HW.1

H.W-1

1. Modeling of 2DOF Bicycle Model

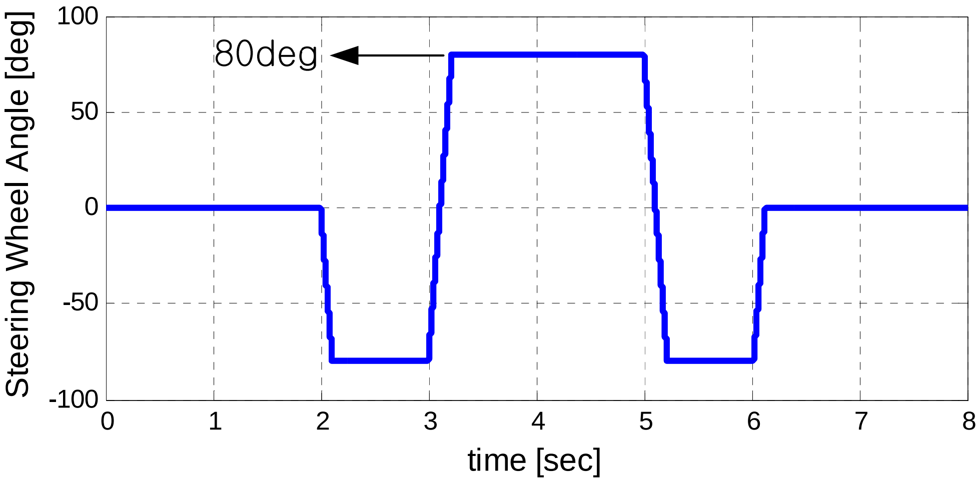
• Vehicle parameters of 2 DOF bicycle model are listed in Table.1. Simulate the vehicle behaviors using the steering wheel angle maneuver as shown in Fig.1.

1) Plot body slip angle and yaw rate. (Vx = 30, 50 and 70 kph)
2) Plot vehicle trajectory . (Vx = 30, 50 and 70 kph)
3) Discussion – Why the Vehicle Behavior (body slip and yaw rate) is different in the situation of same steering wheel angle with different vehicle velocity?

Table.1 Vehicle Parameters

Symbol	Value	Symbol	Value
m	1723.8 kg	L	2.7 m
I_z	4175 kgm^2	l_f	1.24 m
C_f	67248 N/rad	l_r	$L - l_f$
C_r	53248 N/rad	Steering Ratio	15

Fig.1 Steering Wheel Angle Maneuver



H.W-1

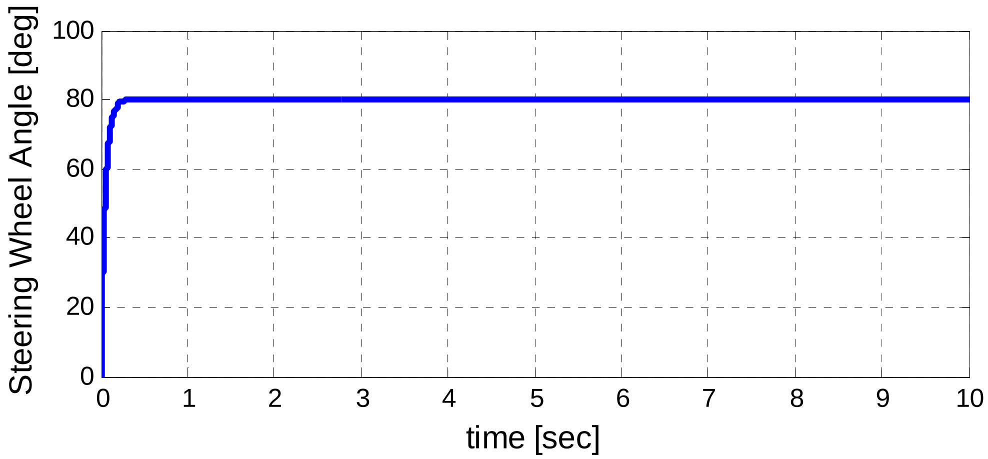
2. Understeer/oversteer

1) Determine l_f and l_r for Neutral Steer Vehicle at Vx = 50 kph.
2) Determine l_f and l_r for $K_{us} = 2\deg$ at Vx = 50 kph
3) Determine l_f and l_r for $K_{us} = -1\deg$ at Vx = 50 kph
4) Plot vehicle behaviors and vehicle trajectory of the above simulations using the below steering Behaviors

Table.2 Vehicle Parameter

Symbol	Value	Symbol	Value
m	1723.8 kg	L	2.7 m
I_z	4175 kgm²	l_f	?
C_f	67248 N/rad	l_r	?
C_r	53248 N/rad	Steering Ratio	15

Fig.2 Steering Wheel Angle Maneuver



H.W-1

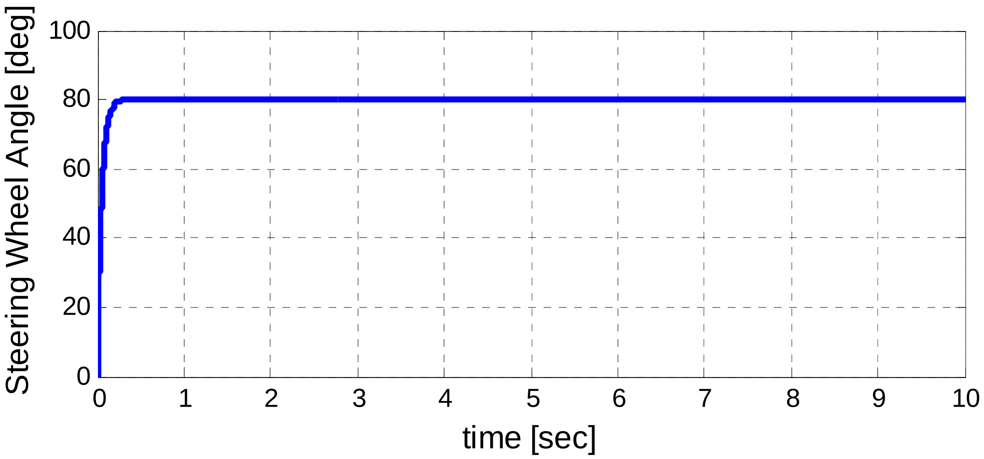
3. Understeer/oversteer

1) Determine C_f and C_r for Neutral Steer Vehicle at Vx = 30 kph. ($C_f + C_r = 1.2 \times 10^5 \, N/rad$)
2) Determine C_f and C_r for $K_{us} = 2\deg$ at Vx = 30 kph
3) Determine C_f and C_r for $K_{us} = -1\deg$ at Vx = 30 kph
4) Plot vehicle behaviors and vehicle trajectory of the above simulations using the below steering Behaviors

Vehicle Parameter

Symbol	Value	Symbol	Value
m	1723.8 kg	L	2.7 m
I_z	4175 kgm^2	l_f	1.24 m
C_f	?	l_r	$L - l_f$
C_r	?	Steering Ratio	15

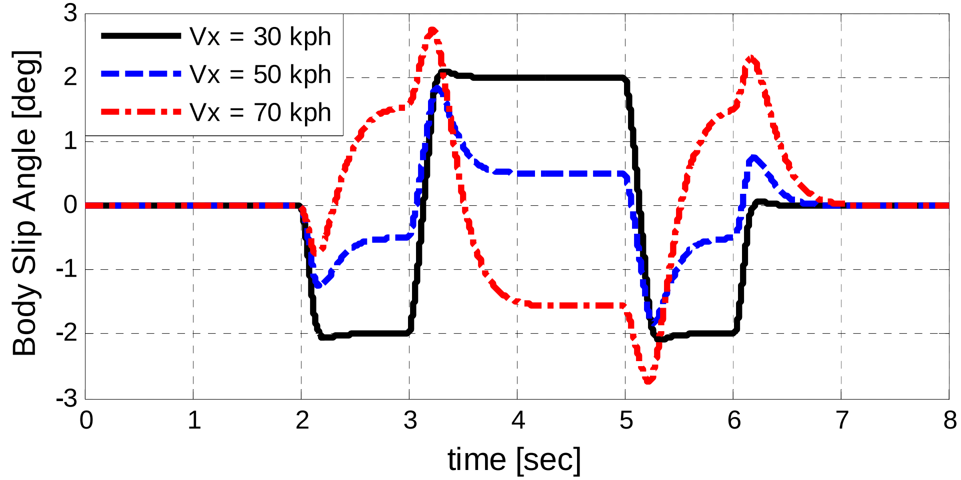
Steering Wheel Angle Maneuver



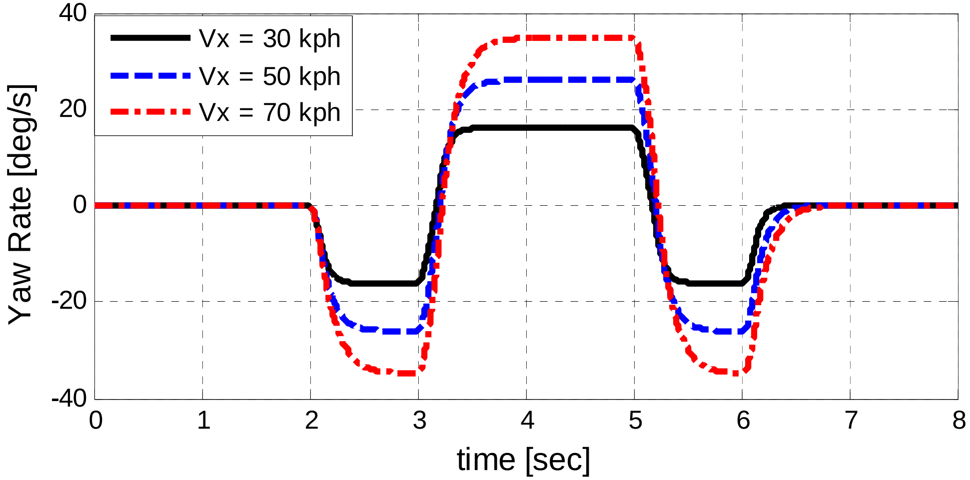
H.W-1

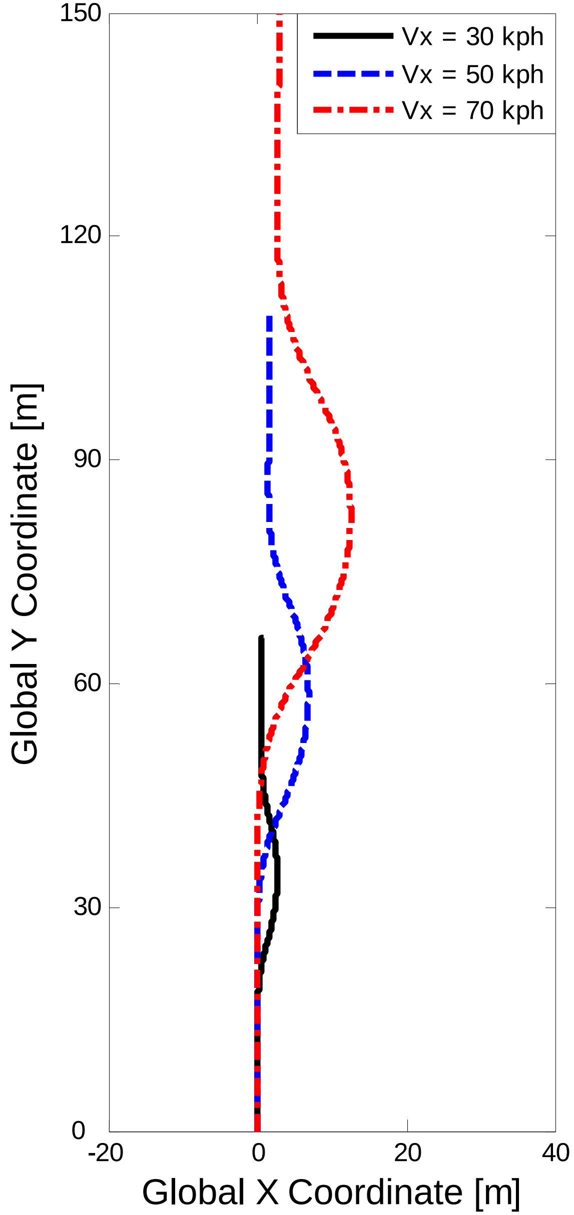
1. Modeling of 2DOF Bicycle Model (Example)

Body Slip Angle [deg]



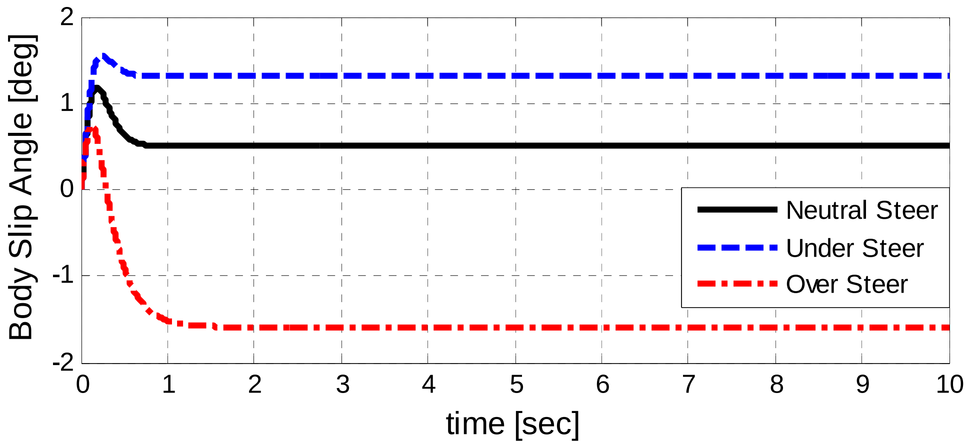
Vehicle Yaw Rate [deg/s]



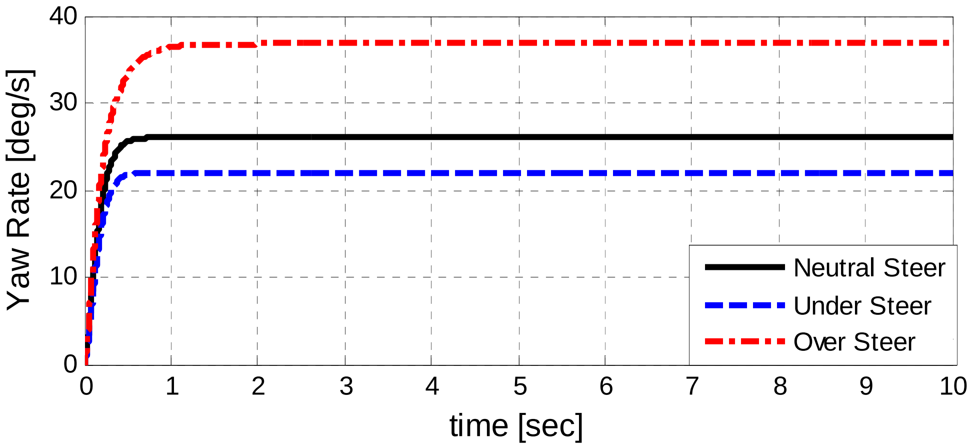


Understeer/oversteer (Example)

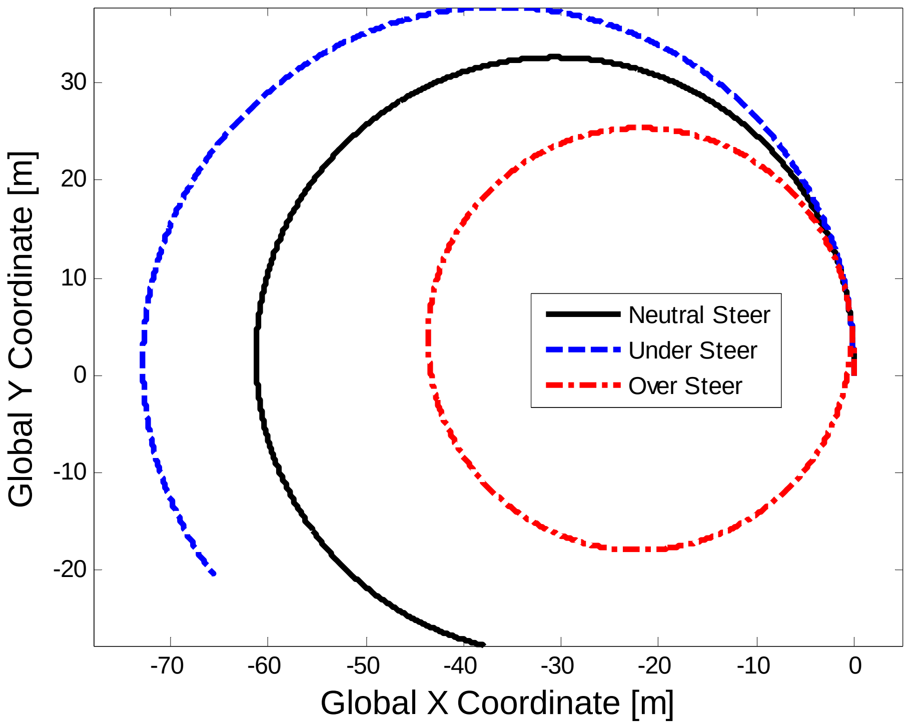
Body Slip Angle [deg]



Vehicle Yaw Rate [deg/s]



Vehicle Trajectory



HW.2

H.W-2: Design of Lane Keeping Controller

Consider a lane keeping system as follows:

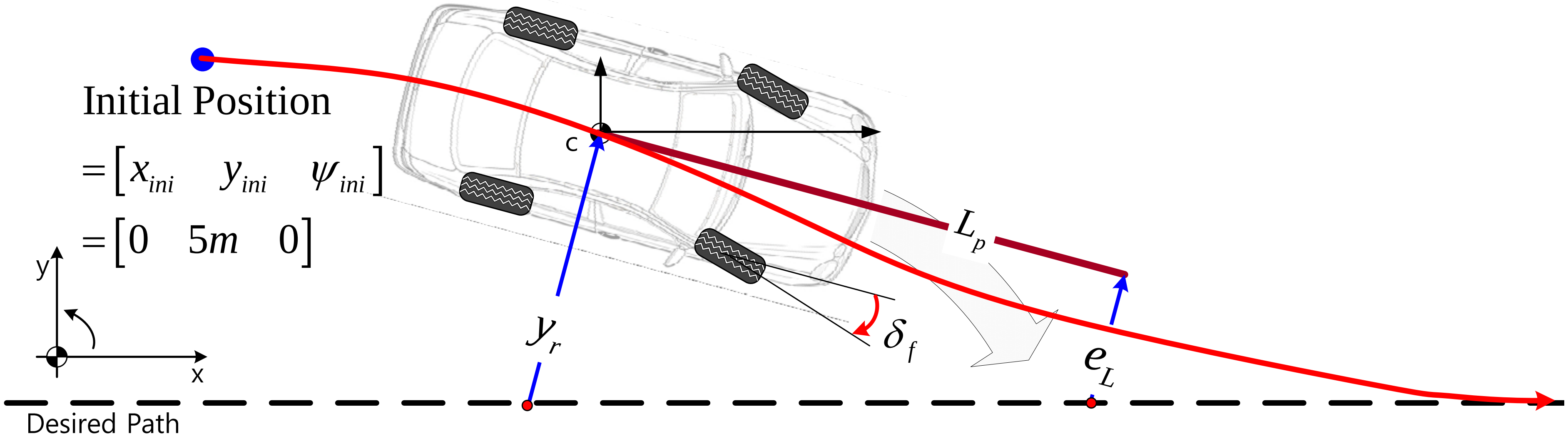


Fig.1 Lane Keeping System

1. Design a lane keeping control algorithm and evaluate the controller through numerical simulations. The vehicle simulations should be conducted under the following conditions.

- Vehicle speed is 30 km/h.
- 2 DOF bicycle model in the **HW#1** is used for vehicle model.
- Initial position of vehicle is set to be as follows: $[x_{ini} \quad y_{ini} \quad \psi_{ini}] = [0 \quad 5m \quad 0]$
- Desired path is straight road as shown in Fig.1

H.W-2: Design of Lane Keeping Controller

Consider a lane keeping system as follows:

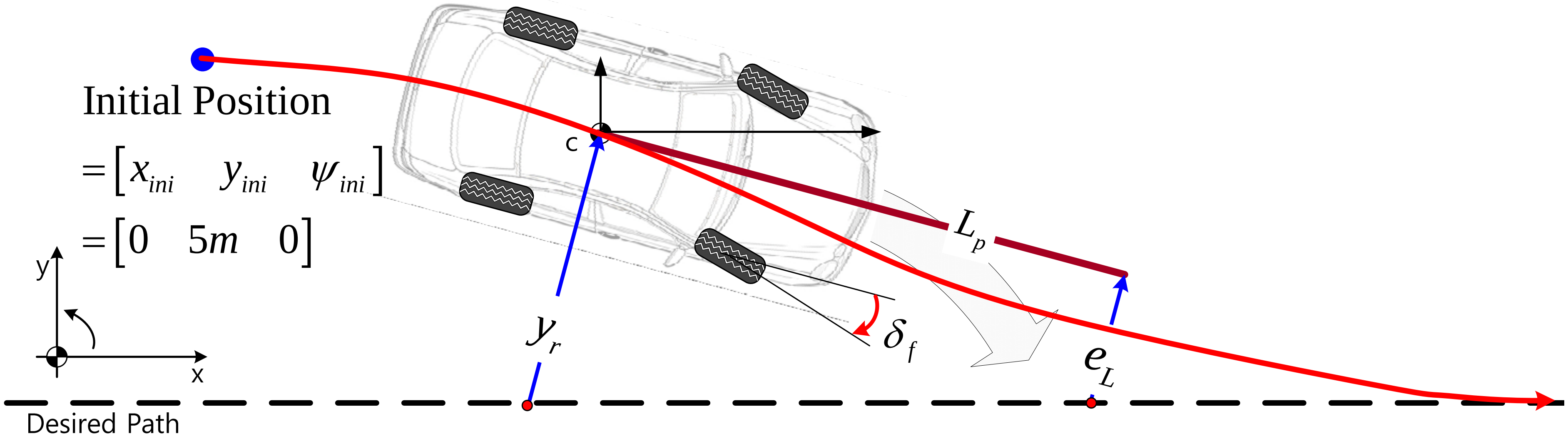


Fig.1 Lane Keeping System

(1) Plot lateral position error (y_r) and preview distance error (e_L) when preview distance (L_p) is set to be 5m, 10m and 15m.

(2) Plot the front steering angle for lane keeping. (L_p = 5, 10 and 15m)

(3) Plot body slip angle and yaw rate. (L_p = 5, 10 and 15m)

(4) Plot vehicle trajectory. (L_p = 5, 10 and 15m)

(5) Discussion on the control performance and the vehicle behaviors for same control gains at different preview distances.

H.W-2: Design of Lane Keeping Controller

Tip for a lane keeping system

▪ A lane keeping system for numerical simulation consists of three parts: a vehicle model, a lane keeping controller and a tacking error calculator as shown in Fig.2

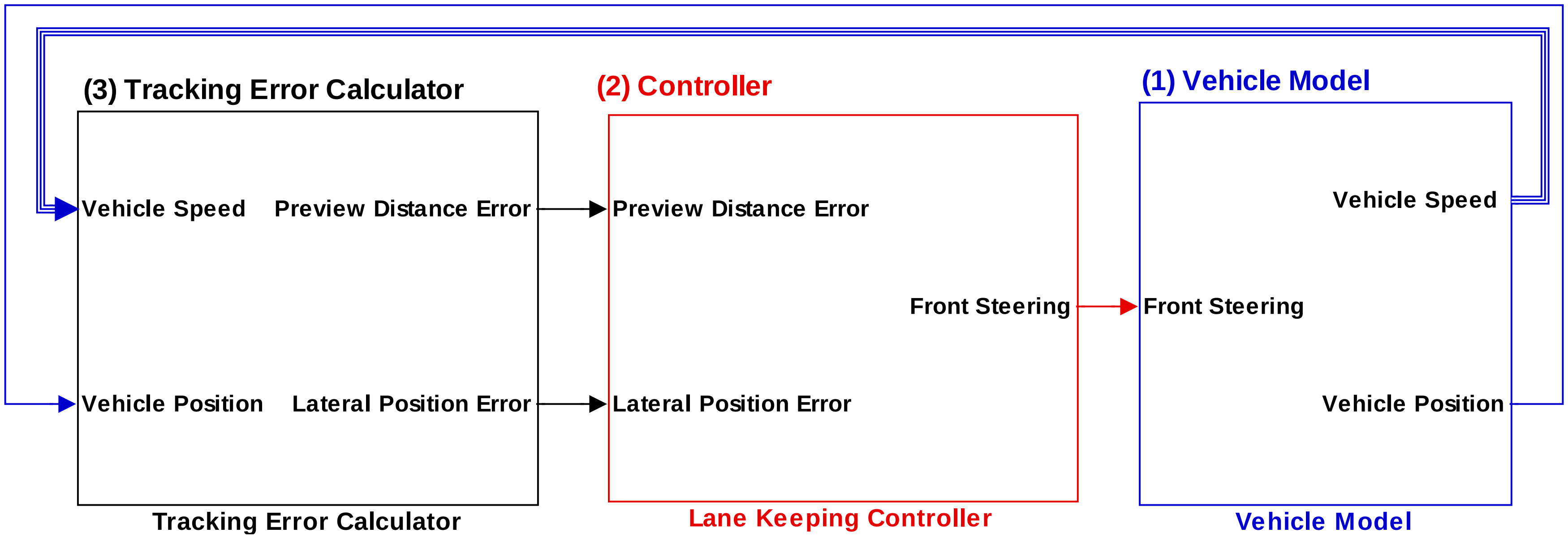


Fig.2 Lane Keeping Model

H.W-2: Design of Lane Keeping Controller

Tip for a lane keeping system

- Tracking Error Calculator: When a desired path is a straight road ($\psi_d = 0$), the tracking error can be calculated as shown in Fig.3.

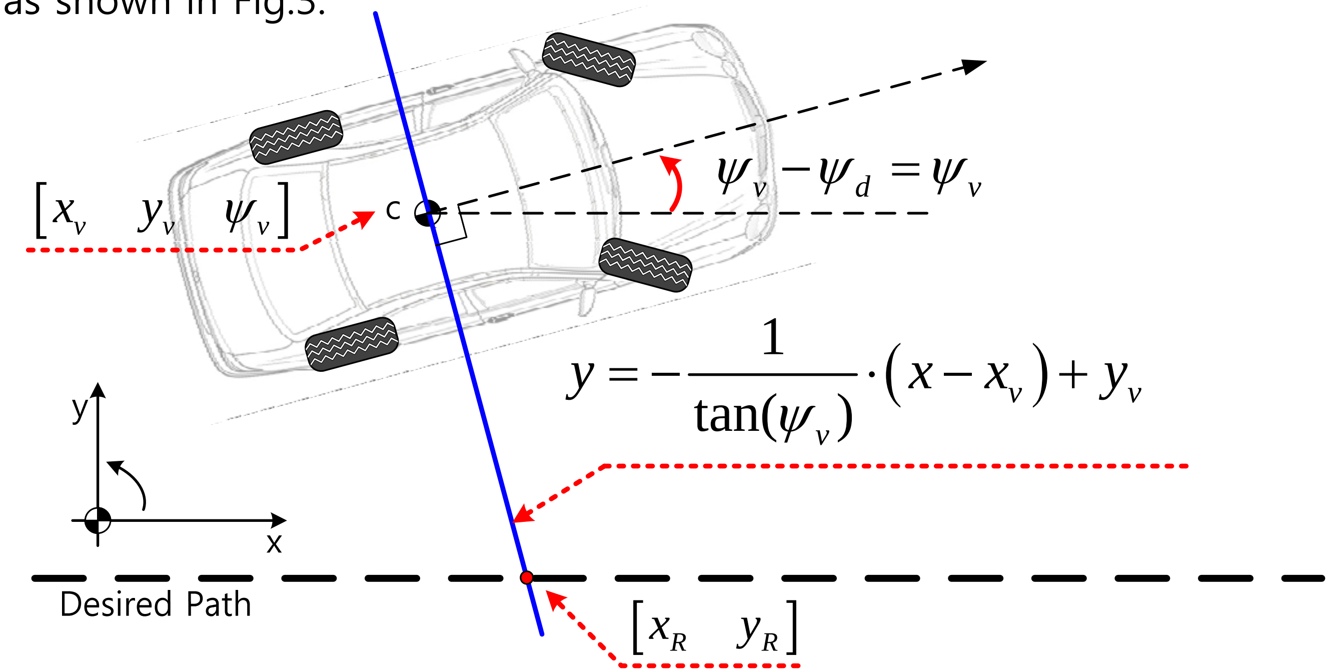


Fig.3 Tracking Error Calculator

- Reference Road Position

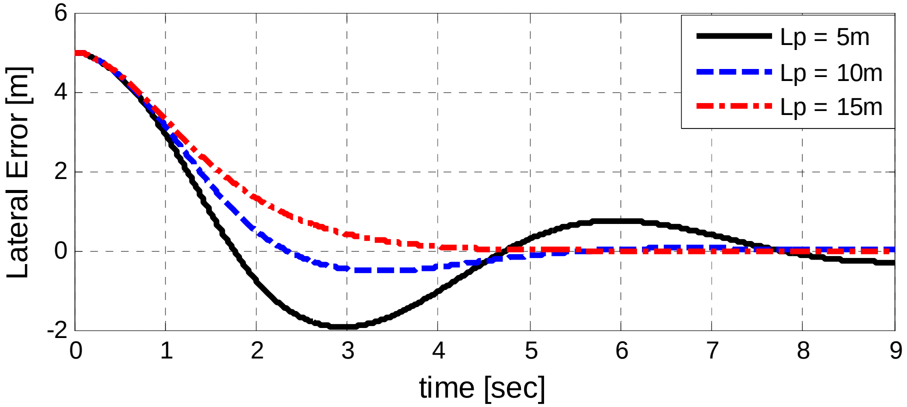
$$\begin{bmatrix} x_R \\ y_R \end{bmatrix} = \begin{bmatrix} x_v + \tan^{-1}(\psi_v) \cdot y_v \\ 0 \end{bmatrix}$$

- Lateral Position Error

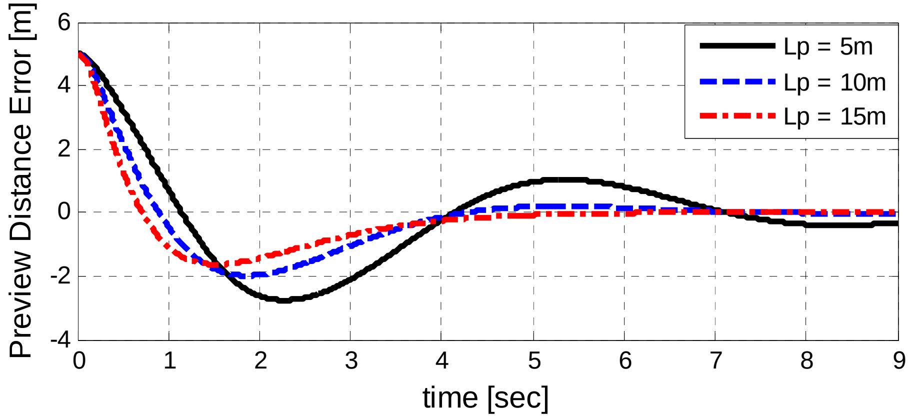
$$y_r = \begin{cases} \sqrt{(x_v - x_R)^2 + (y_v - y_R)^2} & if\,(y_v \geq 0) \\ -\sqrt{(x_v - x_R)^2 + (y_v - y_R)^2} & elsewhere \end{cases}$$

H.W-2: Design of Lane Keeping Controller

(1) Plot lateral position error (y_r) and preview distance error (e_L) when preview distance (L_p) is set to be 5m, 10m and 15m.

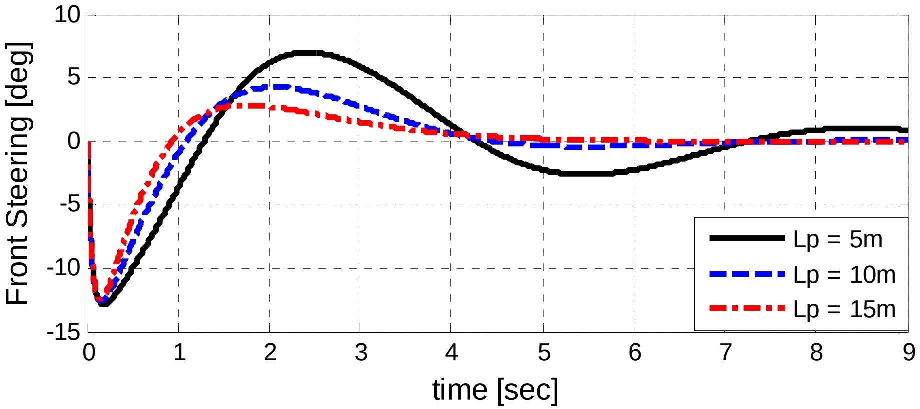


Lateral Position Error [m]



Preview Distance Error [m]

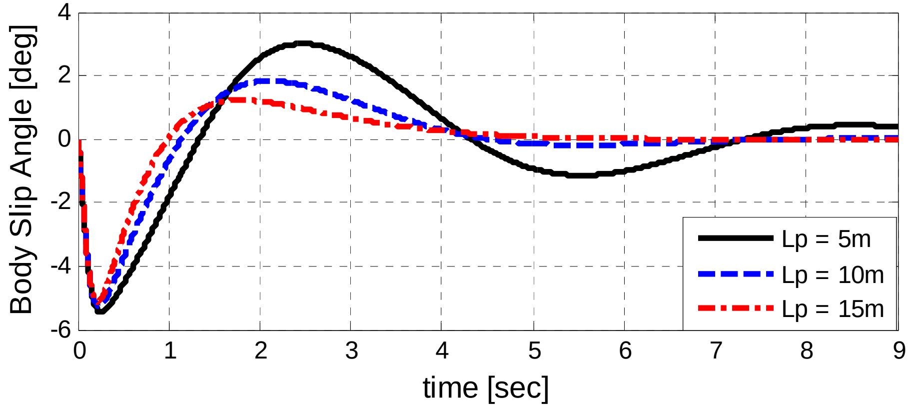
(2) Plot the front steering angle for lane keeping. (L_p = 5, 10 and 15m)



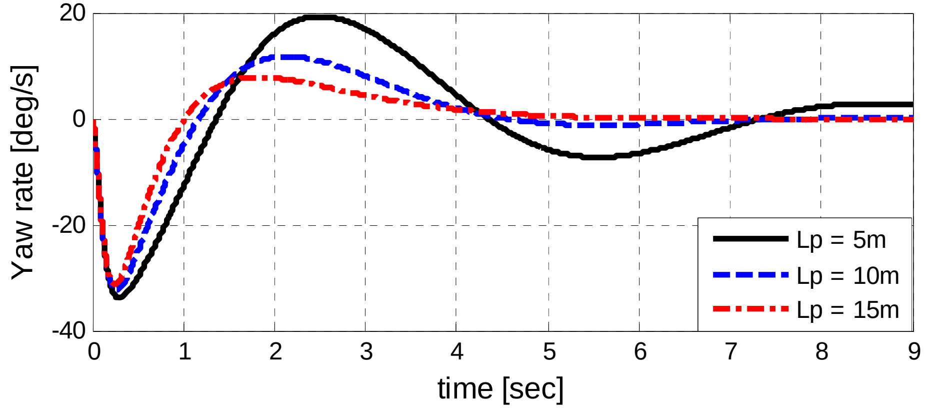
Front Steering Angle [deg]

H.W-2: Design of Lane Keeping Controller

(3) Plot body slip angle and yaw rate. (L_p = 5, 10 and 15m)

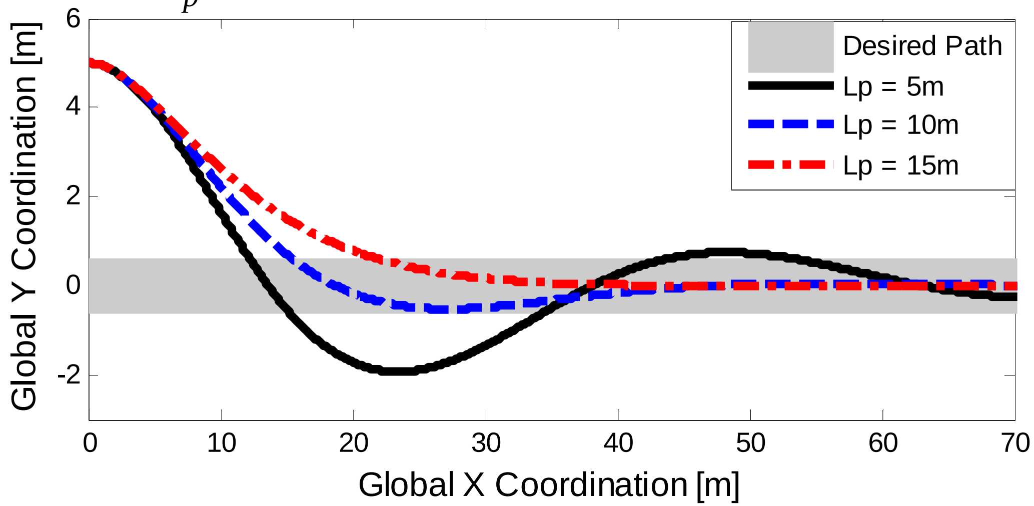


Body Slip Angle [deg]



Yaw Rate [deg/s]

(4) Plot vehicle trajectory. (L_p = 5, 10 and 15m)



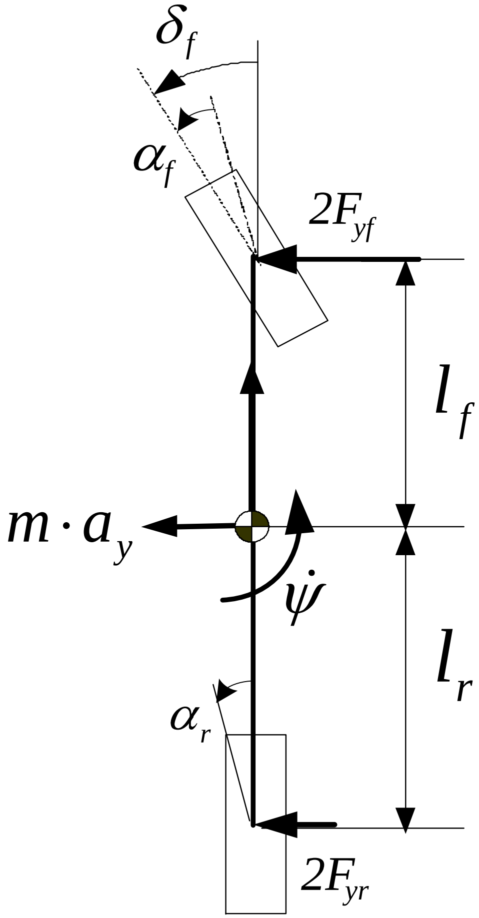
Vehicle Trajectory

HW.3

H.W-3: Phase Plane Analysis

Consider a 2 DOF bicycle Model as follows:

$$\begin{bmatrix} \dot{\beta} \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} \dfrac{2 \cdot F_{tyf} + 2 \cdot F_{tyr}}{m \cdot v_x} - \gamma \\ \dfrac{2 \cdot l_f \cdot F_{tyf} - 2 \cdot l_r \cdot F_{tyr} + \sum_{i=1}^{4} M_{tzi}}{I_z} \end{bmatrix}$$



Vehicle parameters of the 2 DOF bicycle model are listed in Table.1

	Symbol	Value		Symbol	Value
Vehicle mass	m	2450 kg	Length from C.G. to the rear wheel axis	l_r	$L - l_f$
Moment of inertia about the yaw axis	I_z	4331.6 kgm^2	Front Cornering Stiffness	C_f	73305 N/rad
Vehicle Length	L	2.85 m	Rear Cornering Stiffness	C_r	58850 N/rad
Length from C.G. to the front wheel axis	l_f	1.070 m	Friction Coefficient	μ	0.85

H.W-3: Phase Plane Analysis

In Eq.1, lateral tire forces at front and rear wheels can be calculated using a non-linear function as follows:

- Slip Angle

$$\alpha_f = \delta_f - \frac{v_y + l_f \cdot \gamma}{v_x}, \qquad \alpha_r = -\frac{v_y - l_r \cdot \gamma}{v_x}$$

- Normal Vertical Tire Force

$$2 \cdot F_{zf} = \frac{m \cdot l_r}{l_f + l_r} \cdot g, \qquad 2 \cdot F_{zr} = \frac{m \cdot l_f}{l_f + l_r} \cdot g$$

- Non-Linear Lateral Tire Force Modeling

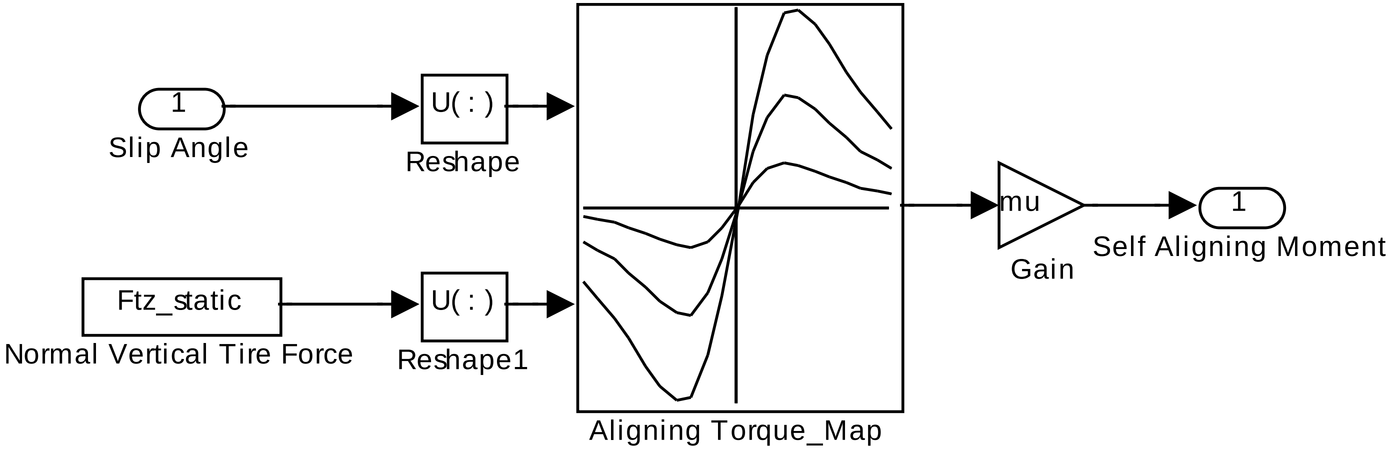
$$F_{tyf} = \frac{2}{\pi} \cdot \mu \cdot F_{zf} \cdot \tan^{-1}\left(\frac{\pi}{2 \cdot \mu \cdot F_{zf}} \cdot C_f \cdot \alpha_f\right)$$

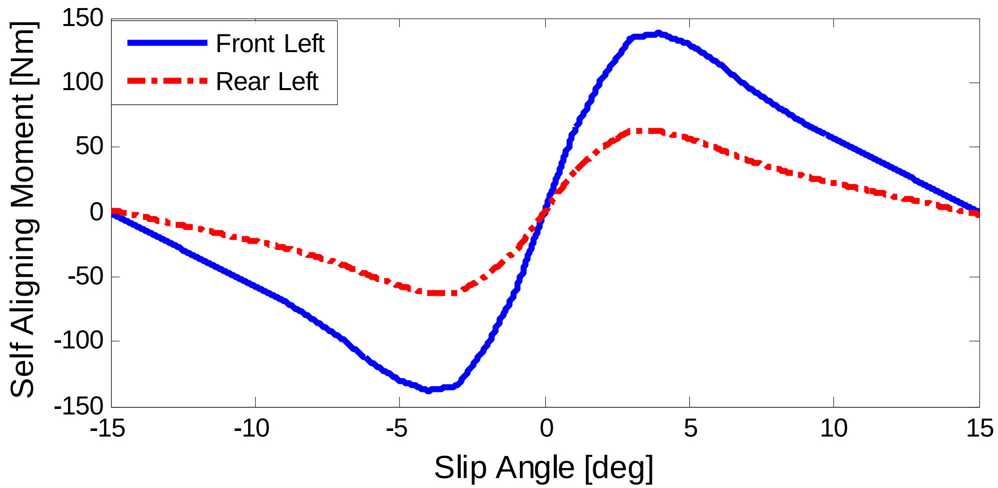
$$F_{tyr} = \frac{2}{\pi} \cdot \mu \cdot F_{zr} \cdot \tan^{-1}\left(\frac{\pi}{2 \cdot \mu \cdot F_{zr}} \cdot C_r \cdot \alpha_r\right)$$

H.W-3: Phase Plane Analysis

Also, a self aligning moment, M_{tzi} , at each wheel is given as 2-D Look-Up Table.:

- Using 2-D Look Up Table





H.W-3: Phase Plane Analysis

- Using the non-linear bicycle model, analyze the vehicle stability based on phase-plane method. The phase plane can be obtained from the state trajectory when a certain initial state is given. The vehicle simulations for phase plane analysis should be conducted under the following conditions:

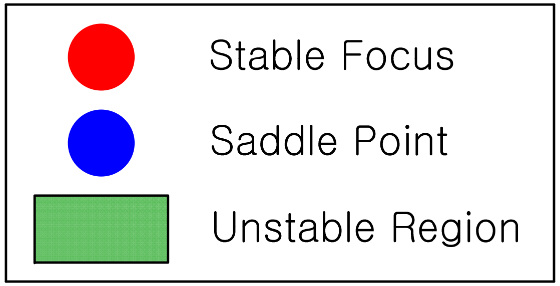
  - Vehicle speed is 100 km/h.
  - Initial body slip angle should be simulated from -1.5 rad to 1.5 rad.
  - Initial yaw rate should be simulated from -1.5 rad to 1.5 rad.
  - Front steering angle, , is constant.

(1) Plot $\beta - \dot{\beta}$ phase plane trajectory and $\beta - \gamma$ phase plane trajectory at $\delta_f = 0\,\text{deg}$

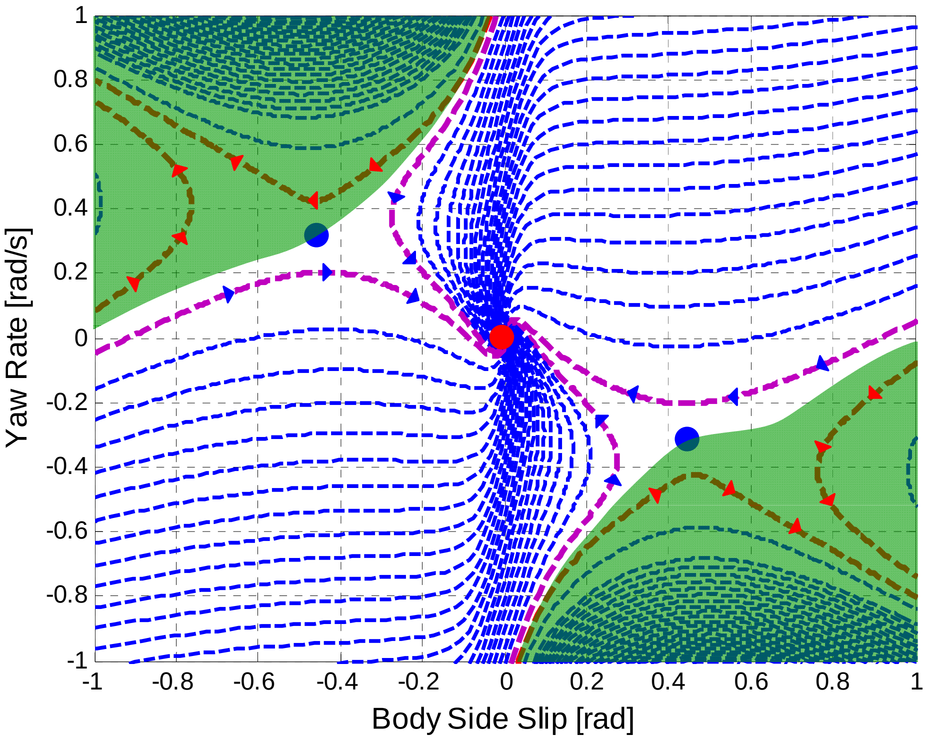
(2) Plot $\beta - \dot{\beta}$ phase plane trajectory and $\beta - \gamma$ phase plane trajectory at $\delta_f = 3\,\text{deg}$

(3) Plot $\beta - \dot{\beta}$ phase plane trajectory and $\beta - \gamma$ phase plane trajectory at $\delta_f = 6\,\text{deg}$

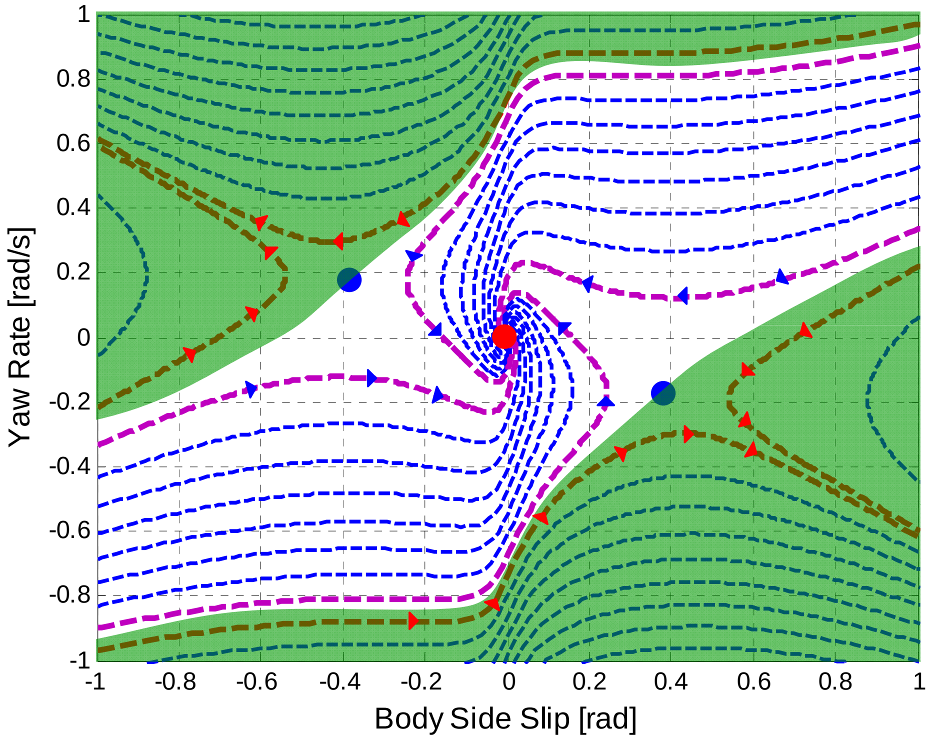
$\beta-\gamma$ Phase Plane Trajectory



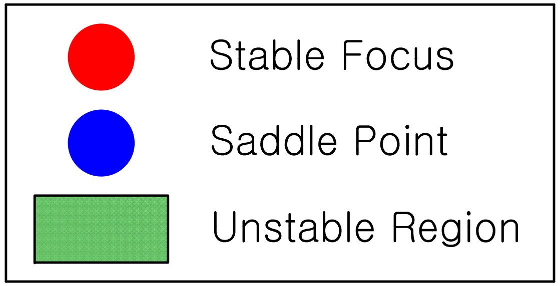
- $v_x = 70kph, \quad \delta_f = 0\deg$



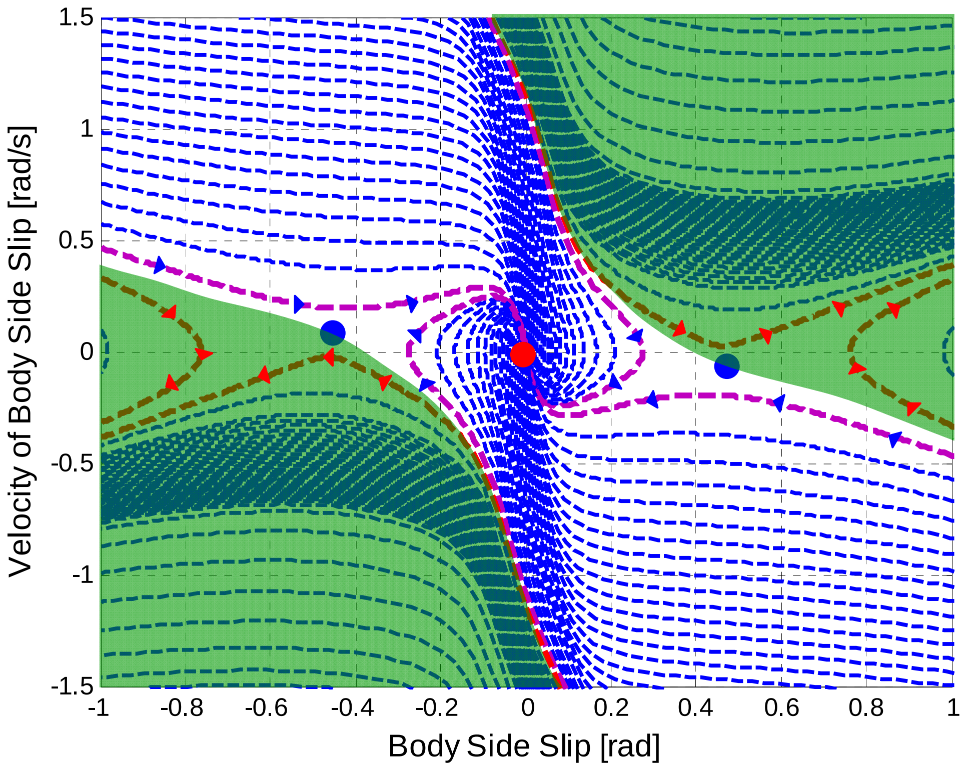
- $v_x = 150kph, \quad \delta_f = 0\deg$



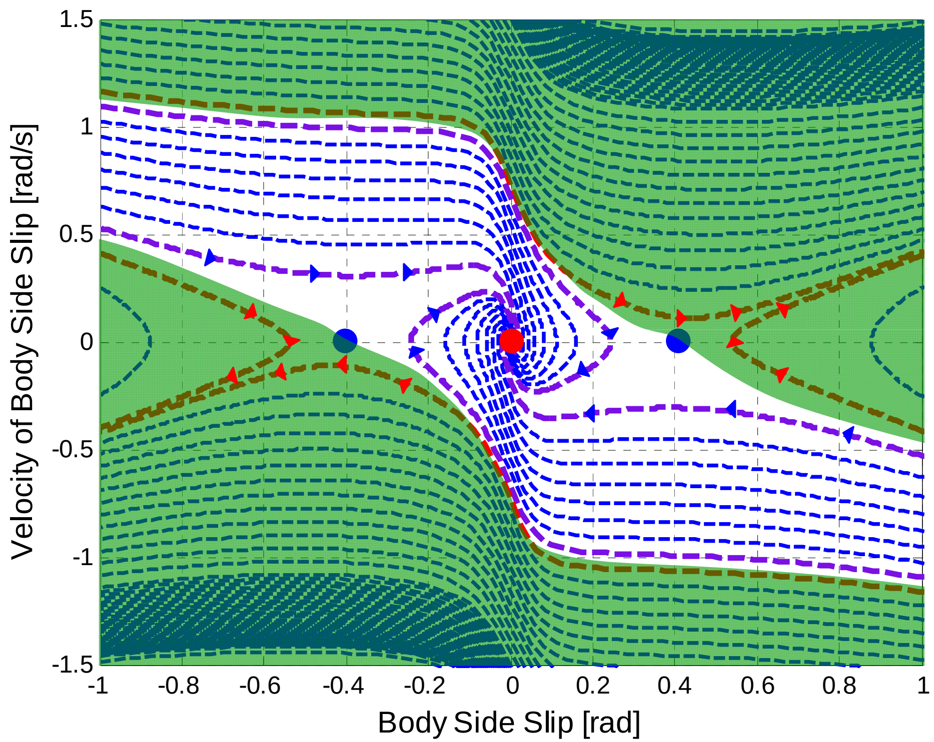
$\beta - \dot{\beta}$ Phase Plane Trajectory



- $v_x = 70kph, \quad \delta_f = 0\deg$

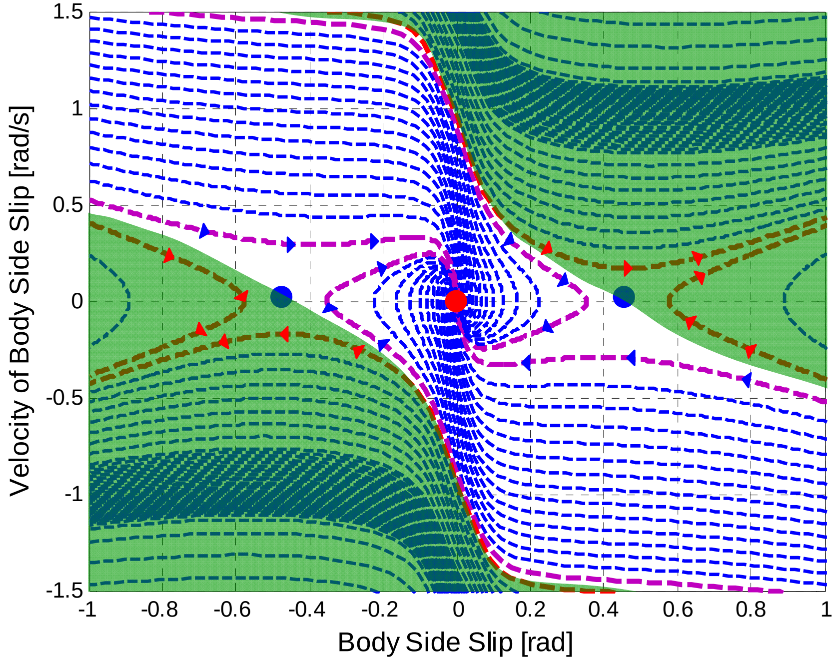


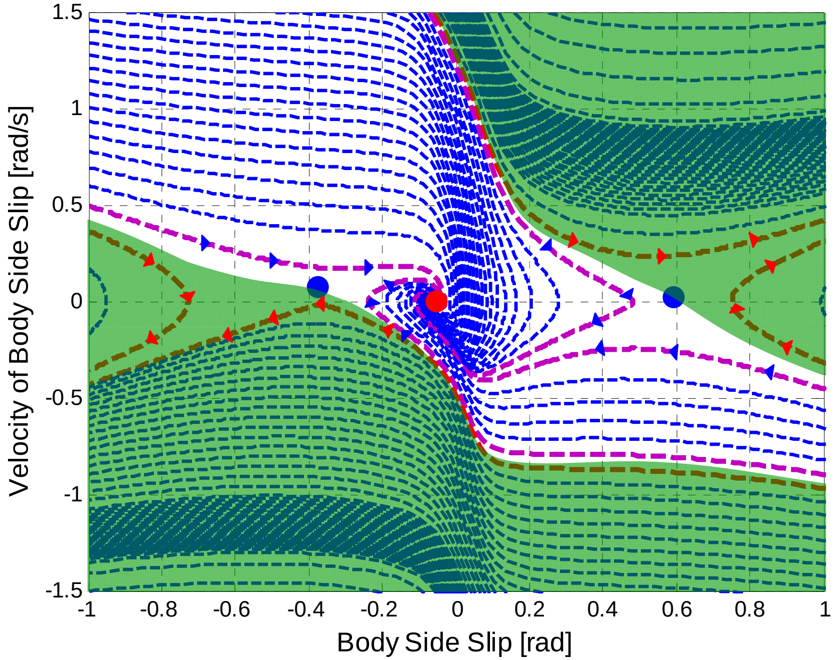
- $v_x = 150kph, \quad \delta_f = 0\deg$

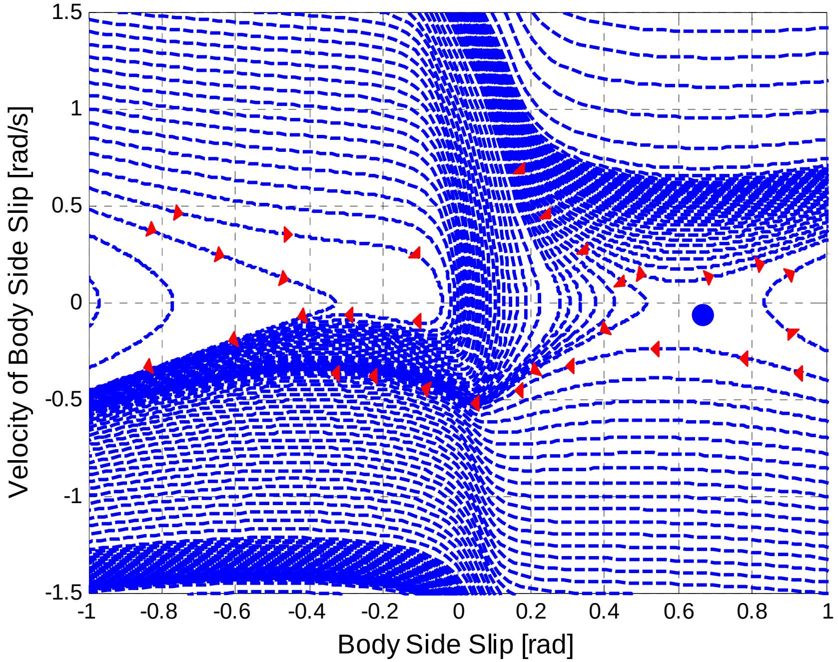


$\beta - \dot{\beta}$ Phase Plane Trajectory

- Vehicle Speed = 100kph
  - Front Steering = 0 deg
  - Front Steering = 3 deg
  - Front Steering = 6 deg

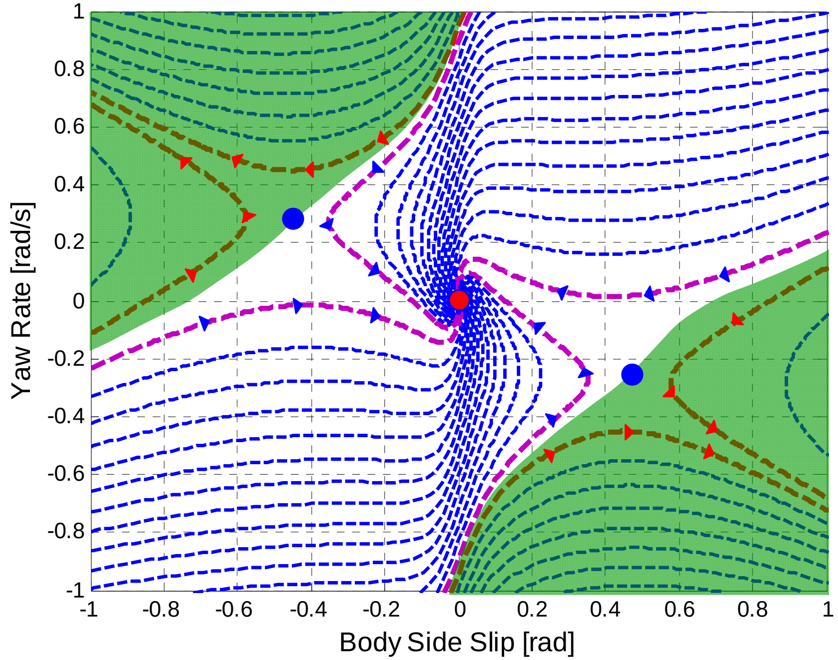


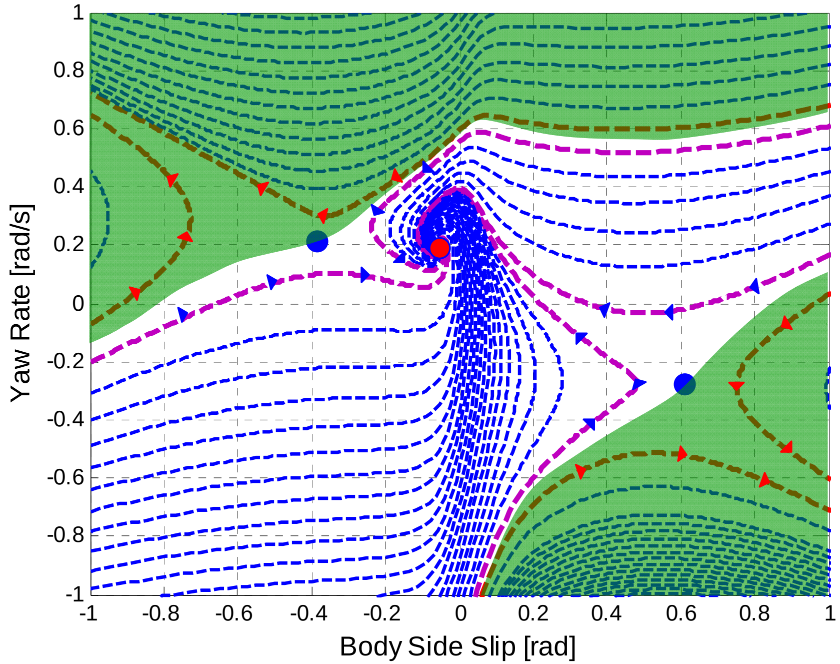


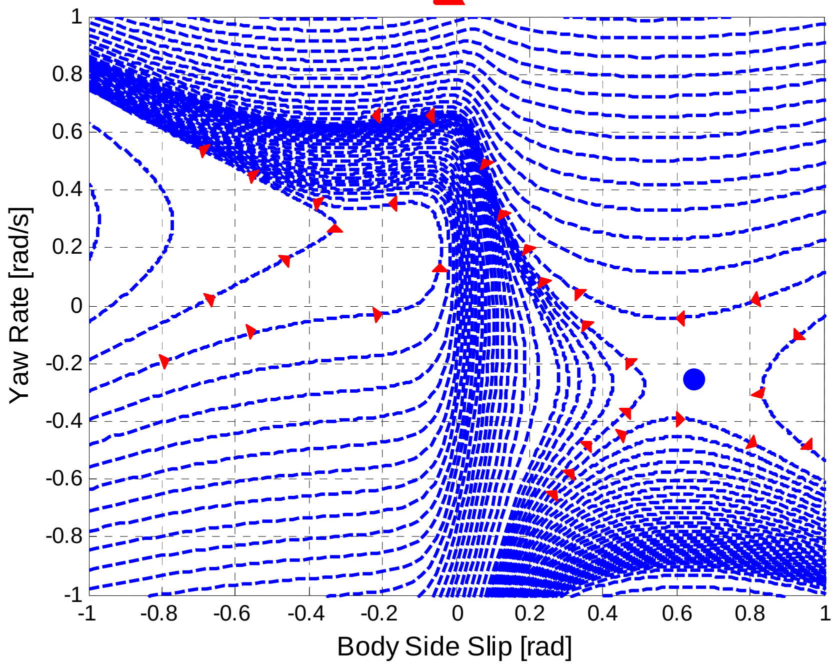


▼ $\beta - \gamma$ Phase Plane Trajectory

- Vehicle Speed =100 kph
  - Front Steering = 0 deg
  - Front Steering = 3 deg
  - Front Steering = 6 deg







HW.4

H.W-3: Vehicle Stability Control

- Design vehicle stability controllers using the sliding surfaces as follows:

$$s_1 = \gamma - \gamma_{desired}$$

$$s_2 = (\gamma - \gamma_{desired}) + \rho \cdot \beta \quad where, \rho \text{ is negative.}$$

- 2. evaluate the controllers through numerical simulations. The vehicle simulations should be conducted under the following conditions:

  - Vehicle speed is 100 km/h.
  - Front steering maneuver by a human driver and tire/road friction is shown in Fig.1.
  - For numerical simulations, use the non-linear bicycle model in HW.3

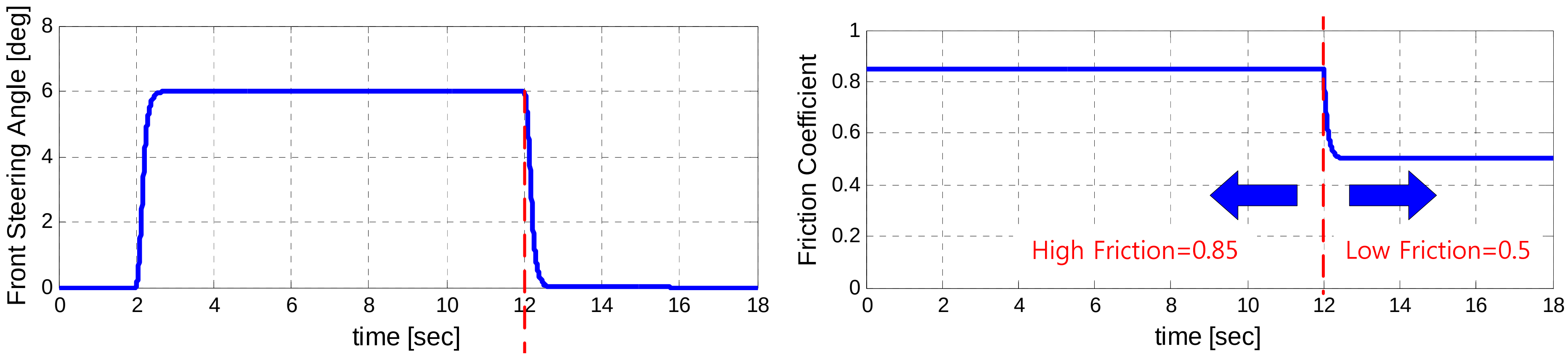


Fig.1 Front steering maneuver and tire/road friction

Hw.4 Sliding Surface 1

(1) Sliding Surface using Yawrate Error

$$s_1 = \gamma - \gamma_{desired}$$

(2) Control Input should satisfy the following sliding conditions:

$$\dot{V} = s_1 \cdot \dot{s}_1 = -K \cdot |s_1| < 0$$

(3) Yaw Moment Input

$$M_{z\_des} = M_{z\_eq} - I_z \cdot K \cdot sat(\frac{\gamma - \gamma_{desired}}{\Phi})$$

Where, $M_{z\_eq} = I_z \cdot \left(\frac{2(l_f \cdot C_f - l_r \cdot C_r)}{I_z} \cdot \beta + \frac{2(l_f^2 \cdot C_f + l_r^2 \cdot C_r)}{I_z \cdot v_x} \cdot \dot{\psi} - \frac{2 \cdot l_f \cdot C_f}{I_z} \cdot \delta_f \right)$

$$K = \text{sliding control gain}$$

Hw.4 Sliding Surface 1

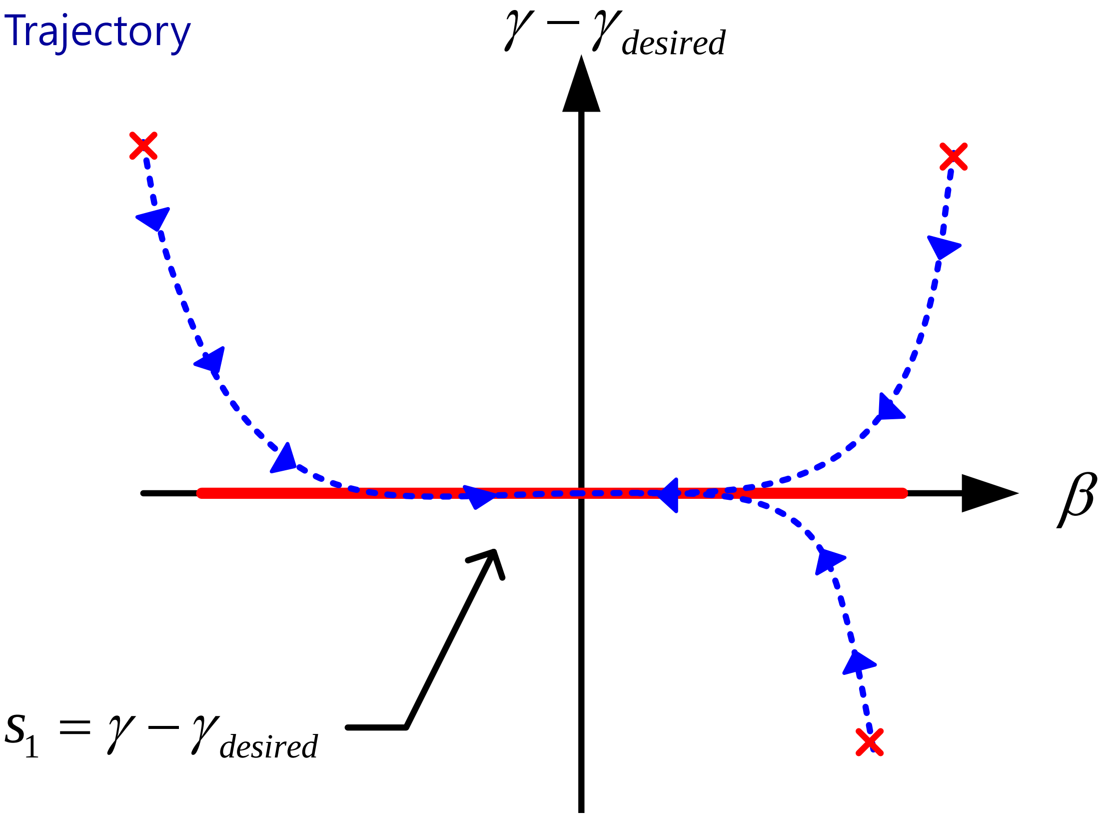
(1) Sliding Surface using Yawrate Error

$$s_1 = \gamma - \gamma_{desired}$$

(2) If sliding surface is zero,

$$s_1 = 0 \quad \Rightarrow \quad \gamma \rightarrow \gamma_{desired}$$

(3) State Trajectory



Hw.4 Sliding Surface 2

(1) Sliding Surface using Yawrate Error and Body Slip Angle

$$s_2 = (\gamma - \gamma_{desired}) + \rho \cdot \beta$$

(2) Control Input should satisfy the following sliding conditions:

$$\dot{V} = s_2 \cdot \dot{s}_2 = -K \cdot |s_2| < 0$$

(3) Yaw Moment Input

$$M_{z\_des} = M_{z\_eq} - I_z \cdot K \cdot sat\left\{ \frac{(\gamma - \gamma_{desired}) + \rho \cdot \beta}{\Phi} \right\}$$

Where, $M_{z\_eq} = -I_z \cdot (\rho \cdot a_{11} + a_{21}) \cdot \beta - I_z \cdot (\rho \cdot a_{12} + a_{22}) \cdot \dot{\psi} - I_z \cdot \left(\rho \cdot \frac{2 \cdot C_f}{m v_x} + \frac{2 \cdot l_f \cdot C_f}{I_z} \right) \cdot \delta_f$

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} -\frac{2(C_f + C_r)}{m \cdot v_x} & -1 - \frac{2(l_f \cdot C_f - l_r \cdot C_r)}{m \cdot v_x^2} \\ -\frac{2(l_f \cdot C_f - l_r \cdot C_r)}{I_z} & -\frac{2(l_f^2 \cdot C_f + l_r^2 \cdot C_r)}{I_z \cdot v_x} \end{bmatrix}$$

Hw.4 Sliding Surface 2

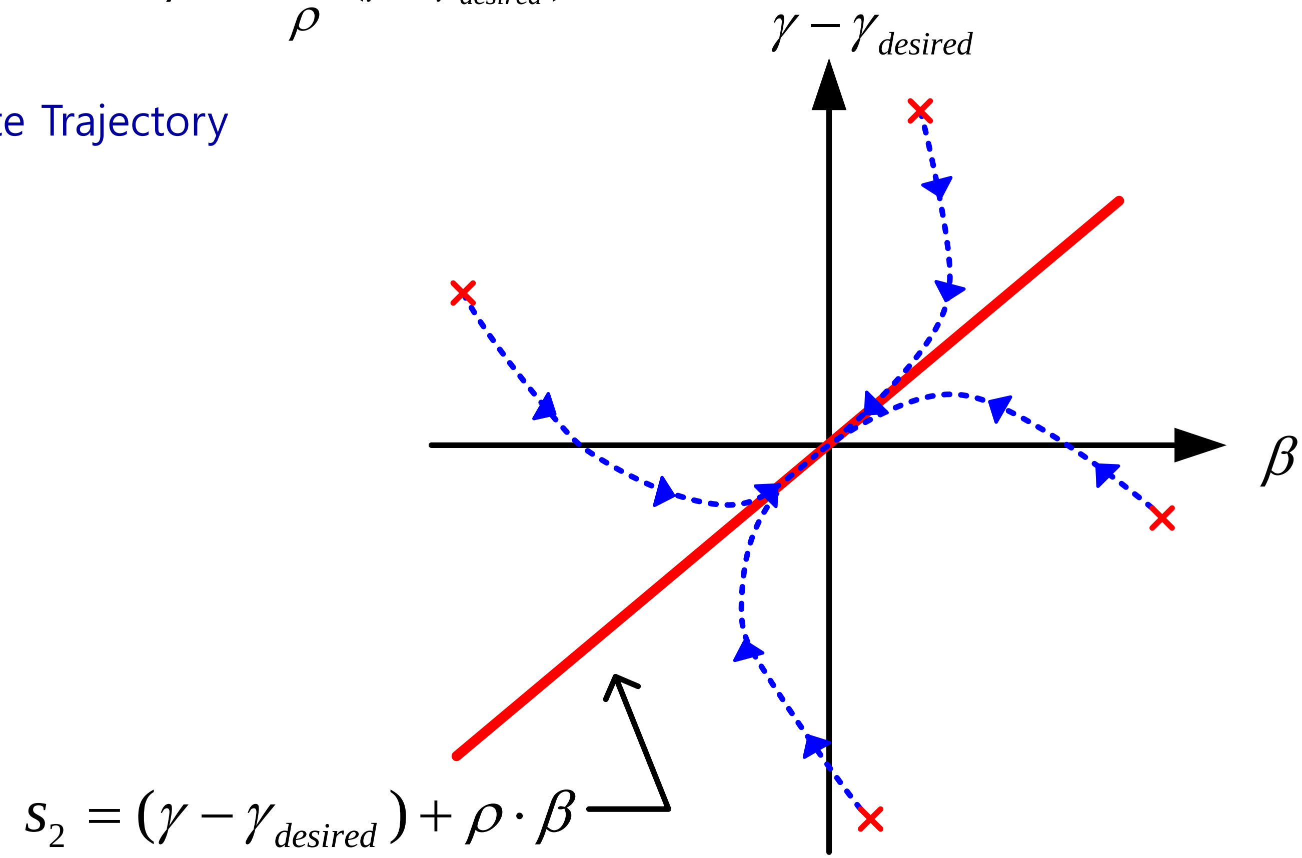
(1) Sliding Surface using Yawrate Error and Body Slip Angle

$$s_2 = (\gamma - \gamma_{desired}) + \rho \cdot \beta$$

(2) If sliding surface is zero,

$$s_2 = 0 \quad \Rightarrow \quad \beta = -\frac{1}{\rho} \cdot (\gamma - \gamma_{desired})$$

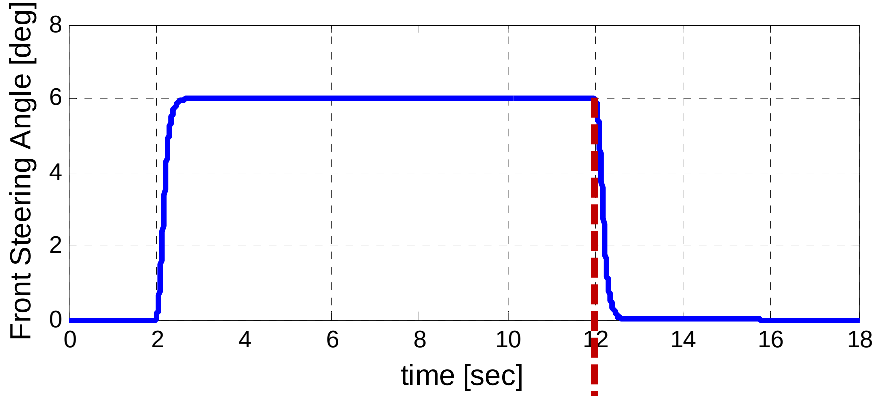
(3) State Trajectory



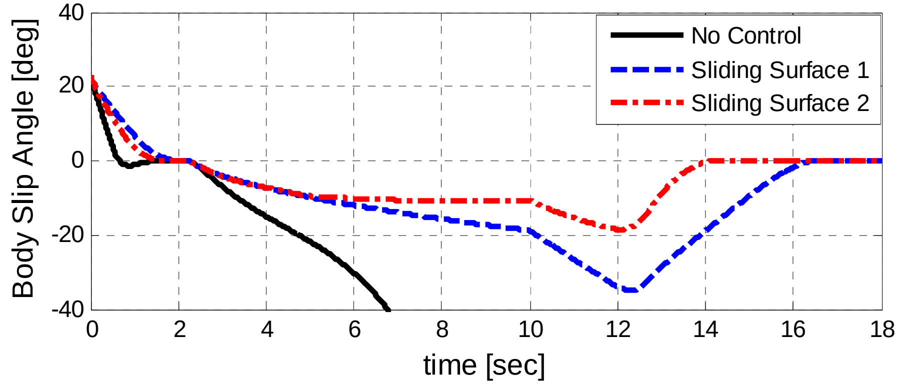
Hw.4 Comparison of Simulation Results

- Front Steering Angle = 6 deg (Unstable)
- Vehicle Speed : 100 km/h
- Initial Condition = $[\beta_{ini} \quad \gamma_{ini}]^T = [0.3\ rad \quad 0.3\ rad/s]^T$

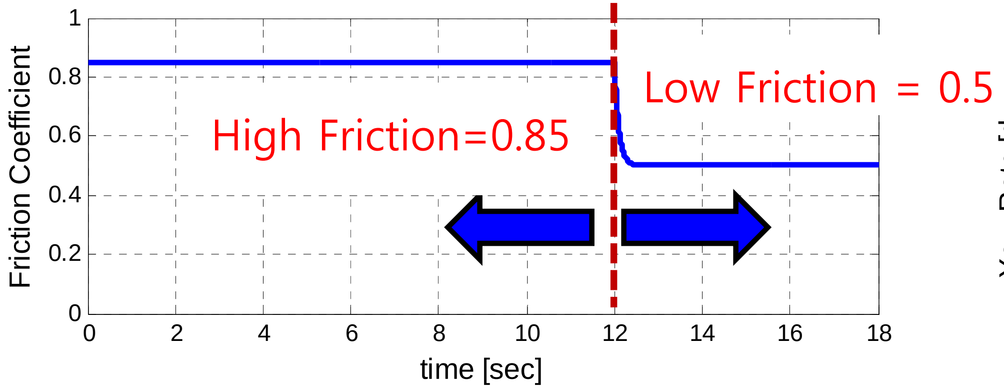
- Front Steering Angle [deg]



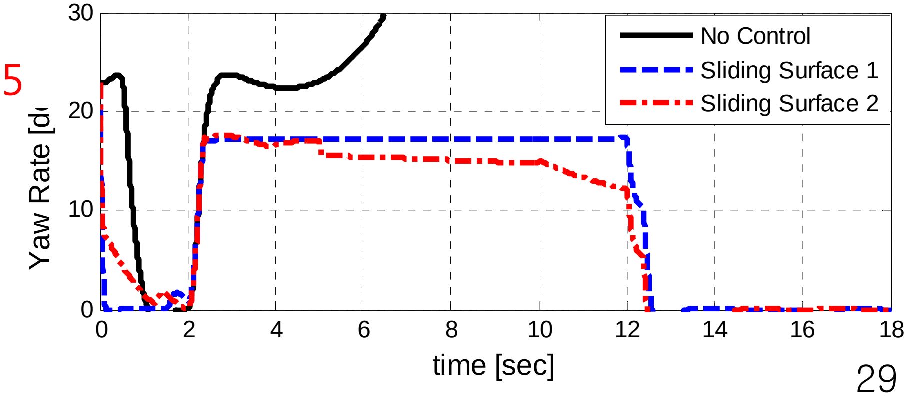
- Body Slip Angle [deg]



- Friction Coefficient



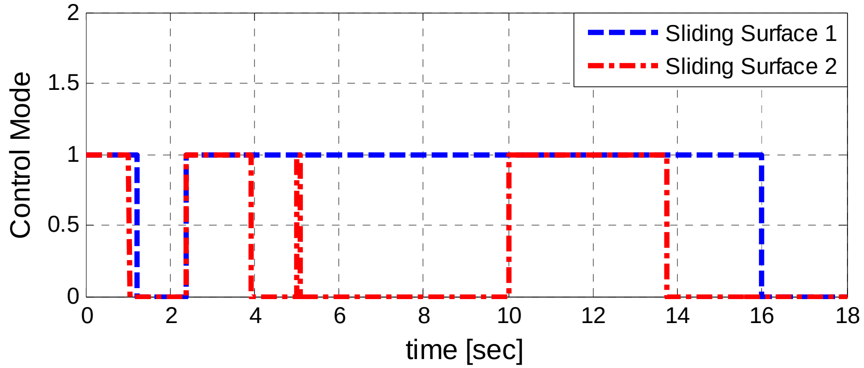
- Vehicle Yaw Rate [deg]



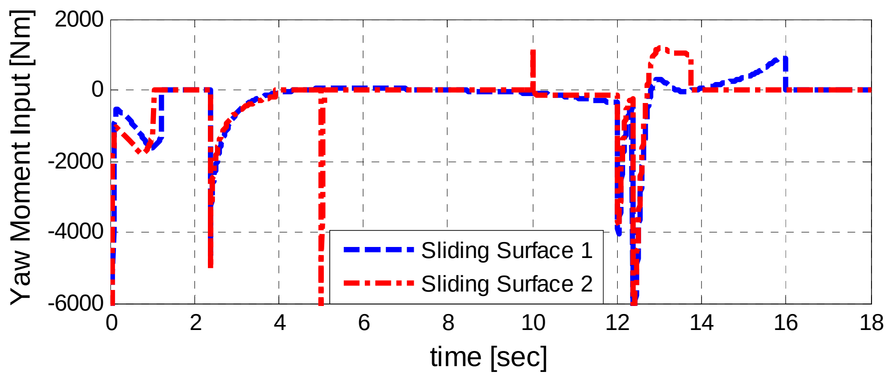
Hw.4 Comparison of Simulation Results

- Front Steering Angle = 6 deg (Unstable)
- Vehicle Speed : 100 km/h
- Initial Condition = $[\beta_{ini} \quad \gamma_{ini}]^T = [0.3\ rad \quad 0.3\ rad/s]^T$

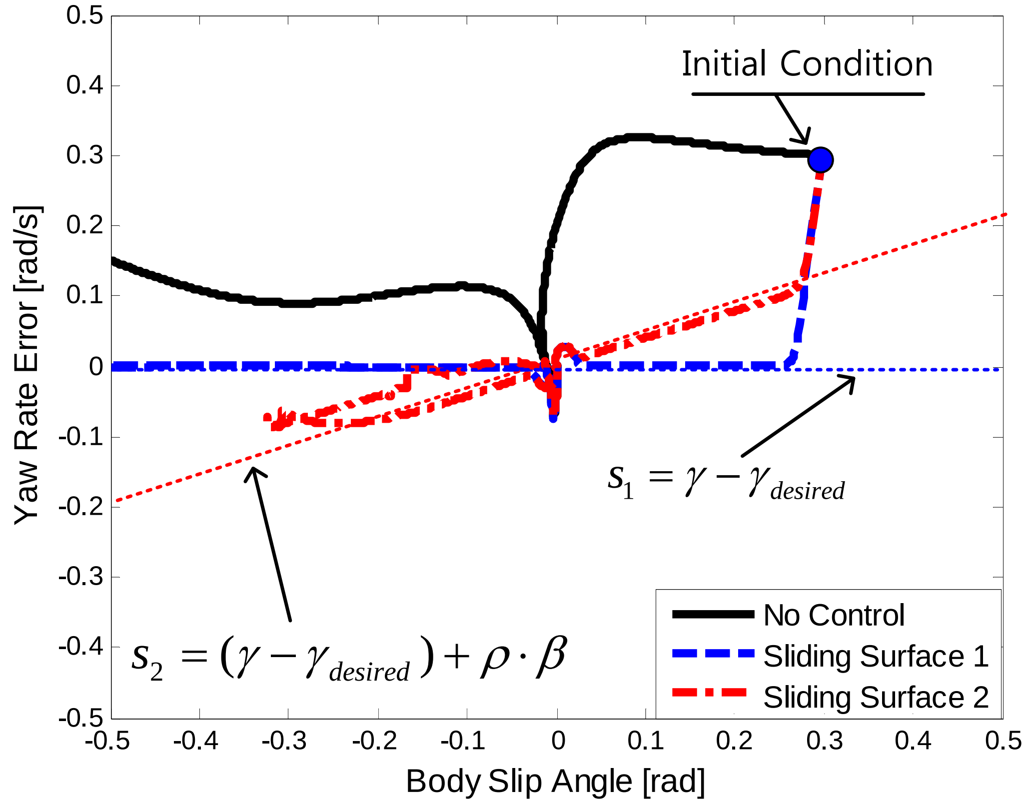
- Control Mode



- Yaw Moment Input [Nm]



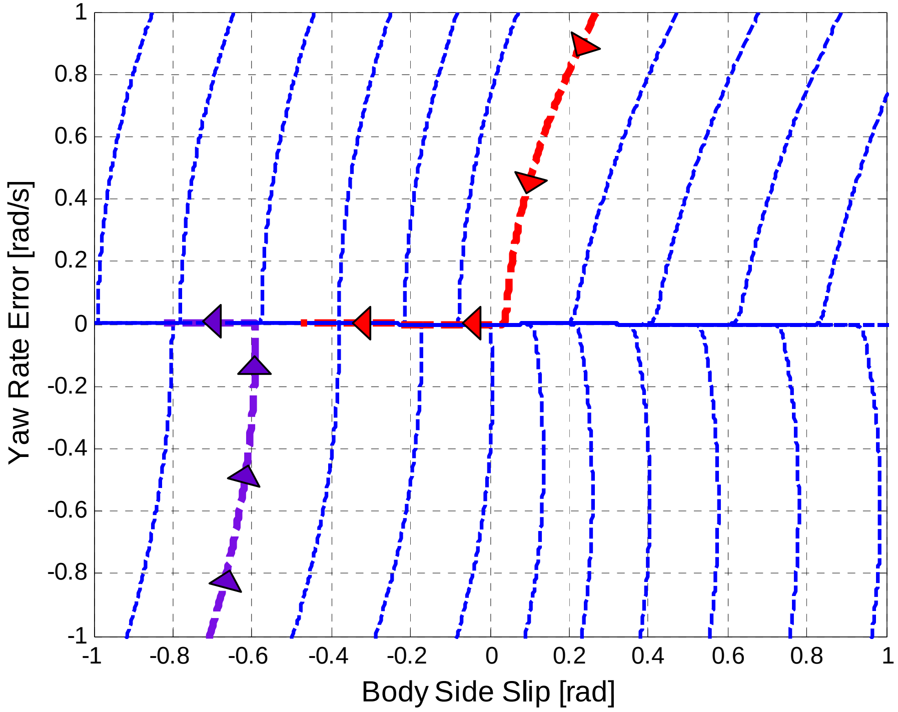
- State Trajectory



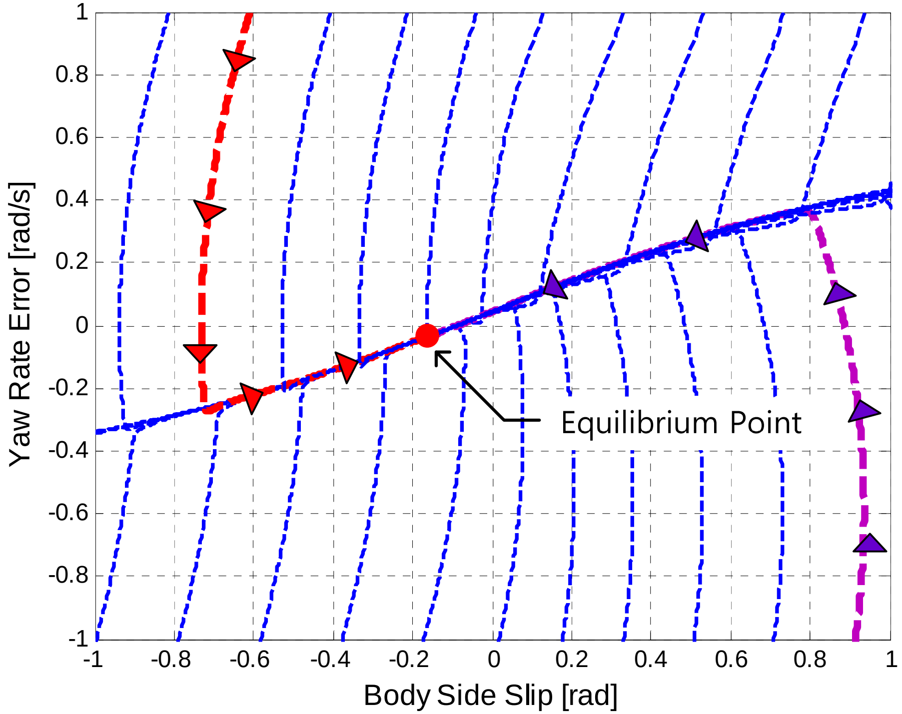
Hw.4 Comparison of Phase Plane

- Front Steering Angle = 6 deg (Unstable)
- Vehicle Speed : 100 km/h

- $s_1 = \gamma - \gamma_{desired}$



- $s_2 = (\gamma - \gamma_{desired}) + \rho \cdot \beta$



HW.5

H.W-5: Smart Cruise Control

Consider a longitudinal vehicle model as follows:

The control inputs of the vehicle model are a throttle angle, brake pressure and a initial vehicle speed. The outputs of the vehicle model are a longitudinal acceleration, a vehicle speed, a shaft torque and a gear degree. The maximum value of throttle angle is 100 %. Also, the maximum caliper pressure is 20MPa. Vehicle parameters for designing the SCC algorithm are listed in Table.1

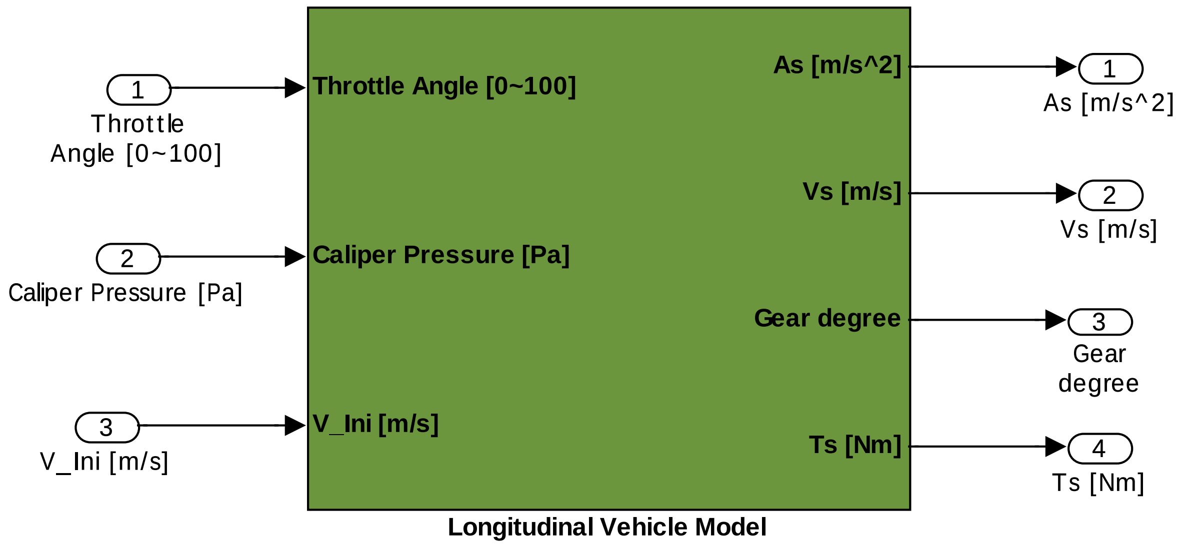


Fig.1 Longitudinal Vehicle Model

Table.1 Vehicle Parameters

Symbol	Value	Symbol	Value
Vehicle Mass	$M_v = 1640\ kg$	Brake Torque Gain	$K_{brake} = 9.6 \cdot 10^{-4}$

H.W-5: Smart Cruise Control

In order to track a desired acceleration for following the set speed or the preceding vehicle, the control input can be calculated as follows:

- **Throttle Angle Input (when the desired acceleration is positive.)**

$$\alpha(t) = -K_{P\_\alpha} \cdot \left(a_x(t) - a_{des}(t)\right) - K_{I\_\alpha} \cdot \int \left(a_x(t) - a_{des}(t)\right) dt$$

- **Brake Control Input (when the desired acceleration is negative.)**

$$P_b(t) = K_{P\_brake} \cdot \left(a_x(t) - a_{des}(t)\right) + K_{I\_brake} \cdot \int \left(a_x(t) - a_{des}(t)\right) dt$$

H.W-5: Smart Cruise Control

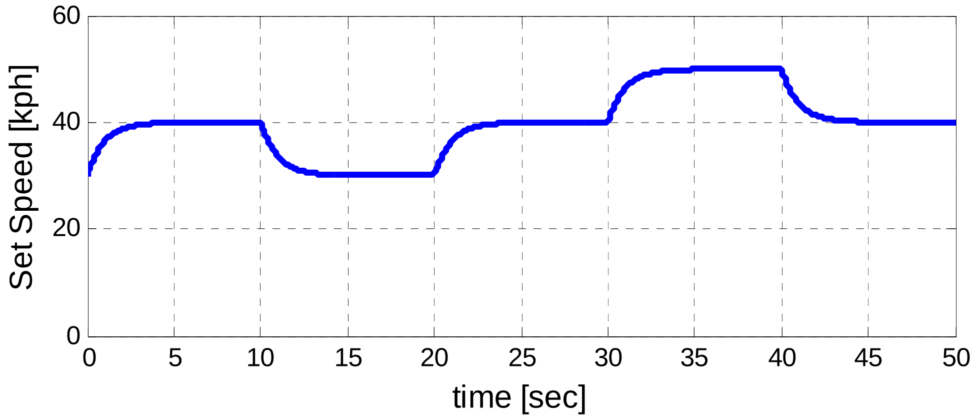
1. Design a speed controller for following the set speed profile as shown in Fig.2

(a) Compare the set speed profile and a longitudinal speed.

(b) Compare the desired acceleration and a longitudinal acceleration.

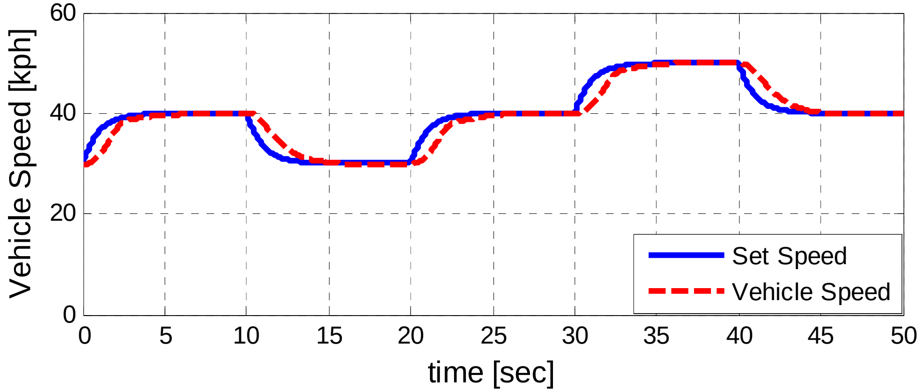
(c) Plot control inputs such as a throttle and a brake pressure.

Set Speed Profile [kph]

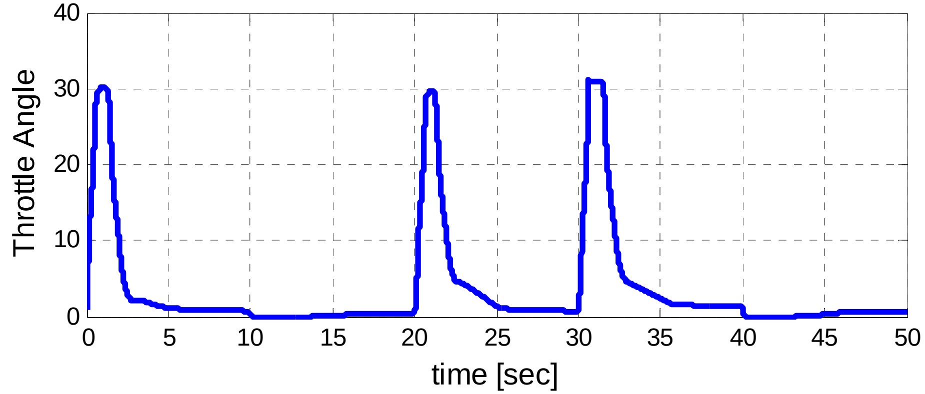


Problem.1 Simulation Results

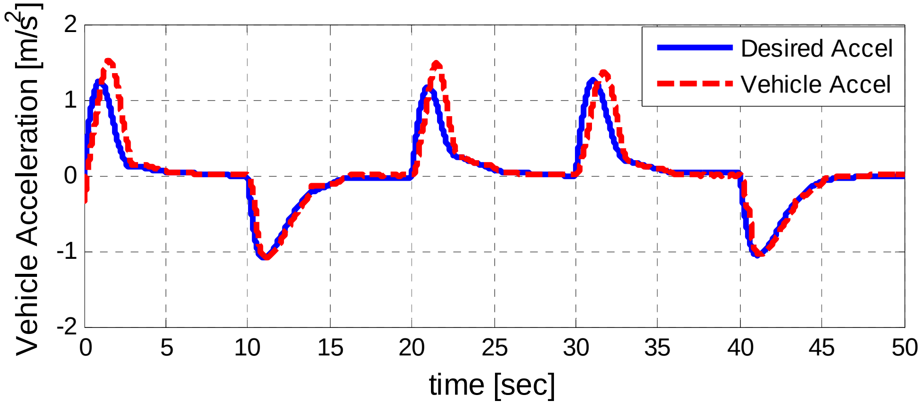
Vehicle Speed [kph]



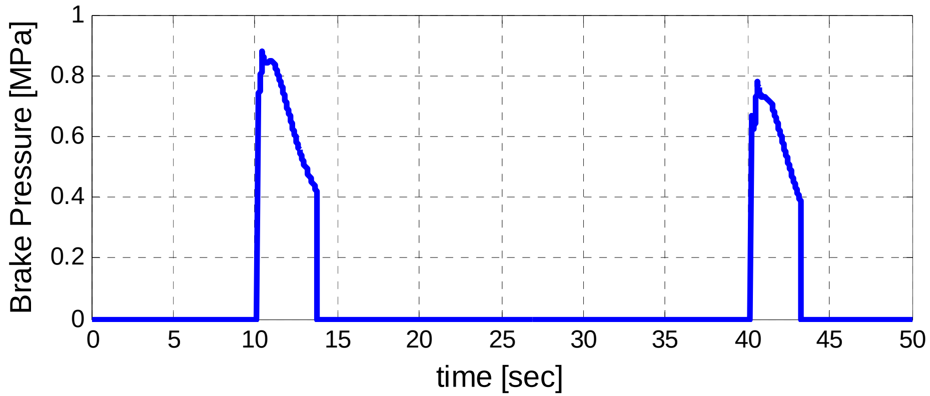
Throttle Angle



Vehicle Acceleration [m/s^2]



Brake Pressure [MPa]



H.W-5: Smart Cruise Control

2. Design a SCC algorithm for following the preceding vehicle as shown in Fig.3

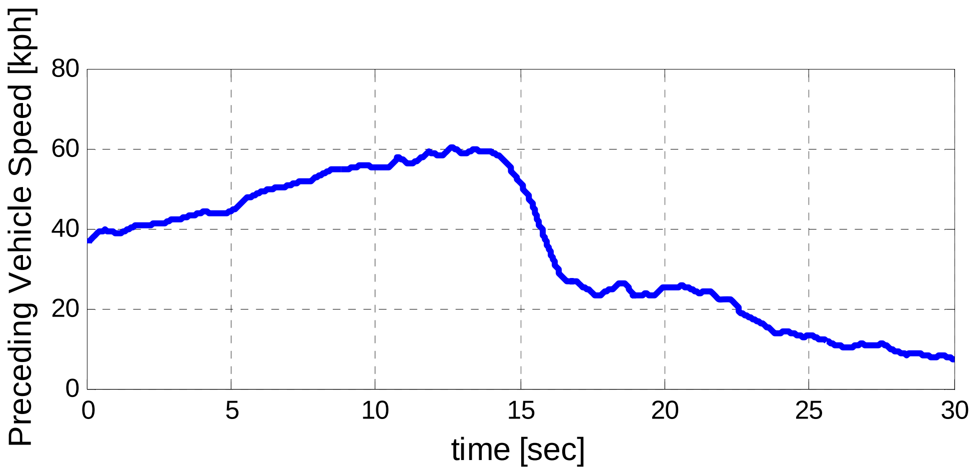
(a) Compare the preceding vehicle speed and a longitudinal speed.

(b) Compare the desired clearance and a clearance between a preceding vehicle and a subject vehicle.

(c) Compare the desired acceleration and a longitudinal acceleration.

(d) Plot control inputs such as a throttle and a brake pressure.

Speed Profile of Preceding Vehicle [kph]



Problem.2 Simulation Results