SIMULATION OF VEHICLE STEERING SYSTEM

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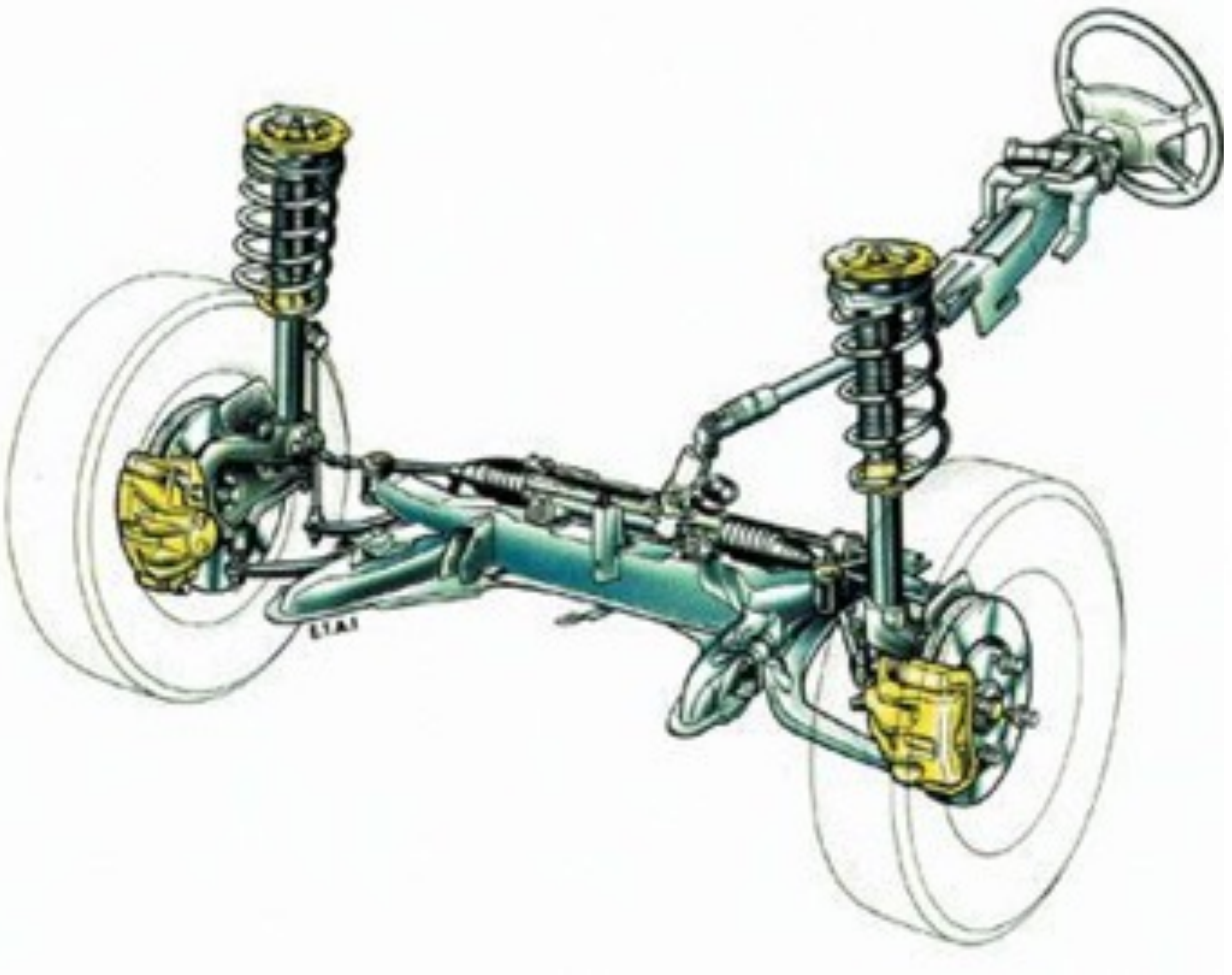
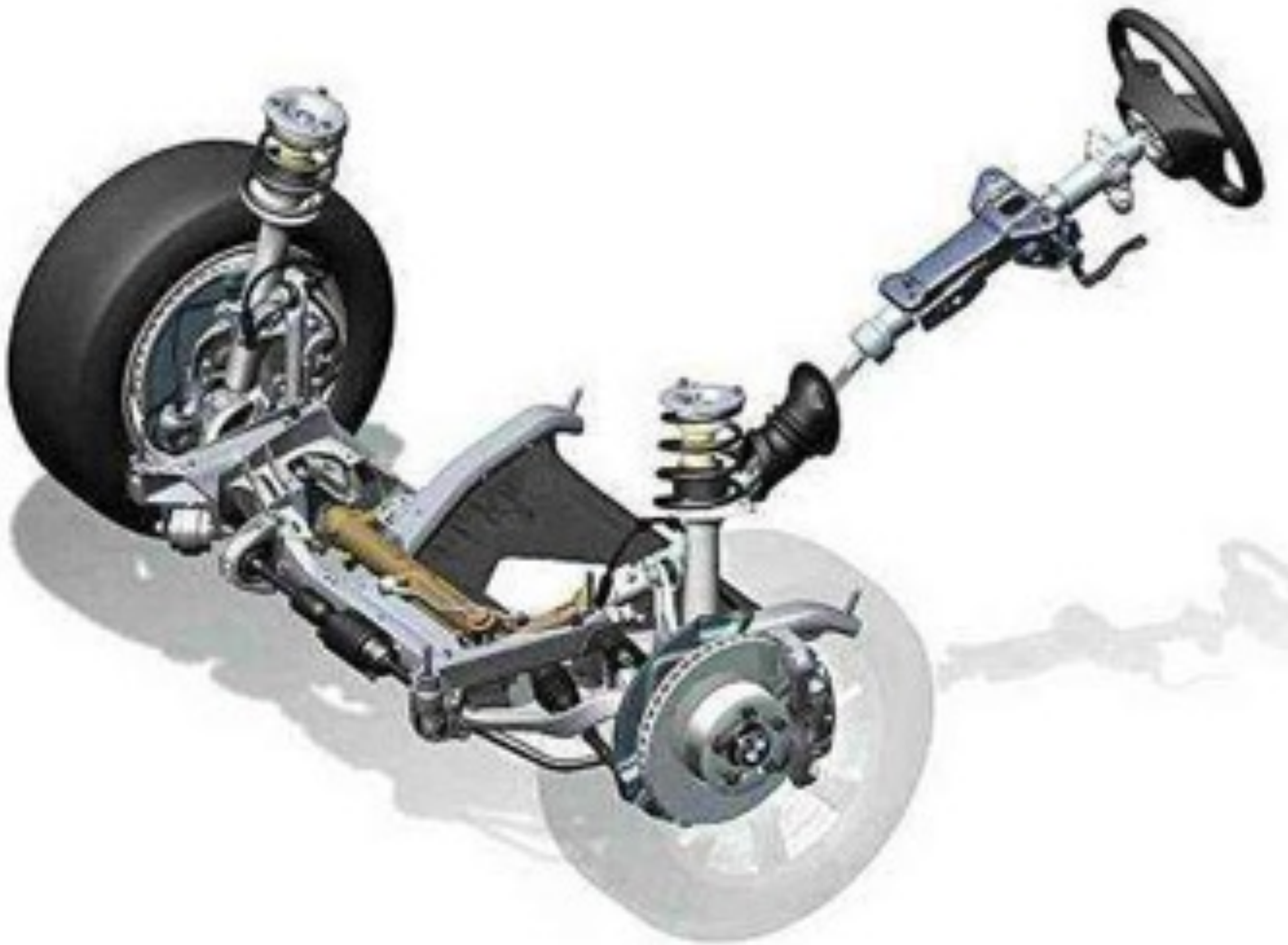
898708

STEPS:

- Study different components of a common steering system
- Mathematically modeling the Steering System
- Include the Steering System within the entire vehicle model
- Apply adequate experiments (simulation) to verify the model

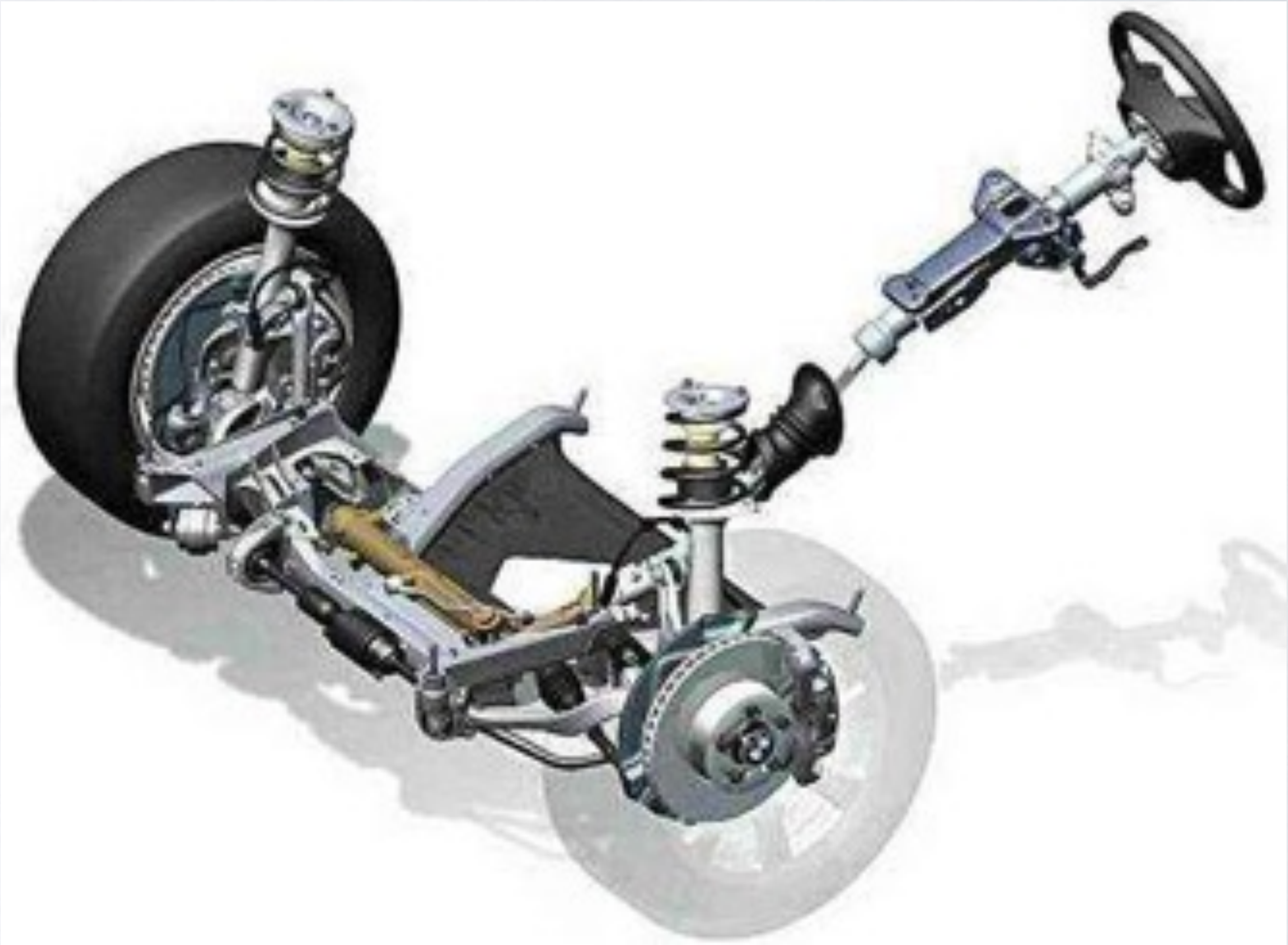




STEERING SYSTEM OF A COMMON COMMERCIAL 4-WHEEL VEHICLE

SIMPLIFIED COMPONENTS:

- Steering Wheel (SW)
- Steering Column (SC)
- Torque Bar
- Diverter
- Hydraulic Power Steering (HPS)
- Ackermann Steering Linkages
- Front Axle
- Kingpins
- Wheels



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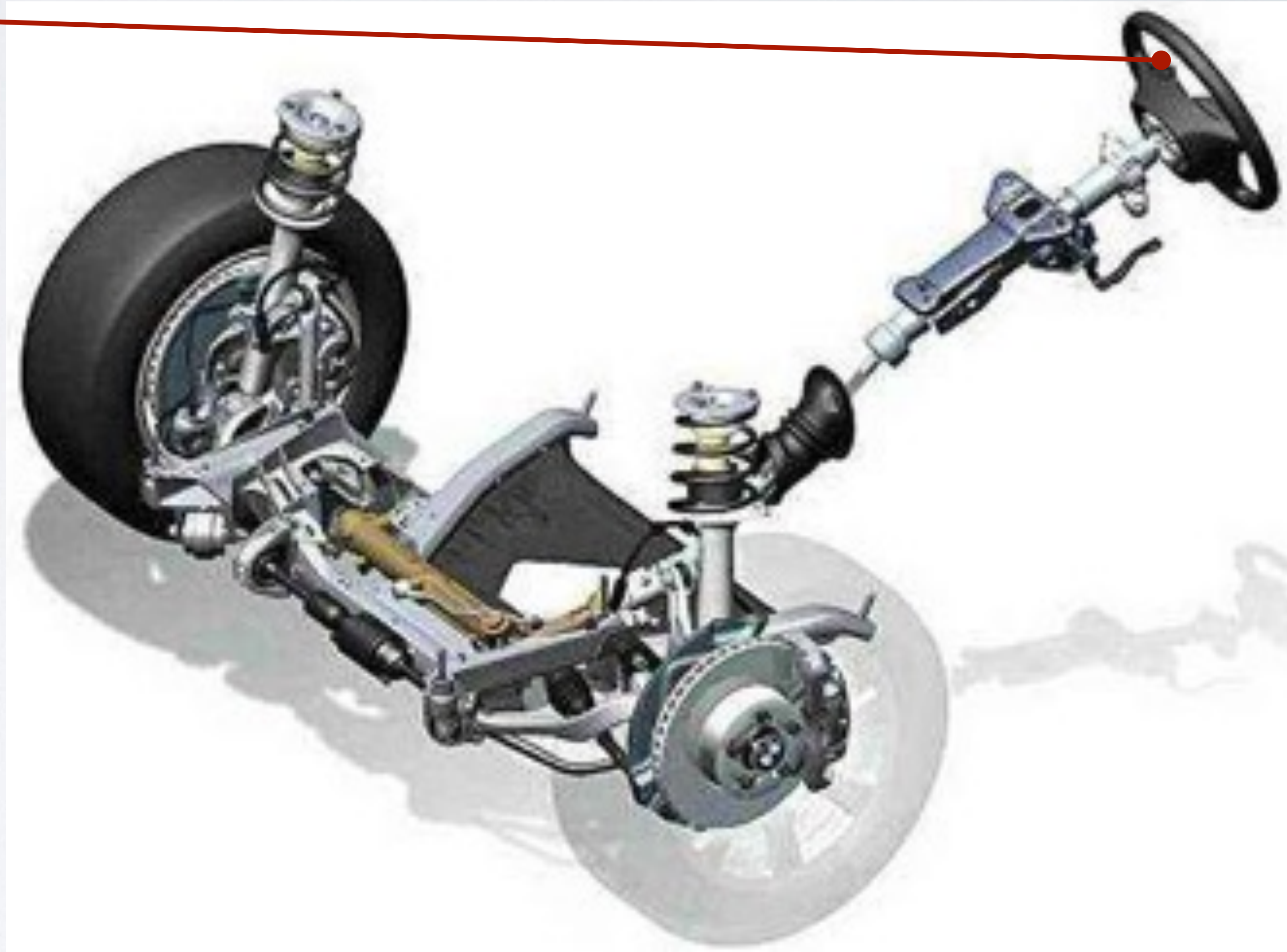

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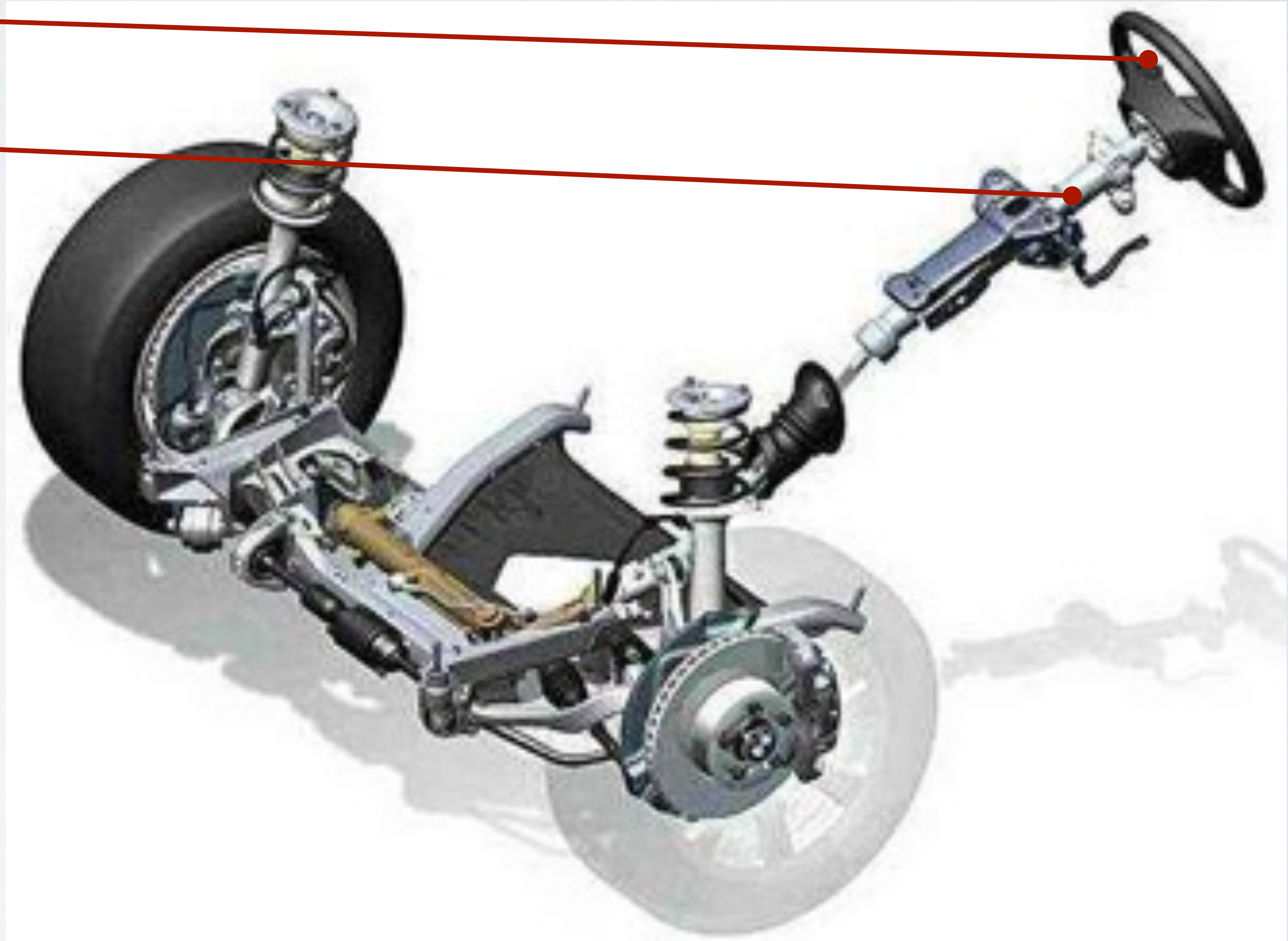

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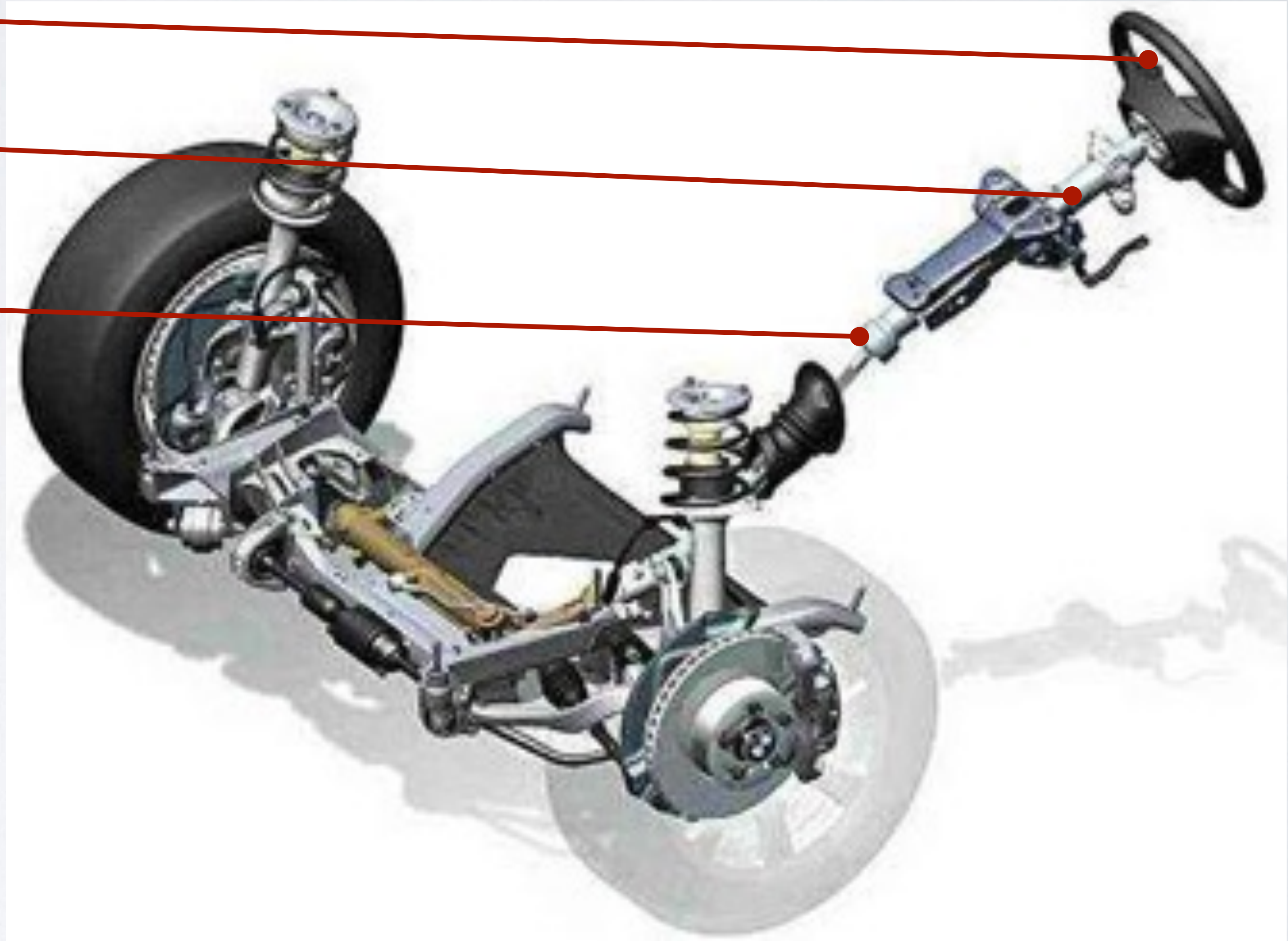

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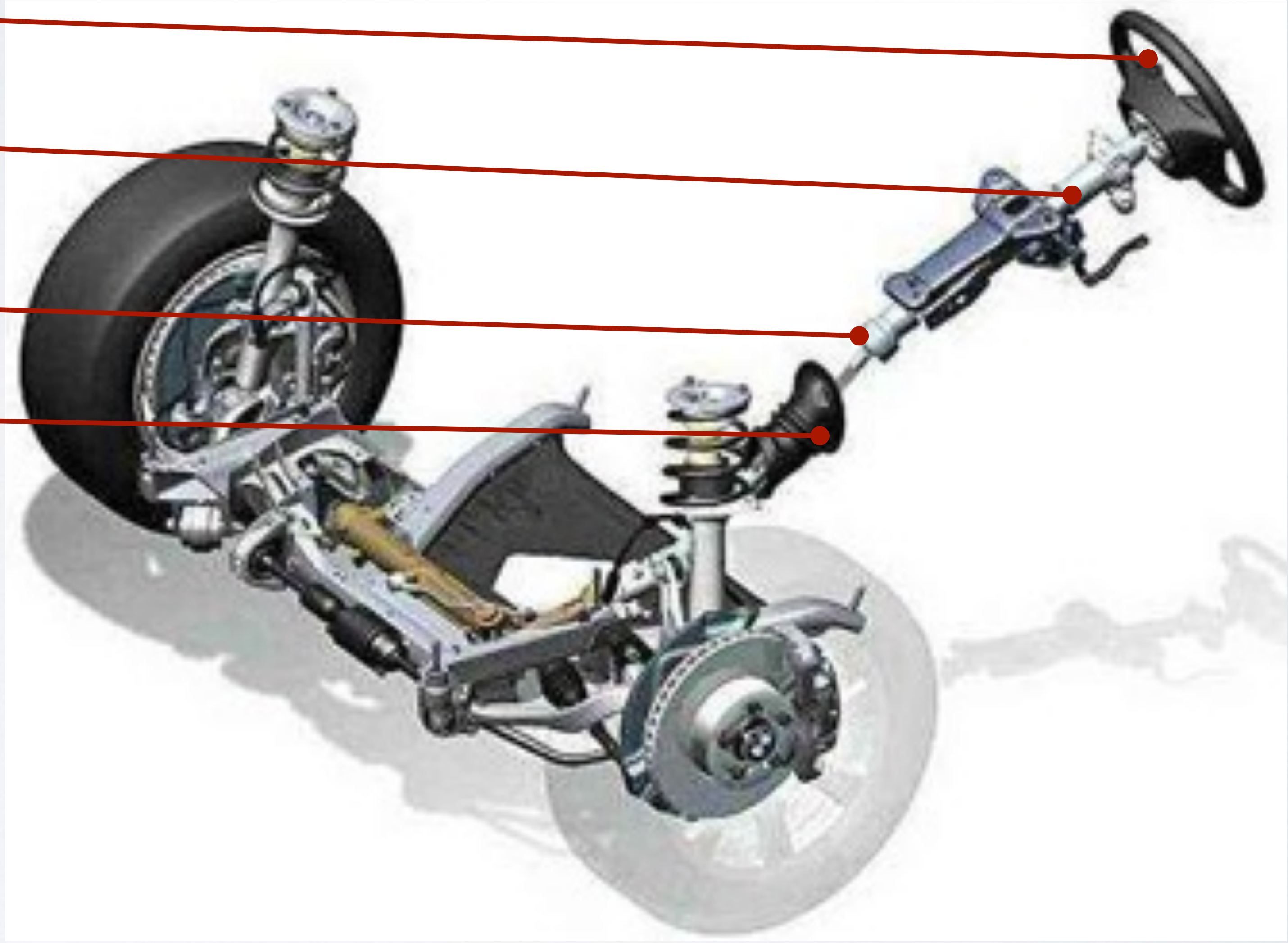

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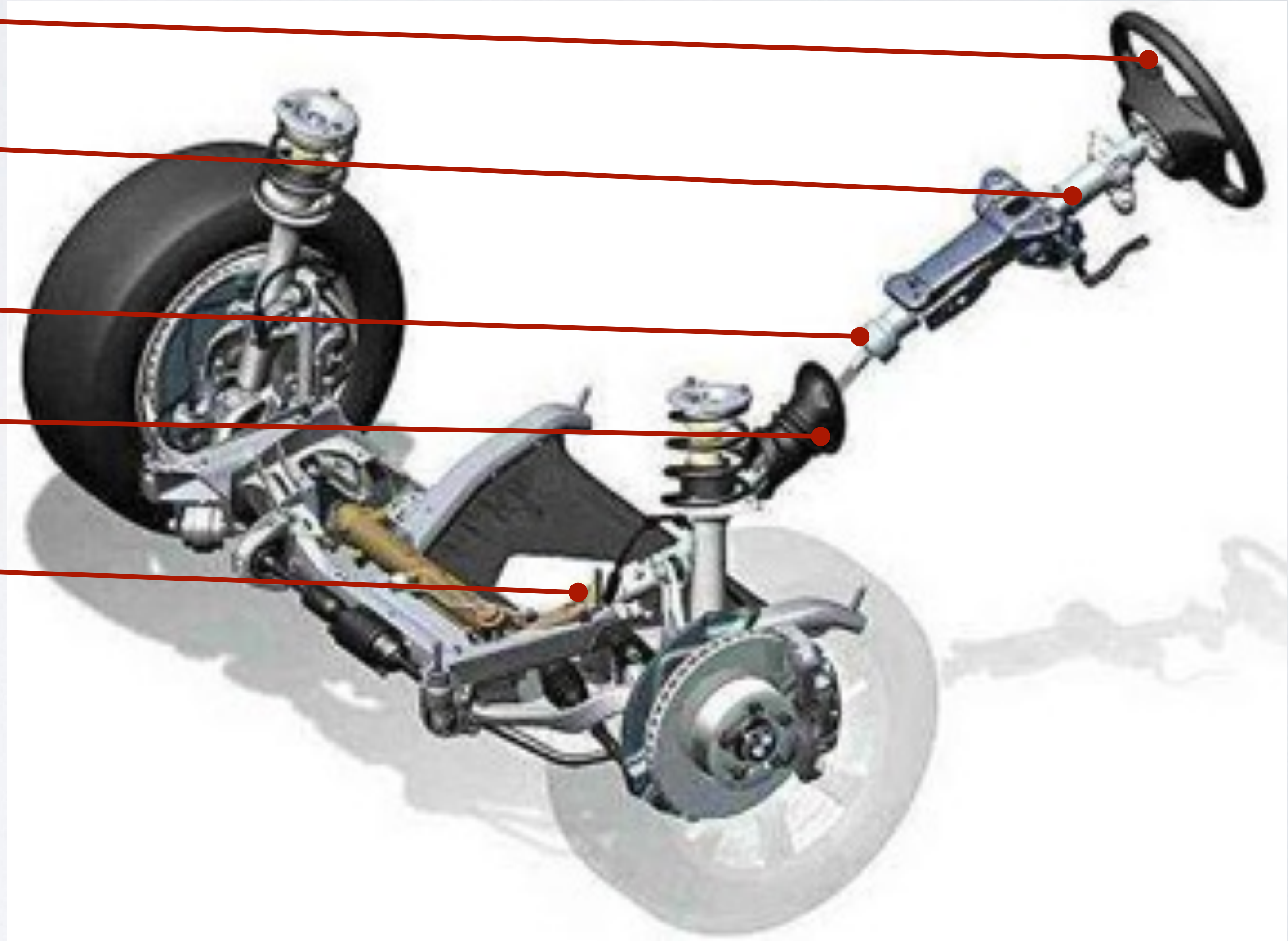

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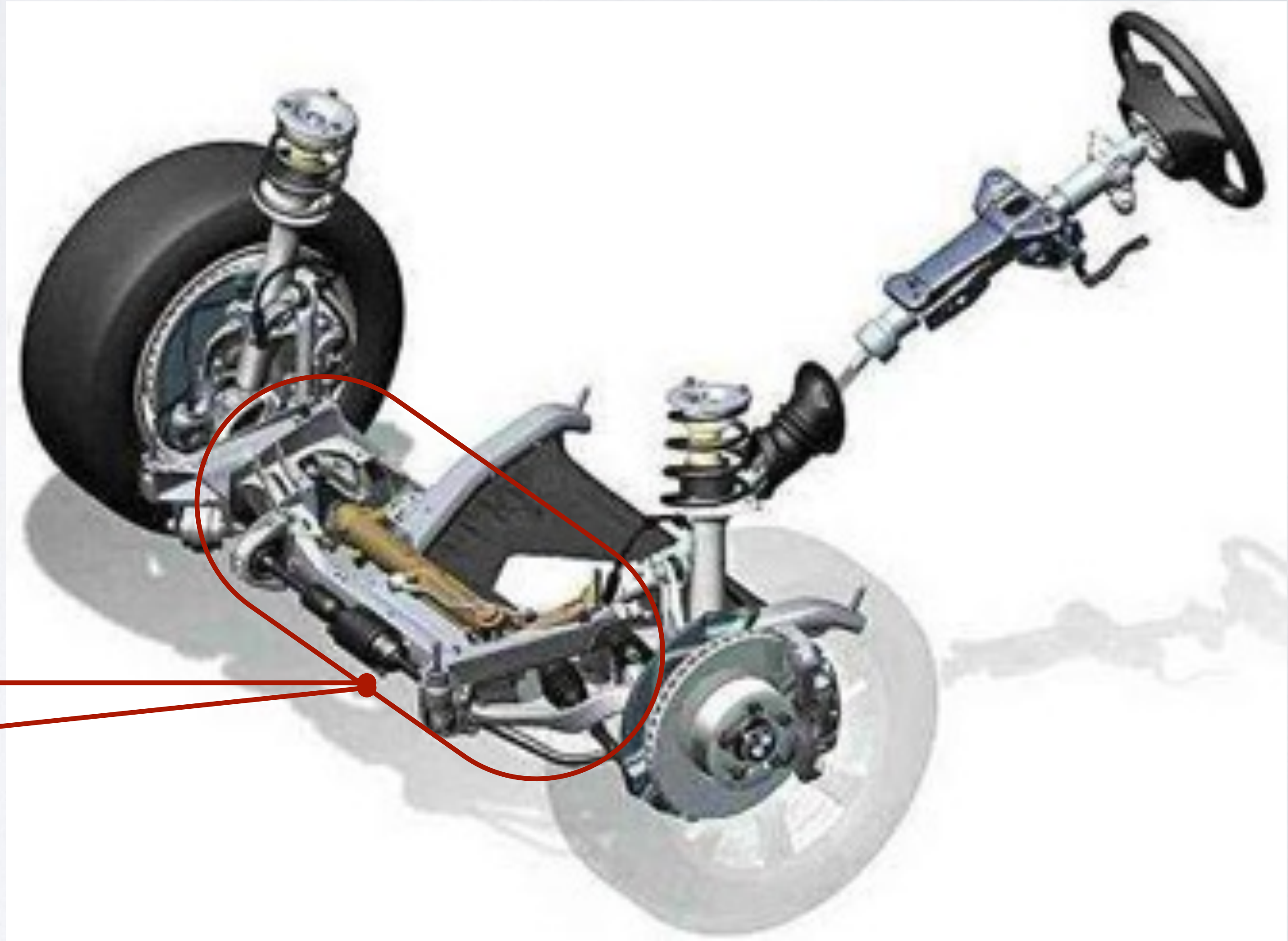

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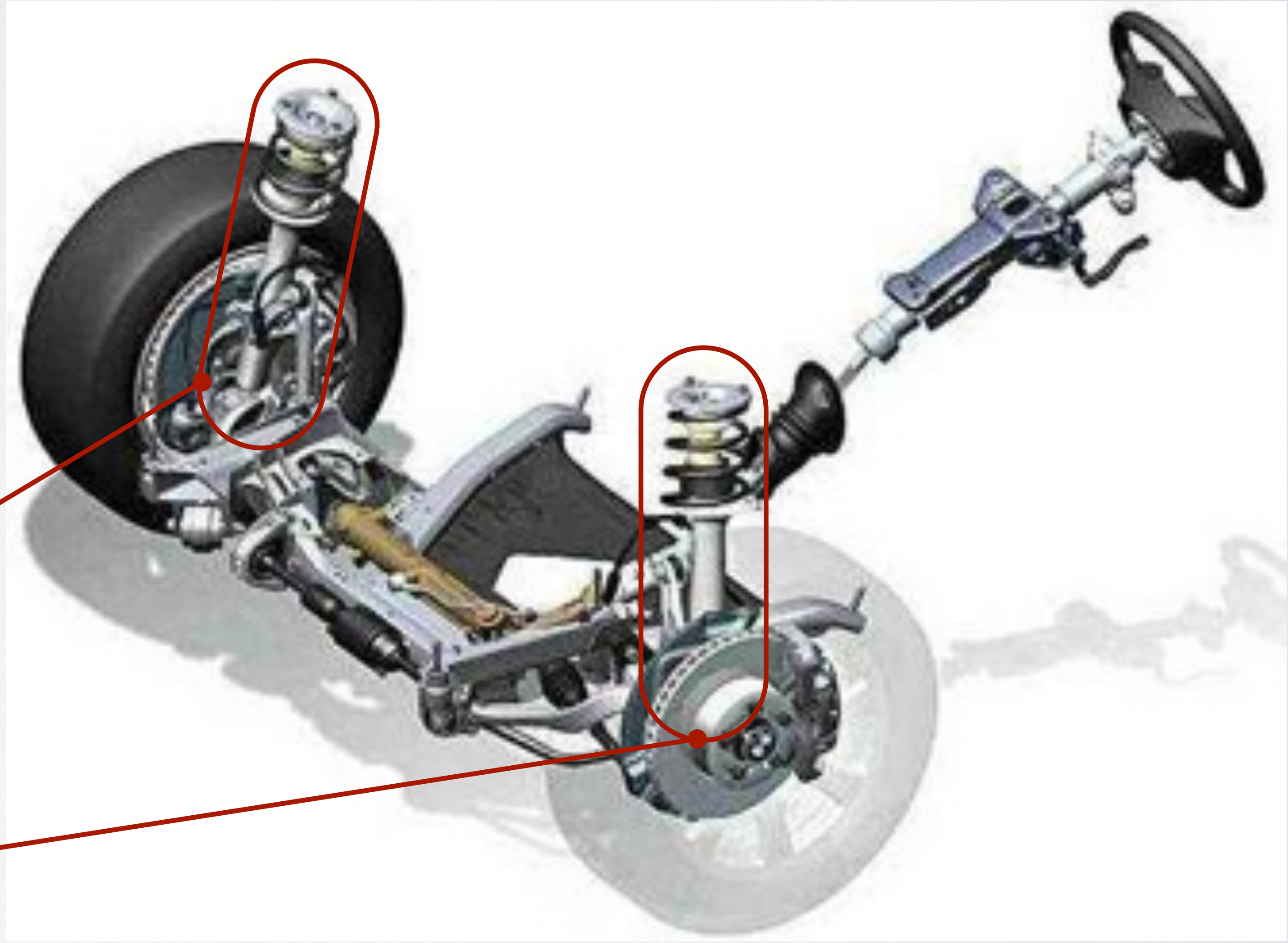

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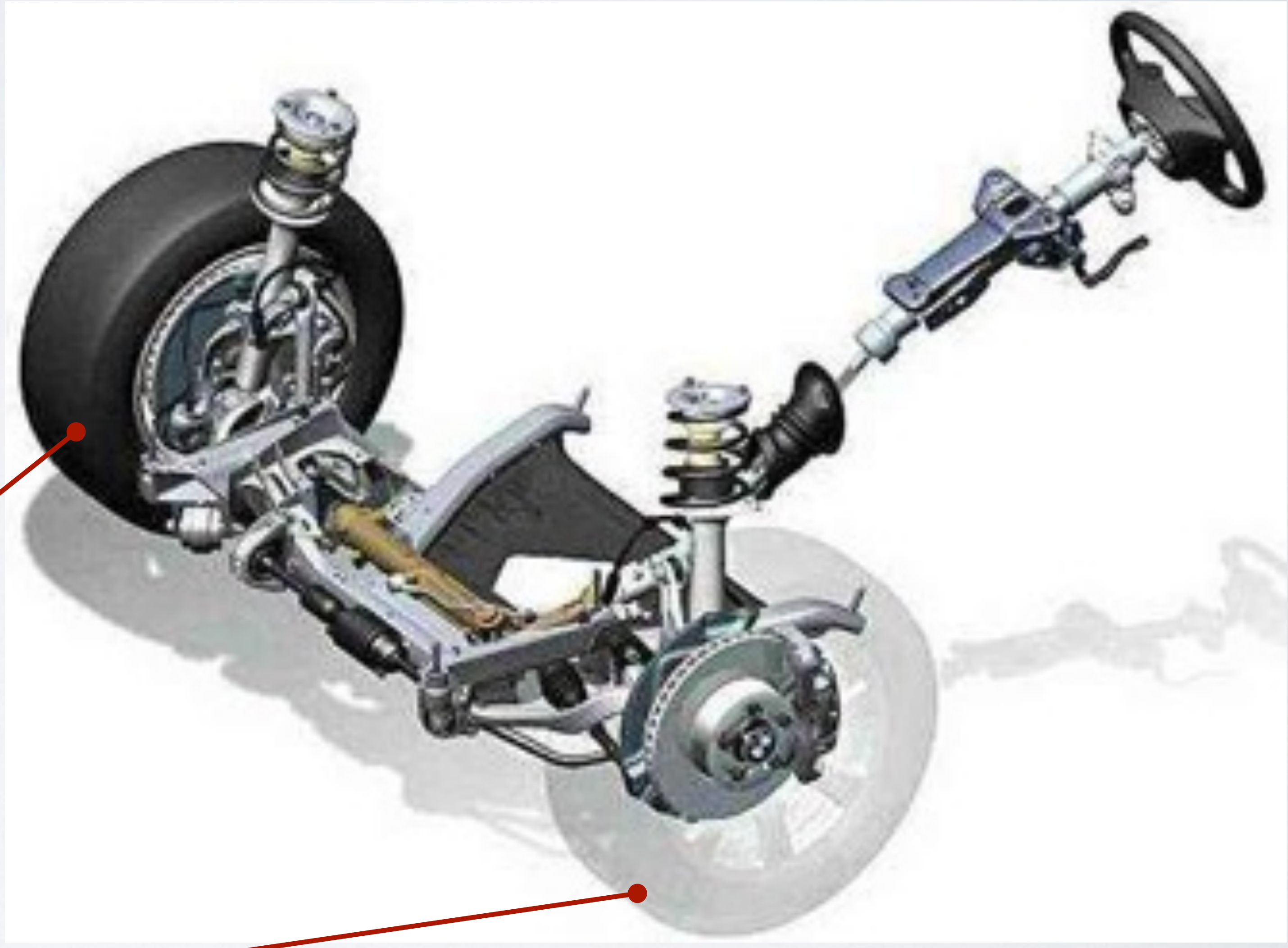
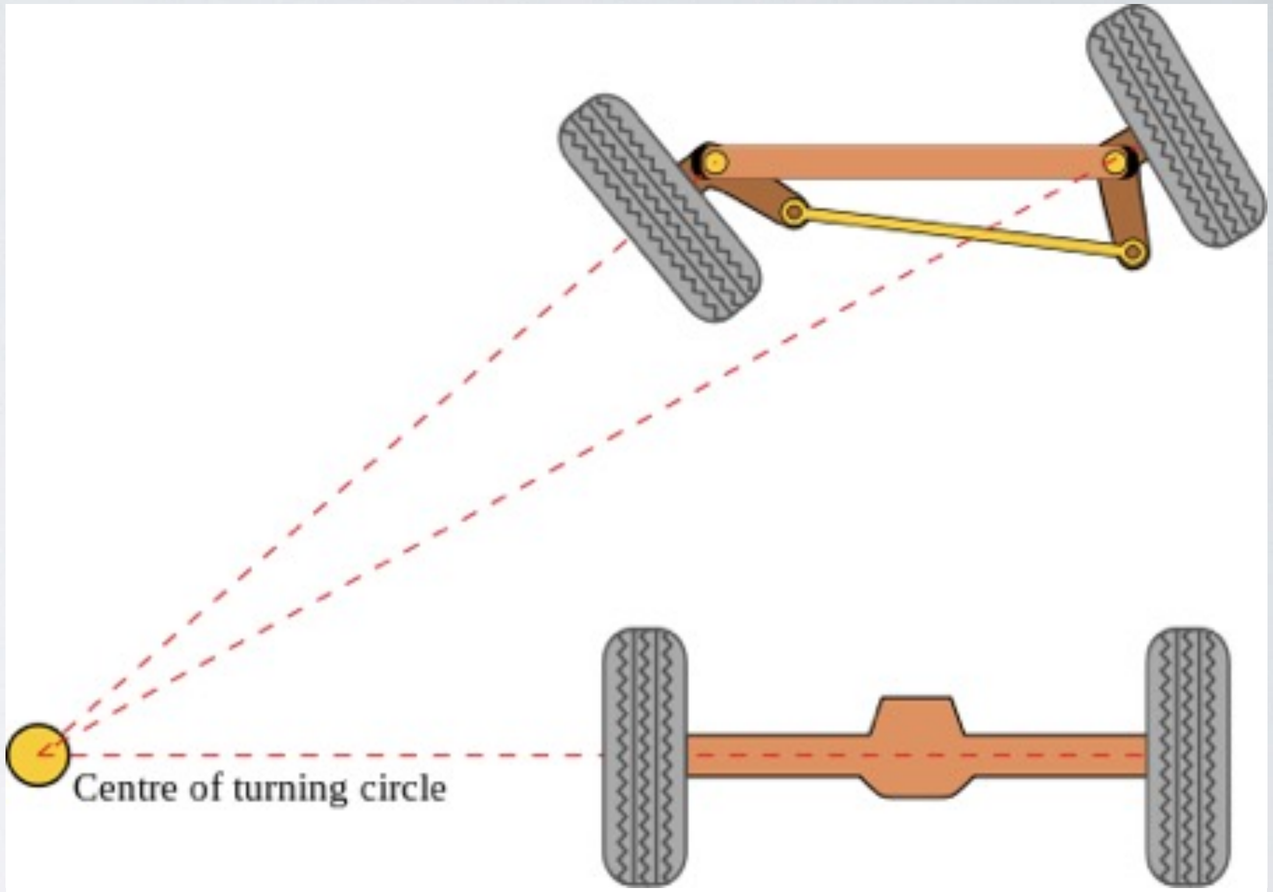


• Ackermann Steering Geometry

From Wikipedia, the free encyclopedia

Ackermann steering geometry is a geometric arrangement of linkages in the steering of a car or other vehicle designed to solve the problem of wheels on the inside and outside of a turn needing to trace out circles of different radii.

It was invented by the German carriage builder Georg Lankensperger in Munich in 1817, then patented by his agent in England, Rudolph Ackermann (1764–1834) in 1818 for horse-drawn carriages. Erasmus Darwin may have a prior claim as the inventor dating from 1758.



• Front Axle

Connects the masses of wheels with the chassis.

- # Ackermann Steering Geometry

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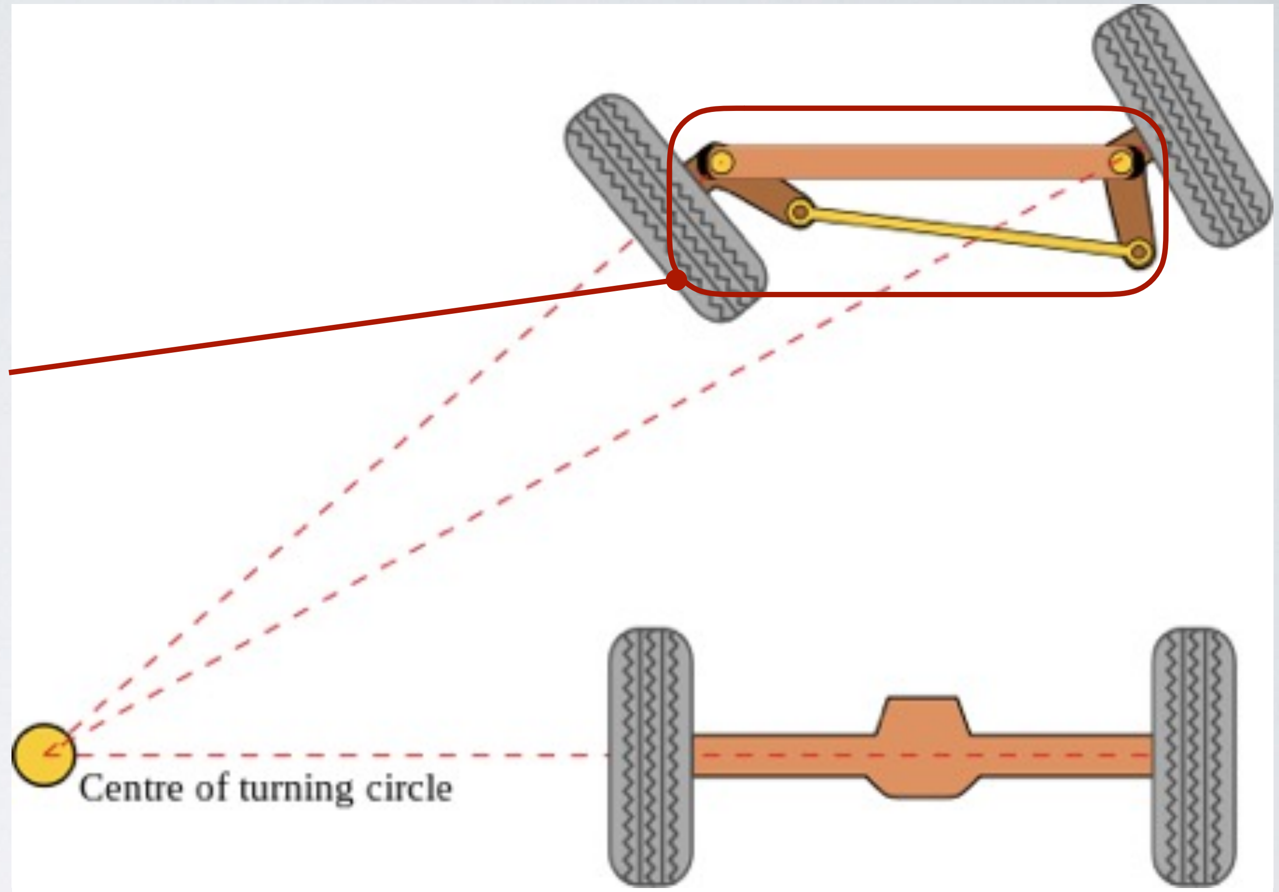
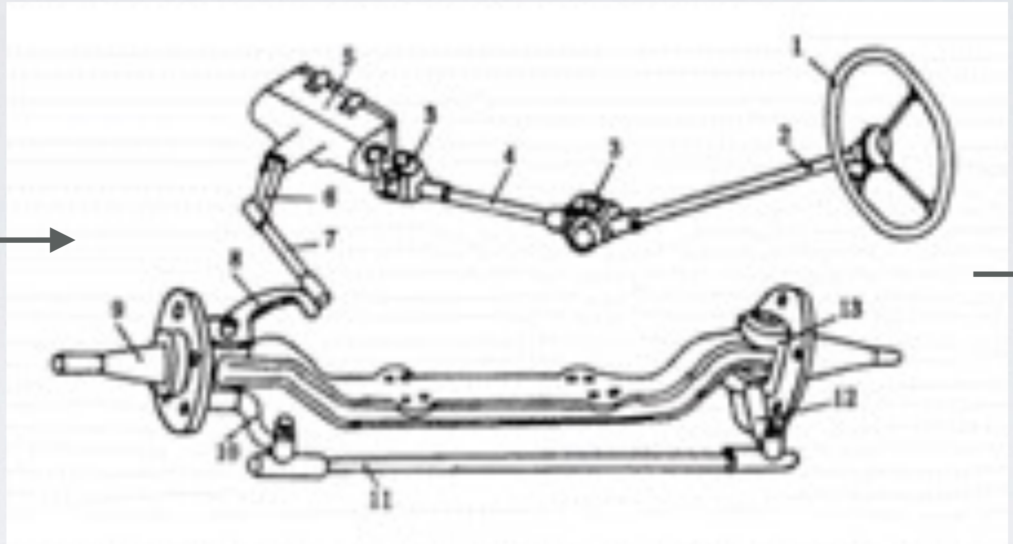
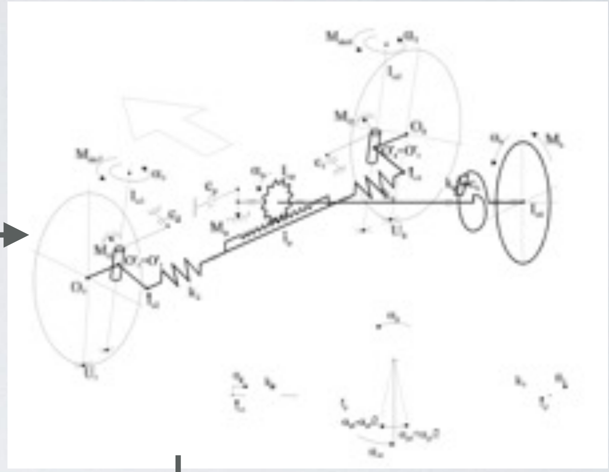


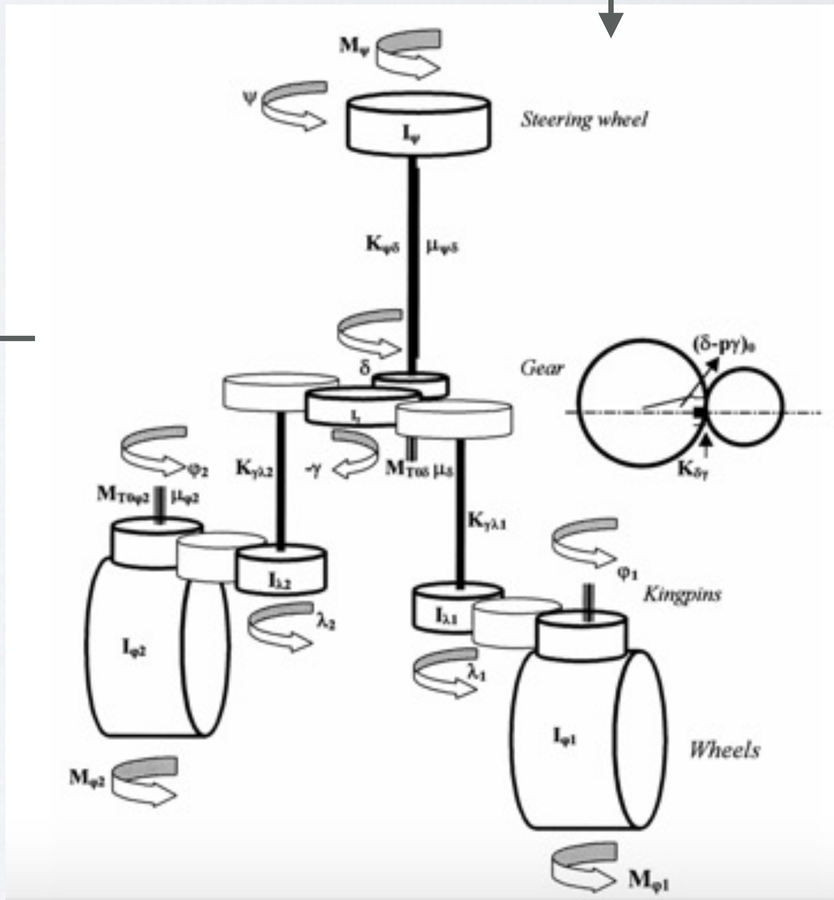
- # Front Axle

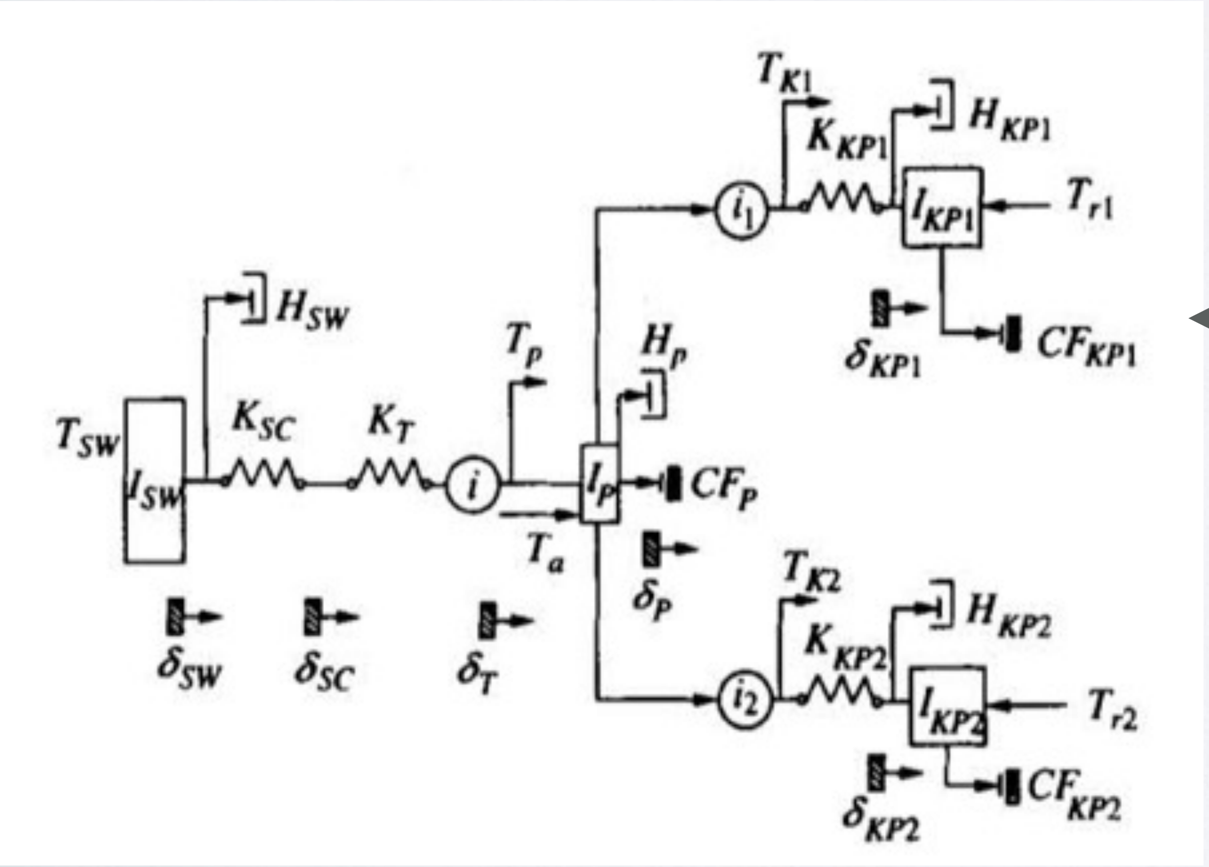
Connects the masses of wheels with the chassis.

SIMPLIFY —> MODELING



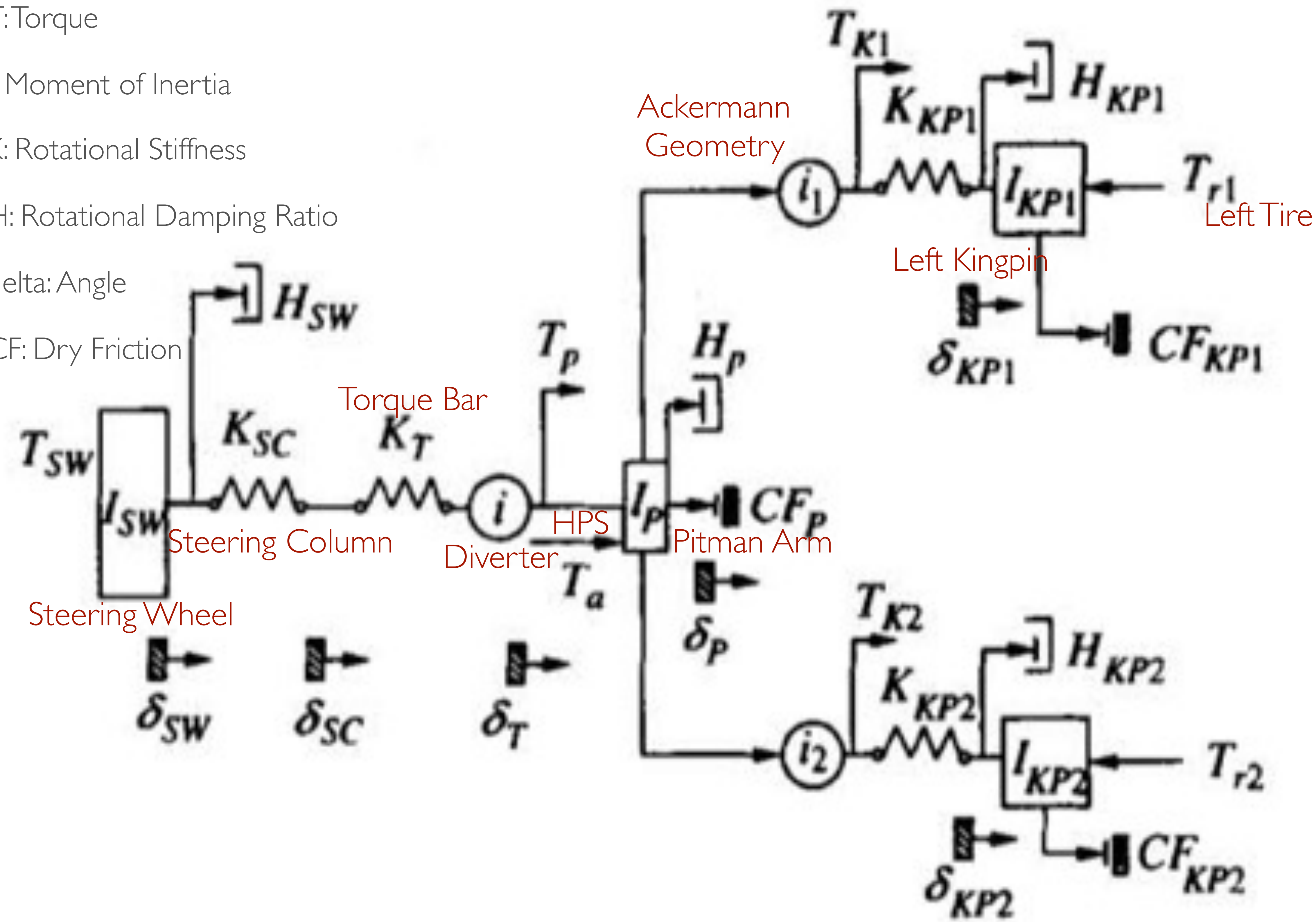




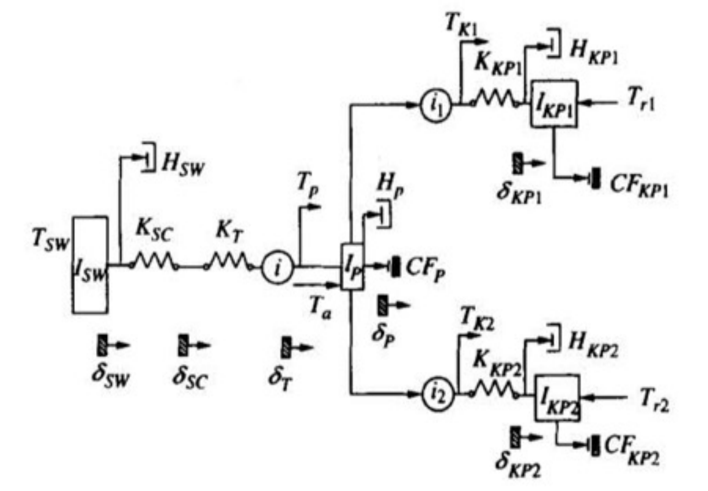


MODELING OF THE STEERING SYSTEM

- T: Torque
- I: Moment of Inertia
- K: Rotational Stiffness
- H: Rotational Damping Ratio
- delta: Angle
- CF: Dry Friction



MODELING OF THE STEERING SYSTEM



$$
\begin{cases}
I_{SW}\ddot{\delta}_{SW} = T_{SW} - H_{SW}\dot{\delta}_{SW} - K_{SC}(\delta_{SW} - \delta_{SC}) \\
I_P\ddot{\delta}_P = T_P\eta_F + T_a\eta_{PS} - H_P\dot{\delta}_P - \frac{T_{K1}}{i_1}\eta_B - \frac{T_{K2}}{i_2}\eta_B - \mathrm{sgn}(\dot{\delta}_P)CF_P \\
I_{KP1}\ddot{\delta}_{KP1} = T_{K1} - T_{r1} - H_{KP1}\delta_{KP1} - \mathrm{sgn}(\ddot{\delta}_{KP1})CF_{KP1} \\
I_{KP2}\ddot{\delta}_{KP2} = T_{K2} - T_{r2} - H_{KP2}\delta_{KP2} - \mathrm{sgn}(\ddot{\delta}_{KP2})CF_{KP2}
\end{cases}
$$

where

I_{SW}: Moment of inertia of steering wheel
I_P: Moment of inertia of pitman arm
I_{KP1}: Moment of inertia of left tire around its kingpin
I_{KP2}: Moment of inertia of right tire around its kingpin

δ_{SW}: Rotation of steering wheel
δ_P: Rotation of pitman arm
δ_{KP1} & δ_{KP2}: Rotation of left & right tire around its kingpin
δ_{SC}: Rotation of steering column, $\delta_{SC} = \frac{K_T \cdot i \cdot \delta_P + K_{SC} \cdot \delta_{SW}}{K_T + K_{SC}}$

K_{SC}: Torsional stiffness of the steering column
K_T: Torsional stiffness of the torque bar
K_{KP1} & K_{KP2}: Torsional stiffness of the left & right kingpin

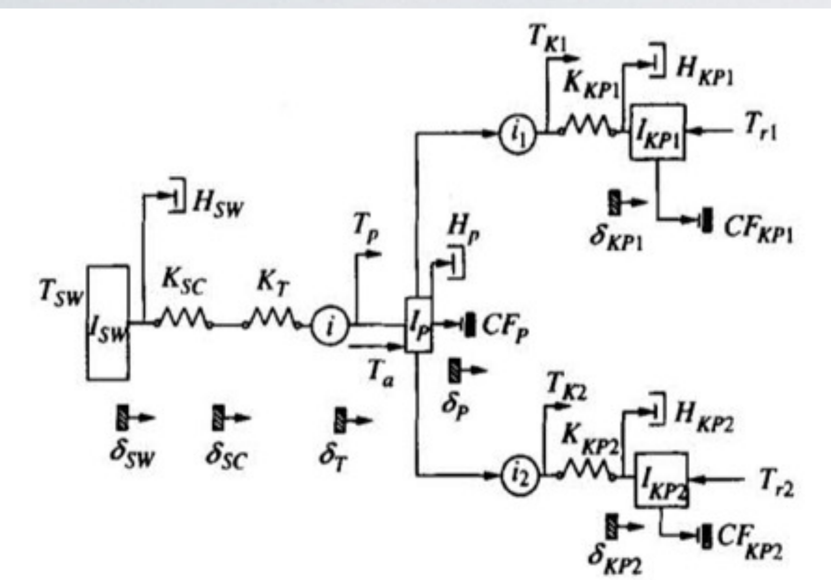
H_{SW}: Damping ratio of the steering wheel module
H_P: Damping ratio of the pitman bar
H_{KP1} & H_{KP2}: Damping ratio of the left & right kingpin

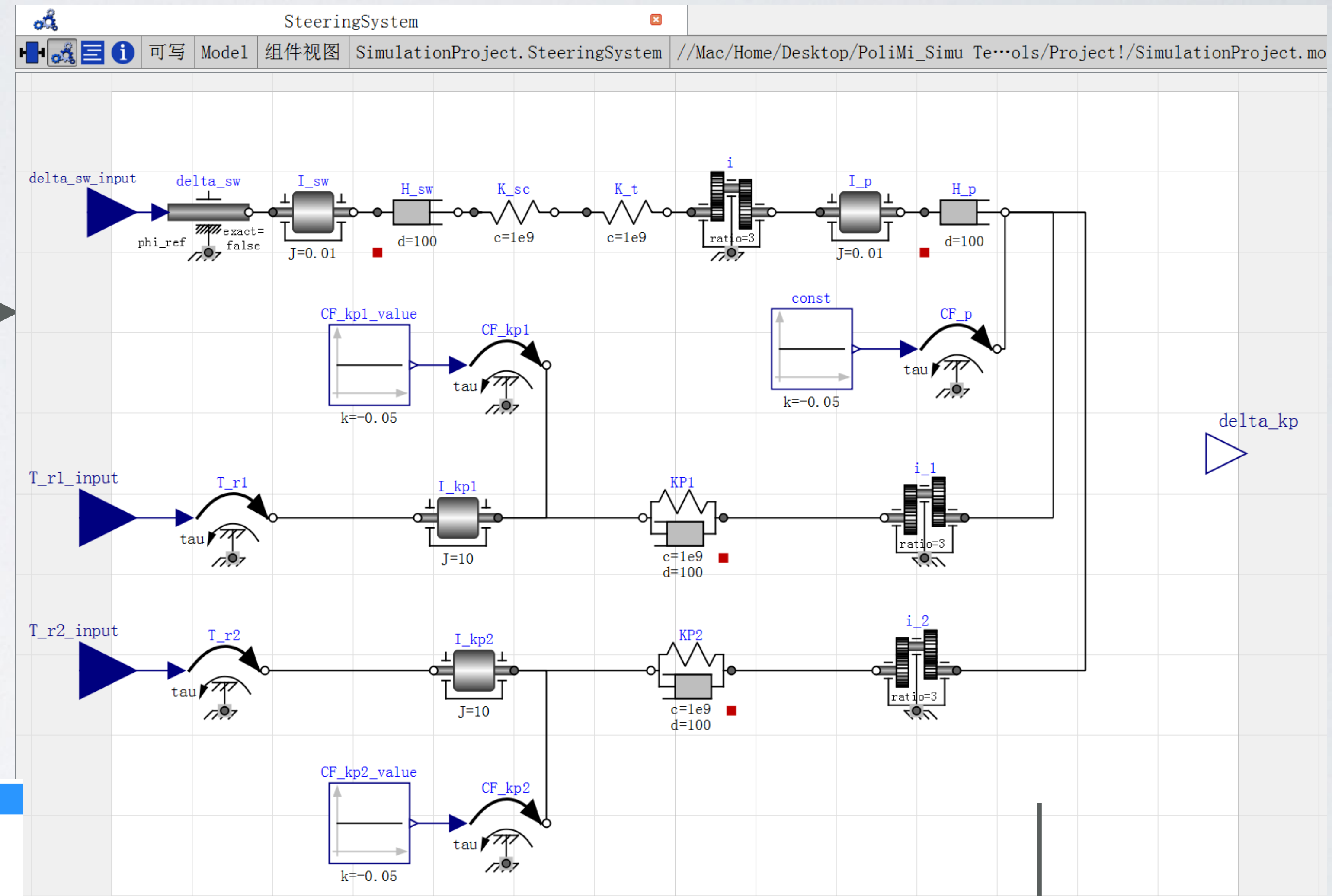
i: Transmission ration of the diverter
i_1 & i_2: Transmission ration of the left & right steering structure

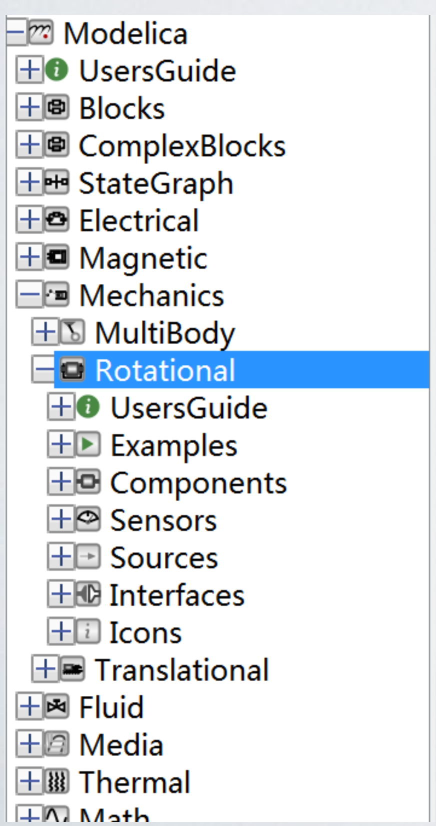
T_{SW}: Acting torque on steering wheel by driver
T_P: Acting torque on pitman arm caused by driver, $T_P = i \cdot K_{SC} \cdot (\delta_{SW} - \delta_{SC})$
T_a: Assisting torque on pitman arm by HPS, $T_a = \frac{i \cdot p \cdot A \cdot t}{2\pi}$ where t is the screw lead, A is the effective area of the oil pressure, p is the pressure difference b/t the two ends of the nut
T_{K1}: Acting torque of left kingpin on the tire, $T_{K1} = K_{KP1}(\frac{\delta_P}{i_1} - \delta_{KP1})$
T_{K2}: Acting torque of right kingpin on the tire, $T_{K2} = K_{KP2}(\frac{\delta_P}{i_2} - \delta_{KP2})$
T_{r1}: Resistant torque of left tire when steering
T_{r2}: Resistant torque of right tire when steering

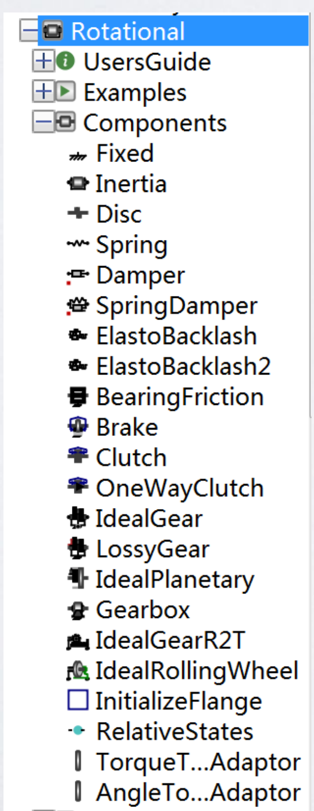
CF_P: Dry friction coefficient of the pitman bar
CF_{KP1} & CF_{KP2}: Dry friction coefficient of the left & right kingpin
η_F: Forward transmission efficiency of the diverter
η_B: Backward transmission efficiency of the diverter
η_{PS}: Efficiency of the power steering system

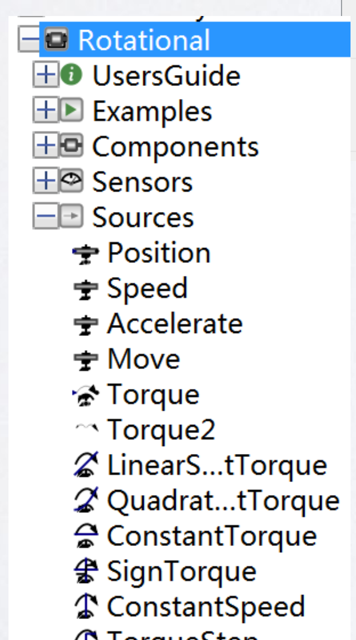
MODELING OF THE STEERING SYSTEM
IN MODELICA:

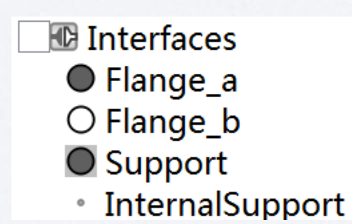


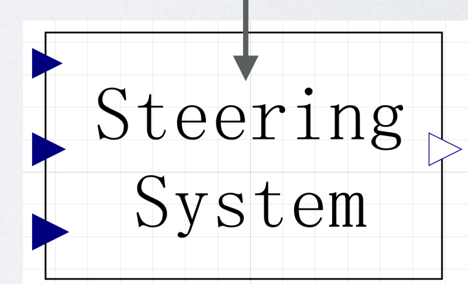












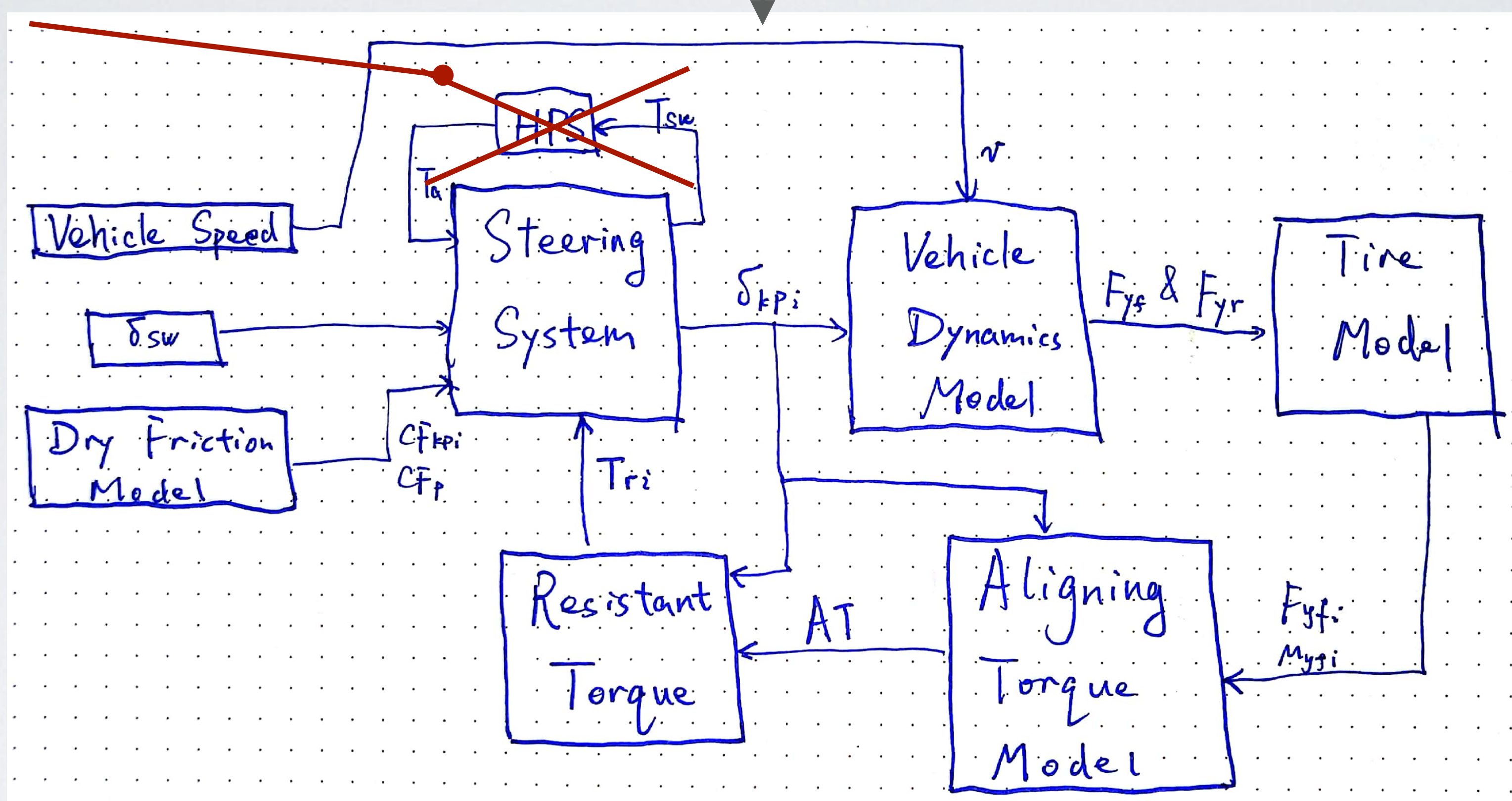
An important library:

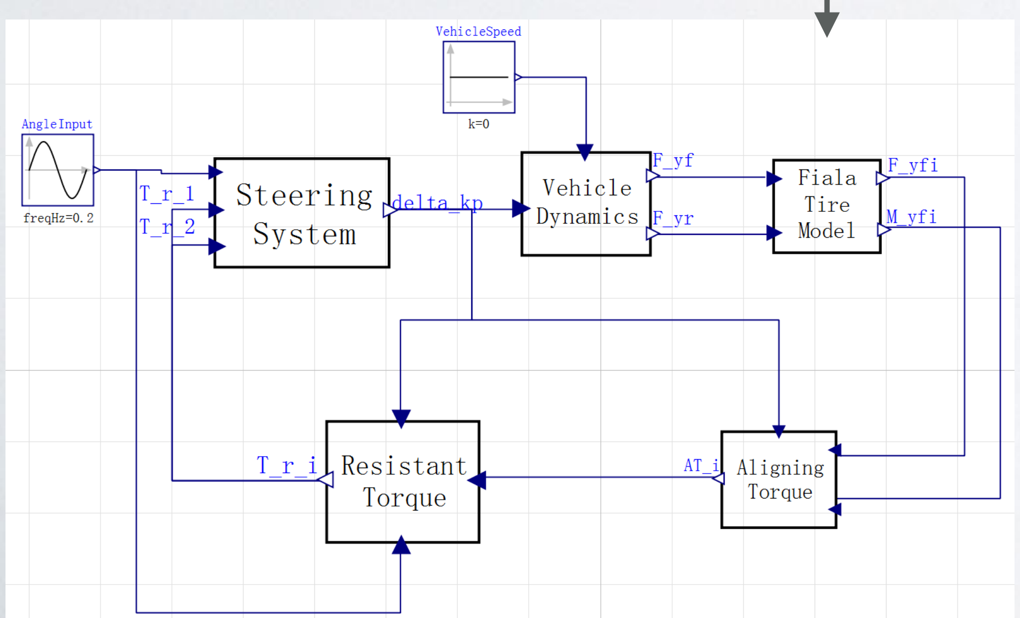
- Modelica/ Mechanics/ **Rotational**

SIMULATION PLATFORM: ENTIRE VEHICLE MODEL

- To verify the steering system, an experiment platform which integrates other parts of vehicle was built.

For verifying the model, assume null torque is provided by HPS.





- An **experiment** is designed: Steering back and forth (SW angle input: sine waveform) while the vehicle remains static (vehicle speed v=0 m/s)

SIMULATION PLATFORM: ENTIREVEHICLE MODEL

- **Vehicle Dynamics Model**: Single-track Model (Bicycle Model)
- Assumption: the steering angle of two front wheels are the same.

2.1 *Equations of motion of the single-track model*

The equations of motion of the single-track model (Figure 1) may be expressed in a body-fixed frame with the origin at the vehicle's Centre of Gravity (CG) as follows:

$$m(\dot{V}_x - V_y\dot{\psi}) = f_{Fx}\cos\delta - f_{Fy}\sin\delta + f_{Rx} \tag{1}$$

$$m(\dot{V}_y + V_x\dot{\psi}) = f_{Fx}\sin\delta + f_{Fy}\cos\delta + f_{Ry} \tag{2}$$

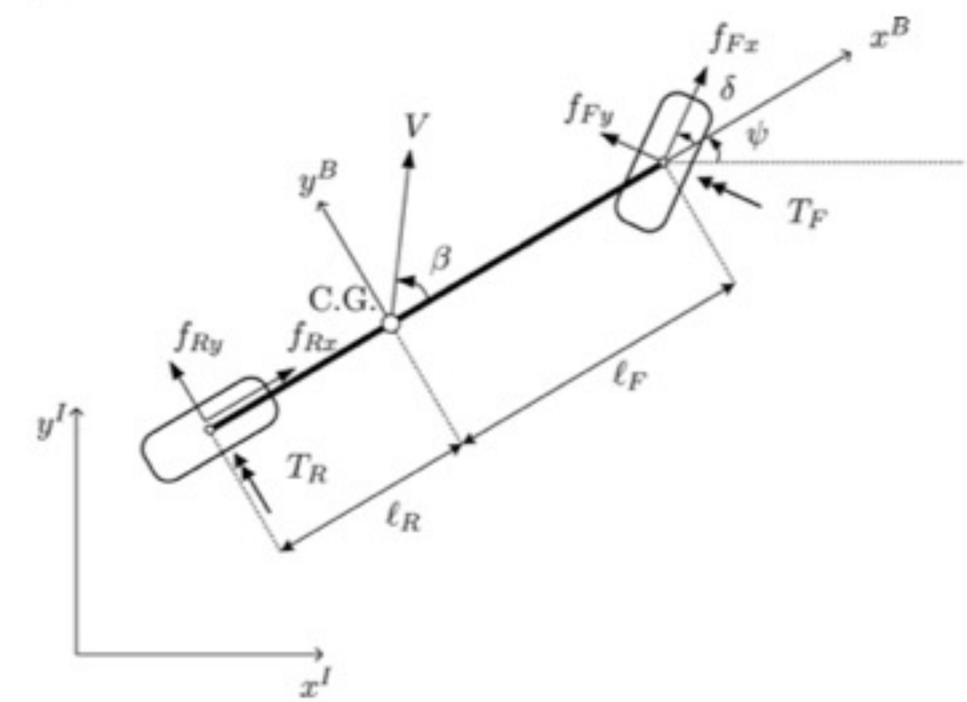
$$I_z\ddot{\psi} = (f_{Fy}\cos\delta + f_{Fx}\sin\delta)\ell_F - f_{Ry}\ell_R, \tag{3}$$

where

$$V_x = V\cos\beta, \quad V_y = V\sin\beta.$$

In the above equations m is the vehicle's mass, I_z is the moment of inertia of the vehicle about the vertical axis, V_x and V_y are the body-frame components of the vehicle velocity V, ψ is the yaw angle of the vehicle, and δ is the steering angle of the front wheel. By f_{ij} ($i = F, R$ and $j = x, y$) we denote the longitudinal and lateral friction forces at the front and rear wheels, respectively.

Figure 1 Single-track vehicle model



The vehicle slip angle is given by

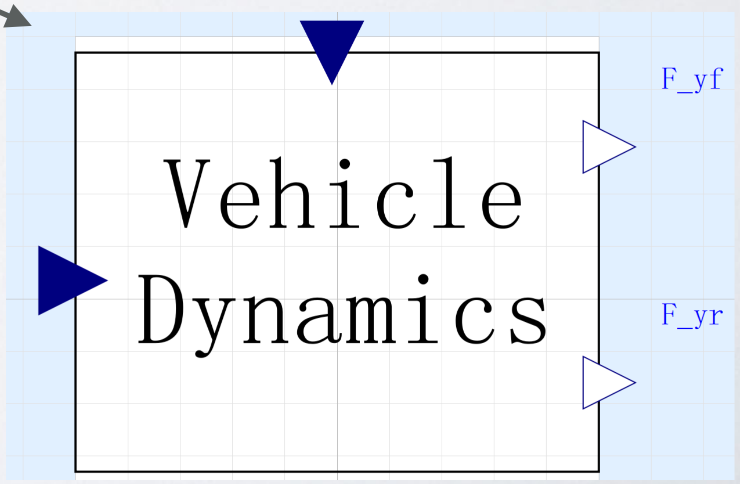
$$\beta = \text{atan}\left(\frac{\dot{y}}{\dot{x}}\right) - \psi = \text{atan}\left(\frac{V_y}{V_x}\right)$$

where $\dot{x}$ and $\dot{y}$ are the inertial frame components of the vehicle speed.

SIMULATION PLATFORM: ENTIRE VEHICLE MODEL

- **Vehicle Dynamics Model**: Single-track Model (Bicycle Model)
- Assumption: the steering angle of two front wheels are the same.
- Simplification: in the **experiment**, v=0 m/s, thus according to the bicycle model, all the lateral tire forces are null.

```
model VehicleDynamics
  Modelica.Blocks.Interfaces.RealInput delta_kp annotation( ...);
  Modelica.Blocks.Interfaces.RealInput v annotation( ...);
  Modelica.Blocks.Interfaces.RealOutput F_yf annotation( ...);
  Modelica.Blocks.Interfaces.RealOutput F_yr annotation( ...);
equation
  F_yf = 0;
  F_yr = 0;
  annotation( ...);
end VehicleDynamics;
```



SIMULATION PLATFORM: ENTIRE VEHICLE MODEL

- Tire Model: **Fiala Tire Model**
- Pros: - Analytical Model (Lower computational load)

  - Consider the tire as a rigid circular plate:

  - Thus good for the study focused on aligning torques and analysis on manipulation performance etc.

$$\bar{M}_z = \bar{F}_y \cdot \frac{D_x}{a} - \bar{F}_x \left(\frac{D_y}{a} + \frac{y_b}{a} \right)$$

Self-aligning torque

Dimensionless lateral/longitudinal force

Dimensionless longitudinal/lateral trail

Dimensionless translational deformation

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- In the **experiment**, the vehicle remains static

SIMULATION PLATFORM: ENTIREVEHICLE MODEL

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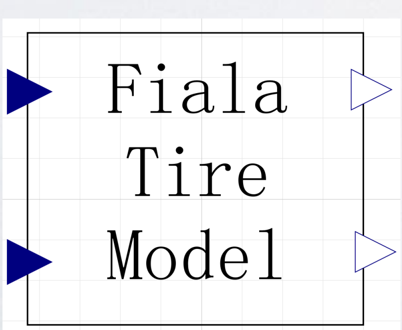



```
model TireModel
  Modelica.Blocks.Interfaces.RealInput F_yf annotation( ...);
  Modelica.Blocks.Interfaces.RealInput F_yr annotation( ...);
  Modelica.Blocks.Interfaces.RealOutput F_yfi annotation( ...);
  Modelica.Blocks.Interfaces.RealOutput M_yfi annotation( ...);
equation
  F_yfi=0;
  M_yfi=0;
  annotation( ...);
end TireModel;
```

SIMULATION PLATFORM: ENTIRE VEHICLE MODEL

- **Aligning Torque Model**

- Consists of three components:

 - Gravitational aligning torque caused by vertical load ***Fz***

$$M_Z = F_Z E_Z \sin\delta_i \cos\delta_c \sin\delta_{KP}$$
$$E_Z = E_{KP} \cos\delta_i$$

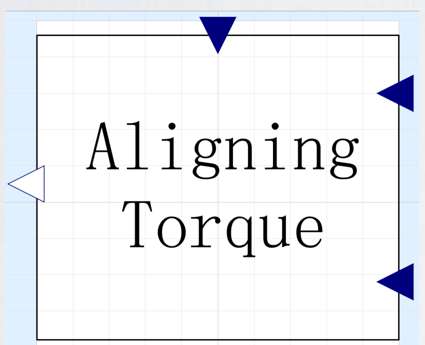
 - Torque caused by lateral force ***Fy***

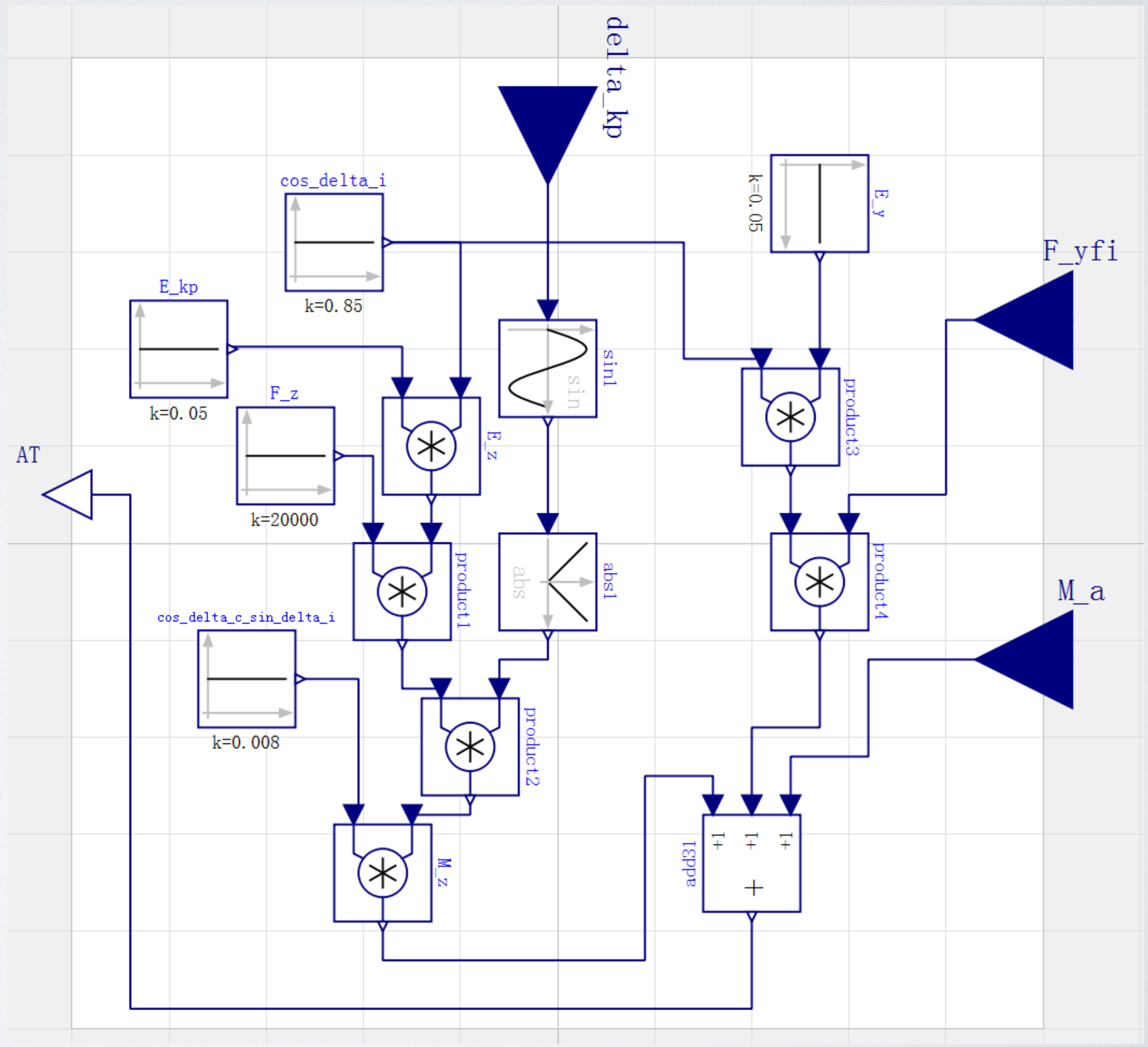
$$M_Y = F_Y \cdot E_Y \cdot \cos\delta_i$$
$$E_Y = R_j \cdot \sin\delta_C$$

 - Self-aligning torque (provided by the tire model)

SIMULATION PLATFORM: ENTIRE VEHICLE MODEL

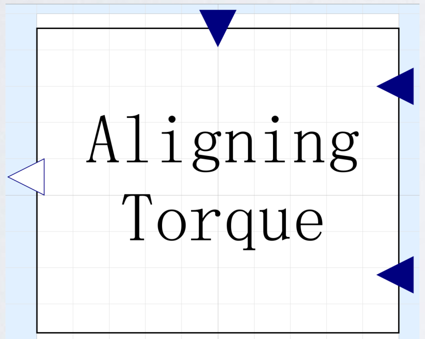
- **Aligning Torque Model**

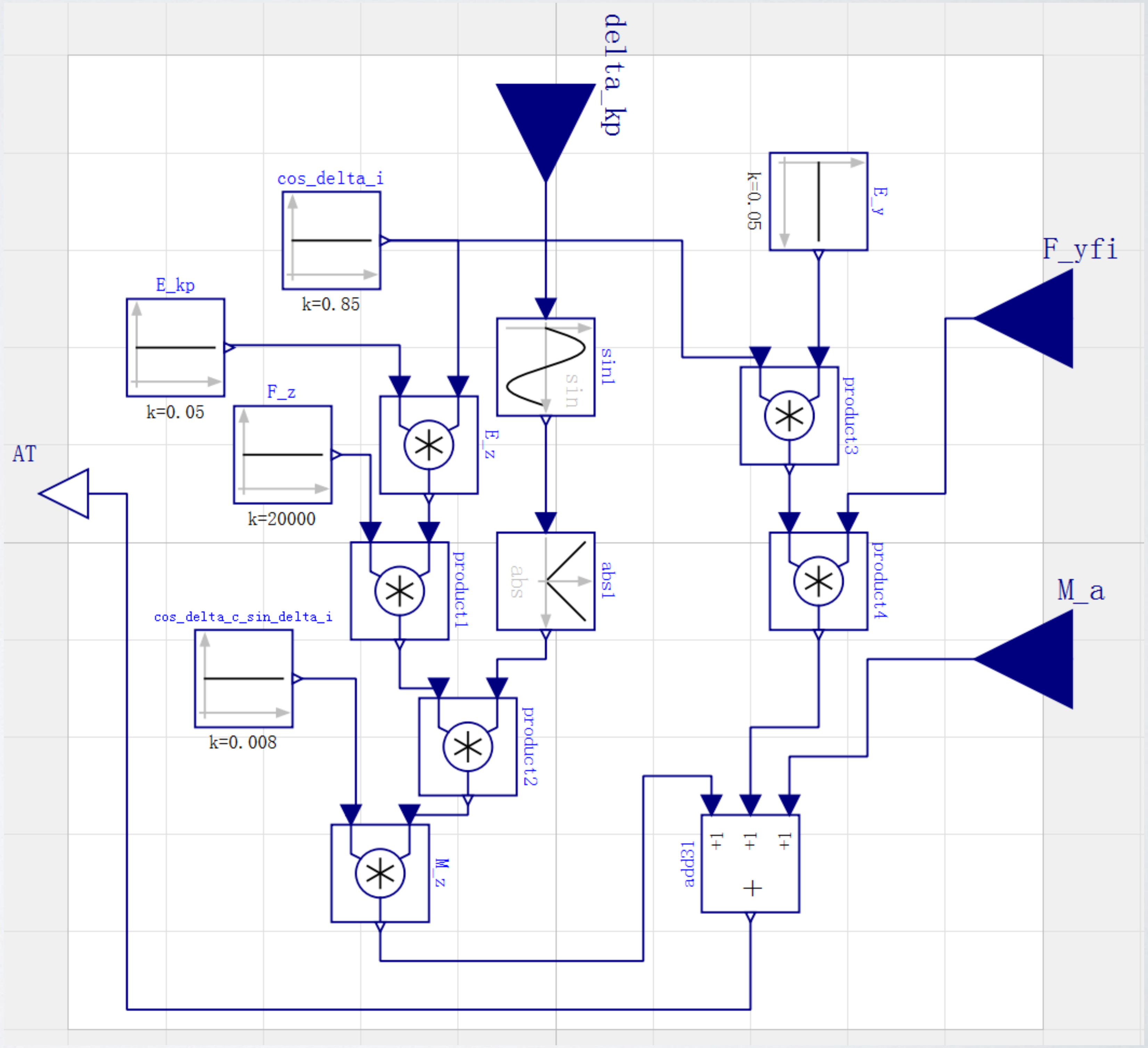




SIMULATION PLATFORM: ENTIREVEHICLE MODEL

- **Aligning Torque Model**





SIMULATION PLATFORM: ENTIRE VEHICLE MODEL

- **Resistant Torque Model**

- Frictional torque ***Tm***:

  - when v <= 5 km/h,

$$T_m = \begin{cases} K_f \delta_{KP} & K_f \delta_{KP} \leqslant T_{m\max} \\ T_{m\max} & K_f \delta_{KP} > T_{m\max} \end{cases}$$

where

$$T_{m\max} = \frac{f}{3N}\sqrt{\frac{G^3}{P}}$$

(= constant)

  - ~~when v > 5 km/h,~~

$$\cancel{T_m = \frac{0.001GKR_j}{N}}$$

- Resistant torque ***Tr***:

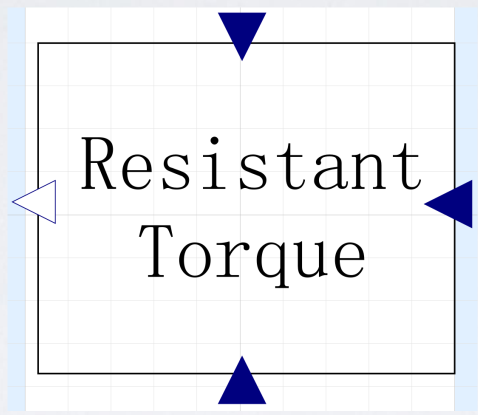
$$T_r = T_m + \mathrm{sgn}(\delta_{SW}\dot{\delta}_{SW}) \cdot AT$$

AT is:

- resistive when steering
- active when aligning

SIMULATION PLATFORM: ENTIRE VEHICLE MODEL

- **Resistant Torque Model**

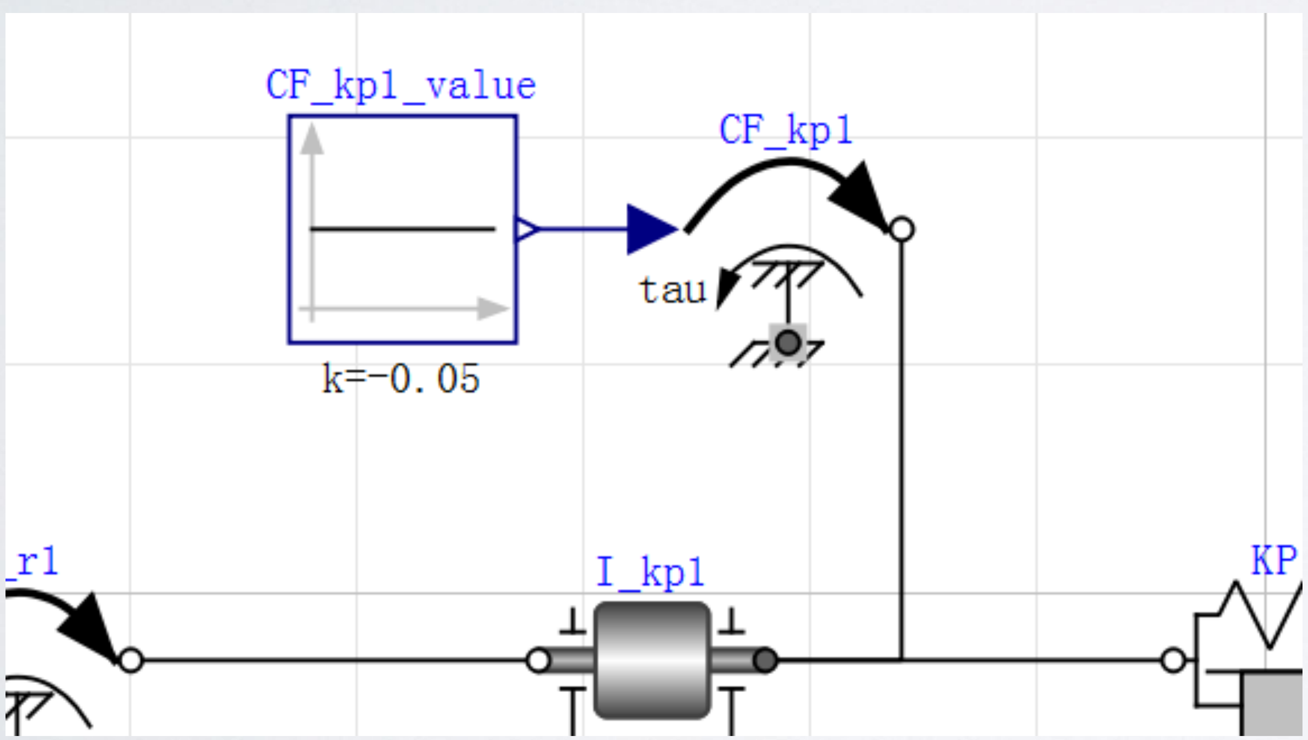


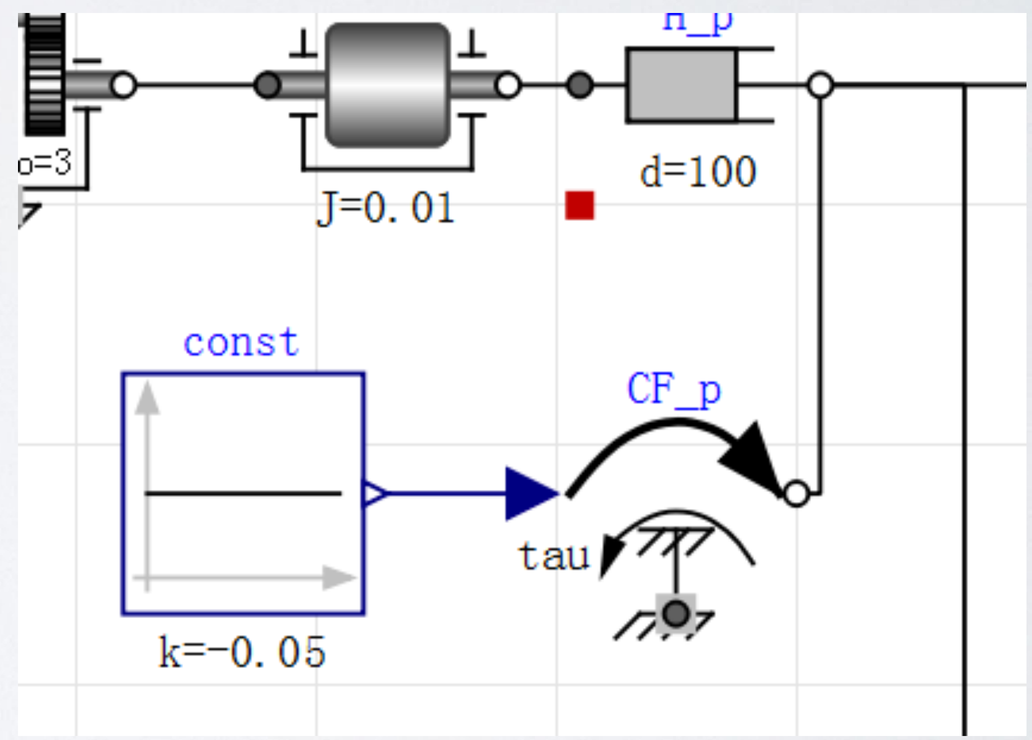

```
model ResistantTorque
  Modelica.Blocks.Interfaces.RealInput AT annotation( ...);
  Modelica.Blocks.Interfaces.RealInput delta_kp annotation( ...);
  Modelica.Blocks.Interfaces.RealInput delta_sw annotation( ...);
  Modelica.Blocks.Interfaces.RealOutput T_r annotation( ...);
  parameter Real T_m_max = 5 "Maximum Tire-Road Friction Torque";
  parameter Real K_f = 2 "Equivalent Stiffness of Tires";
  Real T_m "Tire-Road Friction Torque";
  Real delta_kp_abs "Absolute Value of delta_kp";
equation
  delta_kp_abs = if delta_kp >= 0 then delta_kp else -delta_kp;
  T_m = if K_f * delta_kp_abs <= T_m_max then K_f * delta_kp_abs else T_m_max;
  T_r = if delta_kp * der(delta_kp) >= 0 then T_m + AT else T_m - AT;
  annotation( ...);
end ResistantTorque;
```

SIMULATION PLATFORM: ENTIRE VEHICLE MODEL

- **Dry Friction Model**

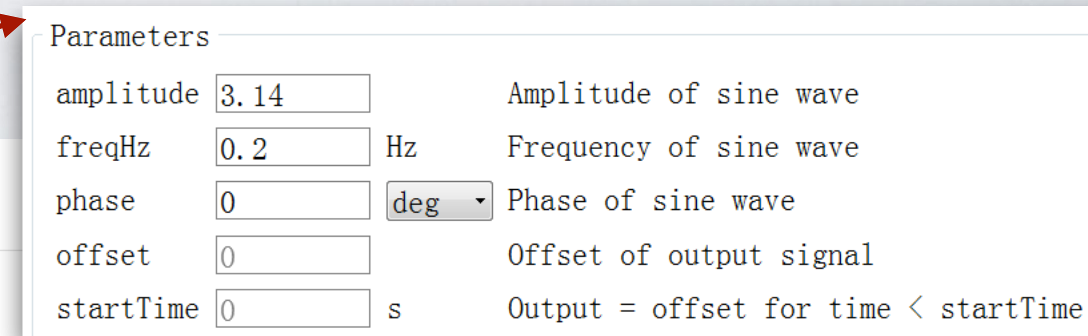
$$CF_{KPi} = \frac{GK}{M}\left(f_1 r_1 + \frac{2E_{KP} f_2 r_2}{L_{AB}}\right) \quad (= \text{constant})$$

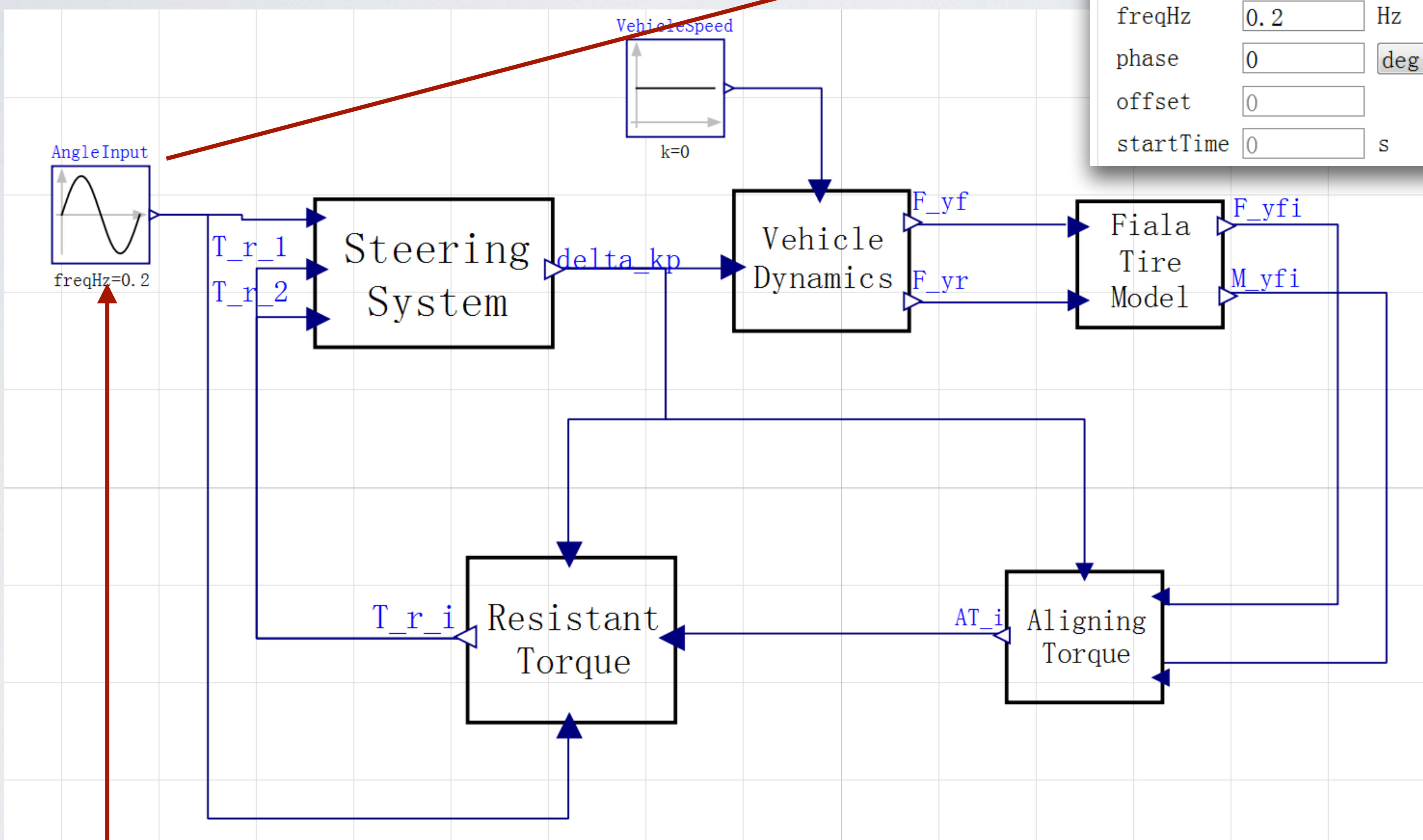


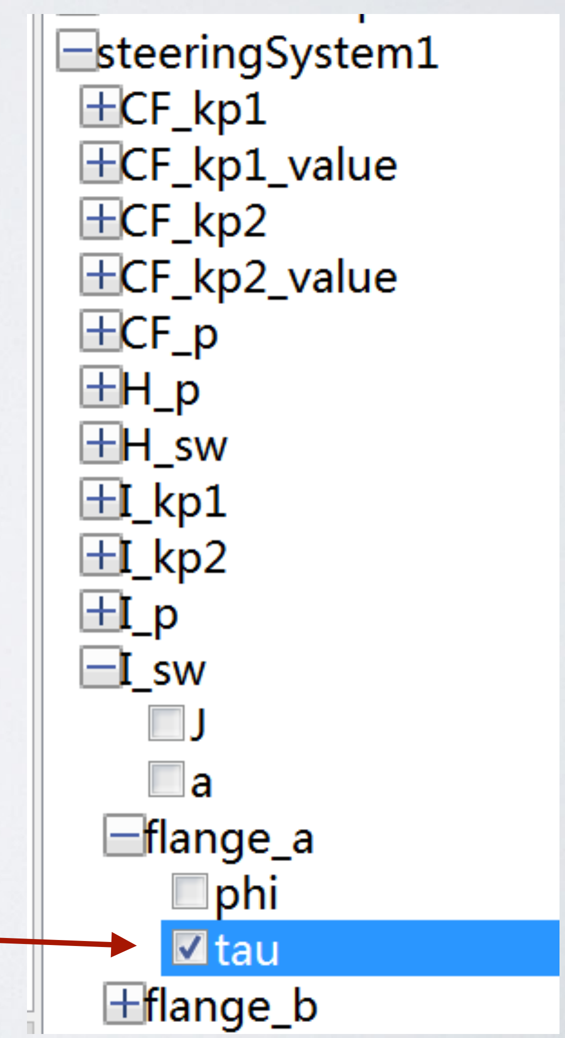


SIMULATION RESULTS

- Experiment: How much force (torque) is required from the driver to steer the SW to a specific position?





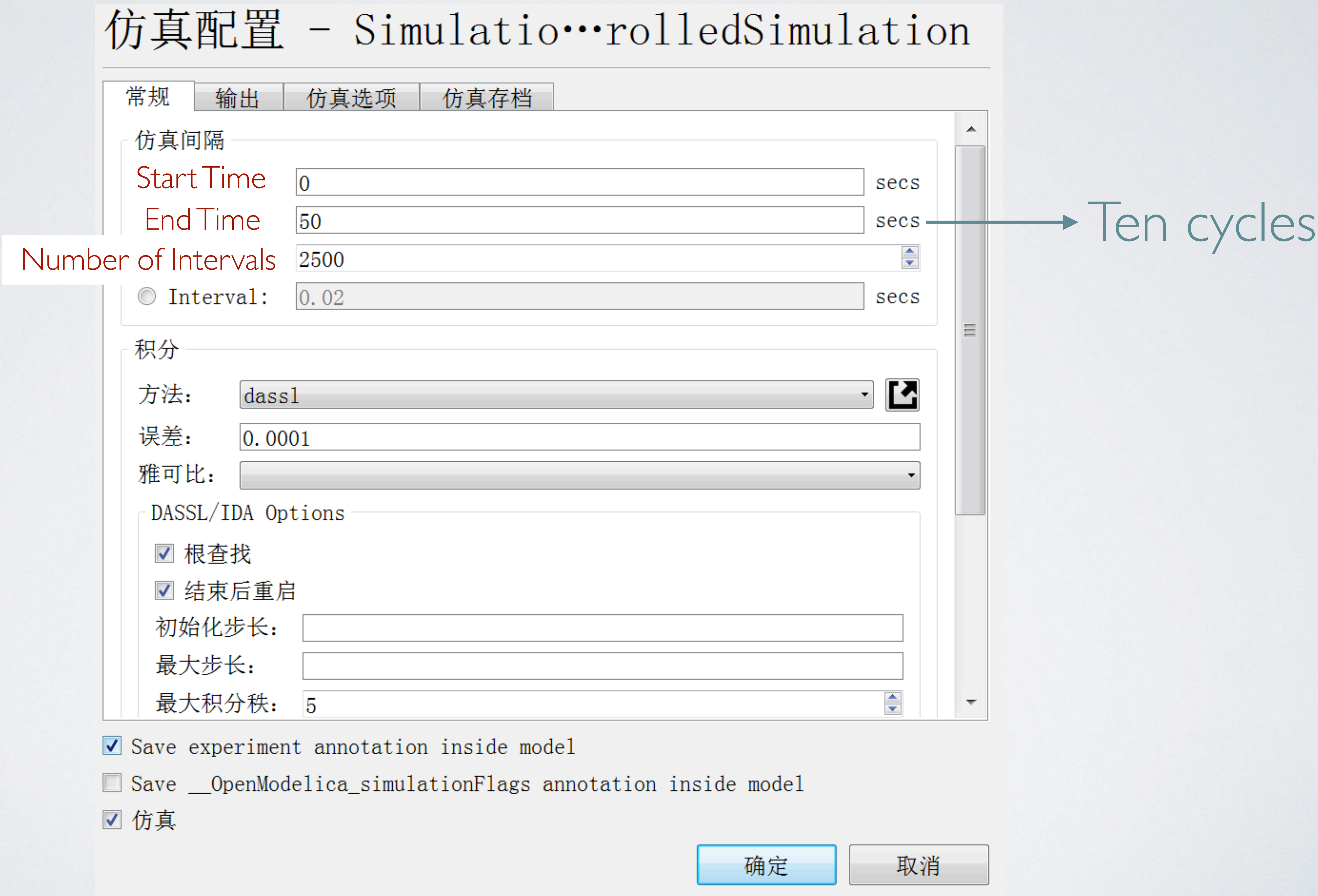


- **Input**: SW angle sine waveform

- **Output**: Torque on SW

SIMULATION RESULTS

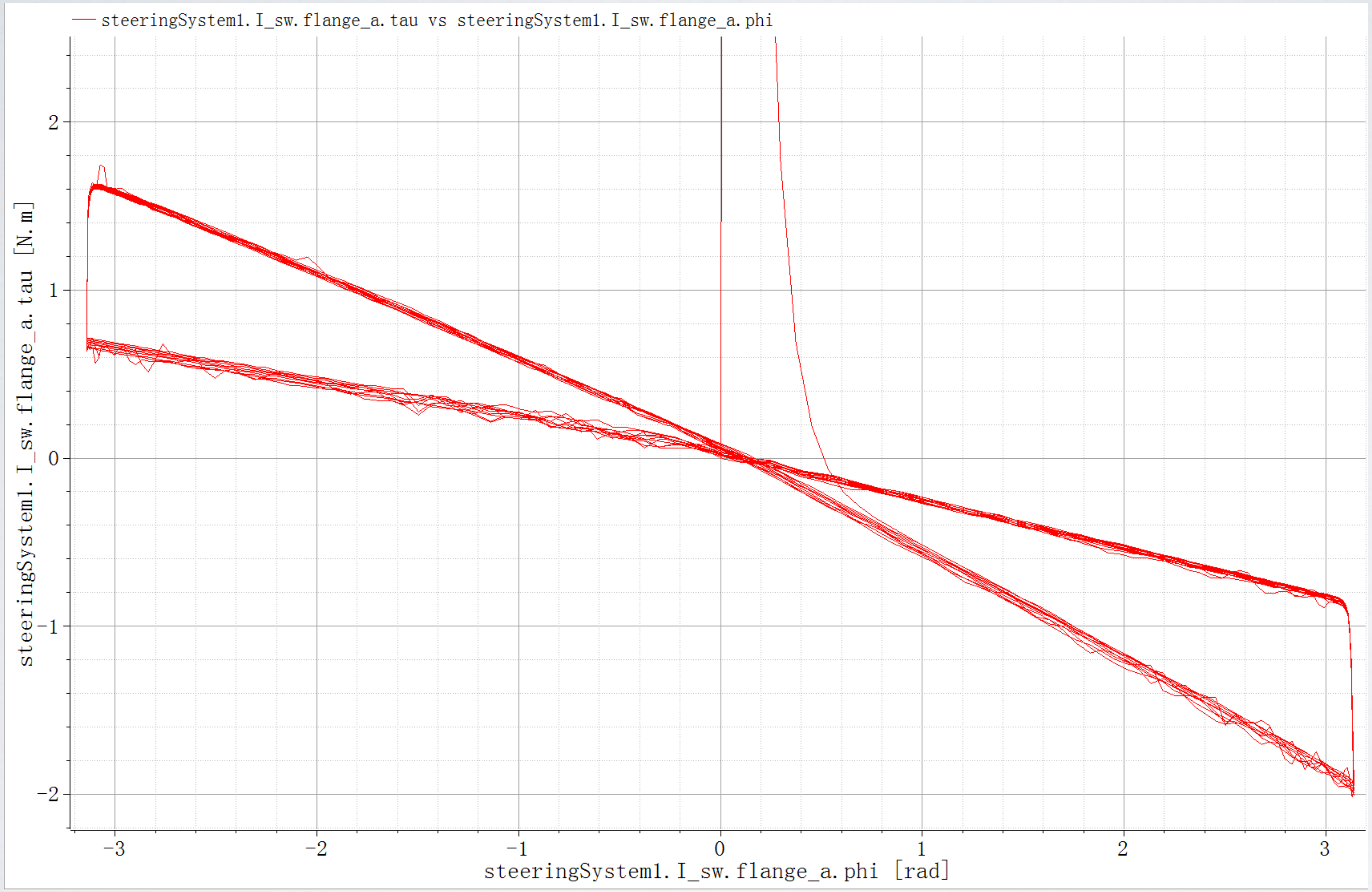
- Question: is the model correct?



SIMULATION RESULTS

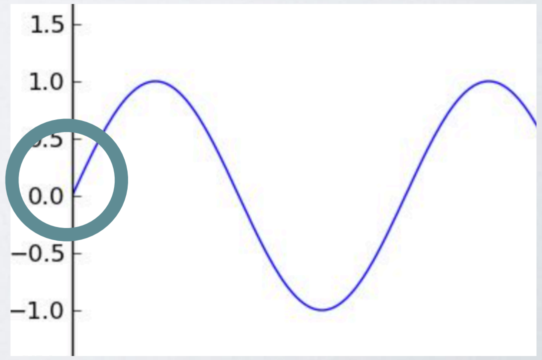
- Question: is the model correct?

Driving torque needed on SW



Steering angle on SW

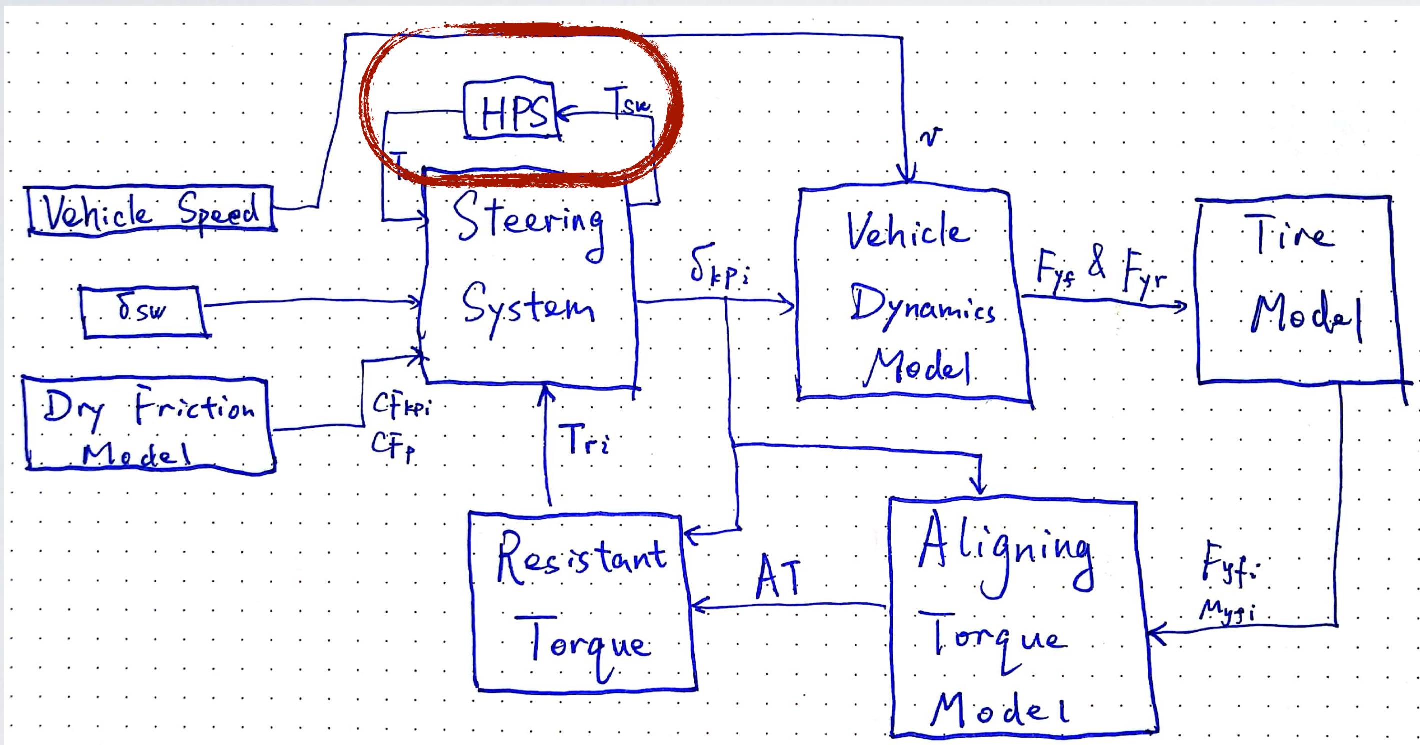
- Intuitively (Qualitatively) speaking correct
- An obvious overshoot because the starting steering accerlation too big.



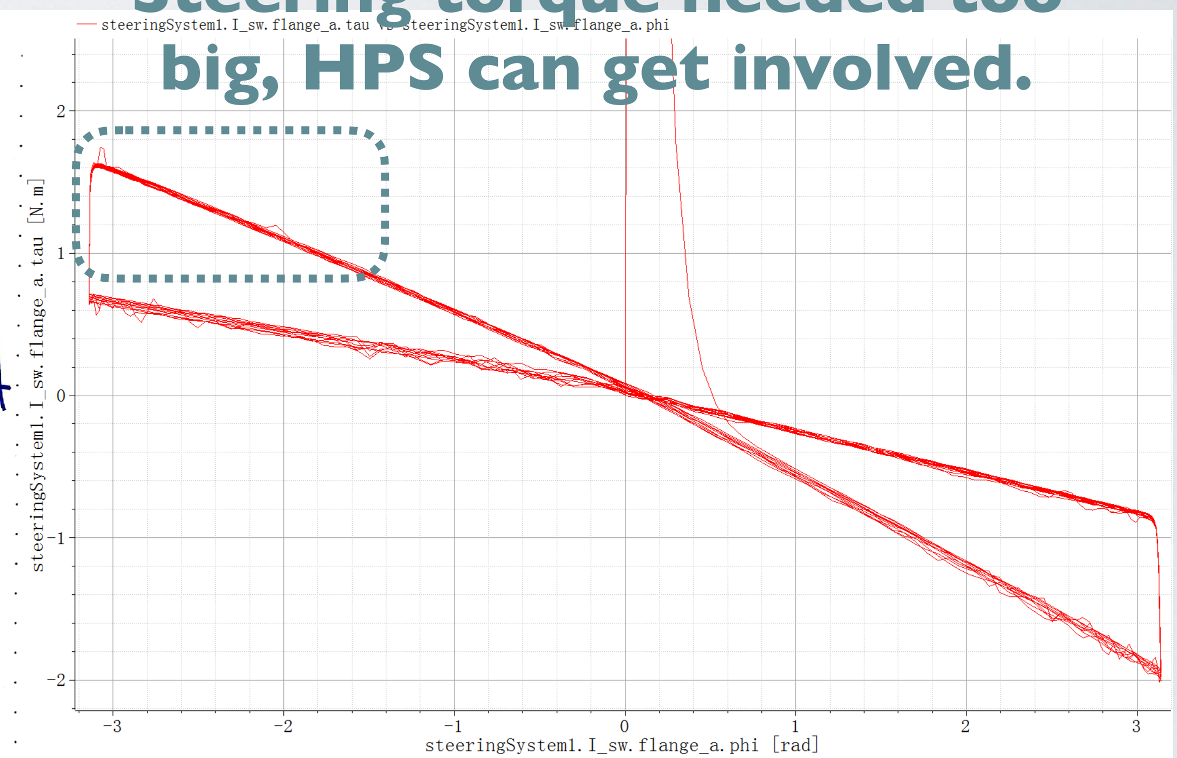
SIMULATION RESULTS

- Question: what can this platform do?

  - As a test platform for further design of HPS



Steering torque needed too big, HPS can get involved.



  - Develop a standard test platform for manipulating performance analysis

  - etc…