evs 27

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Comparison of Braking Performance by Electro-Hydraulic ABS and Motor Torque Control for In-wheel Electric Vehicle

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- Purpose of study
- In-wheel motor torque control
- ABS experiment and simulator
- Simulation results
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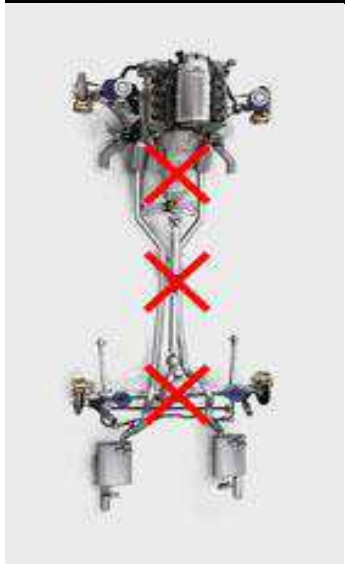
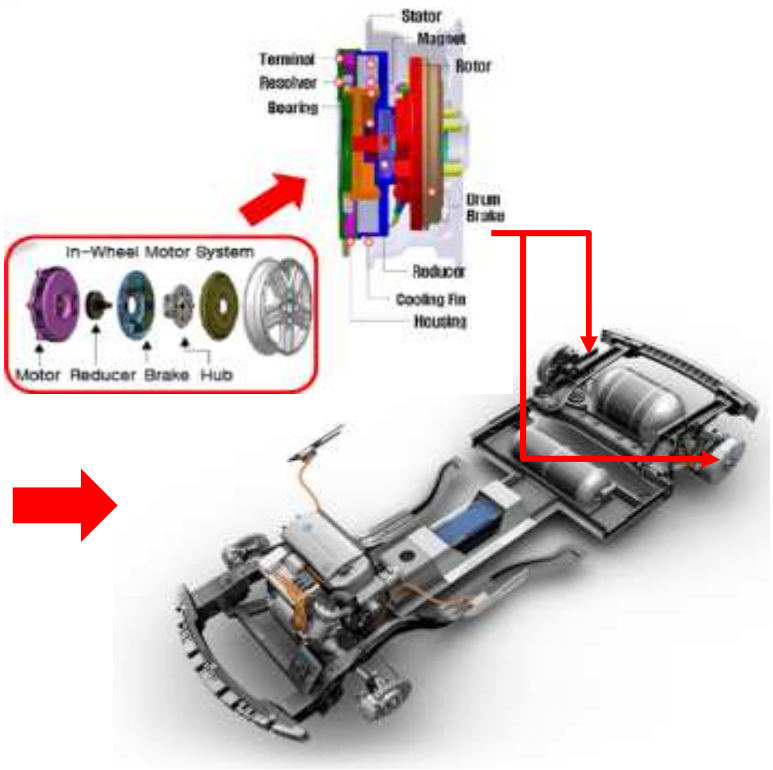
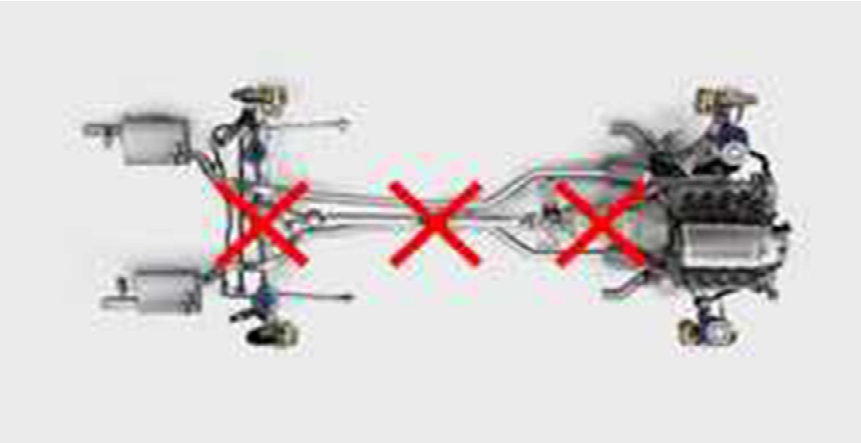
Introduction
- In-wheel electric vehicle





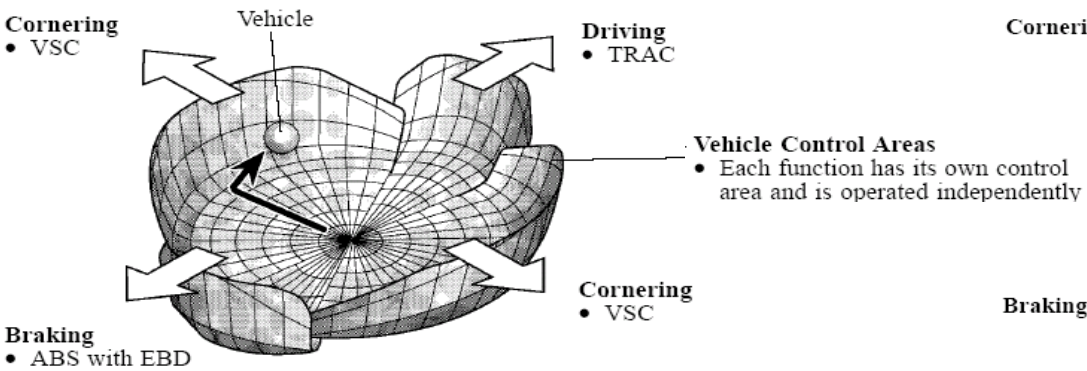
- Equips **drive motor to each wheel** with brake and suspension systems
- Propels the vehicle **only by the electric energy** using in- wheel independent motors

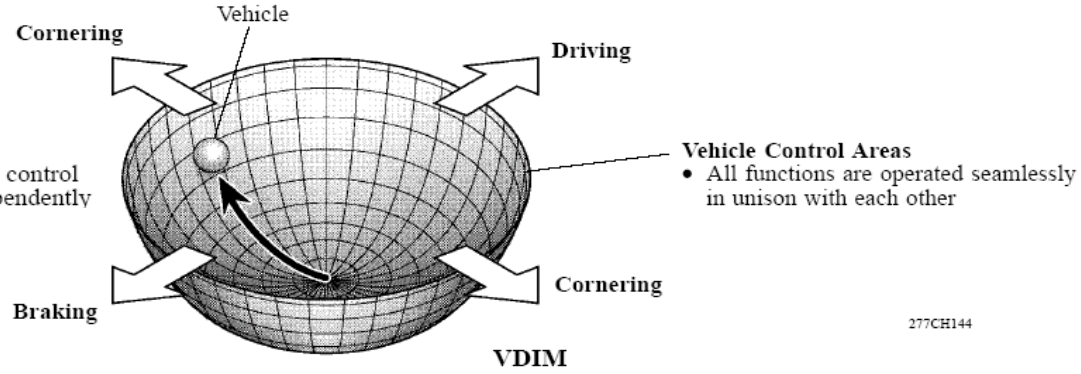
Introduction
- Advantages



✓ No transmission, engine, shaft and axle

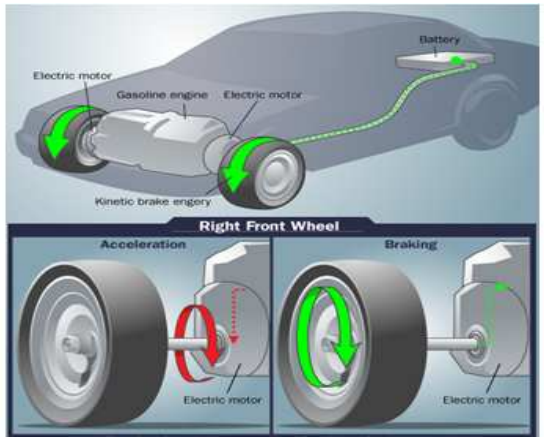
✓ More space





✓ Independent control of each wheel (Extended vehicle control area)

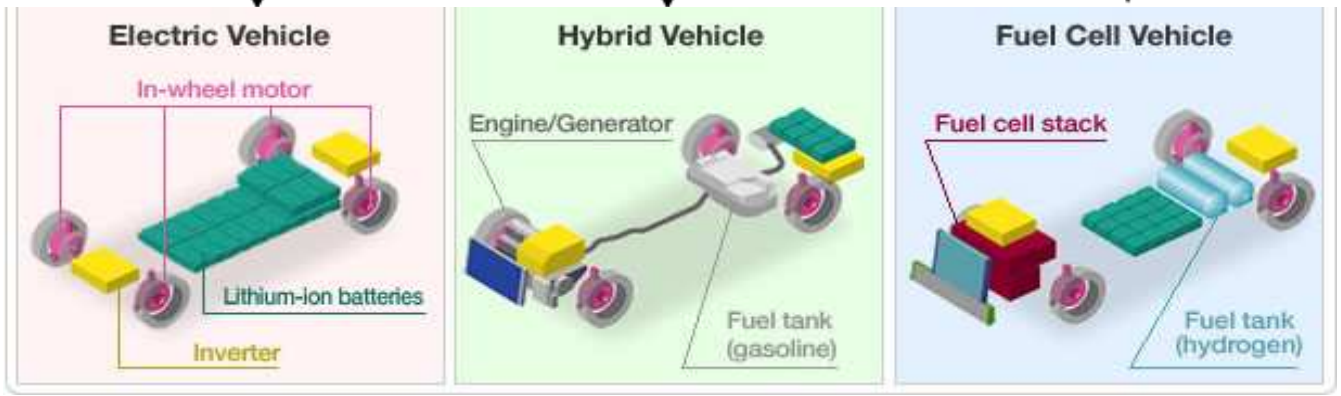
Introduction
- Advantages



✓ High power transmission efficiency

✓ Improved fuel economy by regenerative braking at each wheel

In-wheel system



✓ Possibilities of application on various x-EVs platforms

Purpose of study

- **Develop an in-wheel motor torque control algorithm**

  - Slip control based on μ and λ

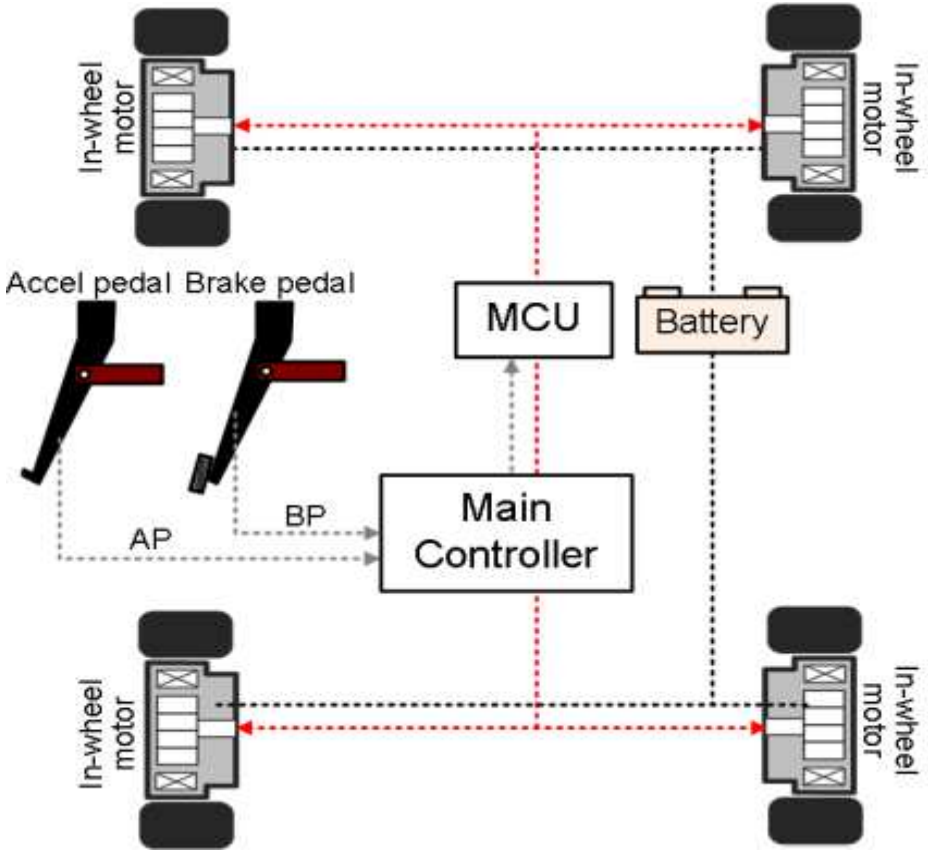
- **Develop ABS experiment environment and ABS simulator**

- **Develop CarSim-MATLAB/Simulink co-simulator**

- **Compare the braking performance of in-wheel motor torque control with that of ABS**

In-wheel motor torque control

- Structure of in-wheel electric vehicle



- Sprung mass : 1700 kg
- Front in-wheel motor power : 35 kW

  reduction gear ratio : 8.45

  maximum torque : 75 Nm

  maximum speed : 11000 rpm
- Rear in-wheel motor power : 16 kW

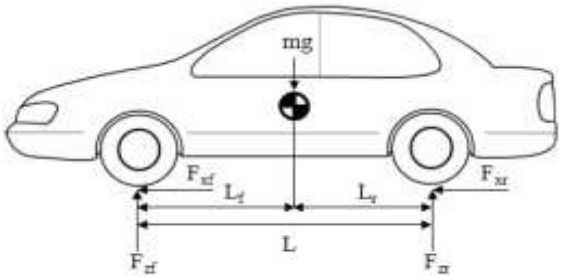
  reduction gear ratio : 4

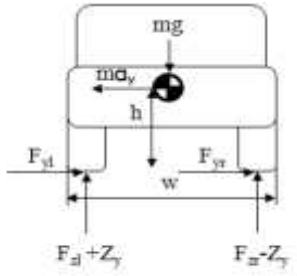
  maximum torque : 123 Nm

  maximum speed : 5000 rpm

In-wheel motor torque control

- Estimated vertical force





< Vehicle dynamics model >

$$F_{zf} = \frac{h\left(-\frac{1}{2}C_d A V_x^{\,2} - mg - m\dot{V}_x\right)}{L} \quad \cdots\cdots (1)$$

$$F_{zr} = \frac{-h\left(-\frac{1}{2}C_d A V_x^{\,2} - mg - m\dot{V}_x\right)}{L} \quad \cdots\cdots (2)$$

$$Zy = \frac{hma_y}{w} \quad \cdots\cdots (3)$$

- Using equation (1), (2), (3), nomal forces at each wheel are obtained

$$F_{z\_fl} = \frac{h\left(-\frac{1}{2}C_d A V_x^{\,2} - mg\sin\beta - m\dot{V}_x\right) + b\cdot mg\cos\beta}{a+b} + \frac{hma_y}{w}$$

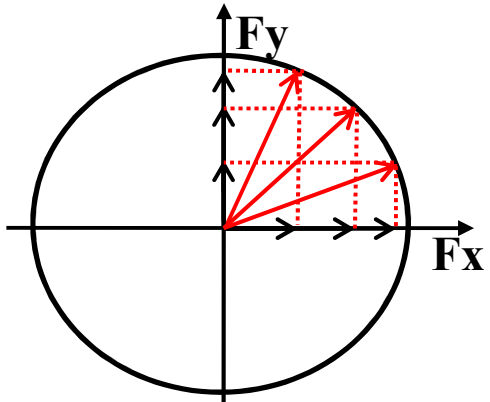
$$F_{z\_rl} = \frac{-h\left(-\frac{1}{2}C_d A V_x^{\,2} - mg\sin\beta - m\dot{V}_x\right) + a\cdot mg\cos\beta}{a+b} + \frac{hma_y}{w}$$

$$F_{z\_fr} = \frac{h\left(-\frac{1}{2}C_d A V_x^{\,2} - mg\sin\beta - m\dot{V}_x\right) + b\cdot mg\cos\beta}{a+b} - \frac{hma_y}{w}$$

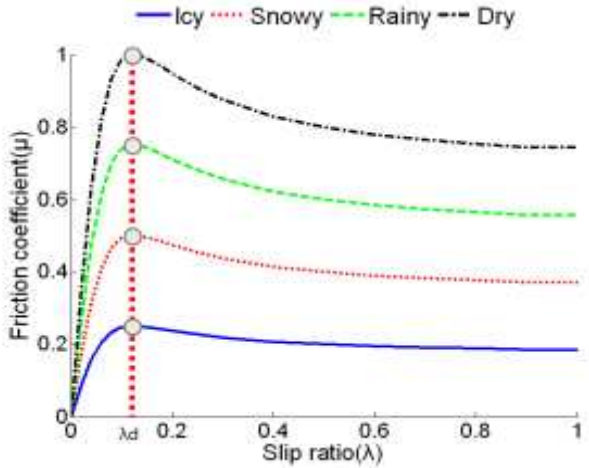
$$F_{z\_rr} = \frac{-h\left(-\frac{1}{2}C_d A V_x^{\,2} - mg\sin\beta - m\dot{V}_x\right) + a\cdot mg\cos\beta}{a+b} - \frac{hma_y}{w}$$

In-wheel motor torque control

- Motor torque control



< Friction circle >



< Non-linear tire model >

- Feed forward term : $T_{x\_limit} = R \times F_{x\_limit} = R \times \mu F_z$

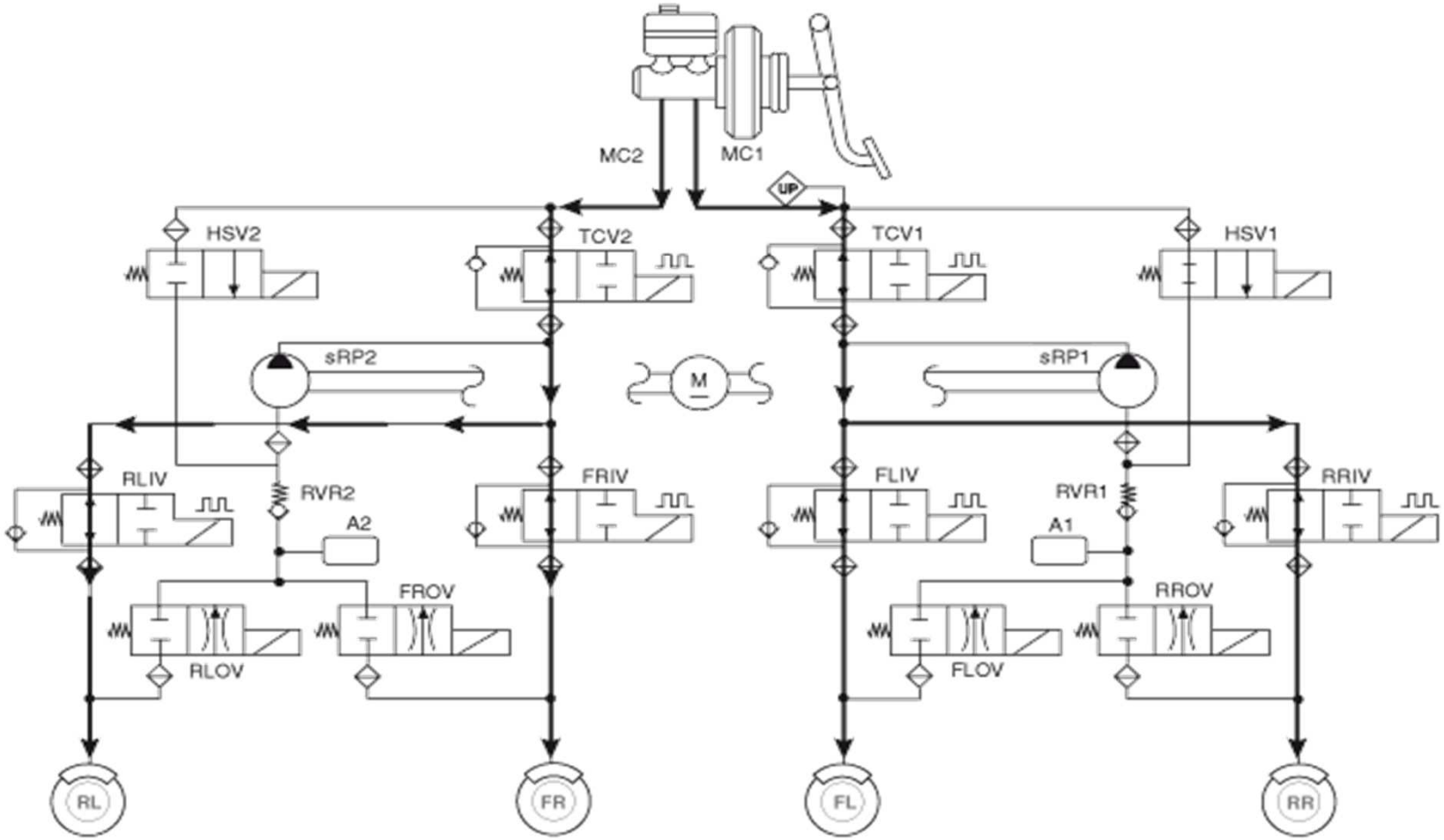
- Feed back term : $T_{x\_limit} = K_{slip\ control}(\lambda_d - \lambda) \times (\lambda > \lambda_d)$

- Limited motor torque:

$$T_{limit} = RF_{x\_limit} + K_{slip\ control}(\lambda_d - \lambda) \times (\lambda > \lambda_d)$$

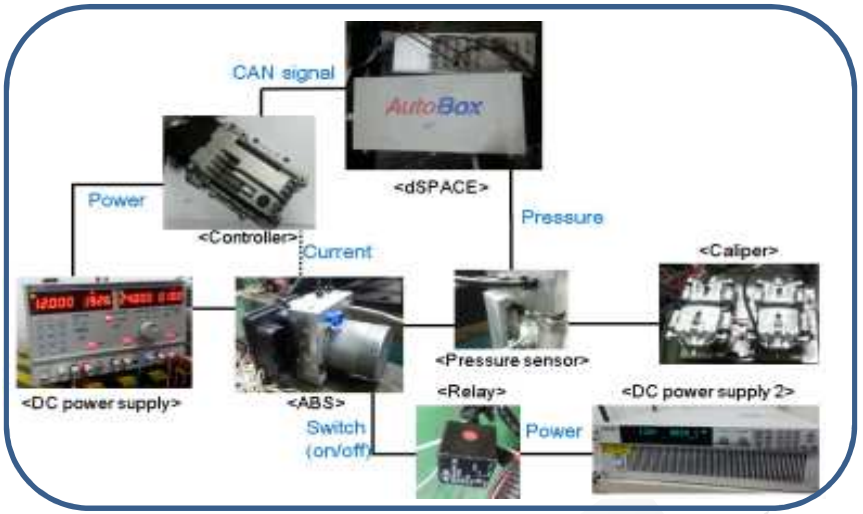
ABS experiment and simulator

- Structure of ABS



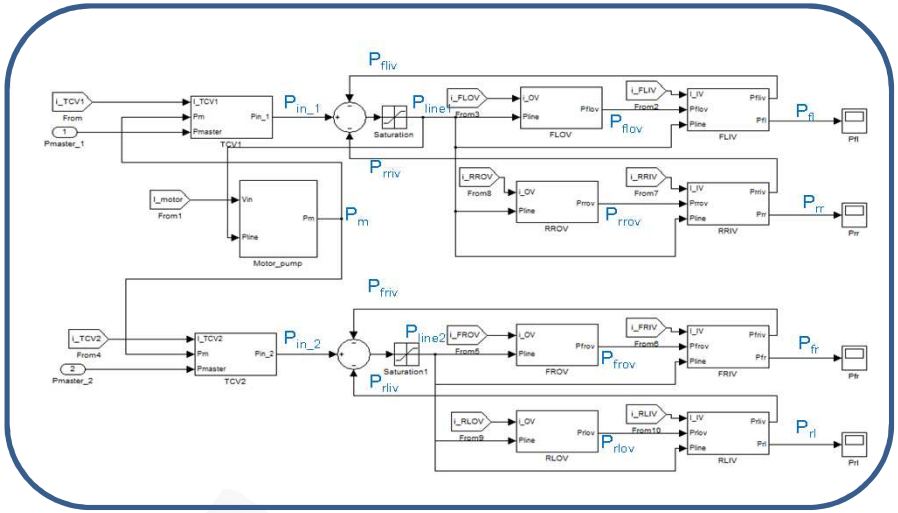
ABS experiment and simulator

- ABS experiment environment



Solenoid valve, motor-pump modeling

- ABS simulator



Verification!

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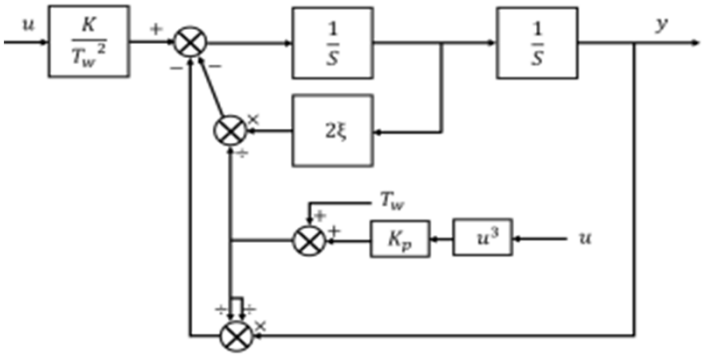
ABS experiment and simulator

- Solenoid valve modeling

- Traction control valve (TCV) modeling

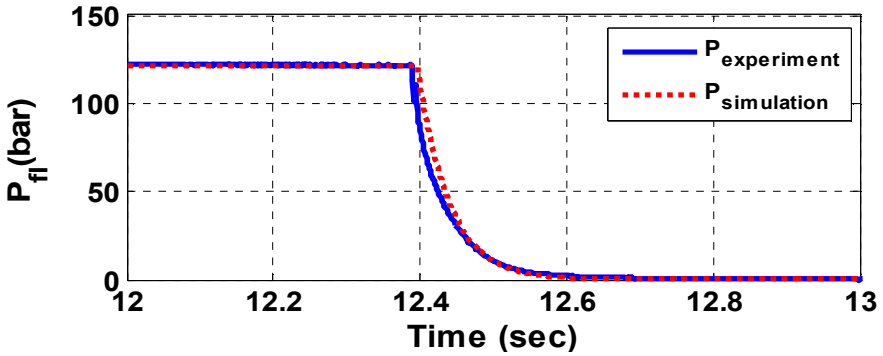


$$P_{tcv} = \frac{K}{T_w(i_{tcv})^2 s^2 + T_w(i_{tcv}) 2\zeta s + 1} e^{-\tau s} i_{tcv}$$

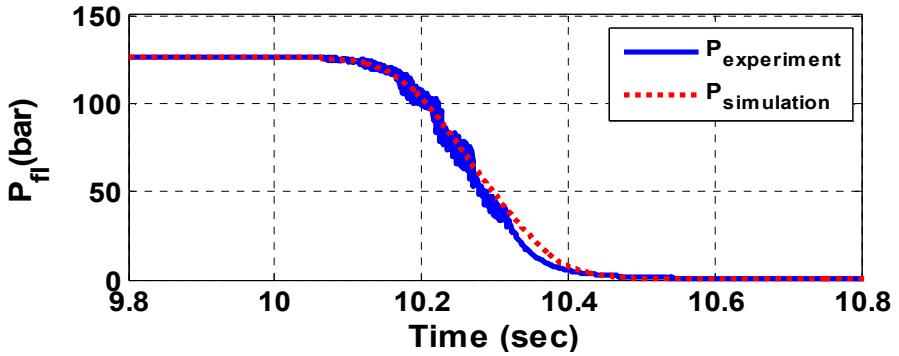
$$P_{tcv\_init} = P_{line}$$

$$T_w(i_{tcv}) = T_w + K_p {i_{tcv}}^3$$

- Verification



< Step input >



< Ramp input >

ABS experiment and simulator

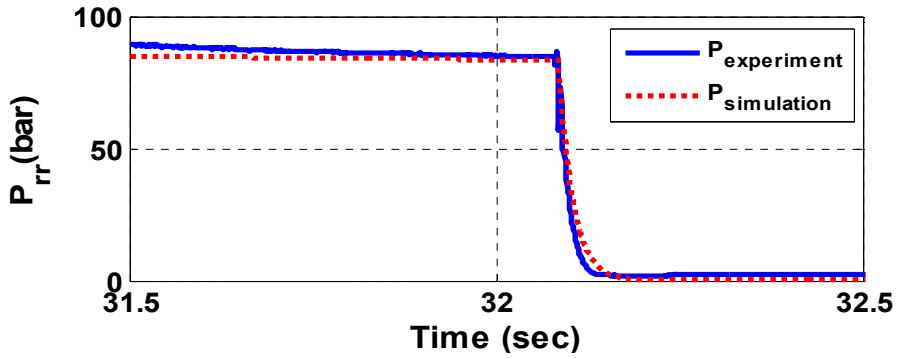
- Solenoid valve modeling

- Outlet valve (OV) modeling - on/off valve

$$P_{ov} = \frac{K}{T_w s + 1} e^{-\tau s} i_{ov}$$

$$P_{ov\_init} = P_{line}$$

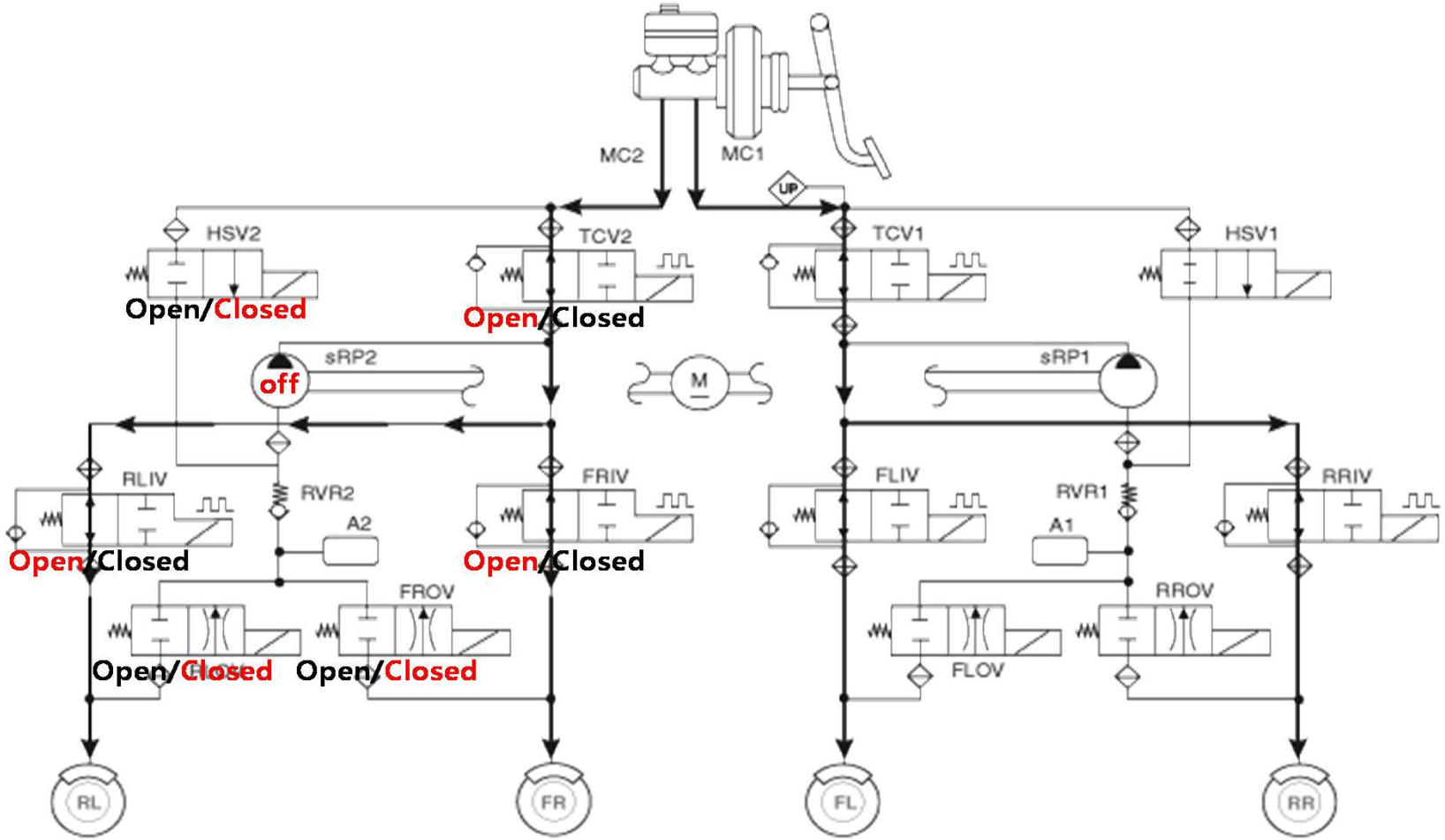
- Verification



< Step input >

ABS experiment and simulator

- Mode1 (default)



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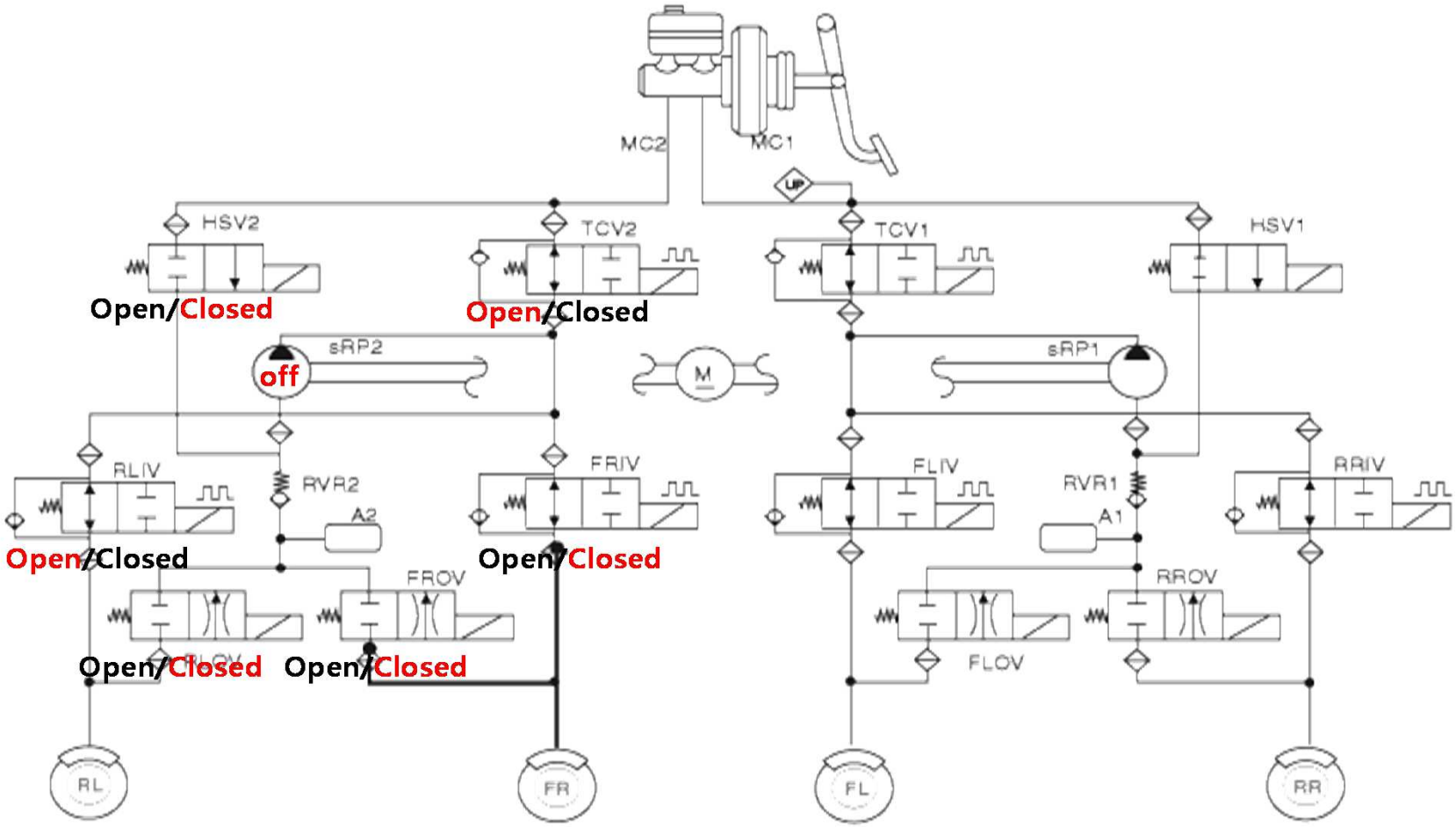
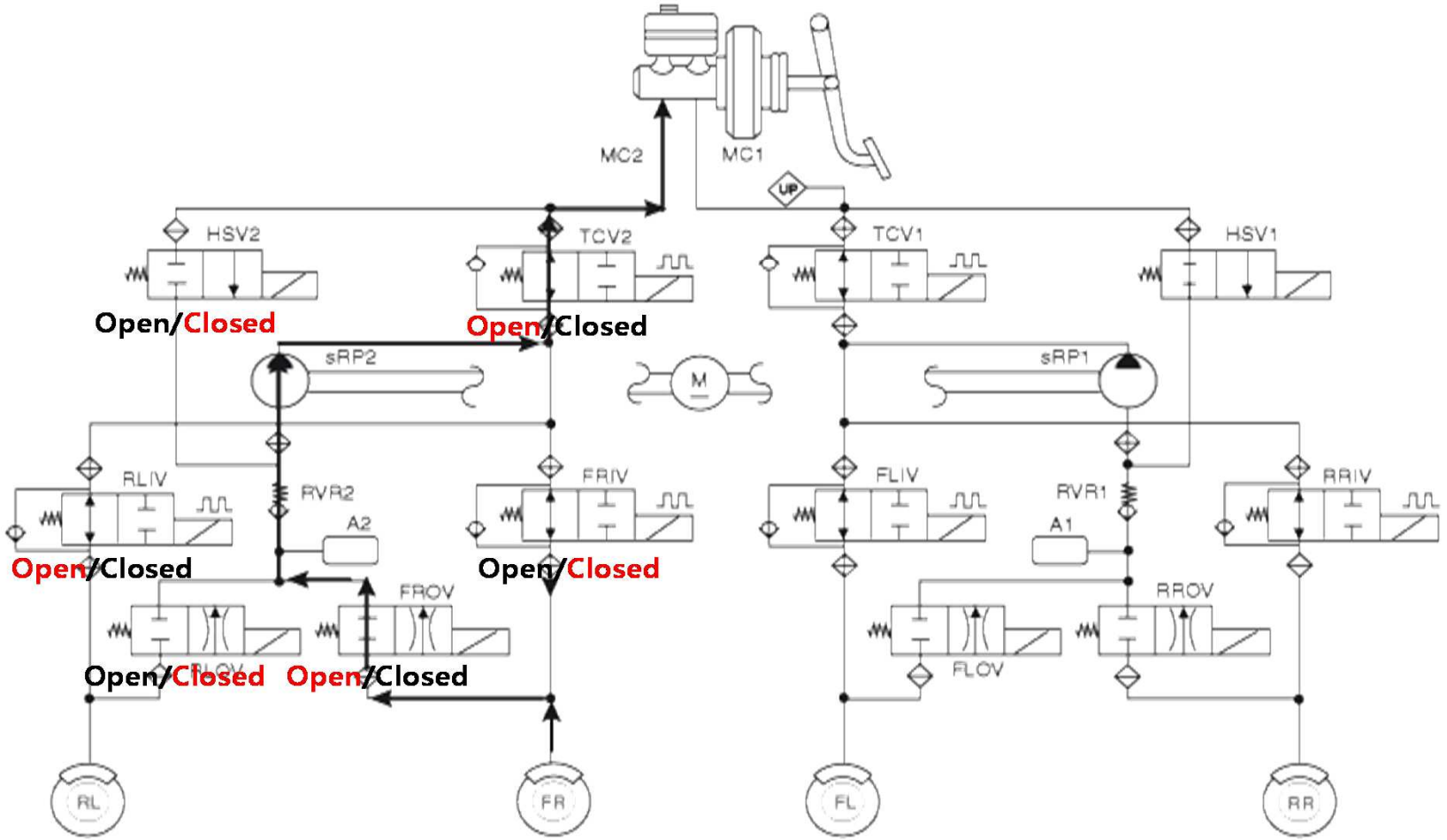
ABS experiment and simulator

- Mode2 (maintaining pressure)



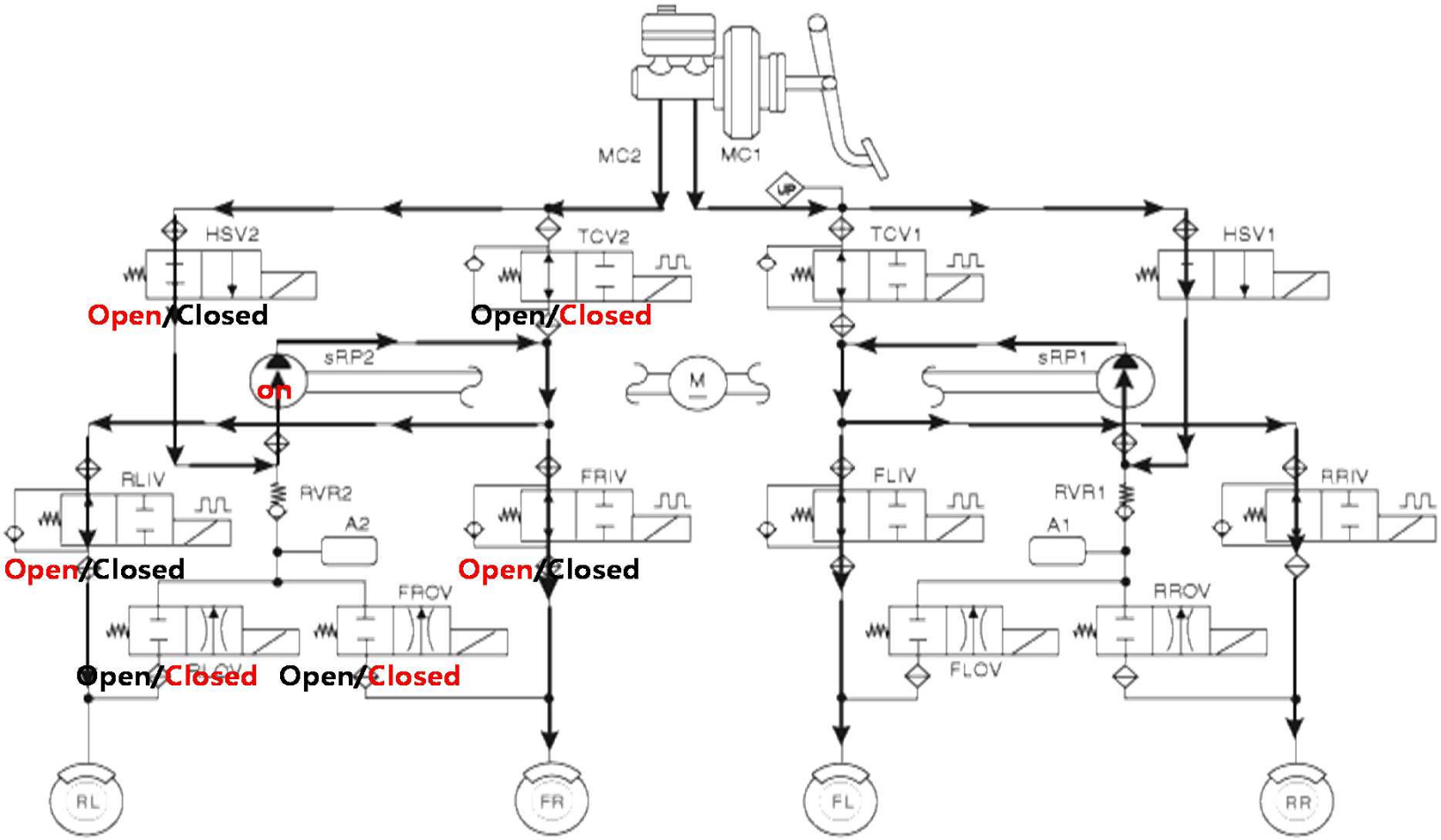
ABS experiment and simulator

- Mode3 (decreasing pressure)



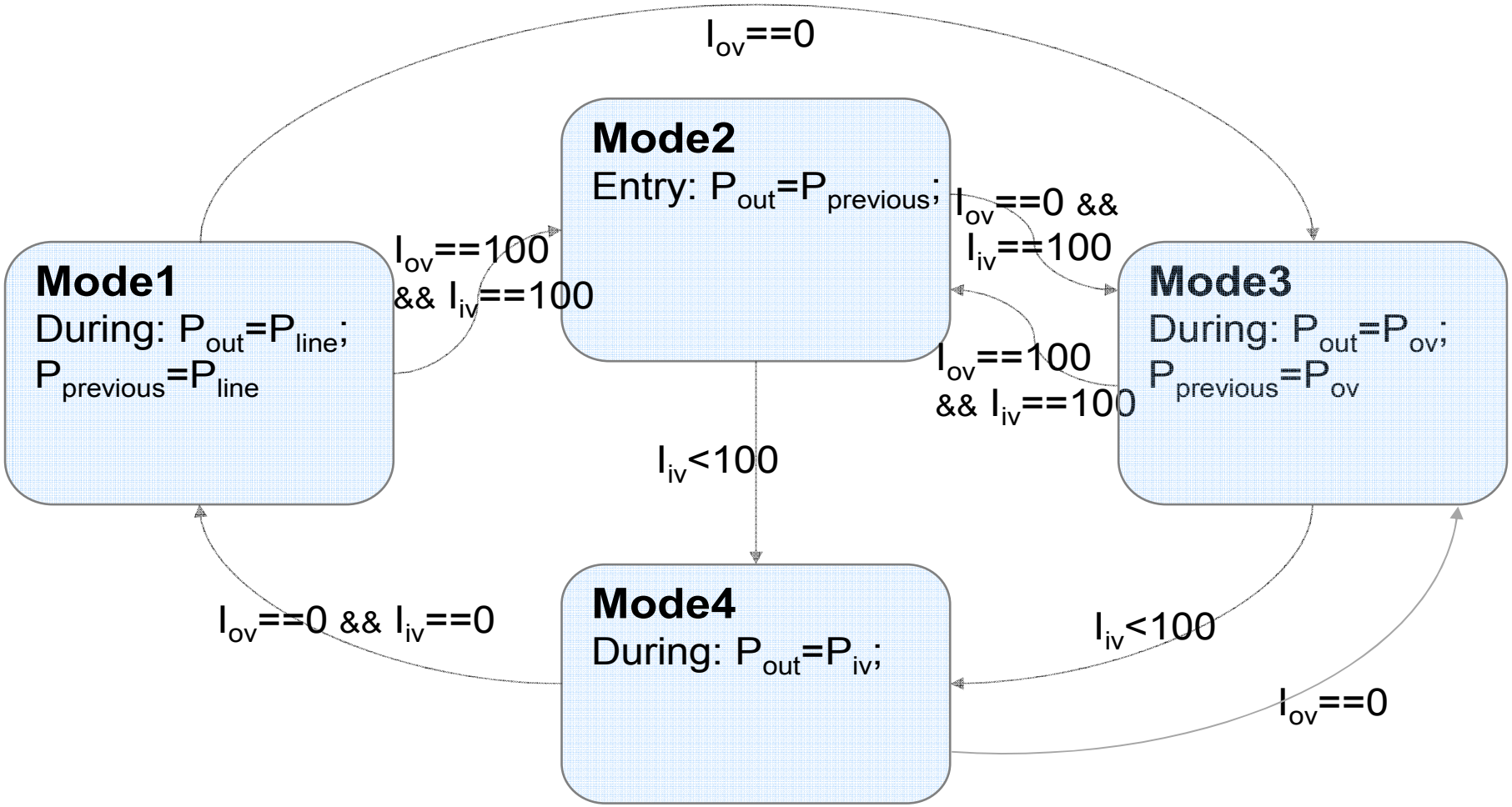
ABS experiment and simulator

- Mode4 (increasing pressure)



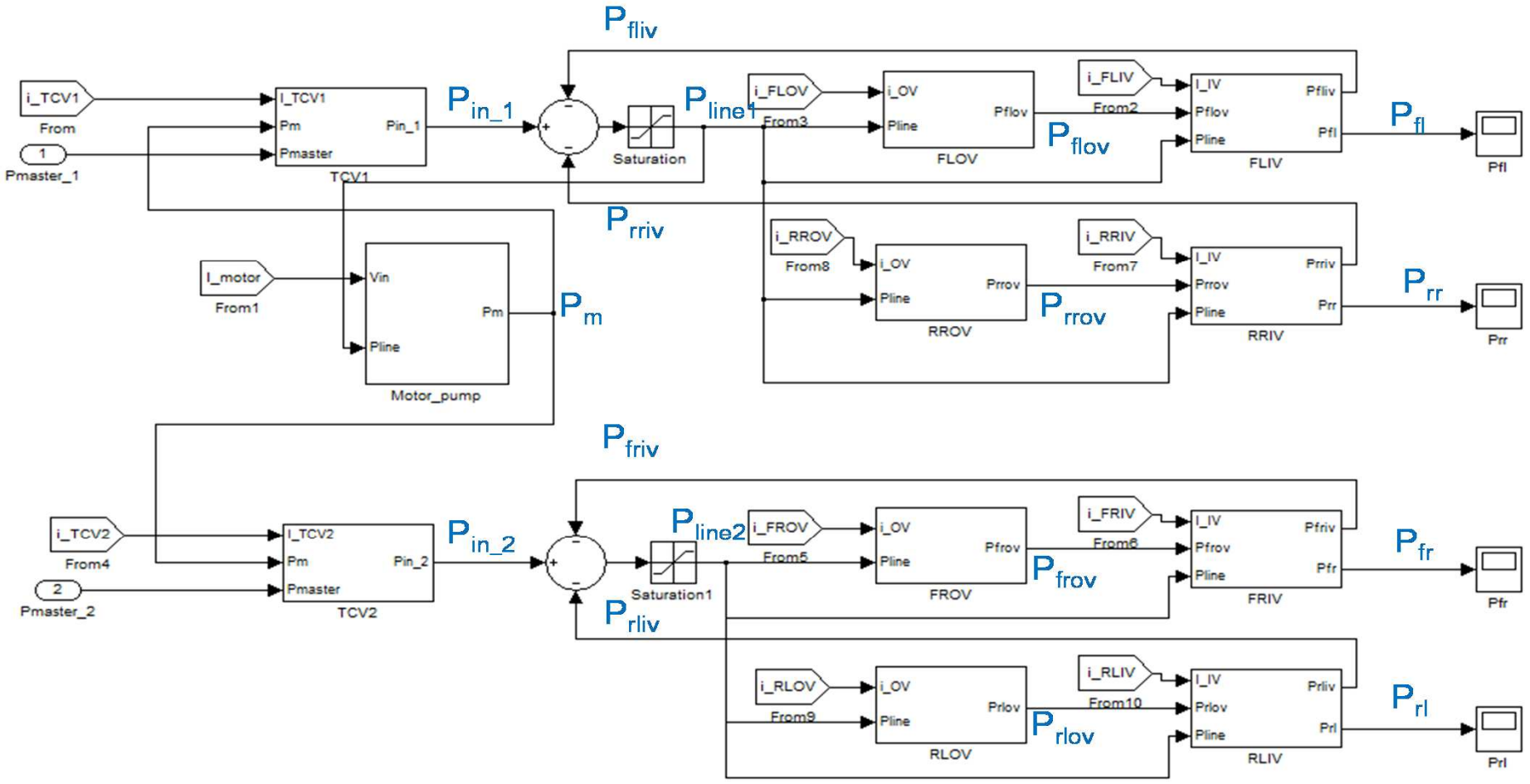
ABS experiment and simulator

- Mode control – MATLAB state flow



ABS experiment and simulator

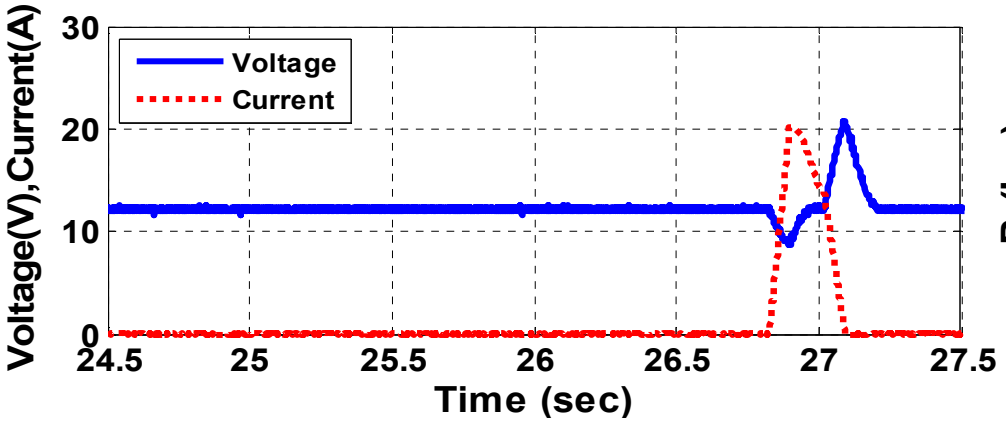
- ABS simulator

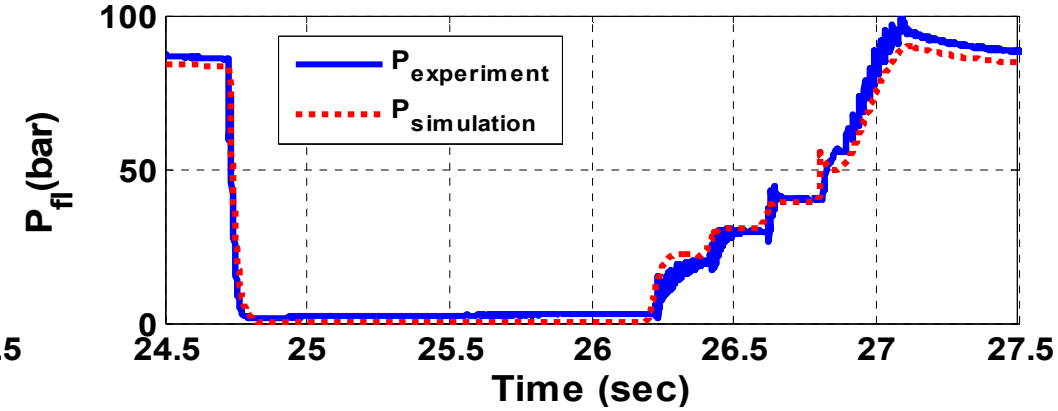


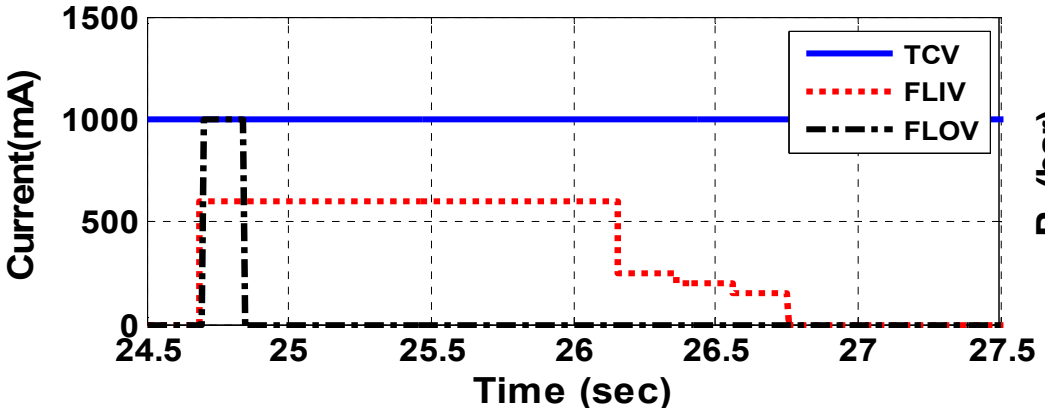
ABS experiment and simulator

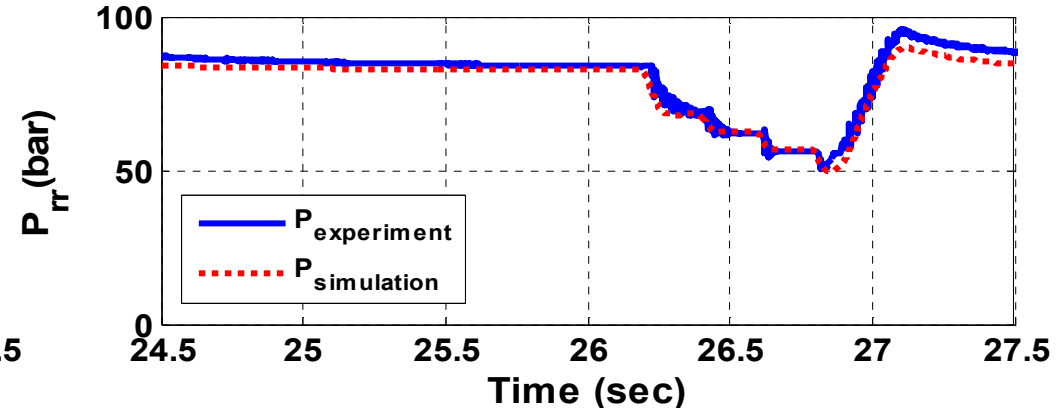
- Experiment and simulation results

- i_{TCV} = 1000mA





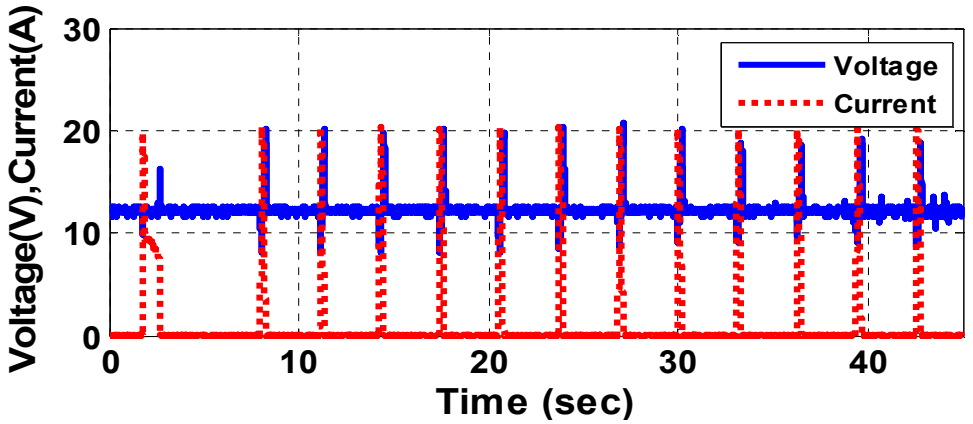


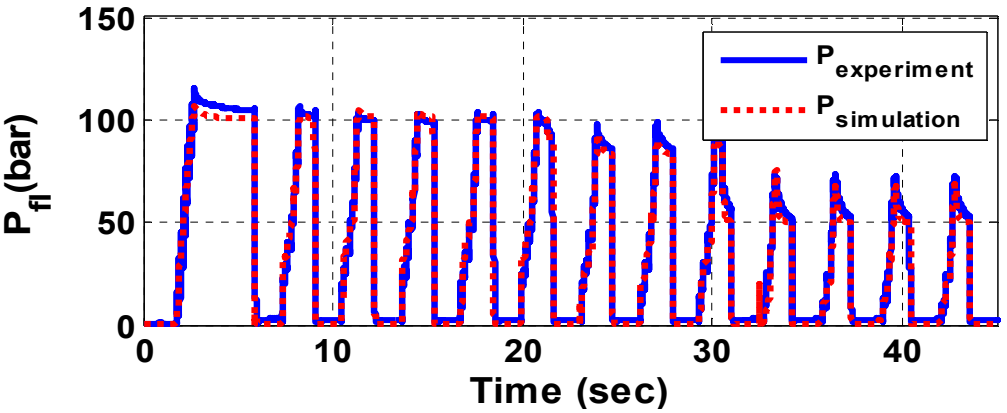


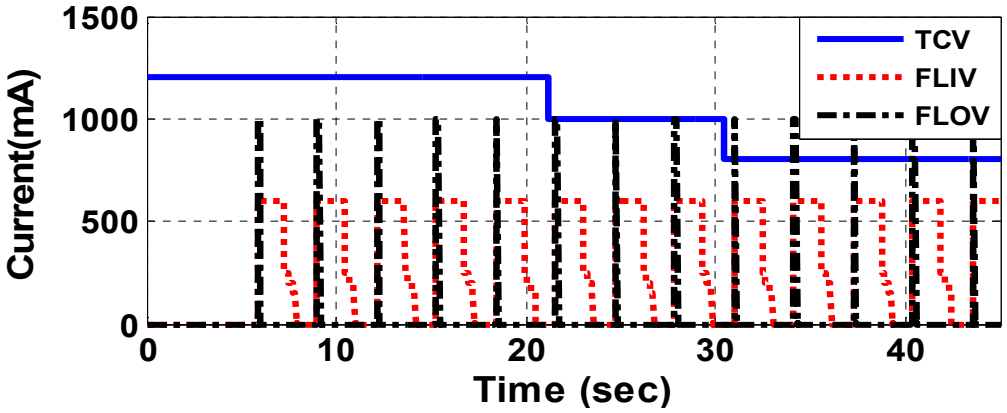
ABS experiment and simulator

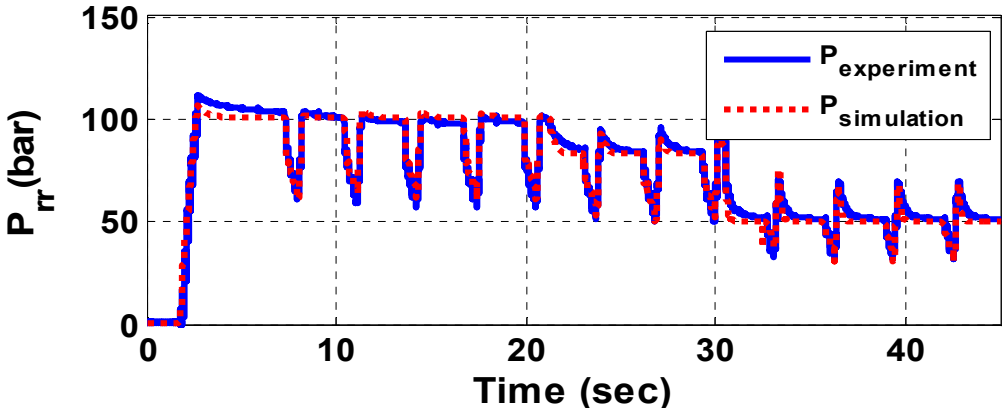
- Experiment and simulation results

- i_{TCV} = 1200~800mA



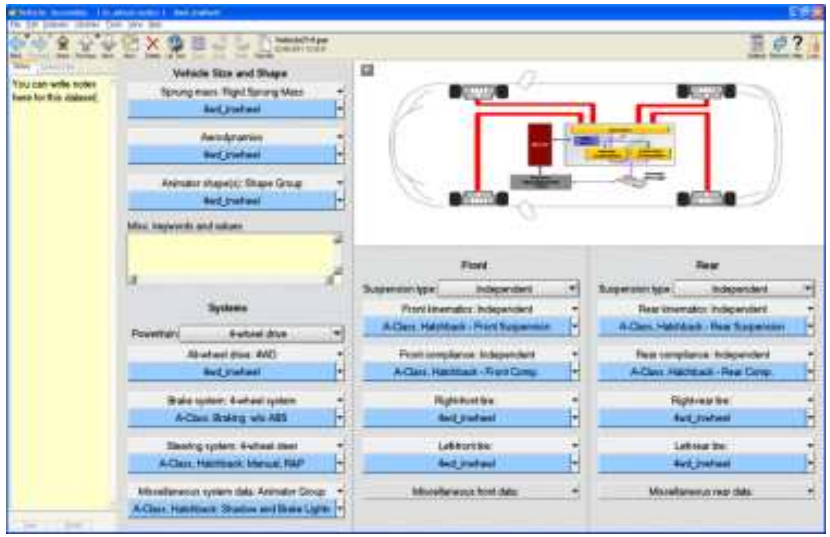




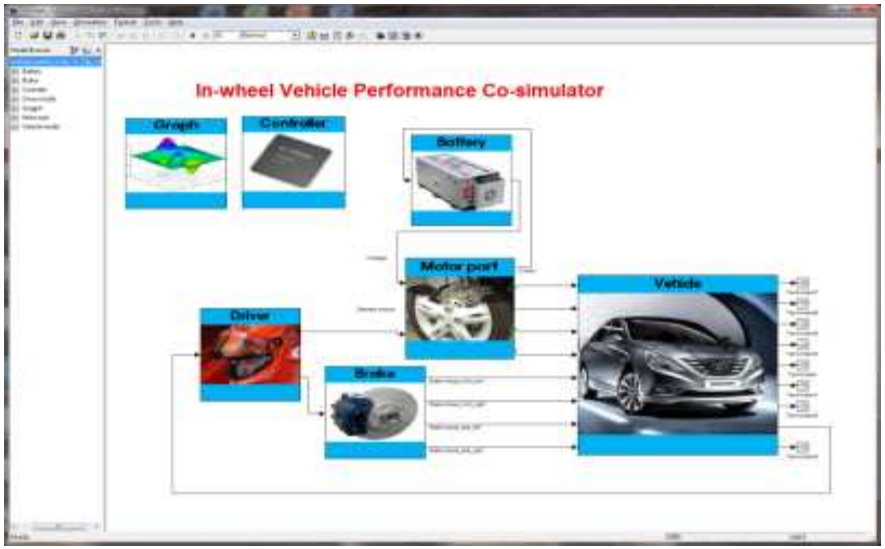


Simulation results

- MATLAB – CarSim co-simulator



< CarSim vehicle model >



< MATLAB/Simulink model >

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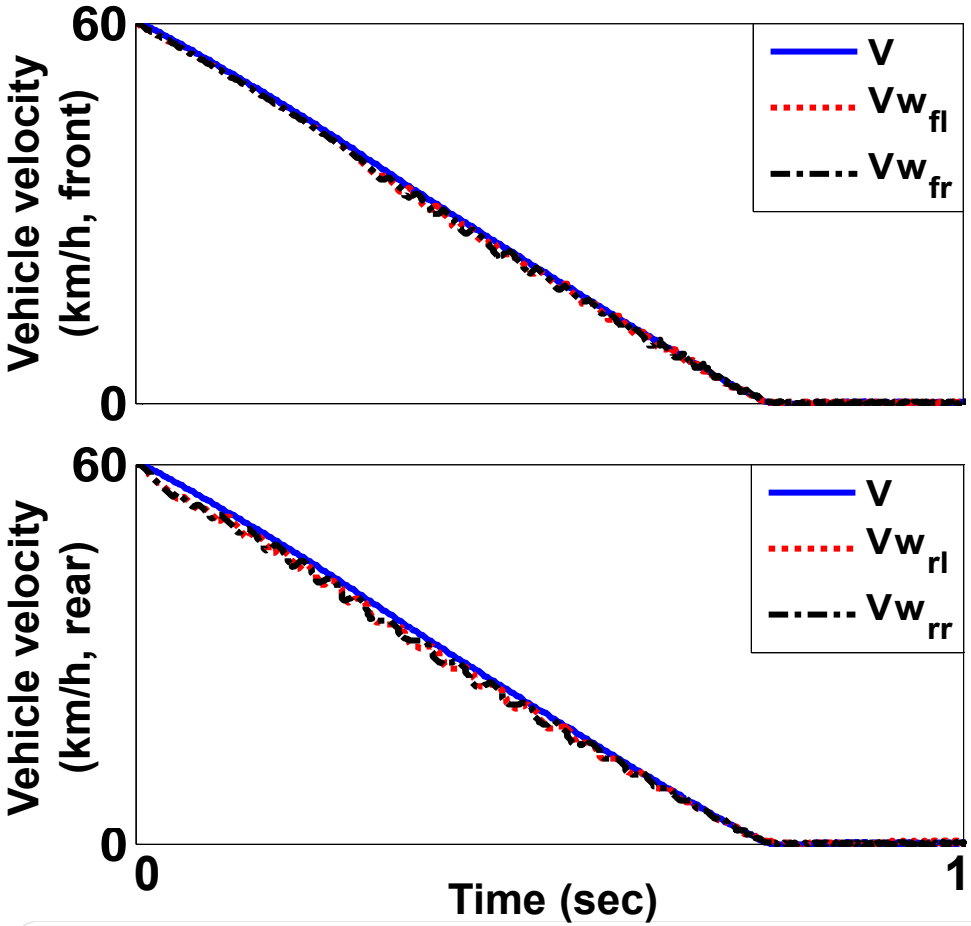
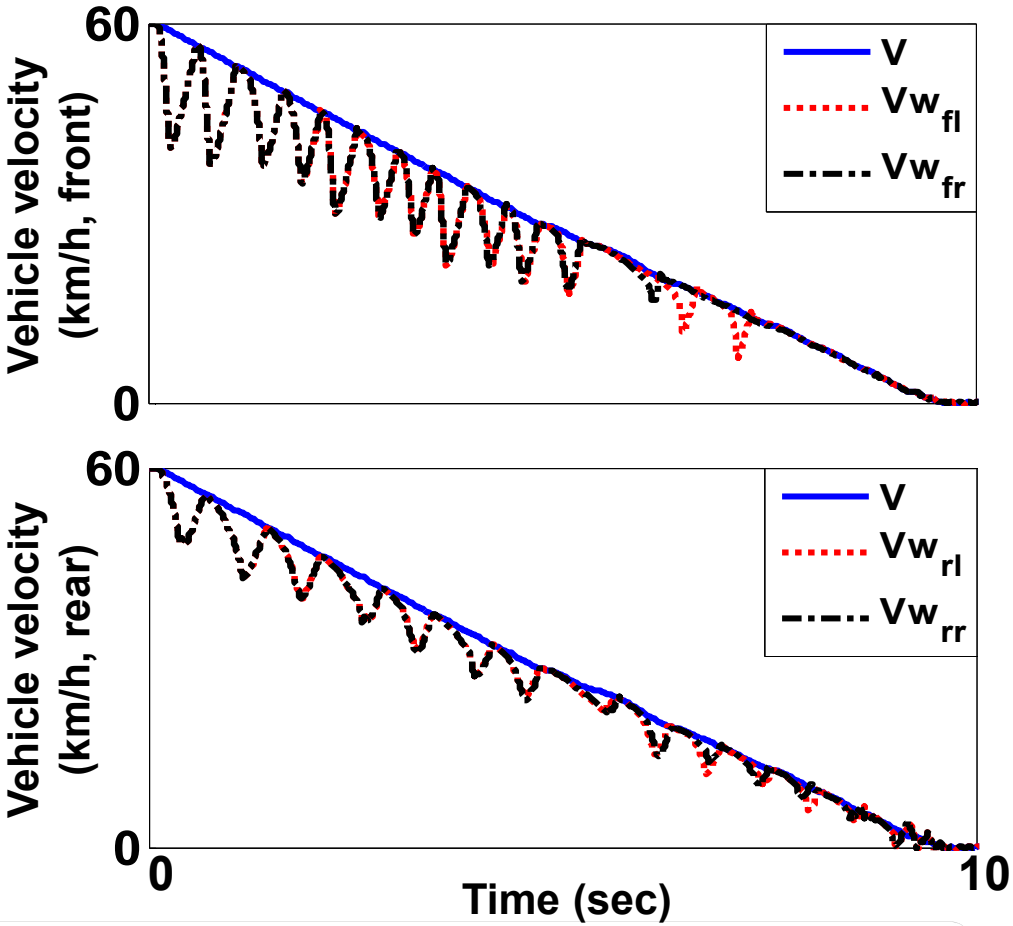
Simulation results

- 60 kph full braking, μ = 0.2

- In-wheel motor torque control



- ABS



Simulation results

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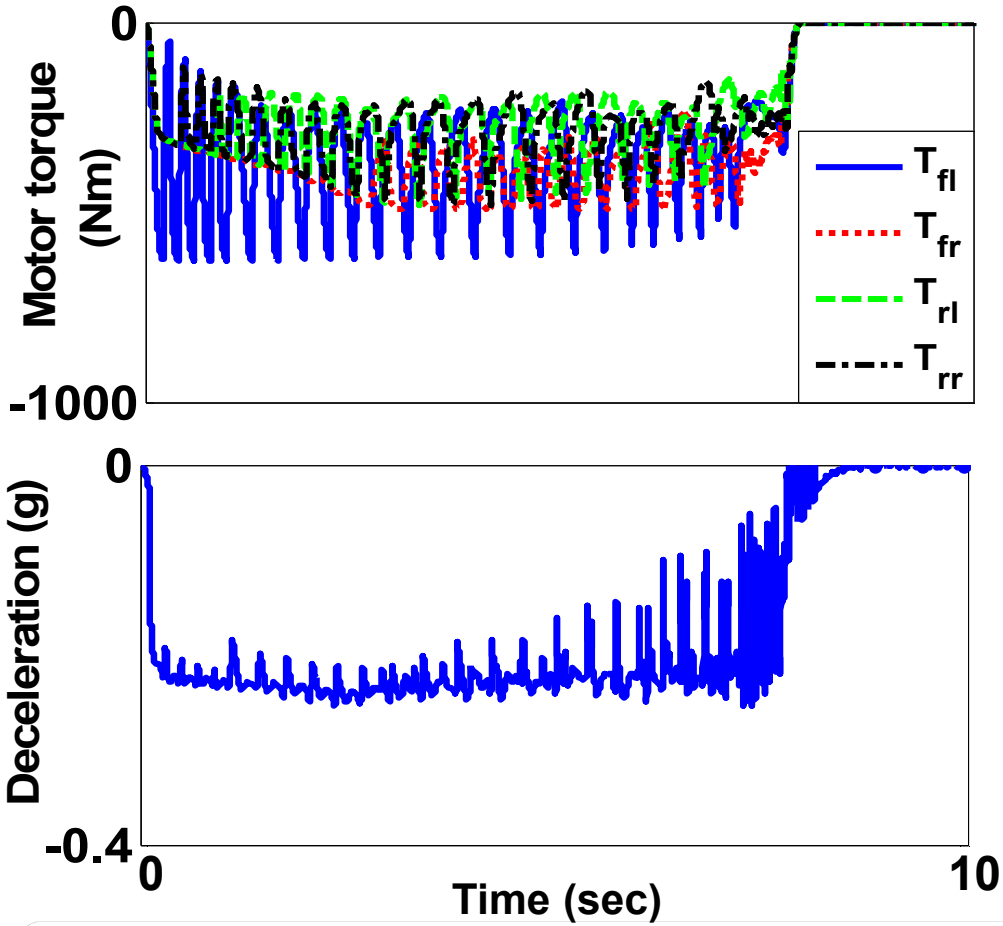
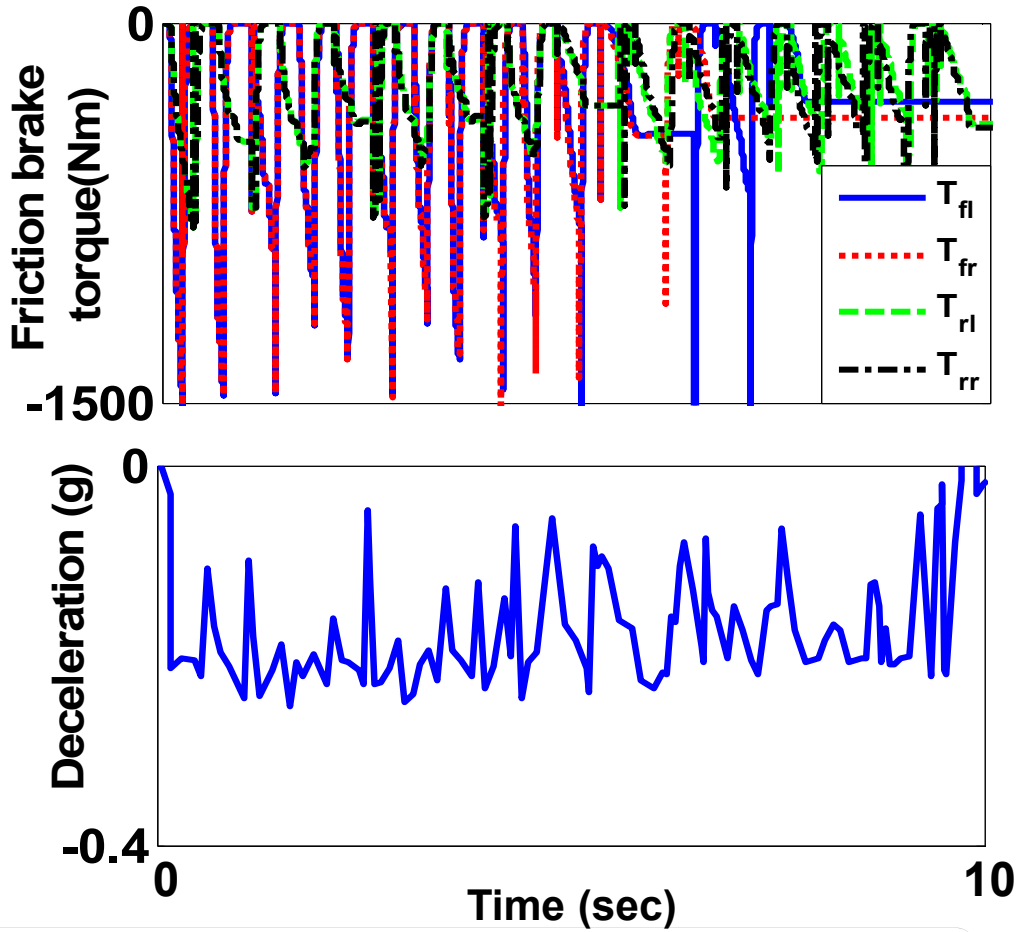


- ABS



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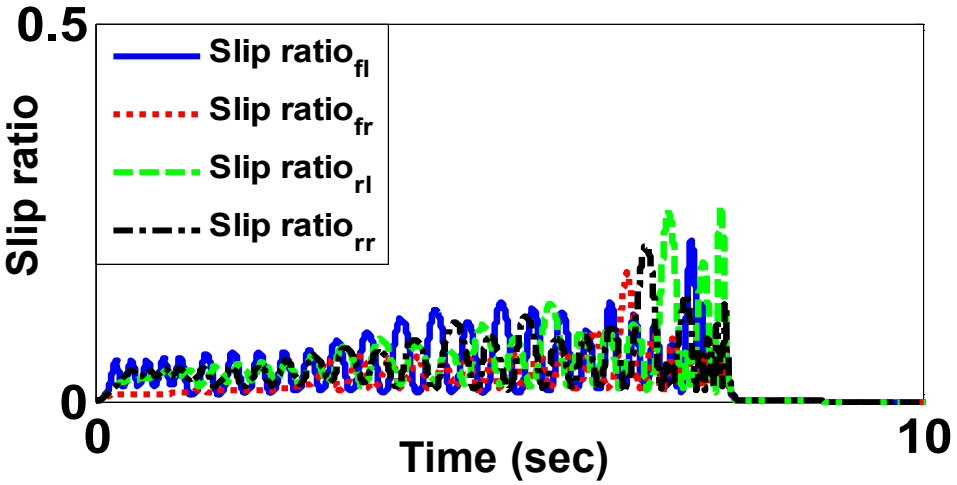
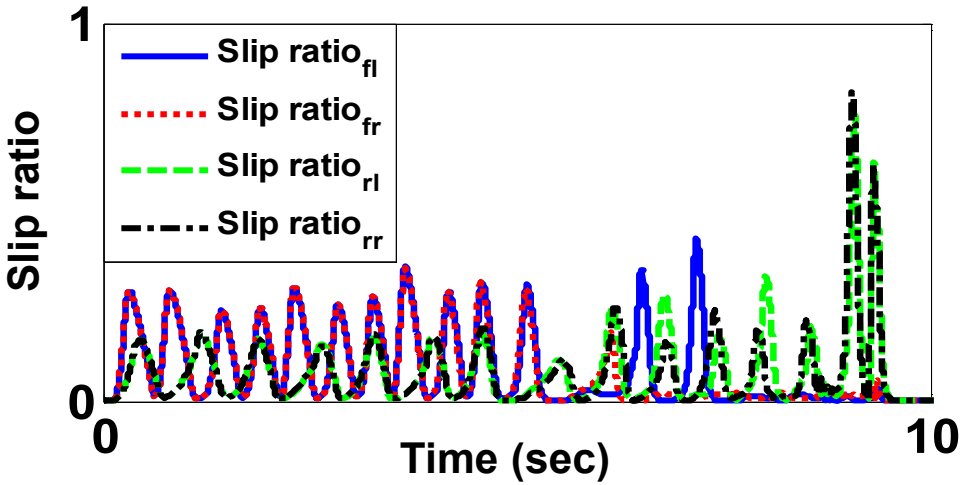


Slip ratio range : 0 ~ 10%
(V≥10kph)
Slip ratio range : 0 ~ 20%
(V<10kph)
Total braking distance : 64.1m

- ABS

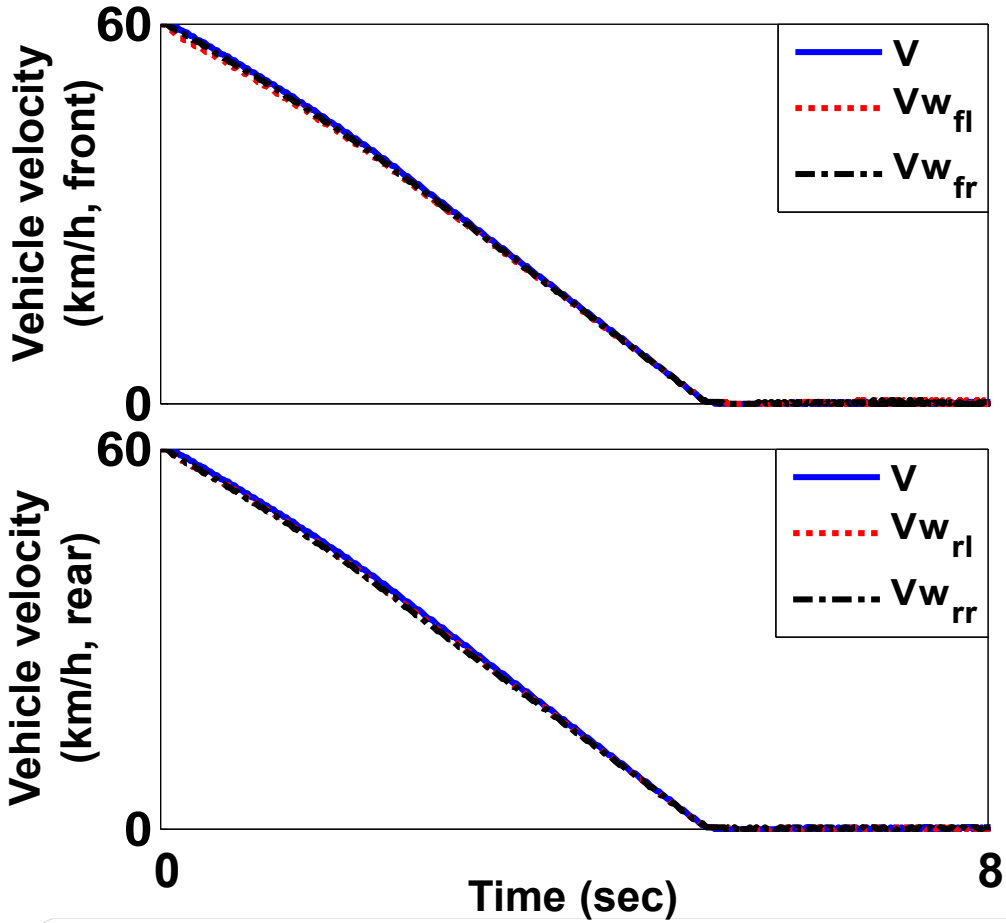


Slip ratio range : 0 ~ 25%
(V≥10kph)
Slip ratio range : 0 ~ 80%
(V<10kph)
Total braking distance : 77.7m

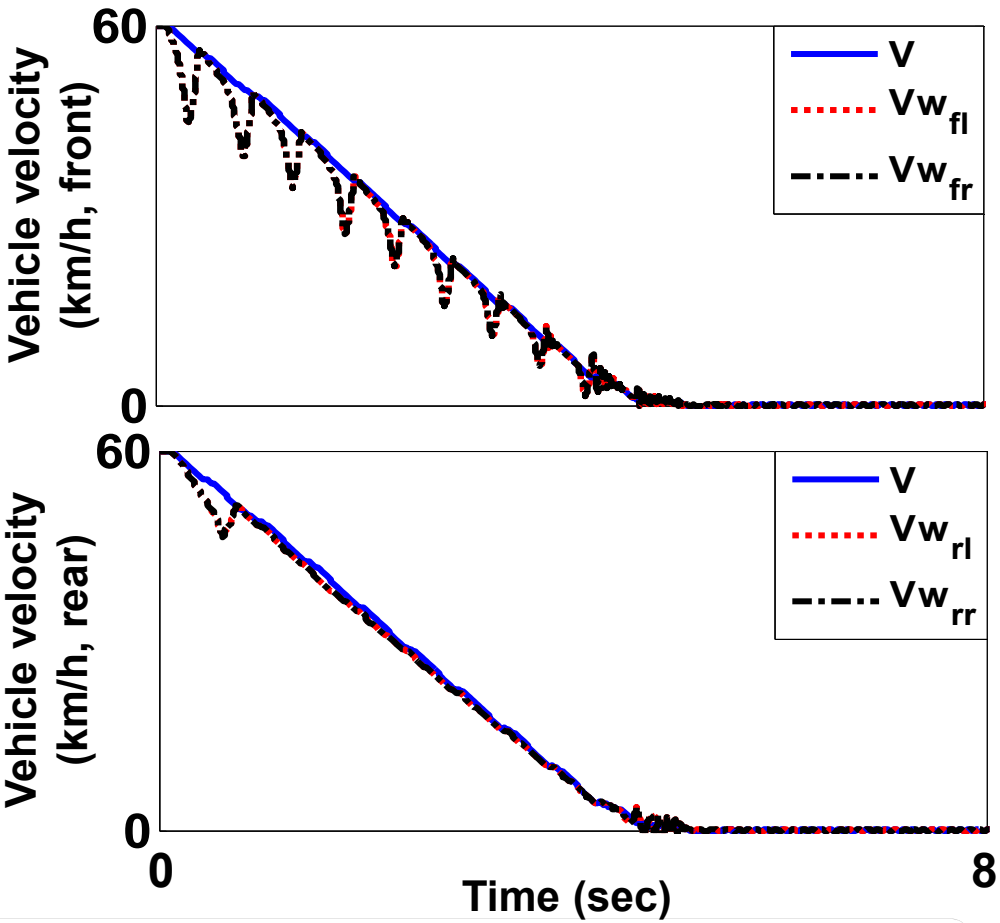
Simulation results

- 60 kph full braking, μ = 0.4

- In-wheel motor torque control



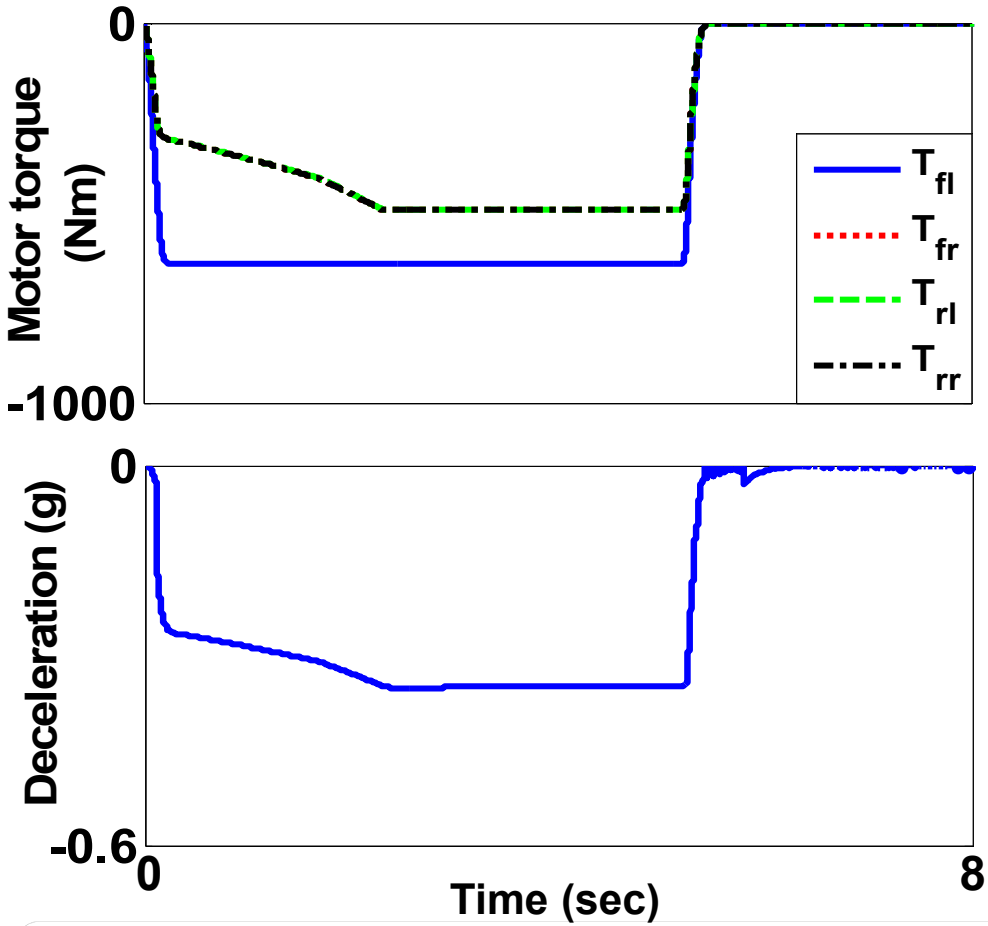
- ABS



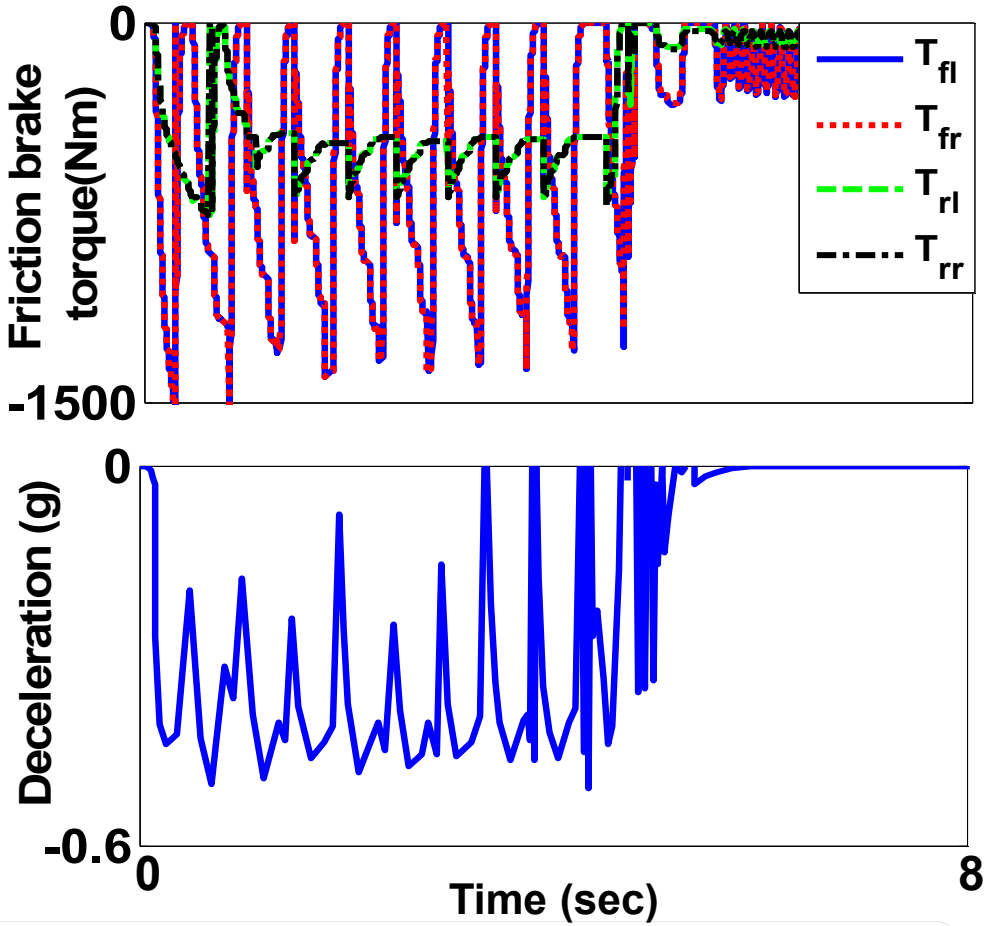
Simulation results

- 60 kph full braking, μ = 0.4

- In-wheel motor torque control



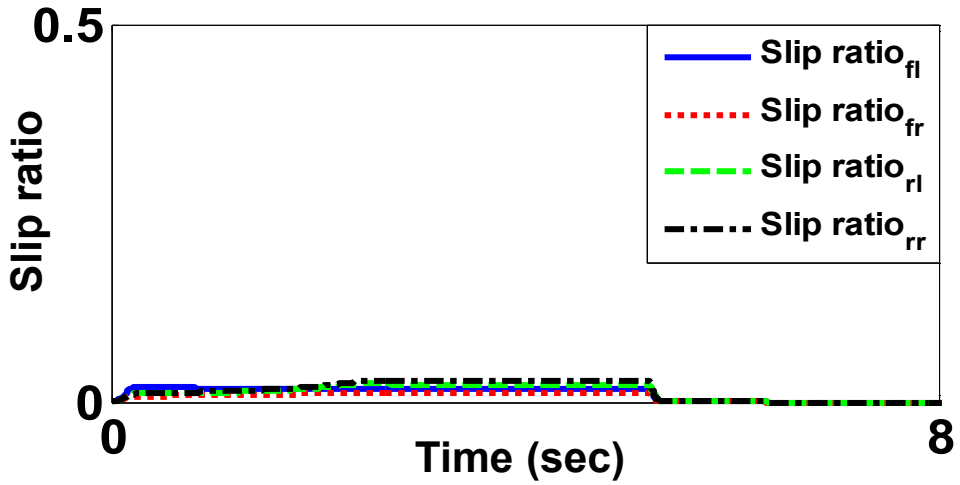
- ABS



Simulation results

- 60 kph full braking, μ = 0.4

- In-wheel motor torque control

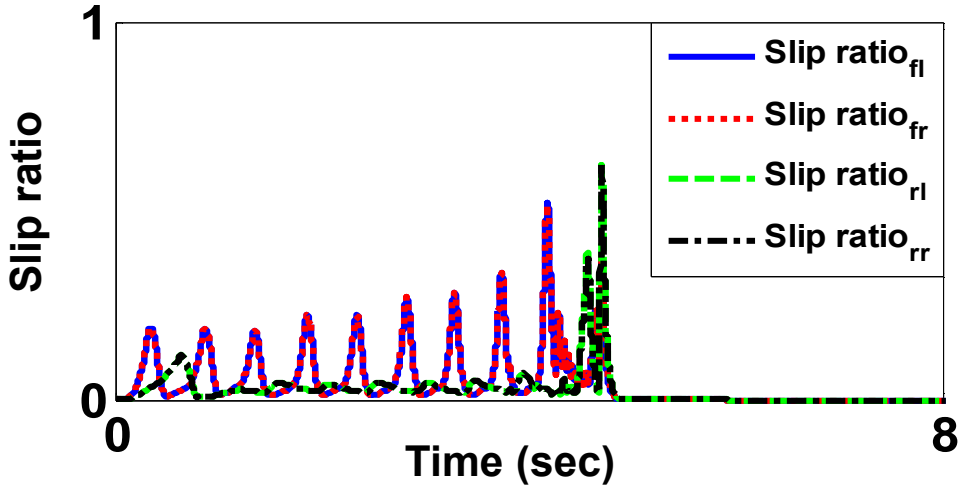


Slip ratio range : 0 ~ 5%

Total braking distance : 47.1m

Insufficient motor torque !

- ABS



Slip ratio range : 0 ~ 25%
(V≥10kph)
Slip ratio range : 0 ~ 60%
(V<10kph)
Total braking distance : 39.8m

Conclusions

- An in-wheel motor torque control algorithm was developed for an in-wheel electric vehicle
- To implement the ABS operation environment, ABS simulator was developed based on the ABS test results
- It was found from the simulation results (60kph full braking, μ=0.2) that the in-wheel motor torque control showed better performance with a smaller slip ratio and a shorter braking distance compared with the ABS
- The in-wheel motor torque control may have the problem of insufficient braking force due to the torque limit of the motor, which requires cooperative control with the friction brake