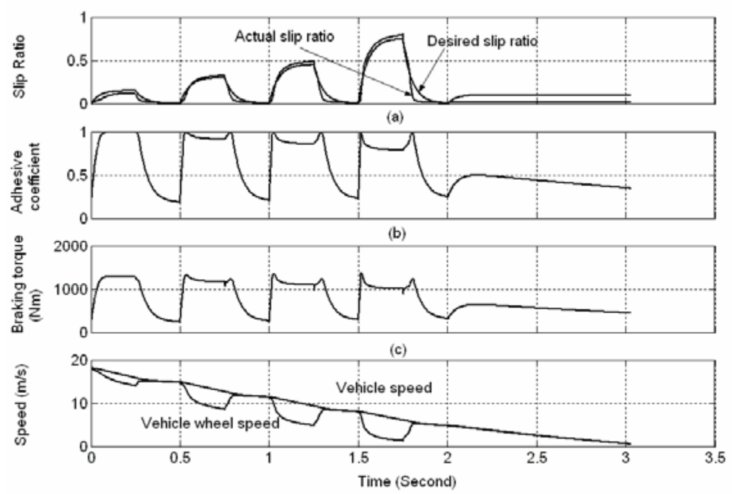
Total Learning Error



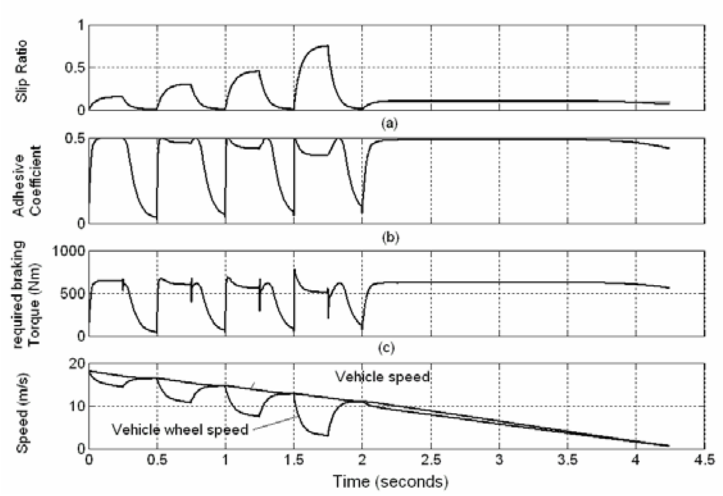
The Learning Process



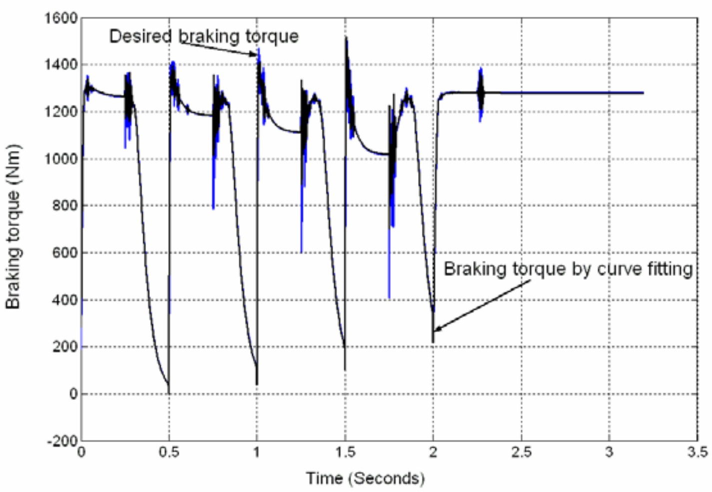
After Third Step of Learning



After Fifth Step of Learning



Motor Torque – Curve Fitting

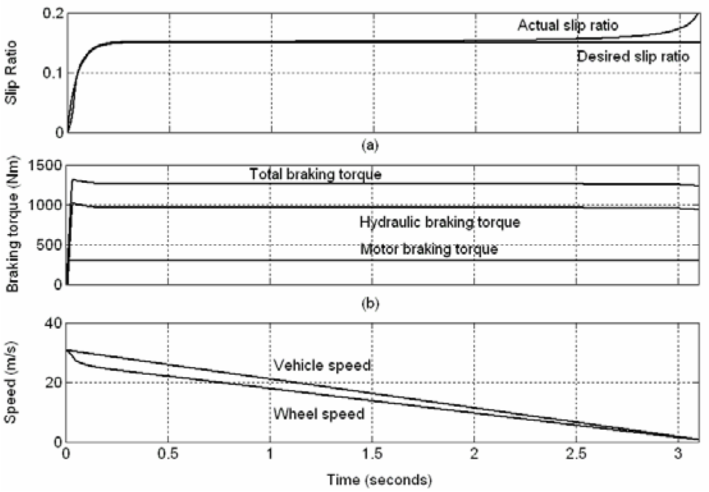


Case Studies

Table II
VEHICLE PARAMETERS

PARAMETERS	SYMBOL	VALUE
Vehicle Mass (kg)	M	1300
Wheel Radius (m)	r	0.3
Rotating Inertia (kg.m^2)	J	0.55
Shaft Gearing ratio	a	3
Maximum Motor torque (Nm)	T_m	300

Braking on a Dry Road Surface



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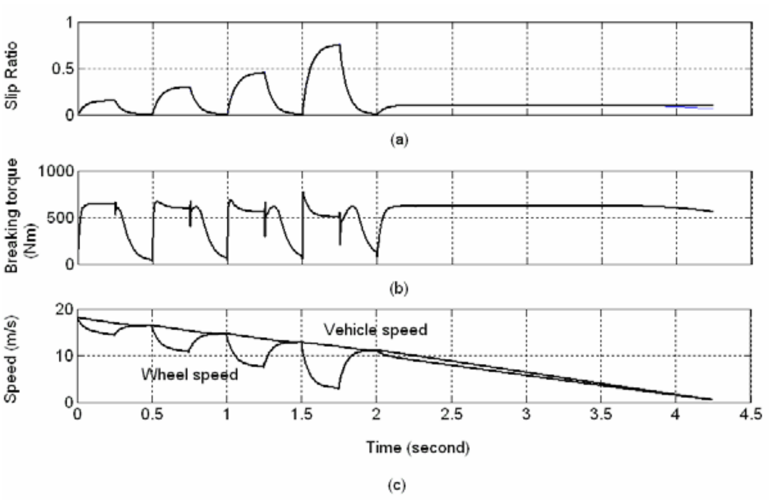
Braking on a Wet Road Surface



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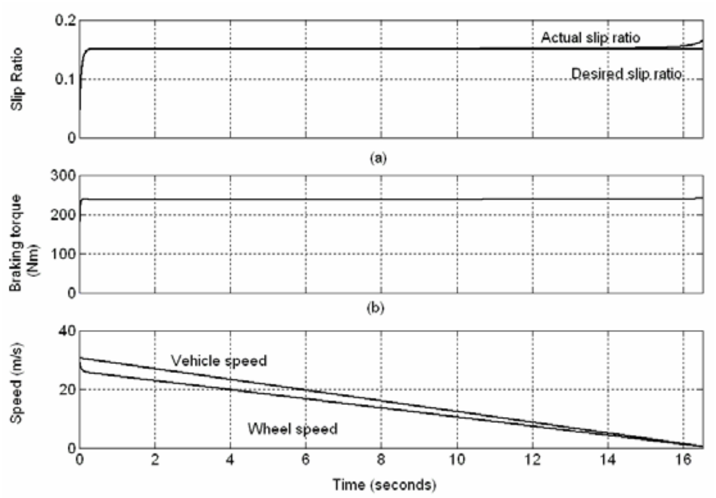
Braking on an Icy Road Surface



To Probe Further

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Thank You !