Introduction of the benchmark problem of optimal motion and energy control of a 4-In-wheel-motor car

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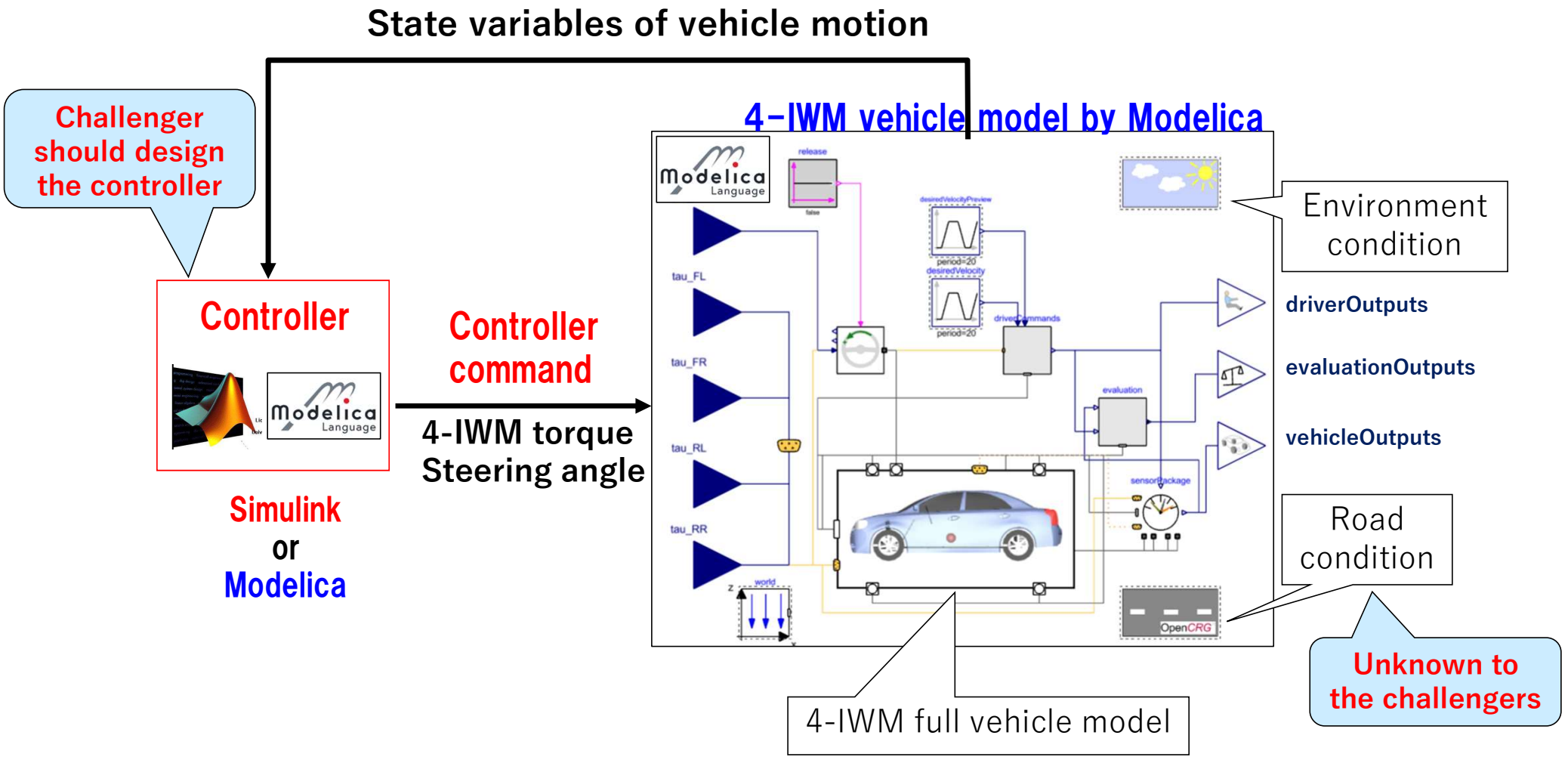
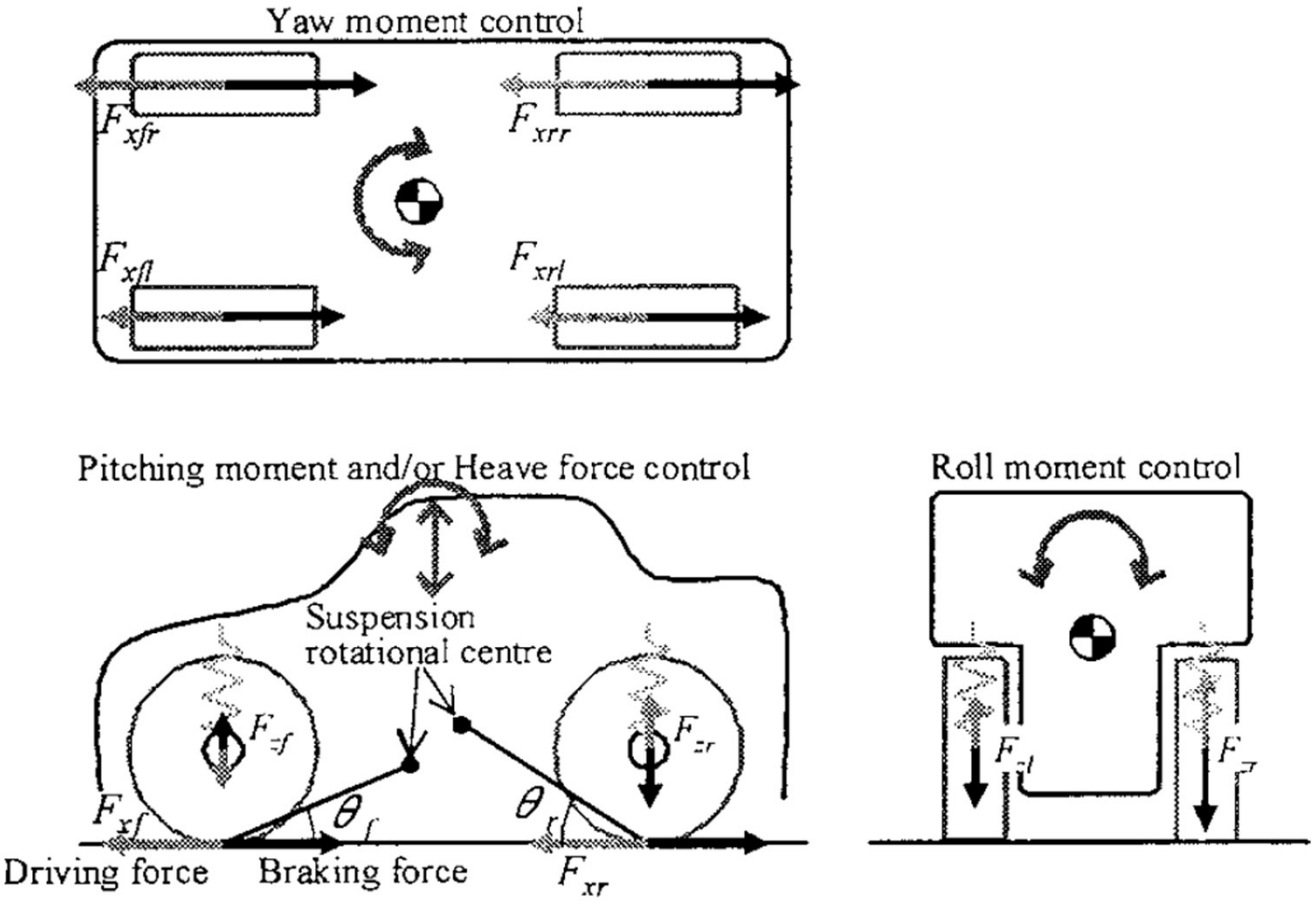
Backgrounds

- In order to promote industry-academia collaboration, JSAE Technical Division Committee of the Automotive Control and Model Research set benchmark problems that apply the latest machine learning and control theory to automobile control.
- As one of them, an optimal control problem for the motion and energy of a four-wheel in-wheel motor vehicle was settled. The object to be controlled is an autonomous vehicle equipped with a four-wheel in-wheel motor and a steer-by-wire system.

Scheme of the Benchmark Problem

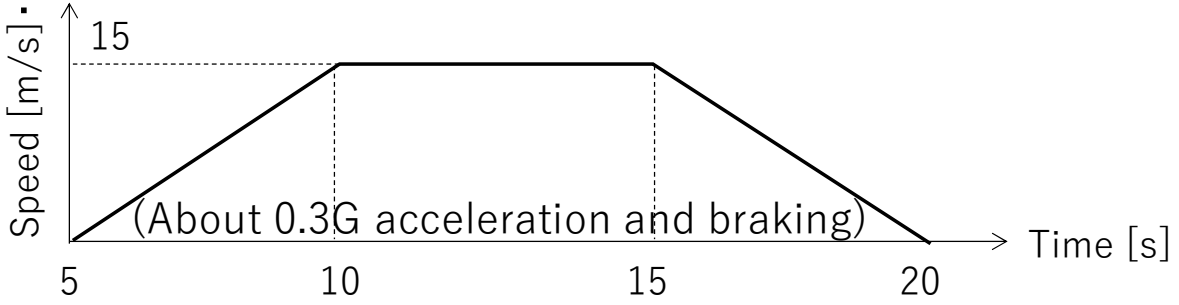


Vehicle dynamics model (3D-MBS model)



Task 1: Definition

- Task 1: Acceleration and braking on rough slippery straight road.
  - Friction coefficient of the road surface : Unknown
  - Desired speed profile :



  - Course: Straight
  - Rough road (Max. height of bump : 5mm, Pattern: Unknown)
    - Treated as unknown external disturbance

Task1: Evaluation Criteria

- **Evaluation criteria: Minimize deviation from the target, body motion and energy consumption.**

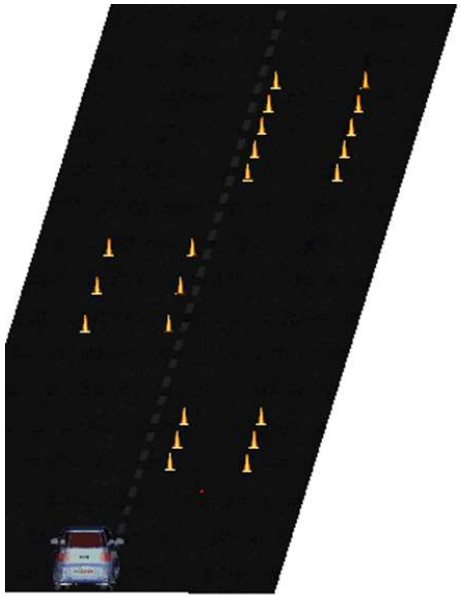
- Evaluation indexes for the Task 1:
  - Requirement 1: Reduce the vertical body motion to below the targets.
    - $|a_z(t)| < a_{z\_Target1}$ (0.4[m/s2])
    - $|\phi(t)| < \phi_{\_Targe}$ (0.004 [rad])
    - $|\psi(t)| < \psi_{\_Target1}$ (0.0015 [rad])
  - Requirement 2: Minimize the deviation of the vehicle speed from the target.
    - $J_{v1} = \int_0^{t_e} \{v(t) - v_{\_Target}(t)\}^2 dt$
  - Requirement 3: Minimize the energy consumption.
    - $J_{e1} = \int_0^{t_e} \{E(t)\} dt$

      $E(t) = \sum_{i=1}^{4} V_B(t) \cdot I_i(t)$ (V_B: Battery voltage, I_i: Current of each IWM)

(v: vehicle velocity, a_z: vertical acceleration, ϕ: roll angle, ψ: pitch angel, E: power consumption)

Task2: Definition

- Task 2: ISO double lane change on rough road.
  - Friction coefficient of the road surface : Unknown
  - Desired speed: 60[km/h]
  - Course: ISO double lane change
  - Rough road (Max. height of bump : 5mm, Pattern: Unknown)
    - Treated as unknown external disturbance



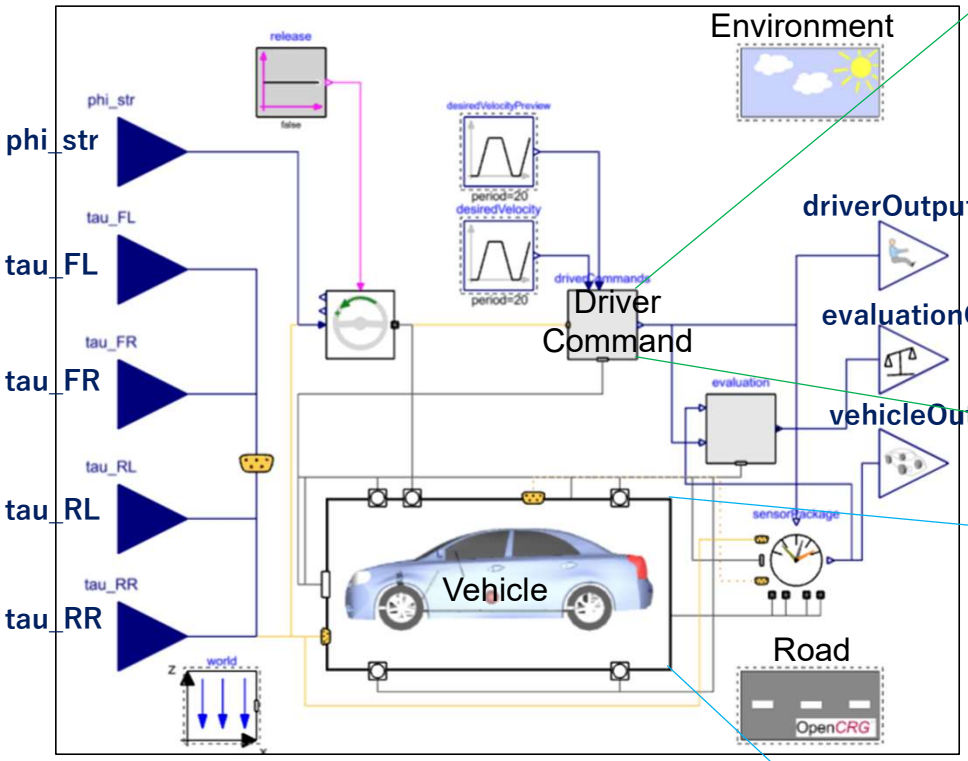
Task2: Evaluation Criteria

- Evaluation indexes for the Task 2:
  - Requirement 1: Reduce the vertical body motion to below the targets.
    - $|a_z(t)| < a_{z\_Target2}$ (1.4[m/s2])
    - $|\phi(t)| < \phi_{\_Targe}$ (0.7[rad])
    - $|\psi(t)| < \psi_{\_Target2}$ (0.14 [rad])
  - Requirement 2: Minimize the deviation of the vehicle trajectory from the target.
    - $J_{v2} = \int_0^{t_e} \left[\{x(t) - x_{\_Target}(t)\}^2 + \{y(t) - y_{\_Target}(t)\}^2 \right] dt$
  - Requirement 3: Minimize the energy consumption.
    - $J_{e2} = \int_0^{t_e} \{E(t)\} dt$

      $E(t) = \sum_{i=1}^{4} V_B(t) \cdot I_i(t)$ (V_B: Battery voltage, I_i: Current of each IWM)

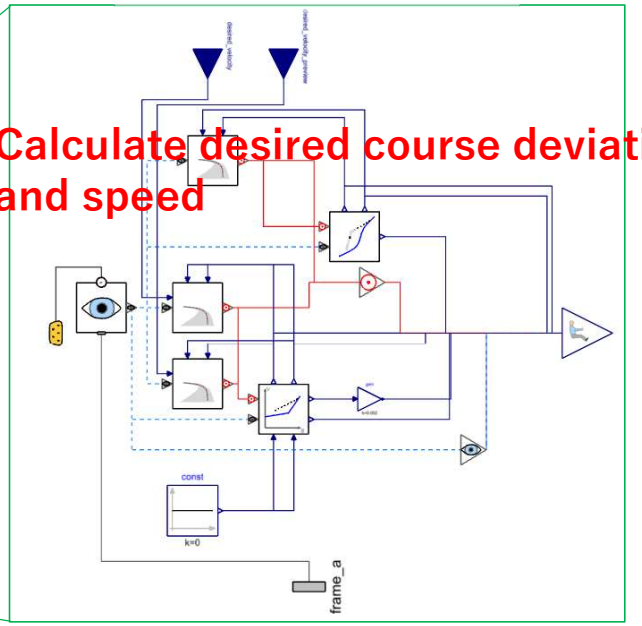
(x: longitudinal position, y: lateral position, a_z: vertical acceleration,
ϕ: roll angle, ψ: pitch angel, E: power consumption)

Modelica Model (Top Layer)

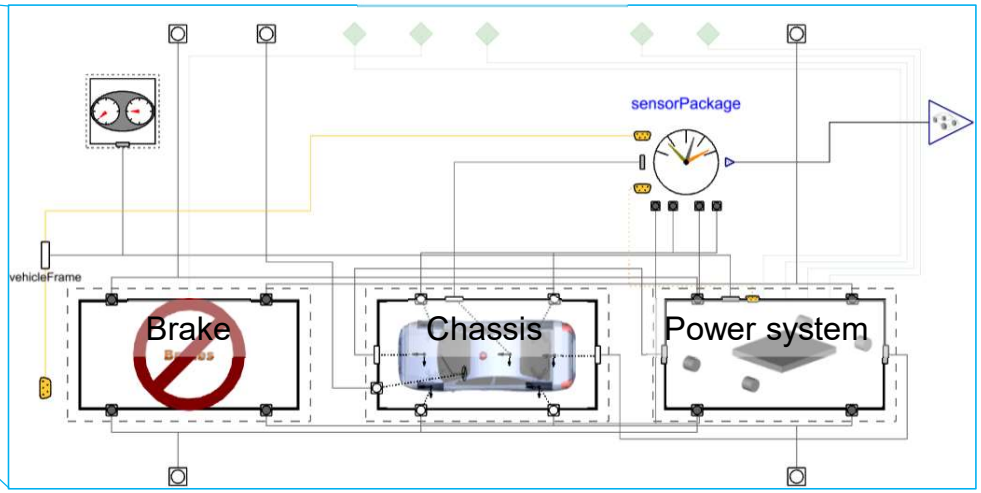


Driver behavior model

Calculate desired course deviation and speed

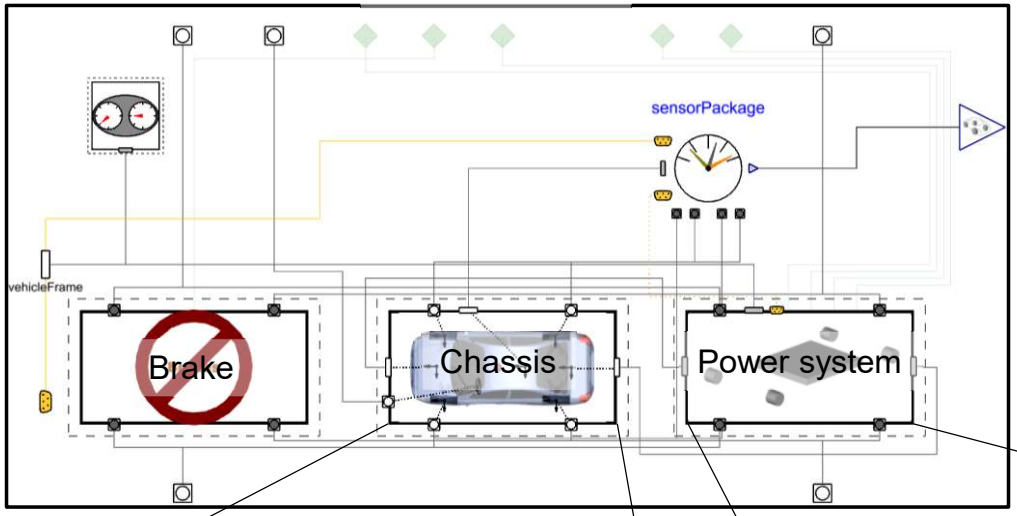


Vehicle model

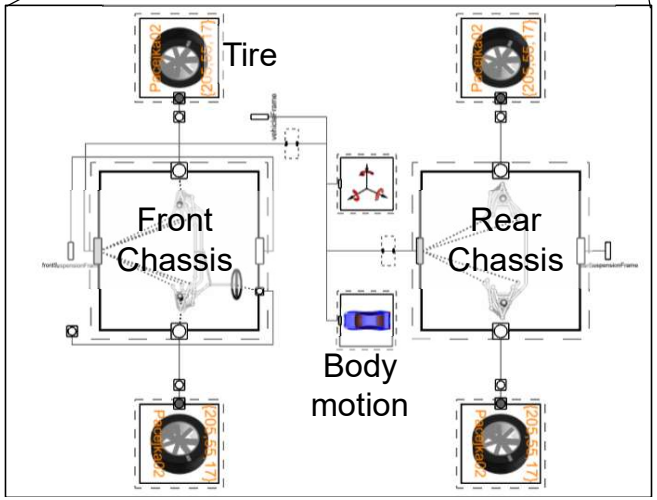


Modelica Model: Vehicle Model

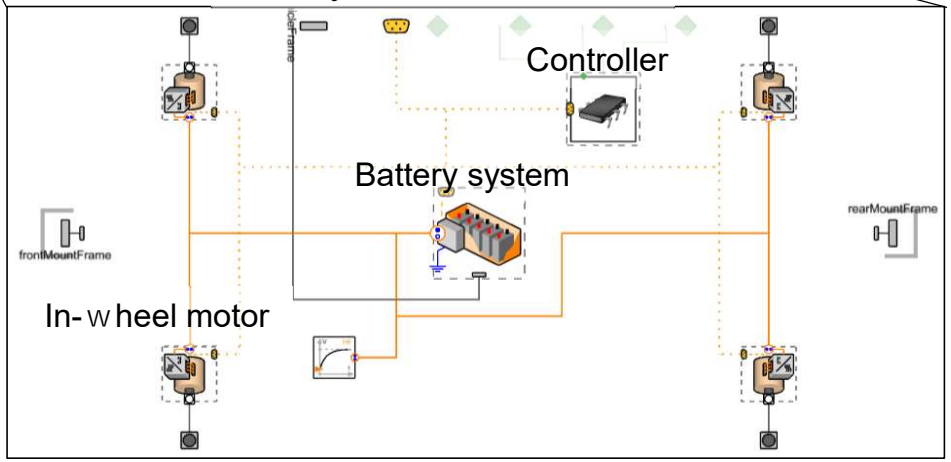
Vehicle model



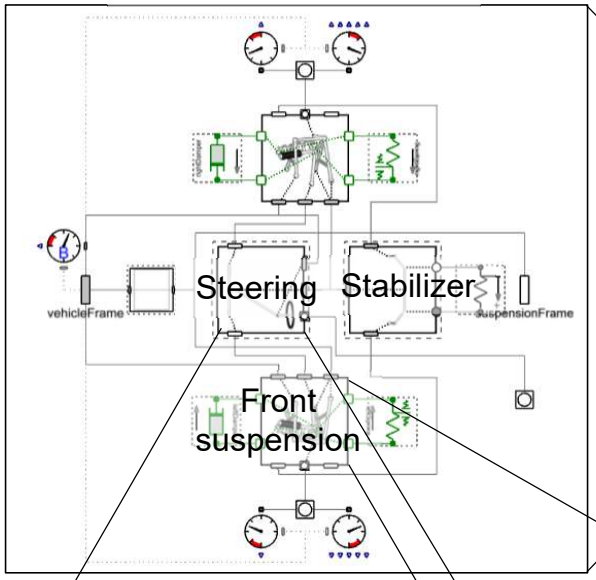
Suspension and body model



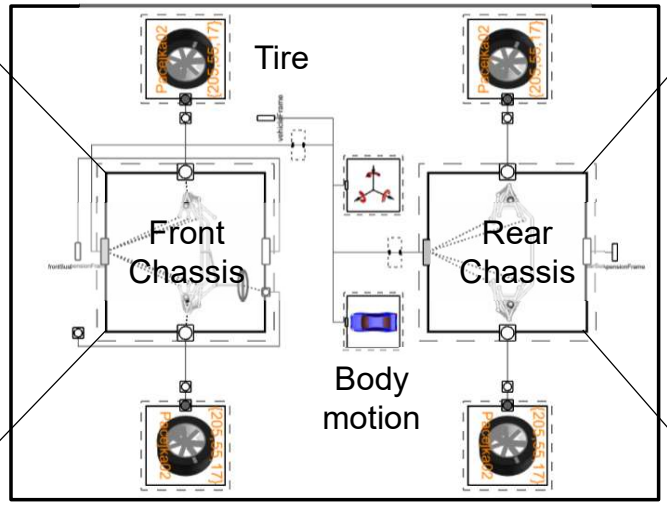
Battery and 4-IWM model



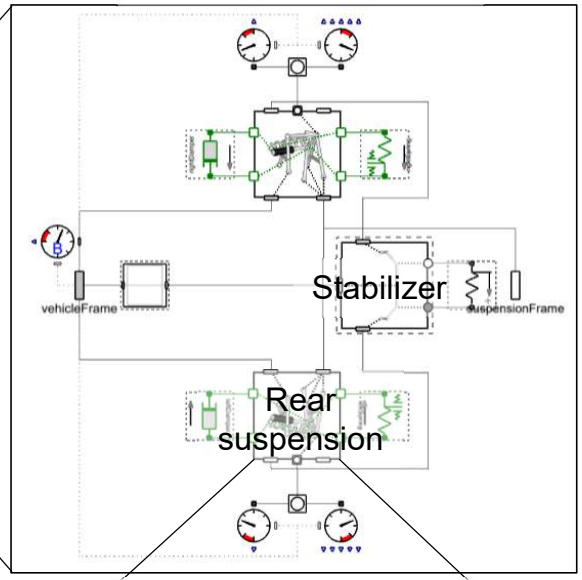
Front chassis model



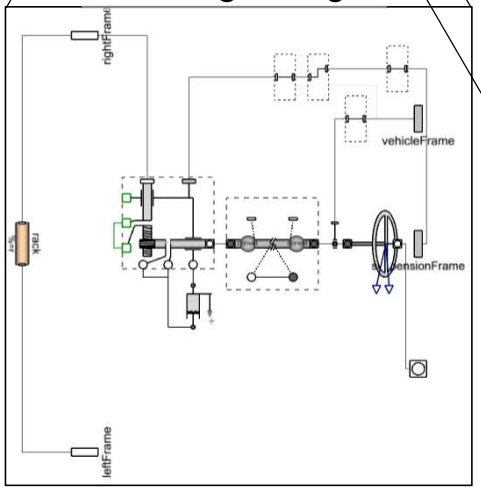
Suspension and body model



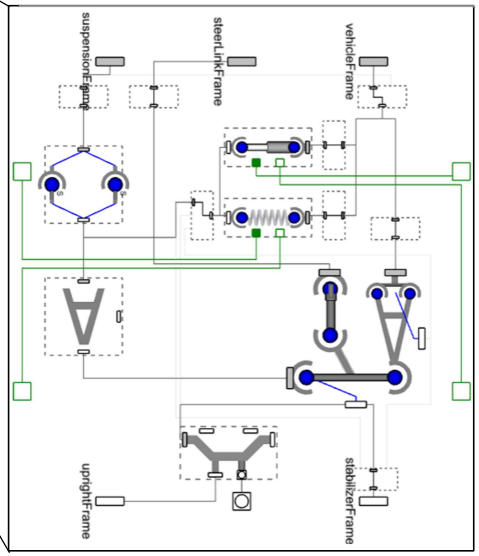
Rear chassis model



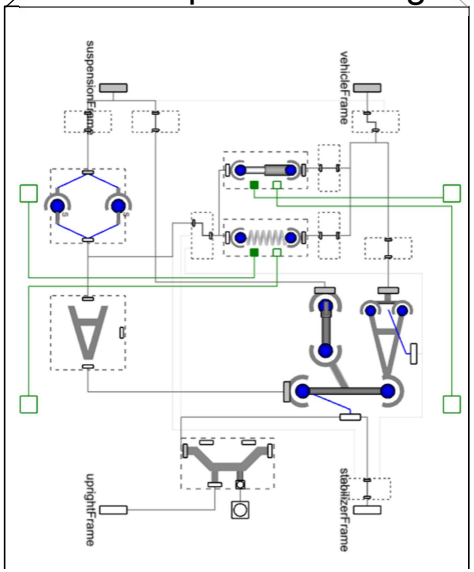
Steering linkage



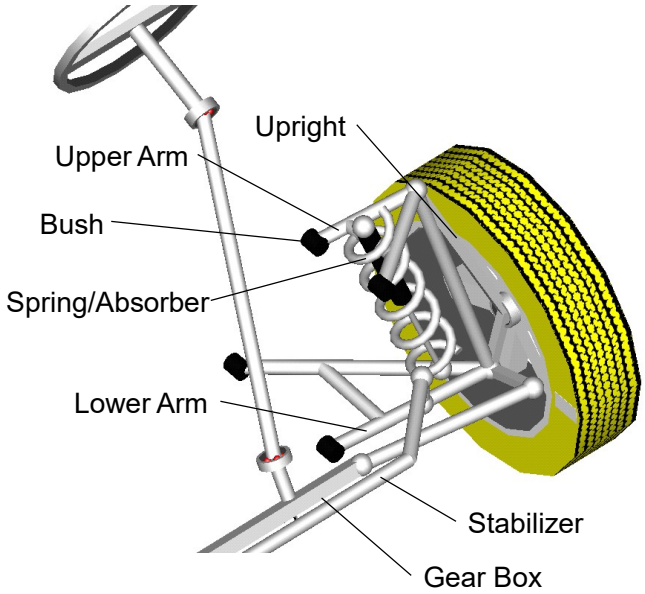
Front suspension linkage

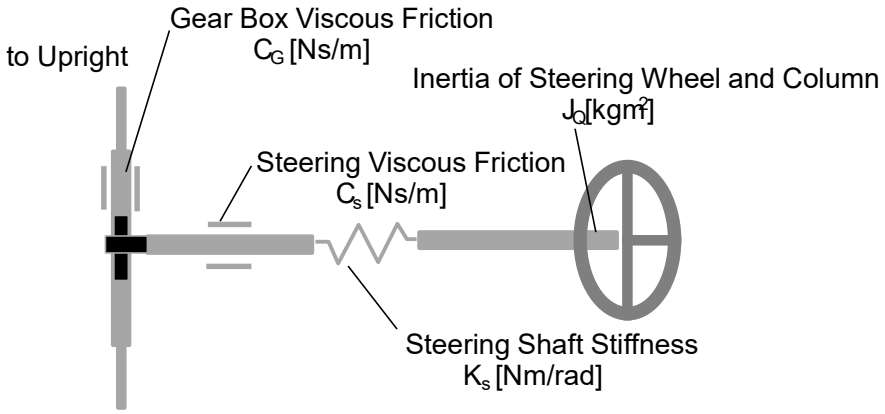


Rear suspension linkage



Details of the Suspension Model

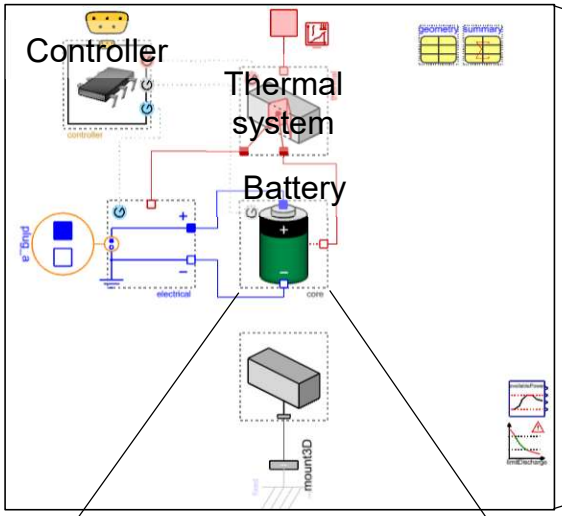




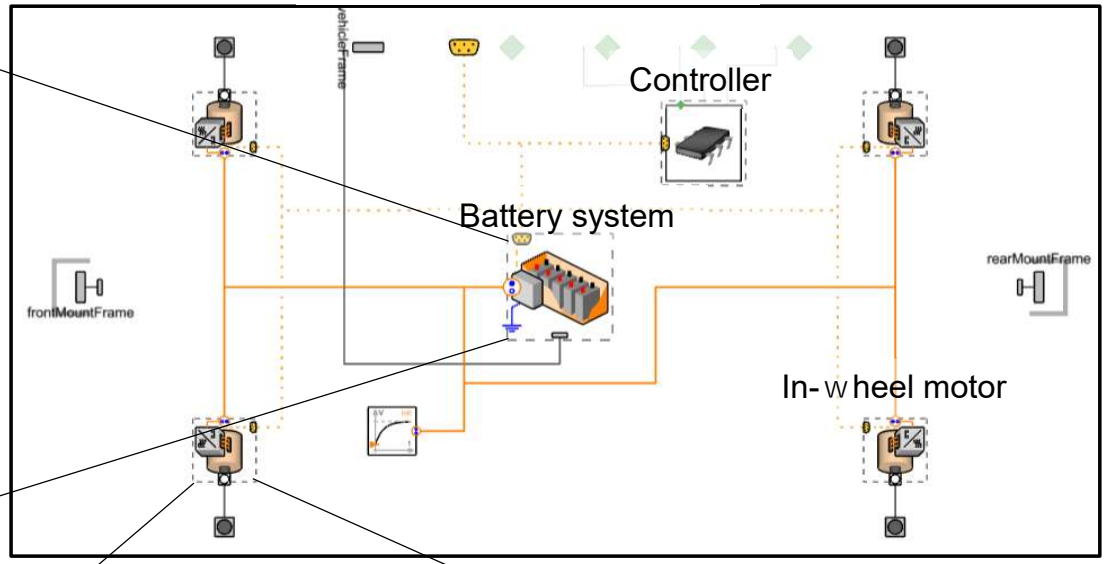
Conventional double wishbone suspension with steering link will be used.
Suspension hard points should be defined to have big anti-dive and anti-squat effects.

Controller can give the steering input angle. But due to the elasticity and friction, the tire angle is not equal to the steering input angle, i.e. there is uncertainty to be compensated by the control.

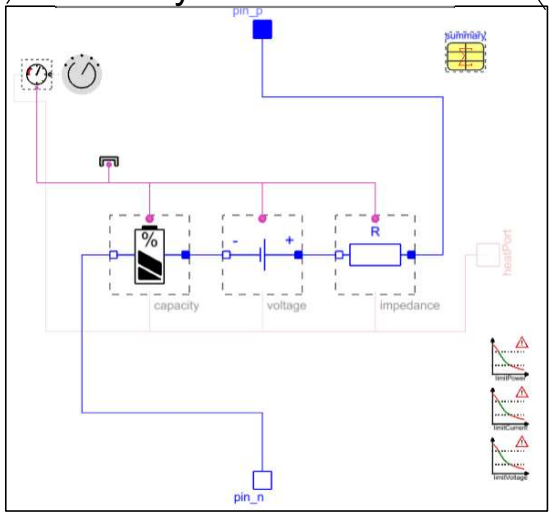
Battery assembly model



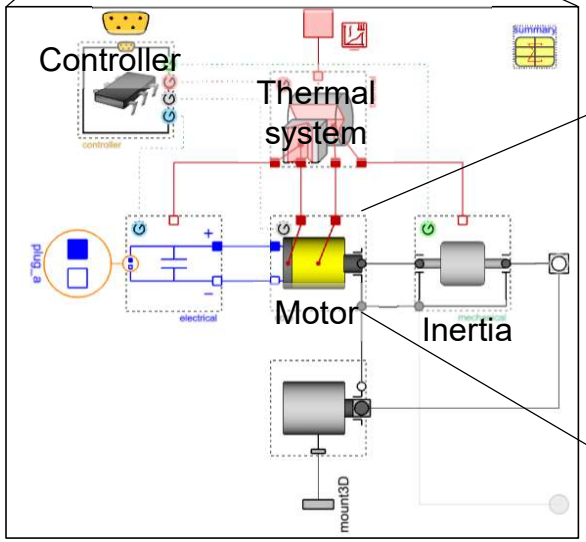
Battery and 4-IWM model



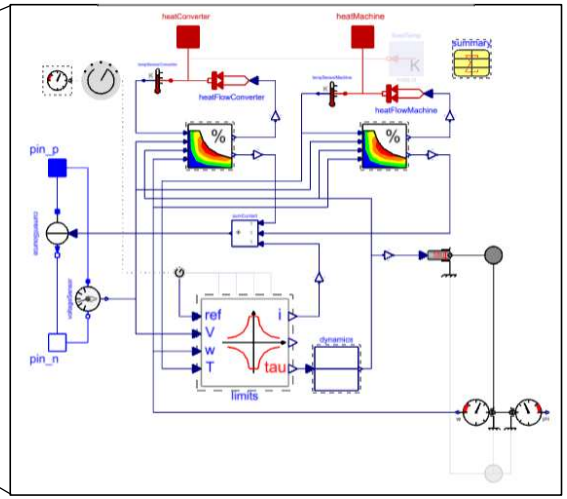
Battery electric model



In-wheel motor model



Motor electric model



Importing FMU from Modelica Model

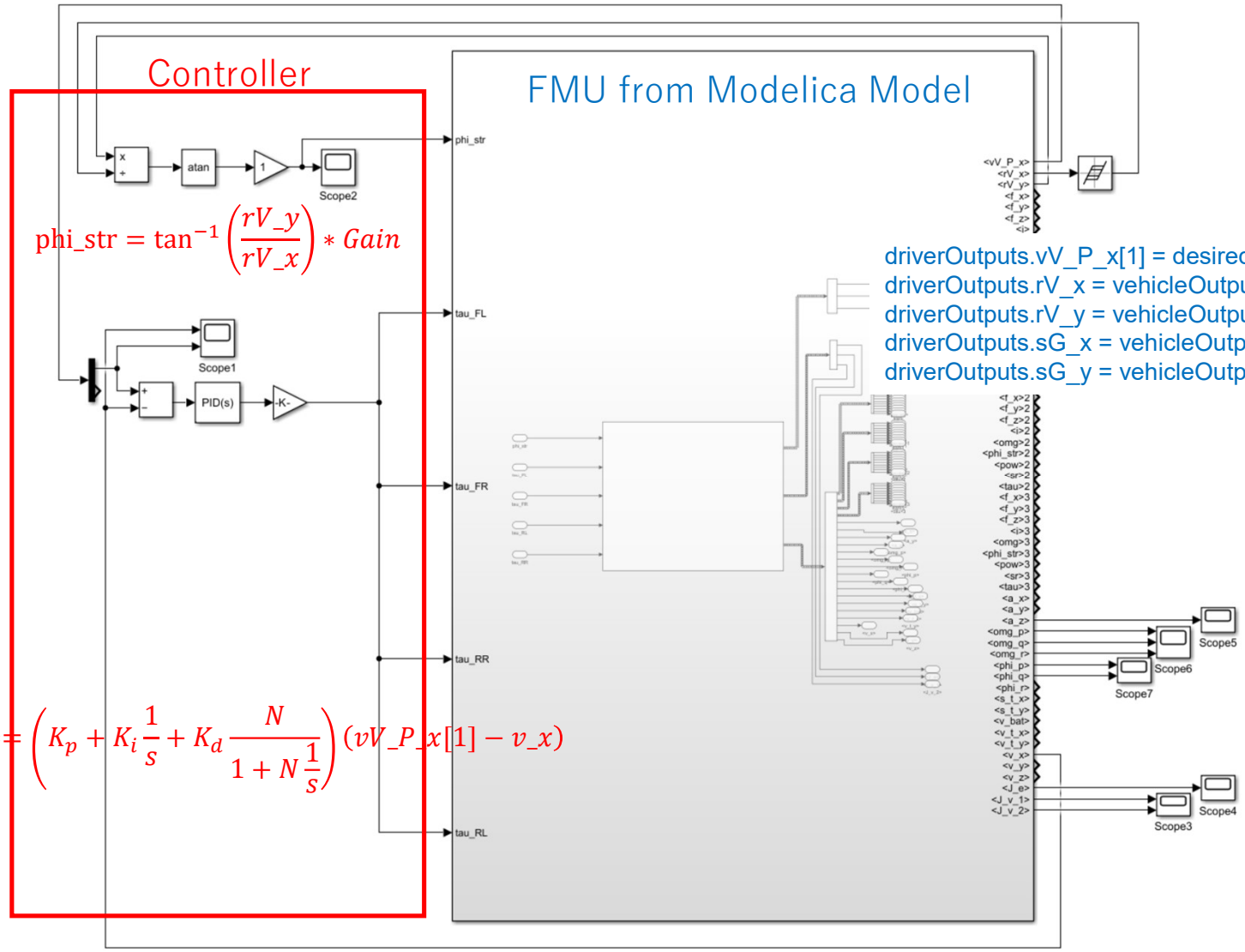
To import a FMU in Simulink, at first open the Library Browser of Simulink and then drag & drop the ‘Simulink Extras -> FMU Import -> FMU’ block into a new Simulink model.

Importing CDC2023.Vehicles.Exports.Acceleration.fmu

Then validate bus connectors of the FMU model by following command by Matlab.

```
>> fmudialog.createBusType('CDC_Task1_Sample/Subsystem/FMU')
  Bus Object for Output Port 1: driverOutputs
  Bus Object for Output Port 2: evaluationOutputs
  Bus Object for Output Port 3: vehicleOutputs
```

Simulink Model with Default Controller

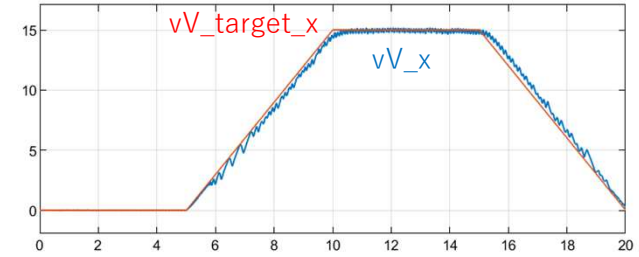


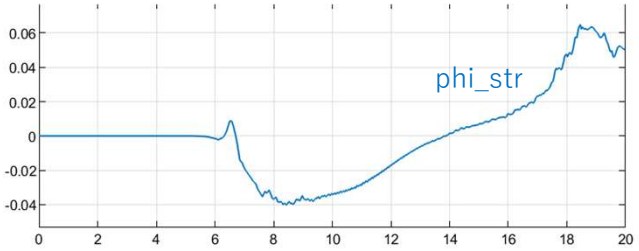
$$\text{phi\_str} = \tan^{-1}\left(\frac{rV\_y}{rV\_x}\right) * Gain$$

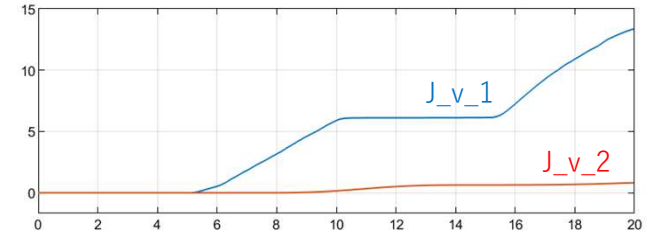
$$tau\_** = \left(K_p + K_i\frac{1}{s} + K_d\frac{N}{1+N\frac{1}{s}}\right)(vV\_P\_x[1] - v\_x)$$

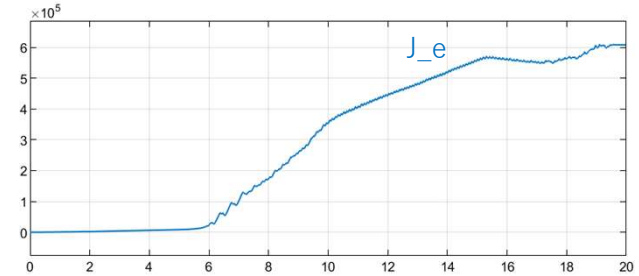
driverOutputs.vV_P_x[1] = desiredVelocity (along path)
driverOutputs.rV_x = vehicleOutputs.v_t_x (Target x position along path)
driverOutputs.rV_y = vehicleOutputs.v_t_y (Target y position along path)
driverOutputs.sG_x = vehicleOutputs.s_t_x (Target x position by ground coordinate)
driverOutputs.sG_y = vehicleOutputs.s_t_y (Target y position by ground coordinate)

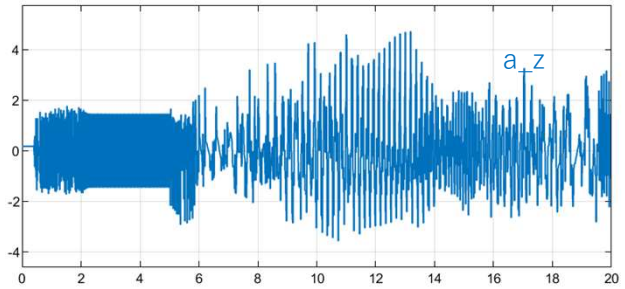
Simulation Result of Task 1 (Simulink)

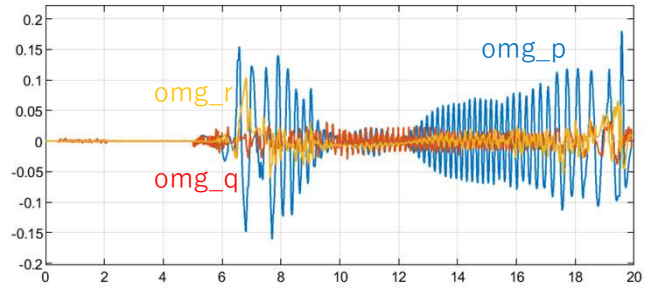


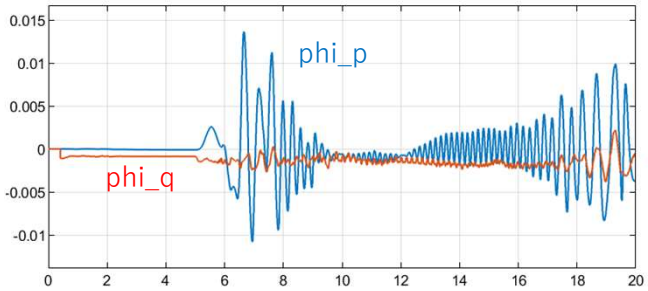




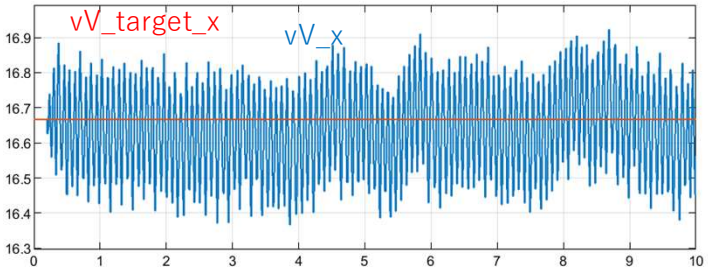


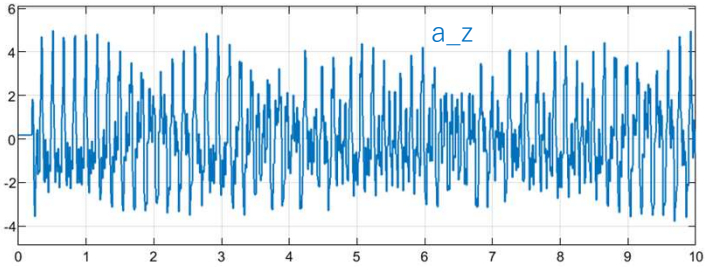


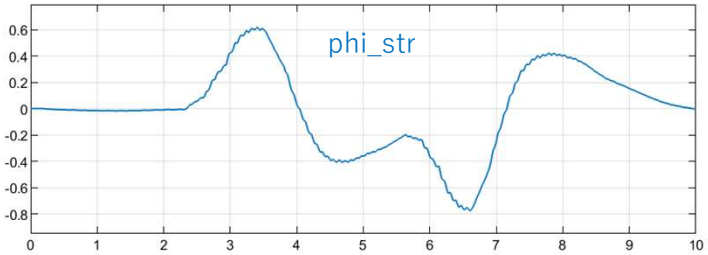


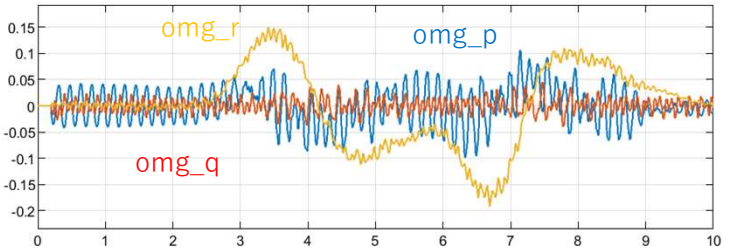


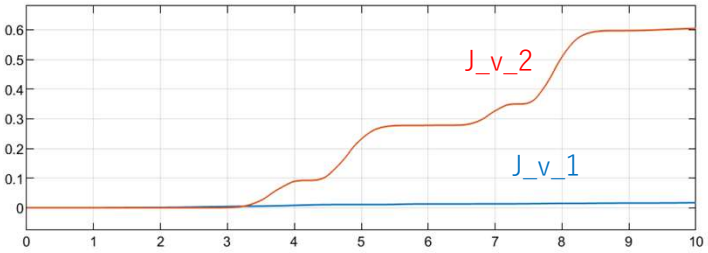
Simulation Result of Task 2 (Simulink)

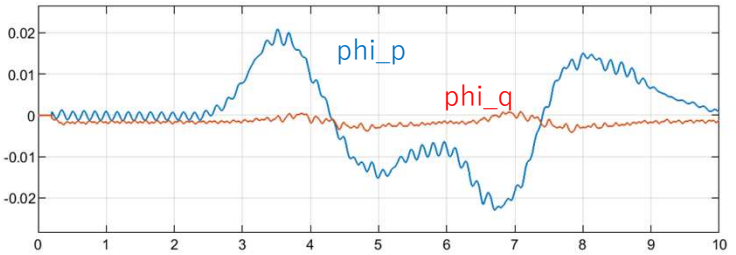


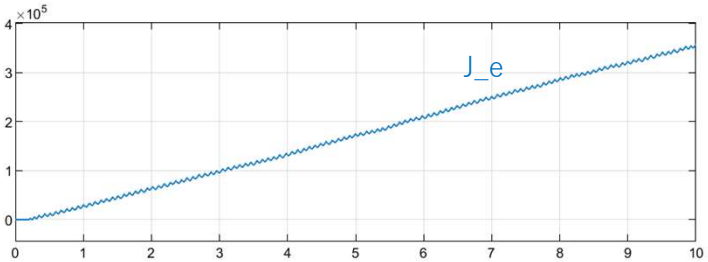




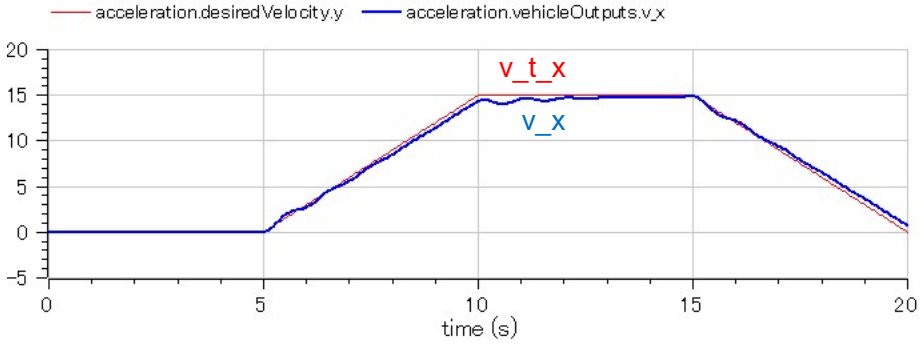


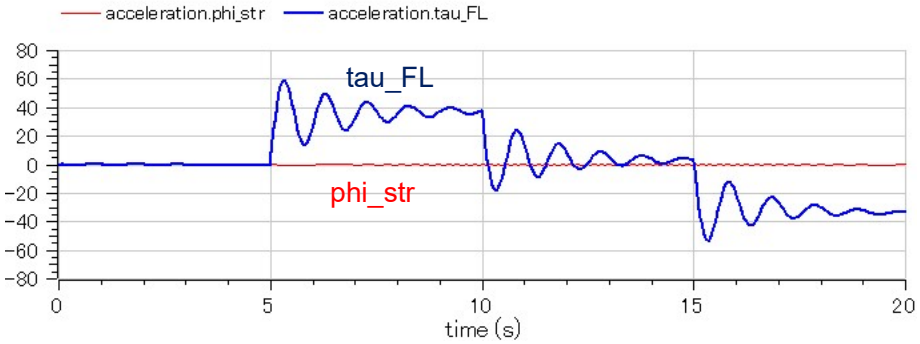


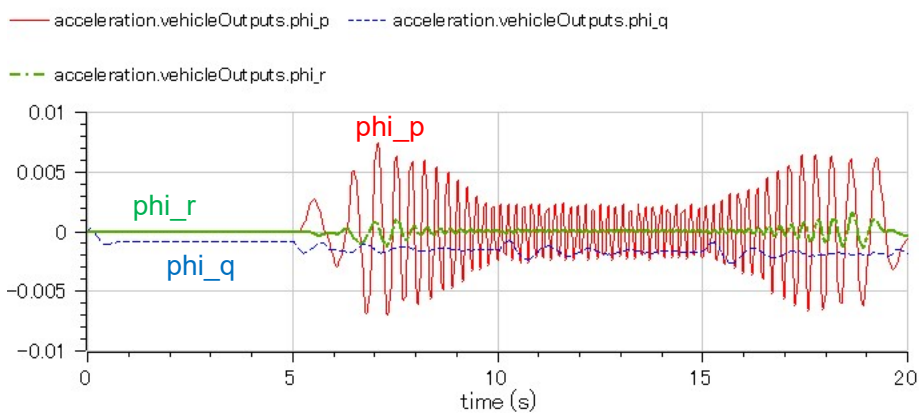


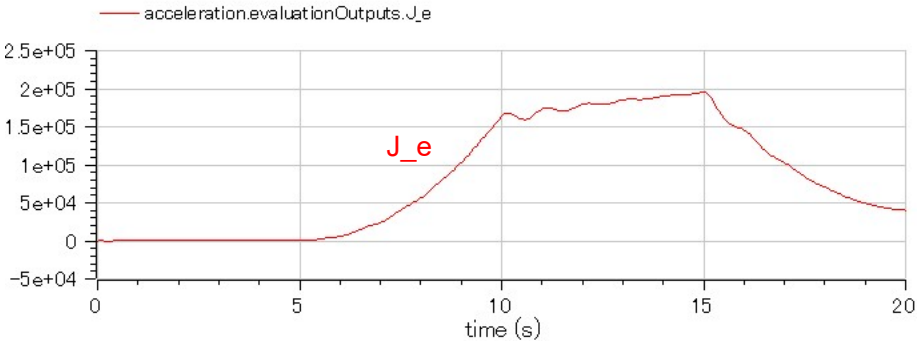


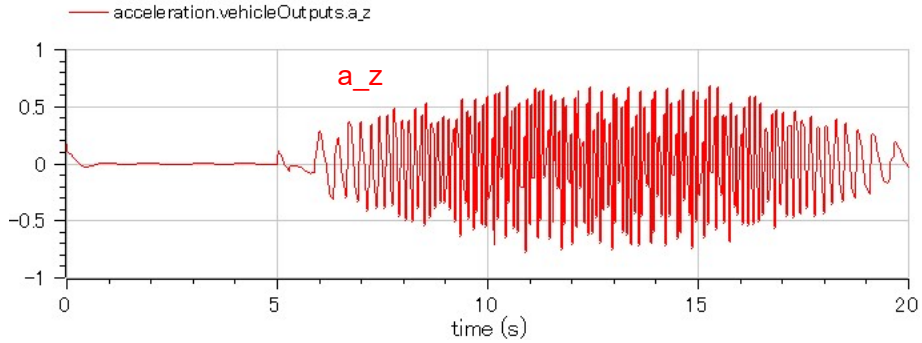
Simulation Results of Task 1 (Modelica Model)

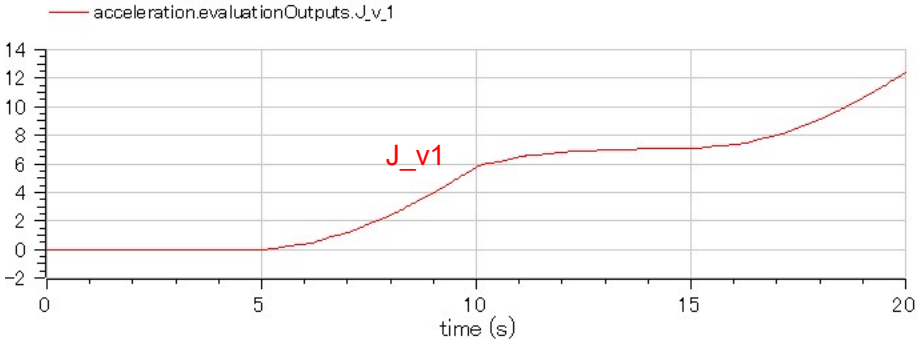




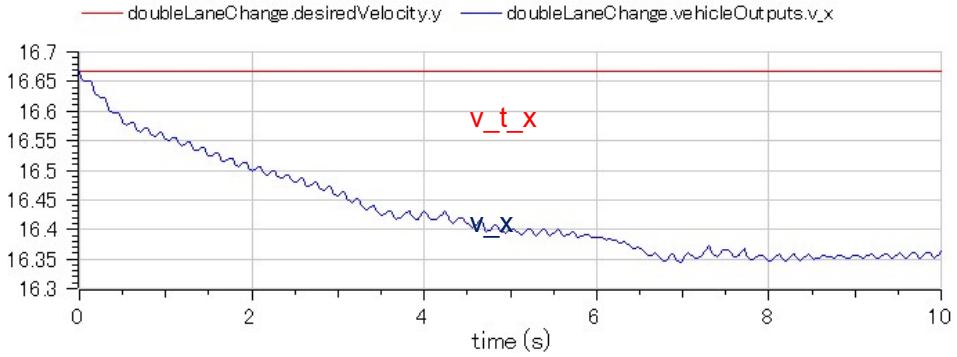


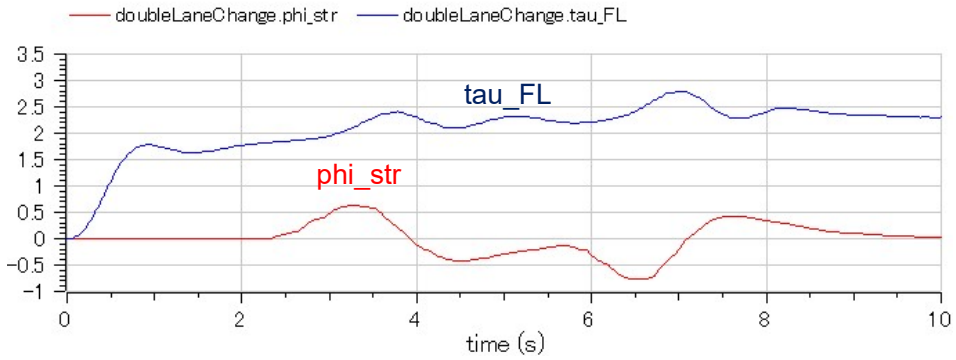


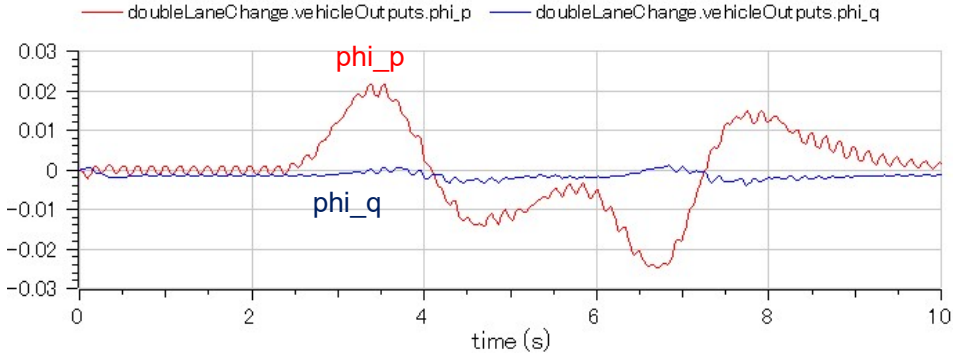


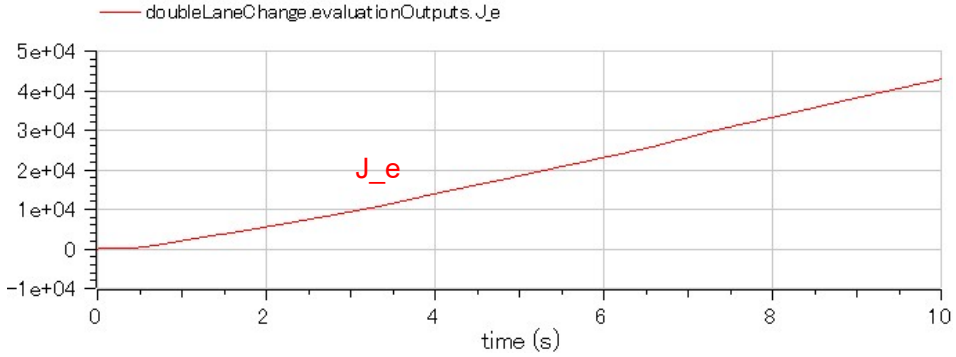


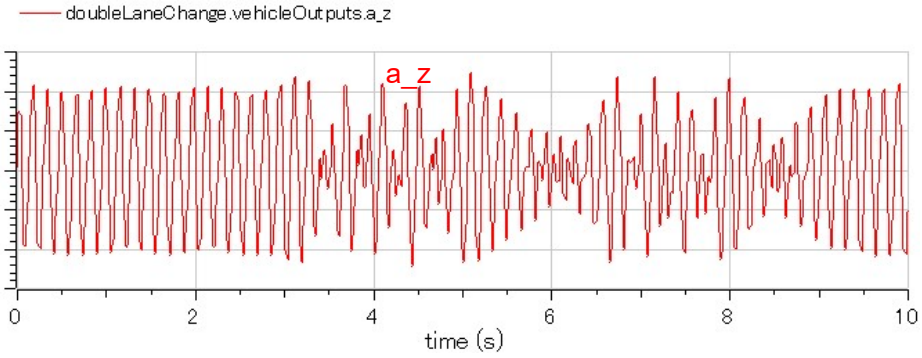
Simulation Results of Task 2 (Modelica Model)

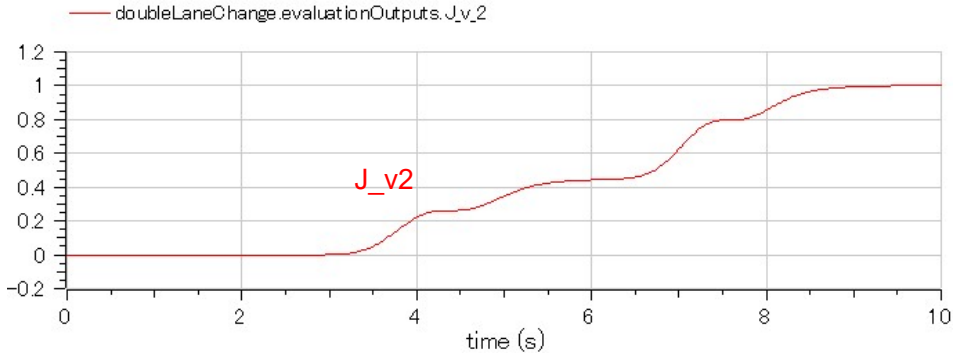












Conclusion

- A benchmark problem of optimal motion and energy control of 4-IWM electric vehicle was introduced.
- Challengers will be provided with Simulink model of the benchmark problem for each two task. Additionally Modelica model with tentative license of a commercial tool (Modelon Impact)will be provided if wanted.
- It is recommended for many researchers to challenge this benchmark problem and present papers in JSAE / SICE conferences.
- Details and registration page will be opened soon. It will be announced by JSAE news letter. (Or contact Yutaka Hirano.)
- First trial was already done at IEEE CDC2023.

  (https://cdc2023.ieeecss.org/benchmark-challenge/)