भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

MODELING AND DYNAMIC ANALYSIS OF ARTICULATED WHEEL LOADER

VEHICLE DYNAMICS(ME 5670)

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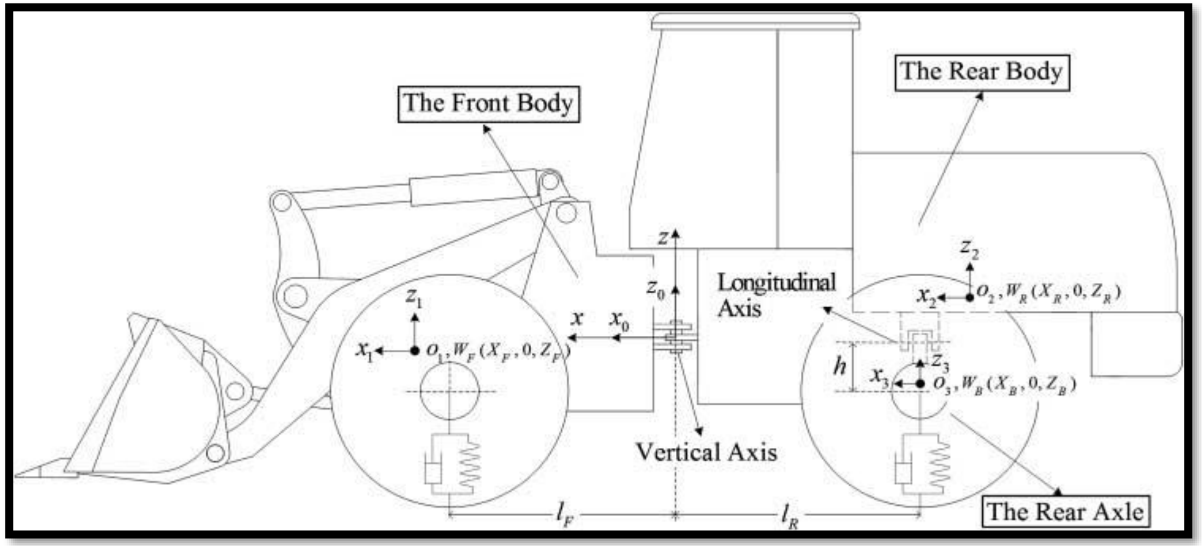
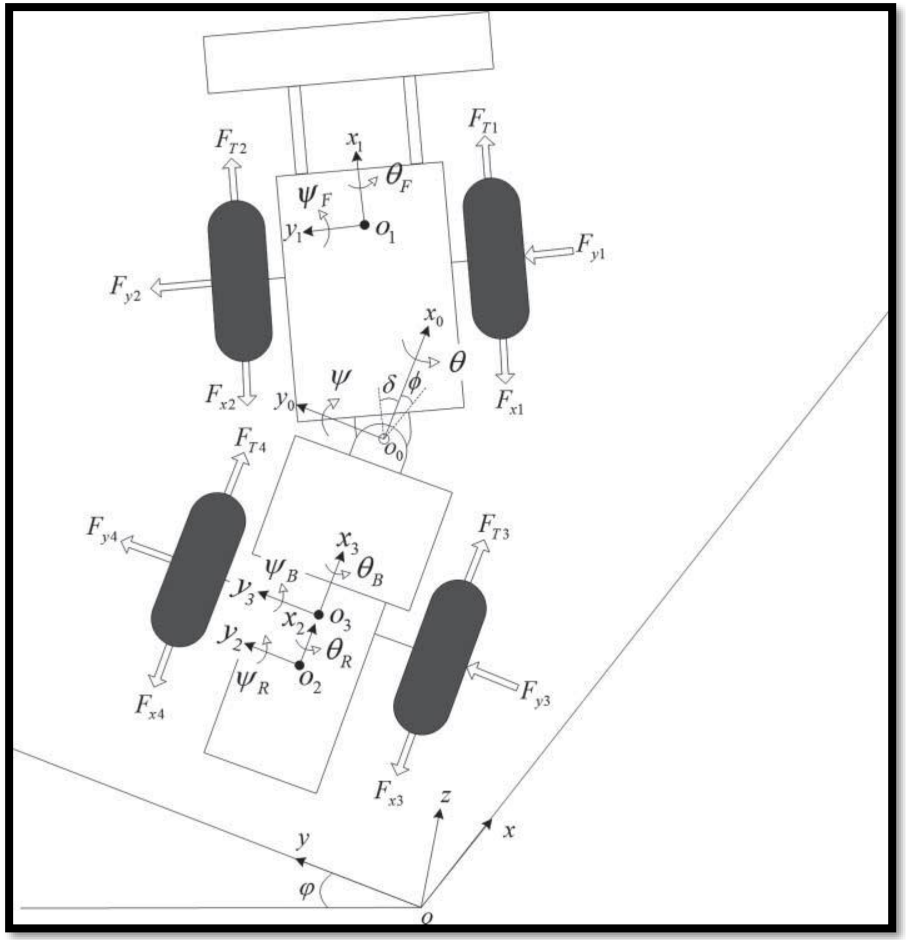
INTRODCUTION ARTICULATED WHEEL LOADER

- An articulated steering wheel loader has two separate parts that are connected by a vertical axis pivot. The relative yaw angle between these two parts is changed by two hydraulic cylinders when the driver turns the steering wheel.
- Research on the wheel loader stability and dynamics could be experiments and computer simulations.
- Experimental methods for studying the wheel loader stability and dynamics are limited because such methods entail a long experimental period, high cost, and higher risks.
- For these reasons, computer simulation is considered to be one of the most powerful methods for the study of the wheel loader stability and dynamics. It is able to predict the response of a wheel loader to operations by the operator and under given terrain conditions.



With respect to the global coordinate system ($o\!-\!xyz$), six motions exist in the local coordinate system ($o0\!-\!x0y0z0$) as listed below:

- Forward displacement (x),
- lateral displacement (y)
- Vertical displacement (z)
- roll (θ)
- pitch (ψ)
- yaw (φ),



MATHEMATICAL MODELLING AND GOVERNING EQUATIONS

(1) Front body

$$
\begin{aligned}
{}^{o}x_{\mathrm{F}} &= x + X_{\mathrm{F}} \cos\delta \cos\psi \cos\varphi - X_{\mathrm{F}} \sin\delta(\cos\theta \sin\varphi - \sin\theta \sin\psi \cos\varphi) \\
&\quad + Z_{\mathrm{F}}(\sin\theta \sin\varphi + \cos\theta \sin\psi \cos\varphi), \\
{}^{o}y_{\mathrm{F}} &= y + X_{\mathrm{F}} \cos\delta \cos\psi \sin\varphi + X_{\mathrm{F}} \sin\delta(\cos\theta \cos\varphi + \sin\theta \sin\psi \sin\varphi) \\
&\quad - Z_{\mathrm{F}}(\sin\theta \cos\varphi - \cos\theta \sin\psi \sin\varphi), \\
{}^{o}z_{\mathrm{F}} &= z - X_{\mathrm{F}} \cos\delta \sin\psi + X_{\mathrm{F}} \sin\delta \sin\theta \cos\psi + Z_{\mathrm{F}} \cos\theta \cos\psi, \\
\theta_{\mathrm{F}} &= \theta \cos\delta + \psi \sin\delta, \\
\psi_{\mathrm{F}} &= \psi \cos\delta - \theta \sin\delta, \\
\varphi_{\mathrm{F}} &= \varphi + \delta.
\end{aligned}
$$

(2) Rear body

$$
\begin{aligned}
{}^{o}x_{\mathrm{R}} &= x + Z_{\mathrm{R}}(\sin\theta \sin\varphi + \cos\theta \cos\varphi \sin\psi) + X_{\mathrm{R}} \cos\psi \cos\varphi \\
{}^{o}y_{\mathrm{R}} &= y - Z_{\mathrm{R}}(\sin\theta \cos\varphi - \cos\theta \sin\psi \sin\varphi) + X_{\mathrm{R}} \cos\psi \sin\varphi, \\
{}^{o}z_{\mathrm{R}} &= z - X_{\mathrm{R}} \sin\psi + Z_{\mathrm{R}} \cos\theta \cos\psi, \\
\theta_{\mathrm{R}} &= \theta, \\
\psi_{\mathrm{R}} &= \psi, \\
\varphi_{\mathrm{R}} &= \varphi.
\end{aligned}
$$

(3) Rear axle

$$
\begin{aligned}
{}^{o}x_{\mathrm{B}} &= x + X_{\mathrm{B}} \cos\psi \cos\varphi + Z_{\mathrm{B}}(\sin\theta_1 \sin\varphi + \cos\theta_1 \cos\varphi \sin\psi), \\
{}^{o}y_{\mathrm{B}} &= y + X_{\mathrm{B}} \cos\psi \sin\varphi - Z_{\mathrm{B}}(\sin\theta_1 \cos\varphi - \cos\theta_1 \sin\psi \sin\varphi), \\
{}^{o}z_{\mathrm{B}} &= z - X_{\mathrm{B}} \sin\psi + Z_{\mathrm{B}} \cos\theta_1 \cos\psi \\
\theta_{\mathrm{B}} &= \theta_1, \\
\psi_{\mathrm{B}} &= \psi, \\
\varphi_{\mathrm{B}} &= \varphi.
\end{aligned}
$$

Governing equations:

Lagrange equations were used to derive the governing equations of motion for the wheel loader system

$$\boxed{\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial T}{\partial \dot{q}_j} - \frac{\partial T}{\partial q_j} + \frac{\partial U}{\partial q_j} = Q_j.}$$

The kinetic energy of the system can be written as

$$\begin{aligned} T = [& m_{\mathrm{F}}({}^{o}\dot{x}_{\mathrm{F}}^{2} + {}^{o}\dot{y}_{\mathrm{F}}^{2} + {}^{o}\dot{z}_{\mathrm{F}}^{2}) + m_{\mathrm{R}}({}^{o}\dot{x}_{\mathrm{R}}^{2} + {}^{o}\dot{y}_{\mathrm{R}}^{2} + {}^{o}\dot{z}_{\mathrm{R}}^{2}) + m_{\mathrm{B}}({}^{o}\dot{x}_{\mathrm{B}}^{2} + {}^{o}\dot{y}_{\mathrm{B}}^{2} + {}^{o}\dot{z}_{\mathrm{B}}^{2}) \\ & + (I_{XX\mathrm{F}}\dot{\theta}_{\mathrm{F}}^{2} + I_{YY\mathrm{F}}\dot{\psi}_{\mathrm{F}}^{2} + I_{ZZ\mathrm{F}}\dot{\varphi}_{\mathrm{F}}^{2}) + (I_{XX\mathrm{R}}\dot{\theta}_{\mathrm{R}}^{2} + I_{YY\mathrm{R}}\dot{\psi}_{\mathrm{R}}^{2} \\ & + I_{ZZ\mathrm{R}}\dot{\varphi}_{\mathrm{R}}^{2}) + (I_{XX\mathrm{B}}\dot{\theta}_{\mathrm{B}}^{2} + I_{YY\mathrm{B}}\dot{\psi}_{\mathrm{B}}^{2} + I_{ZZ\mathrm{B}}\dot{\varphi}_{\mathrm{B}}^{2})]/2 \end{aligned}$$

The potential energy of the system can be written as

$$\boxed{U = m_{\mathrm{F}}g({}^{o}y_{\mathrm{F}}\sin\phi + {}^{o}z_{\mathrm{F}}\cos\phi) + m_{\mathrm{R}}g({}^{o}y_{\mathrm{R}}\sin\phi + {}^{o}z_{\mathrm{R}}\cos\phi) + m_{\mathrm{B}}g({}^{o}y_{\mathrm{B}}\sin\phi + {}^{o}z_{\mathrm{B}}\cos\phi).}$$

The generalized forces that are required to solve Lagrange's equation are as follows:

$$
\begin{aligned}
Q_x &= -(F_{y1} + F_{y2}) \sin(\varphi + \delta) - (F_{y3} + F_{y4}) \sin\varphi + (F_{T1} + F_{T2} - F_{x1} - F_{x2}) \cos(\varphi + \delta) \\
&\quad + (F_{T3} + F_{T4} - F_{x3} - F_{x4}) \cos\varphi, \\
Q_y &= (F_{y1} + F_{y2}) \cos(\varphi + \delta) + (F_{y3} + F_{y4}) \cos\varphi + (F_{T1} + F_{T2} - F_{x1} - F_{x2}) \sin(\varphi + \delta) \\
&\quad + (F_{T3} + F_{T4} - F_{x3} - F_{x4}) \sin\varphi, \\
Q_z &= F_{z1} + F_{z2} + F_{z3} + F_{z4},
\end{aligned}
$$

$$
\begin{aligned}
Q_\theta &= (F_{y1} + F_{y2})(R + h) \cos\delta - F_{z1}(0.5B \cos\delta - l_F \sin\delta) + F_{z2}(0.5B \cos\delta + l_F \sin\delta), \\
Q_{\theta 1} &= (F_{y3} + F_{y4})(R + h) + 0.5B(F_{z4} - F_{z3}), \\
Q_\psi &= -F_{z1}(l_F \cos\delta + 0.5B \sin\delta) - F_{z2}(l_F \cos\delta - 0.5B \sin\delta) + (F_{z3} + F_{z4}) l_R, \\
Q_\varphi &= (F_{y1} + F_{y2}) l_F - (F_{y3} + F_{y4}) l_R. \qquad (8)
\end{aligned}
$$

Given that the loader's longitudinal speed is constant, the traction forces F_{Ti}, rolling resistance forces F_{xi}, and component force of gravity along the longitudinal direction are balanced.
Therefore, the longitudinal forces are:

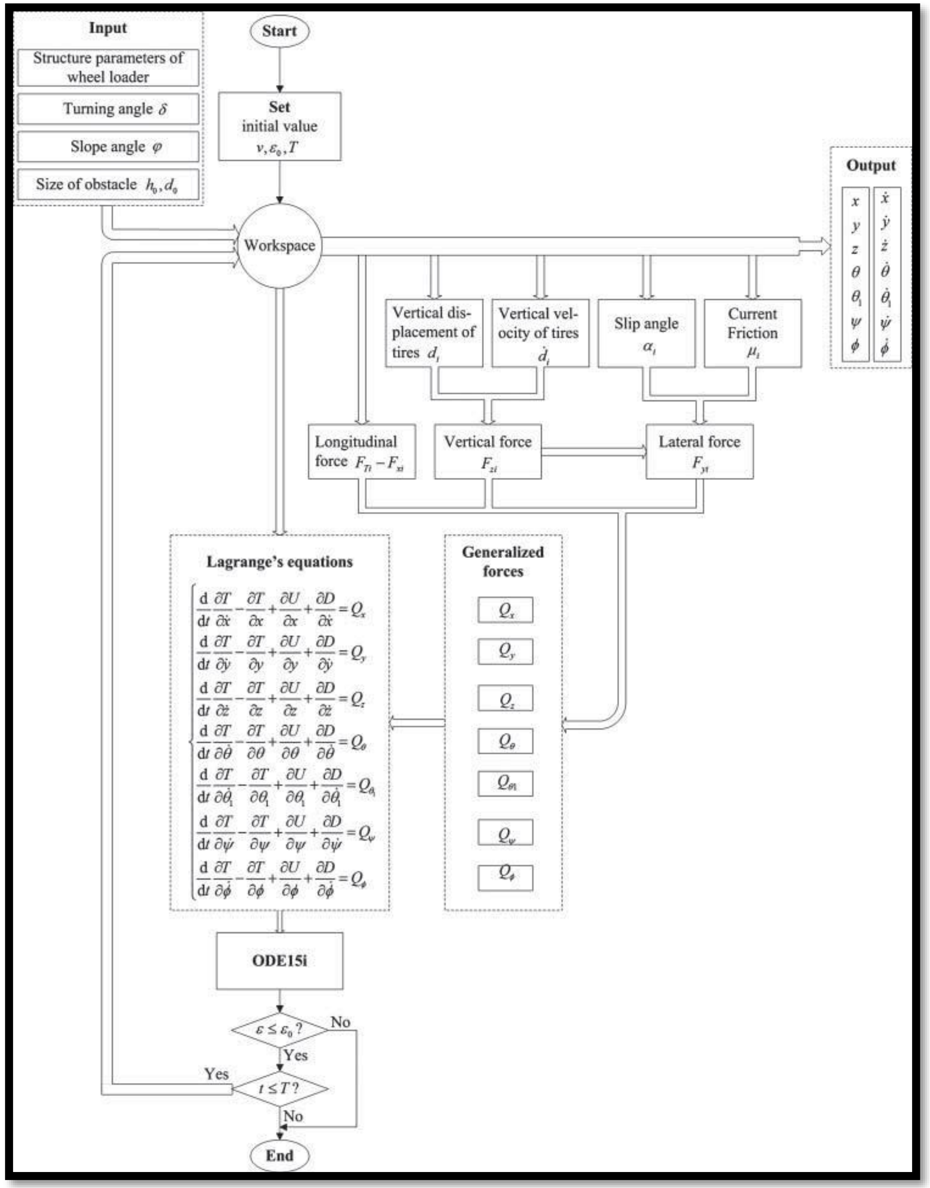
$$F_{T1} - F_{x1} - \frac{m_F g \sin\phi \sin(\varphi + \delta)}{2} = 0,$$

$$F_{T2} - F_{x2} - \frac{m_F g \sin\phi \sin(\varphi + \delta)}{2} = 0,$$

$$F_{T3} - F_{x3} - \frac{(m_R + m_B) g \sin\phi \sin\varphi}{2} = 0,$$

$$F_{T4} - F_{x4} - \frac{(m_R + m_B) g \sin\phi \sin\varphi}{2} = 0.$$

MATHEMATICAL MODELLING FLOWCHART

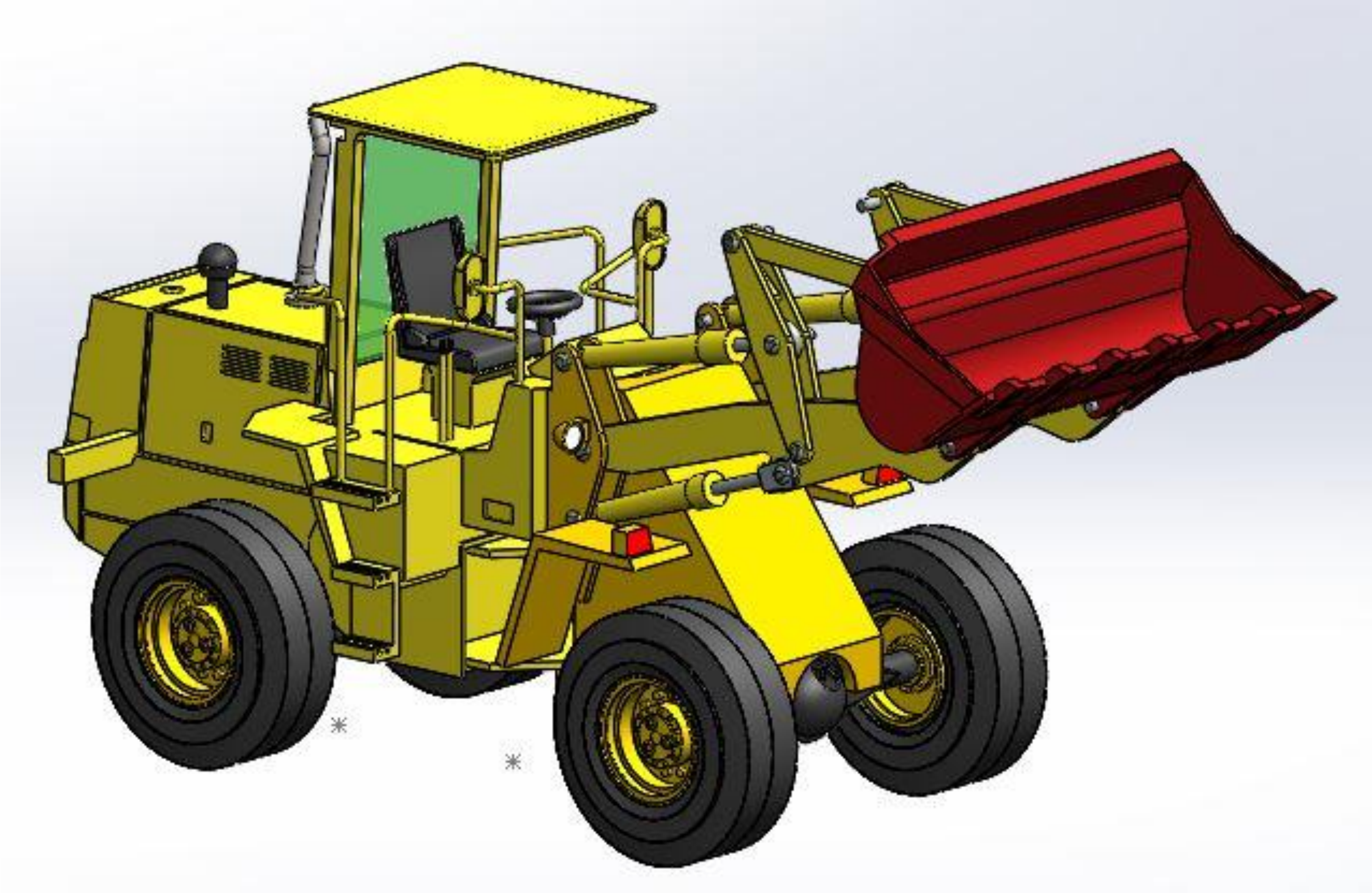


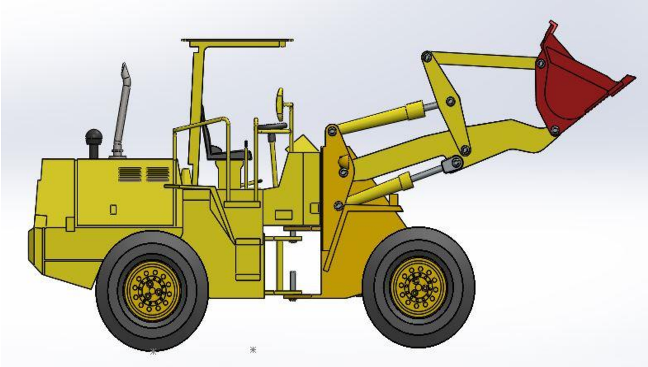
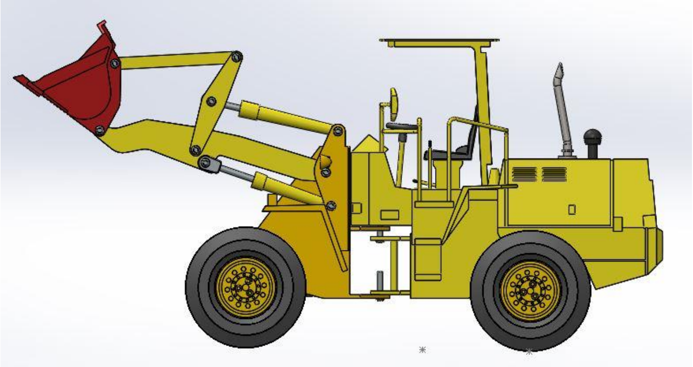
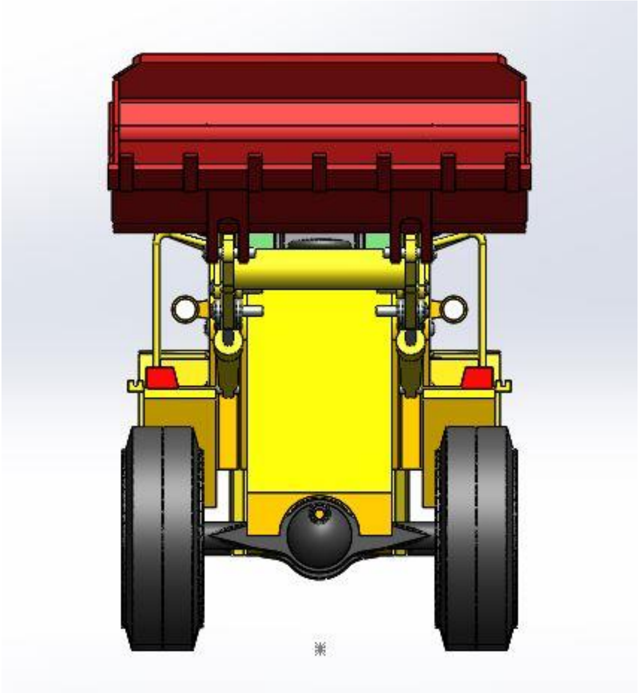
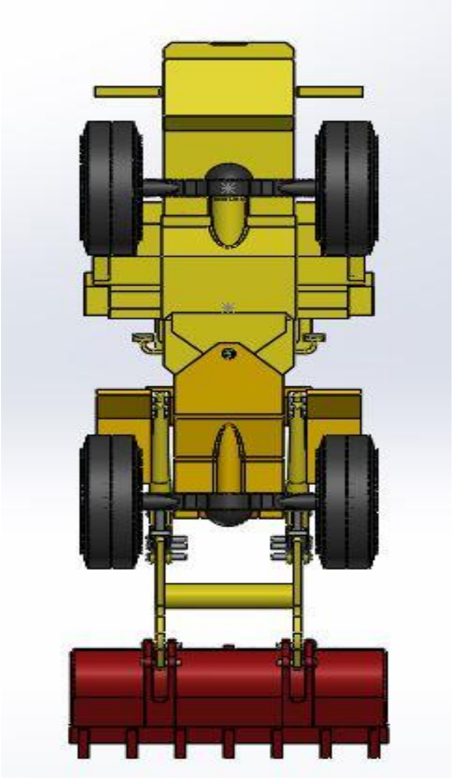
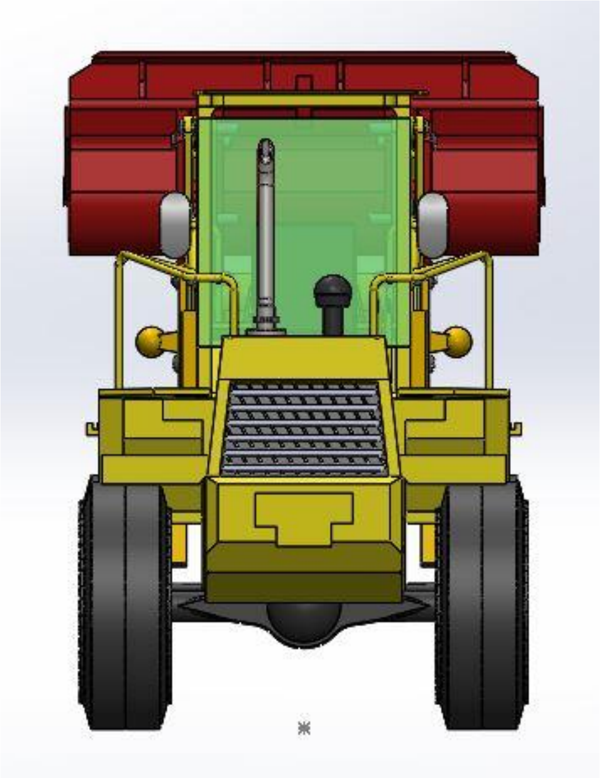
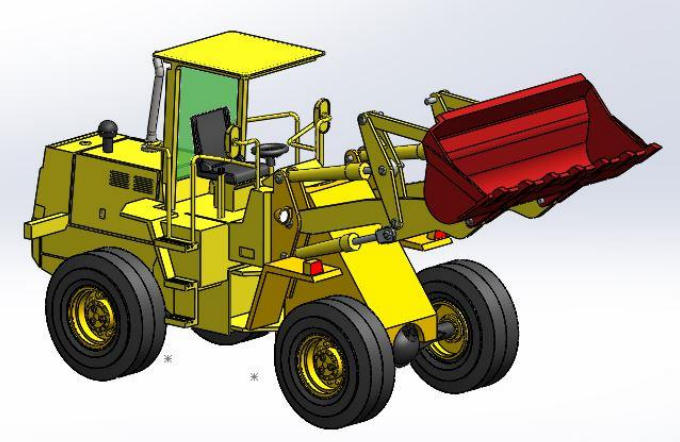
OBJECTIVE

To model wheel loader(kobelco) and testing for dynamic analysis under:

- **Simulations of Wheel loader on level road with obstacle**
- **Simulations of Wheel loader when taking turning on level road without obstacle**
- **Simulations of Wheel loader when taking turning on level road with obstacle**
- **Simulations of Wheel loader on level road with slope**
- **Simulations of Wheel loader on level road with slope with Obstacle**

CAD MODEL:

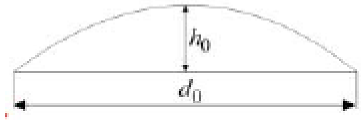


Simulations of Wheel loader on level road with obstacle

Operating conditions:

I. Vehicle speed(m/s) : 0.5
II. Turn Radius : 0.4m
III. Slope angle : 0
IV. Obstacle dimensions: d_o=0.2m, h_o=0.05m.



Obstacle dimensions

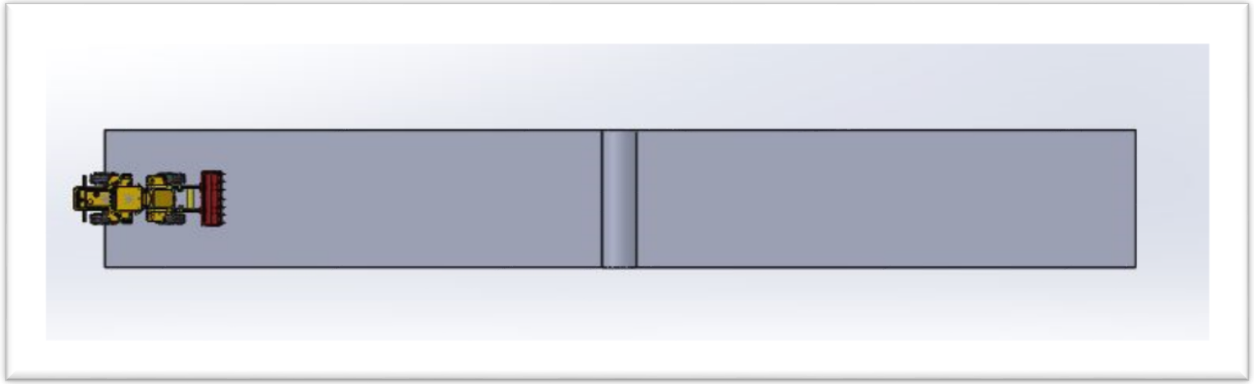
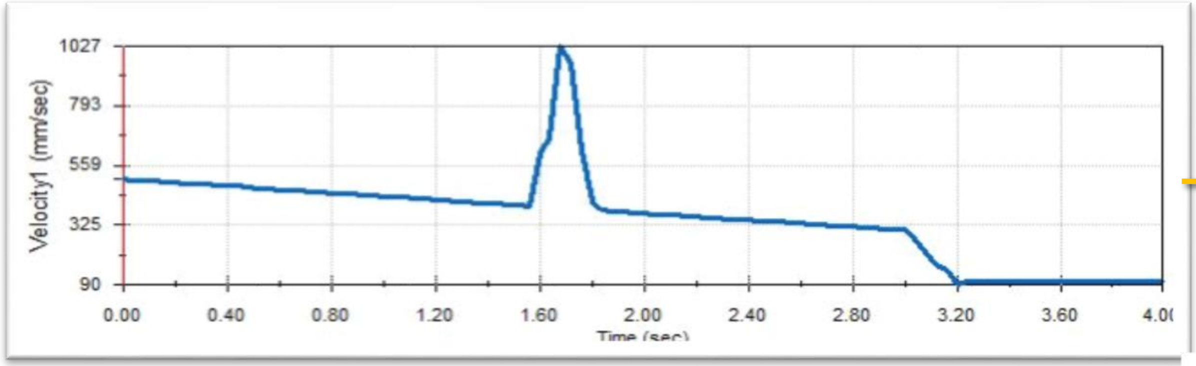
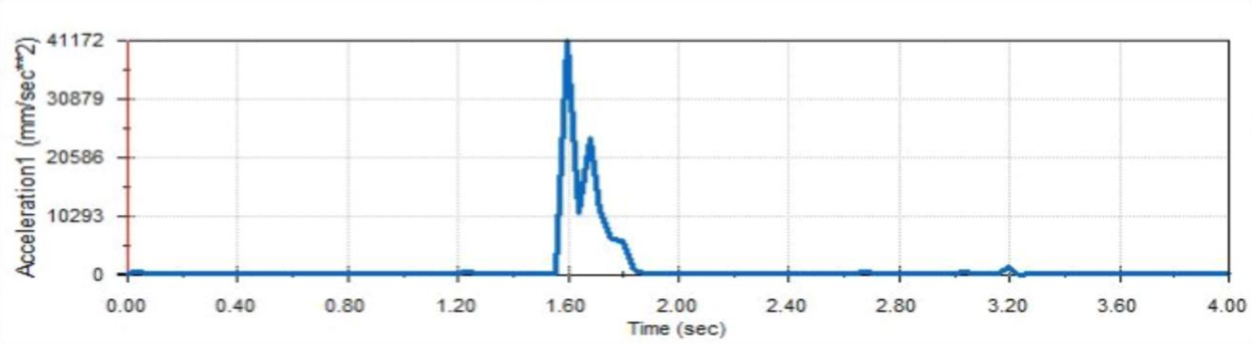


FIG: Wheel loader on level road with obstacle

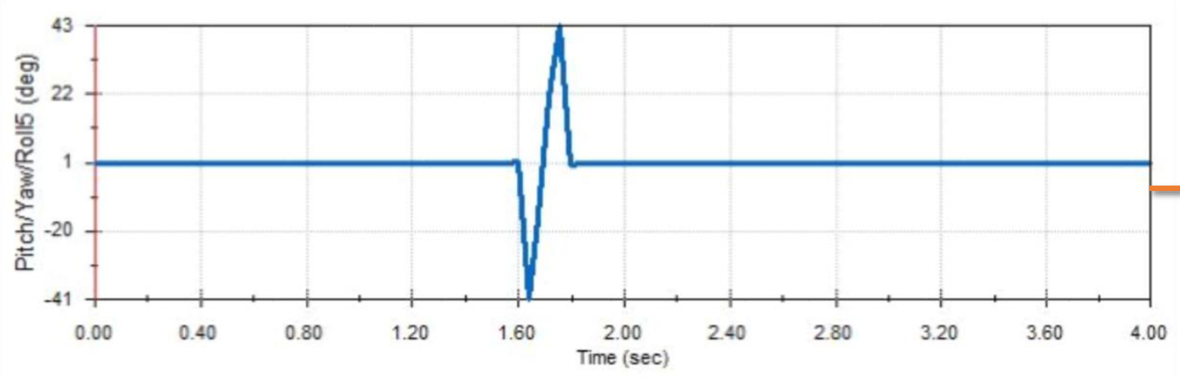
Results of simulation of Wheel loader on level road with obstacle.



Velocity Vs Time



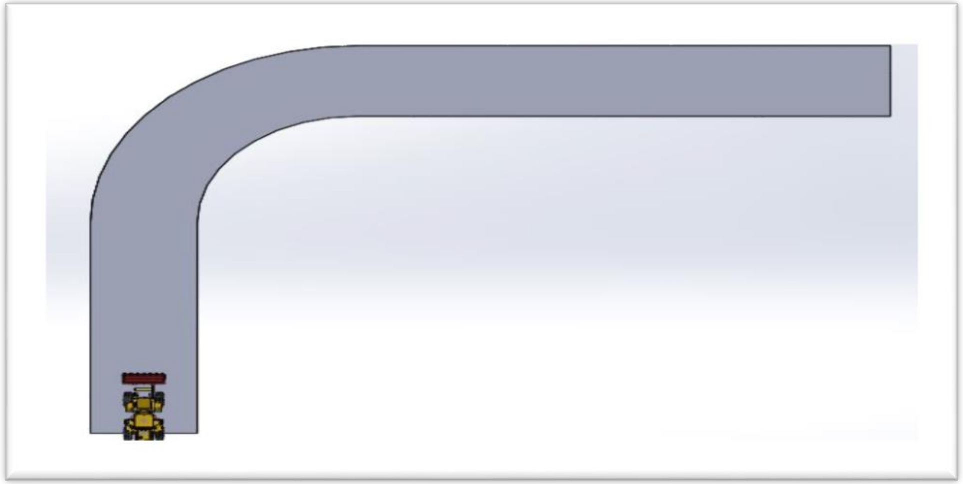
Acceleration vs time

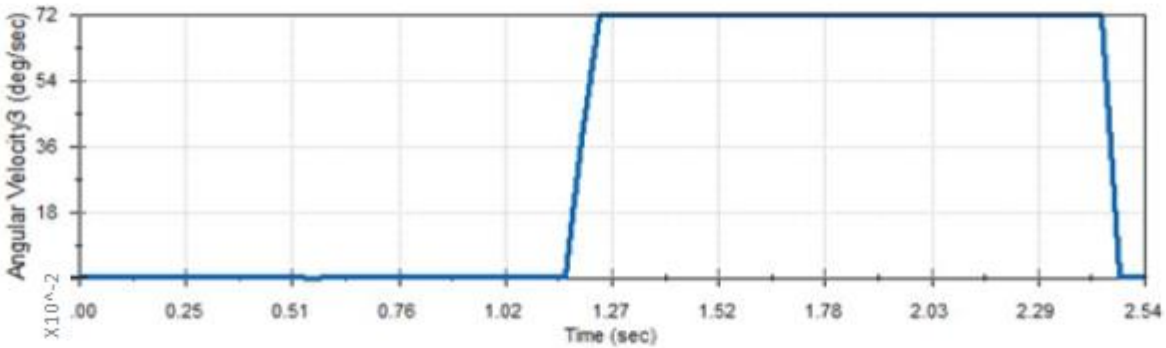


Pitching angle Vs Time

Simulations of Wheel loader when taking turning on level road without obstacle.

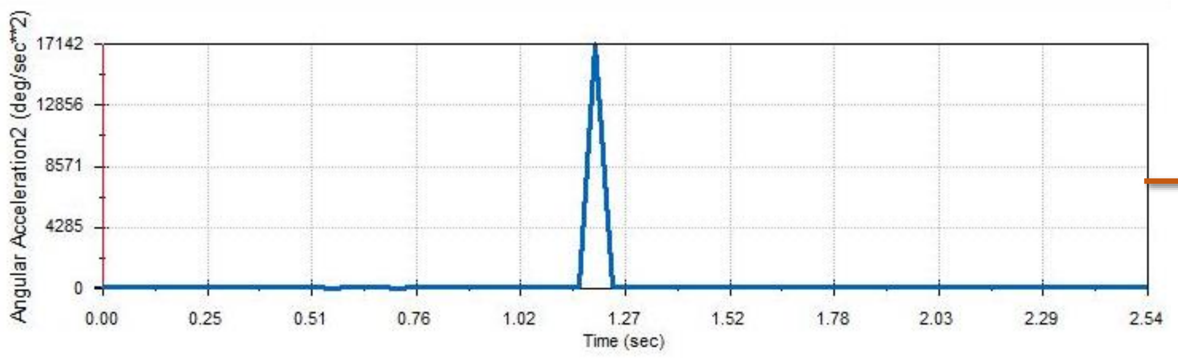
Operating conditions:
Vehicle speed(m/s) : 0.5
Turn Radius : 0.4m
Slope angle : 0



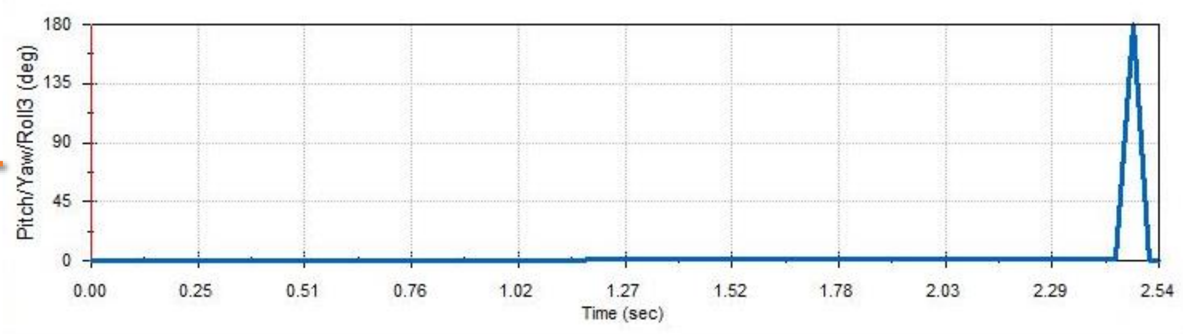


Angular velocity Vs Time

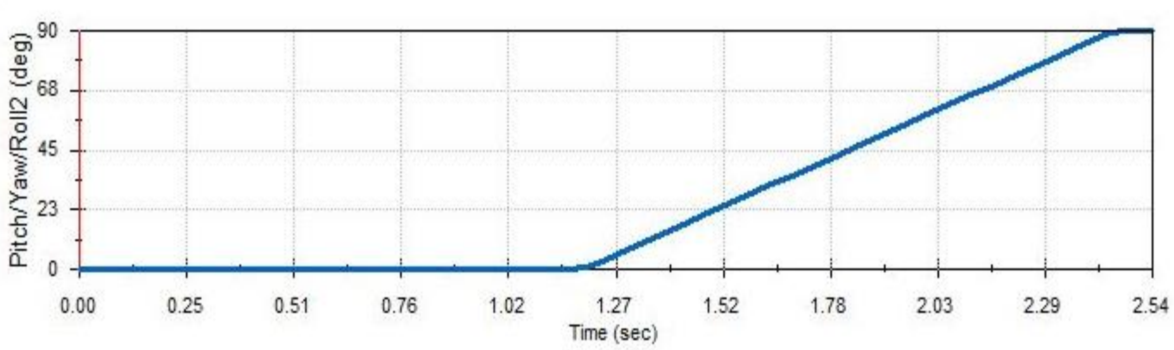
Simulations of Wheel loader when taking turning on level road without obstacle.



Angular acceleration Vs Time



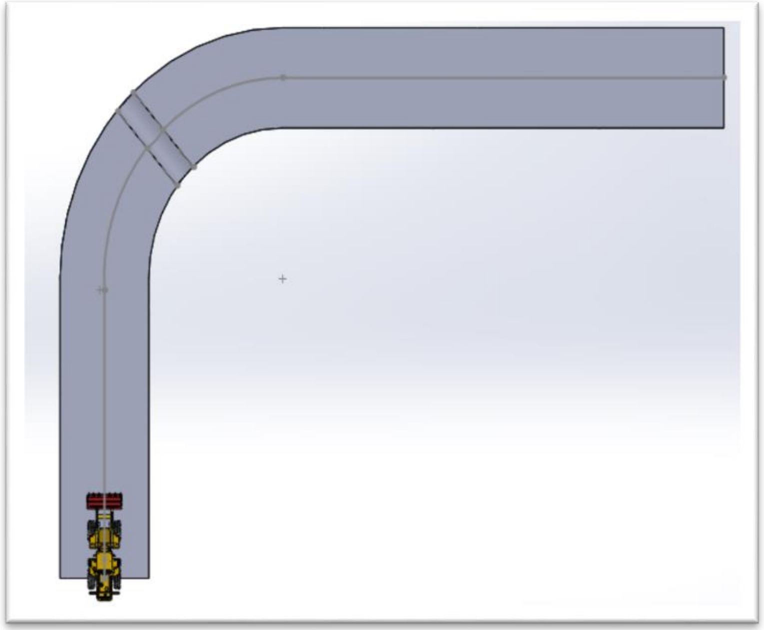
Rollinng angle Vs Time

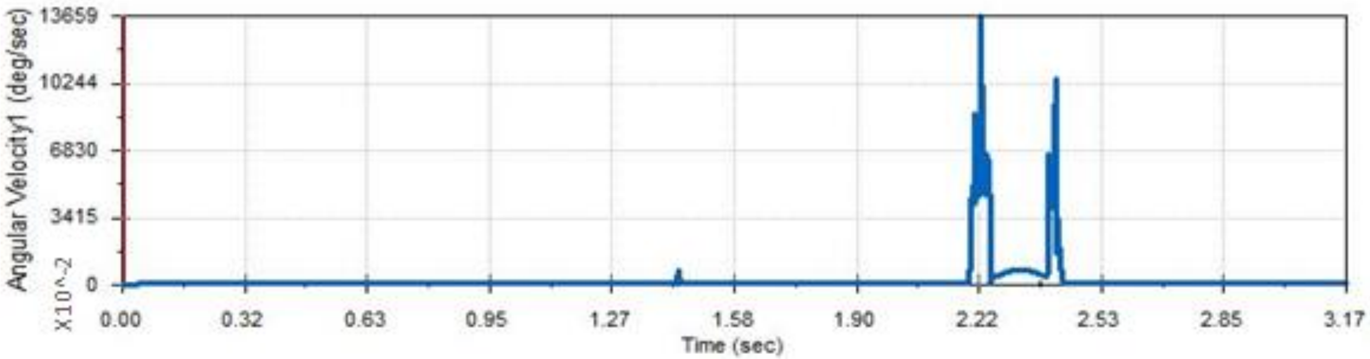


Pitching angle Vs Time

Simulations of Wheel loader when taking turning on level road with obstacle.

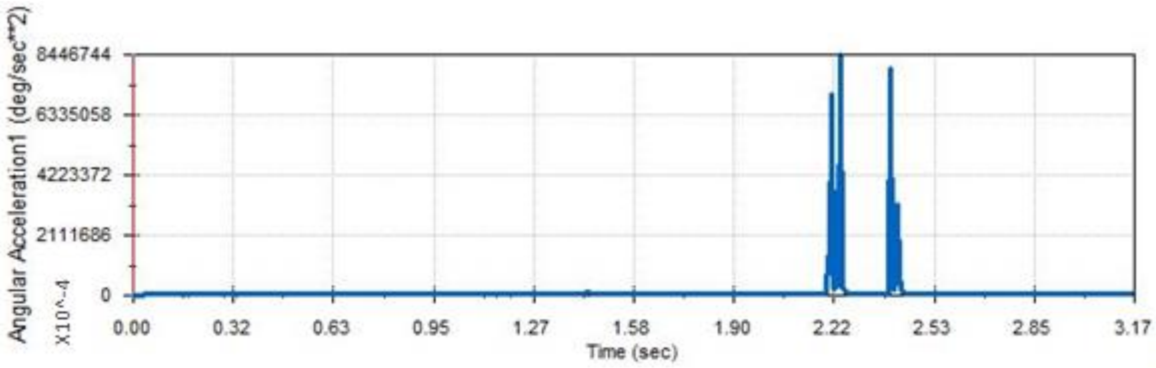
- Operating conditions:
- Vehicle speed(m/s) : 0.5
- Turn Radius : 0.4m
- Slope angle : 0
- Obstacle dimensions: d_o=0.2m, h_o=0.05m.



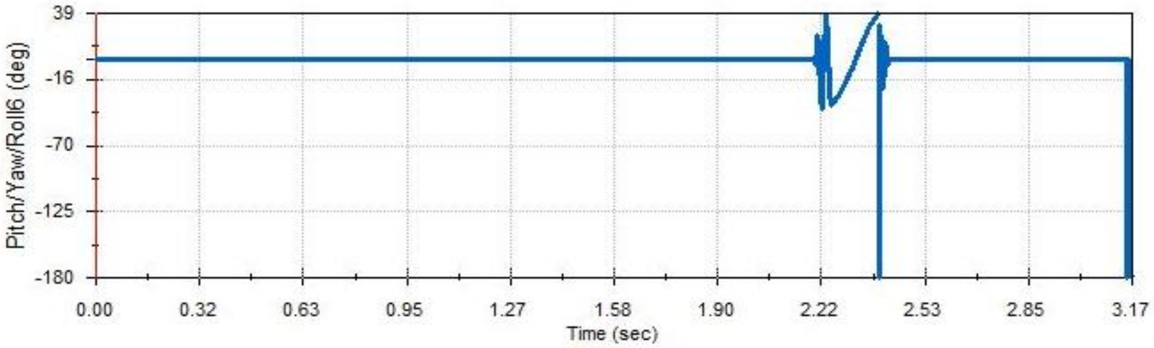


Angular velocity Vs Time

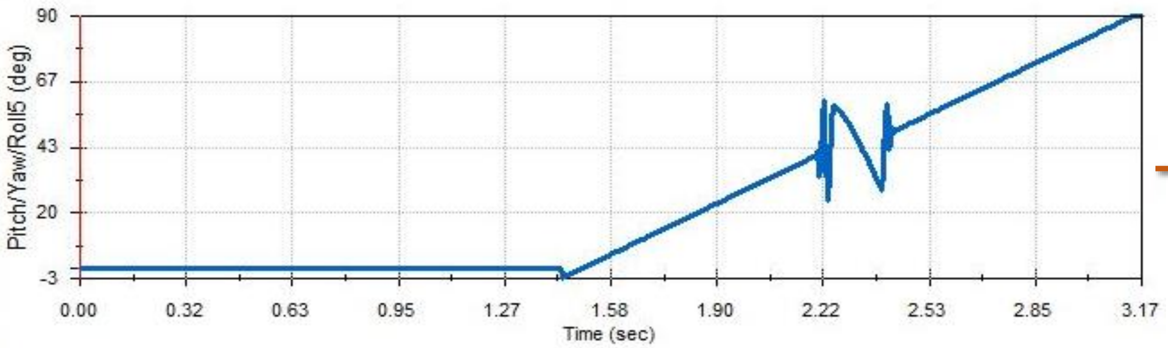
Result of simulations of Wheel loader when taking turning on level road with obstacle.



Angular acceleration Vs Time



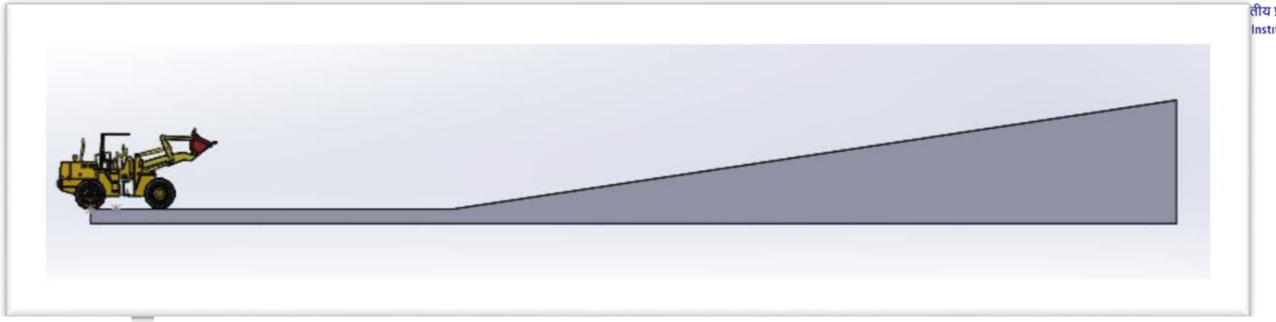
Rollinng angle Vs Time

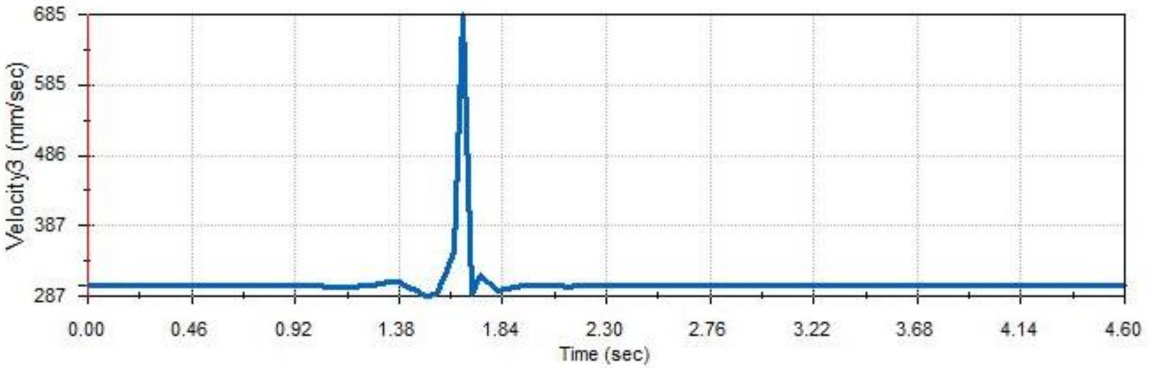


Pitching angle Vs Time

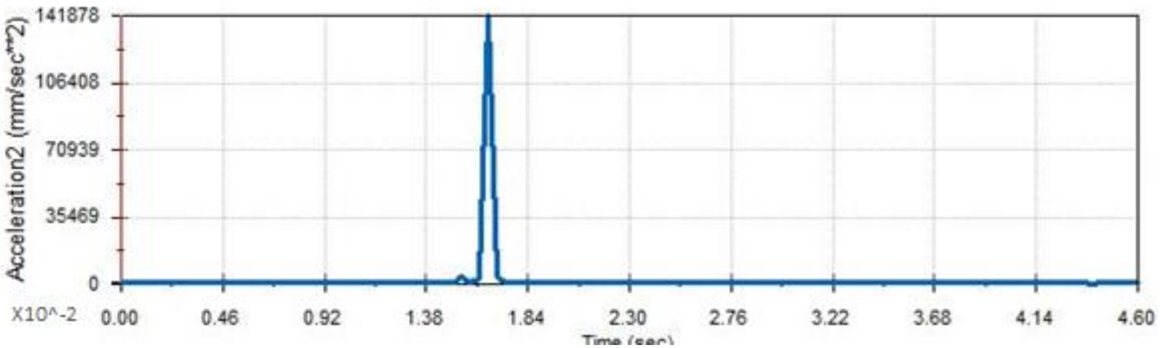
Simulations of Wheel loader on level road with slope.

Operating conditions:
Vehicle speed(m/s) : 0.3
Slope angle(Degree) : 16.69
Height of Slope : 300mm
Length of Slope : 1000mm

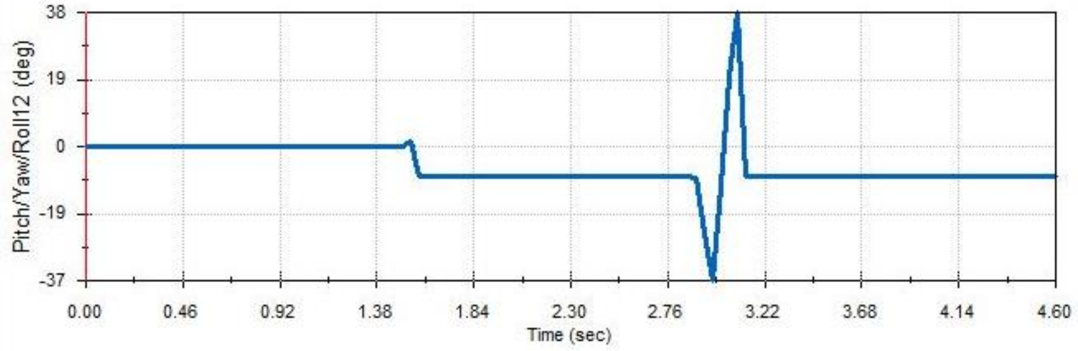




Linear Velocity v/s Time Plot



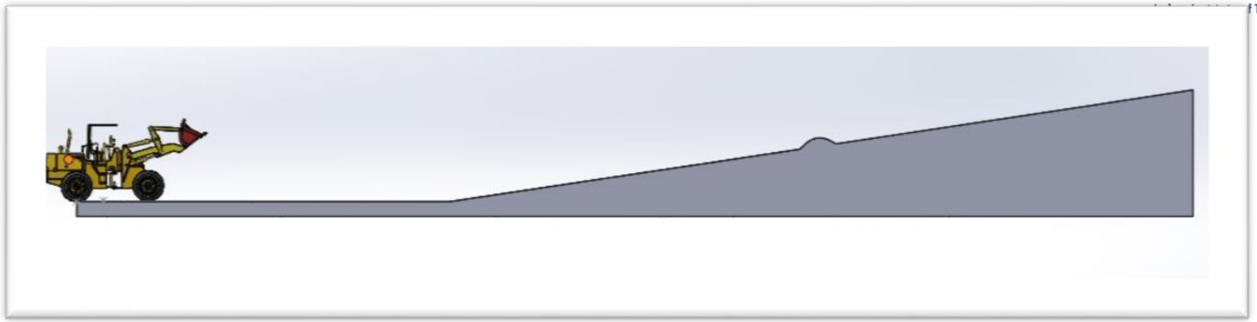
Linear Acceleration v/s Time Plot

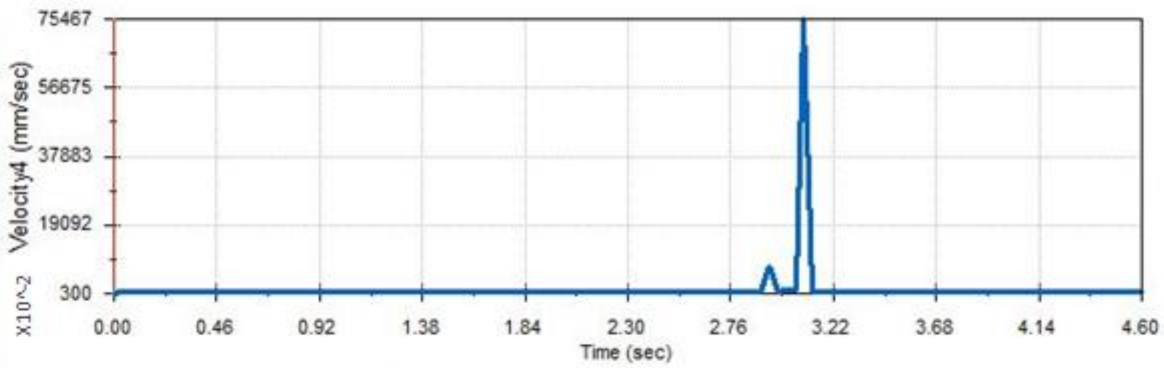


Rolling Angle v/s Time Plot

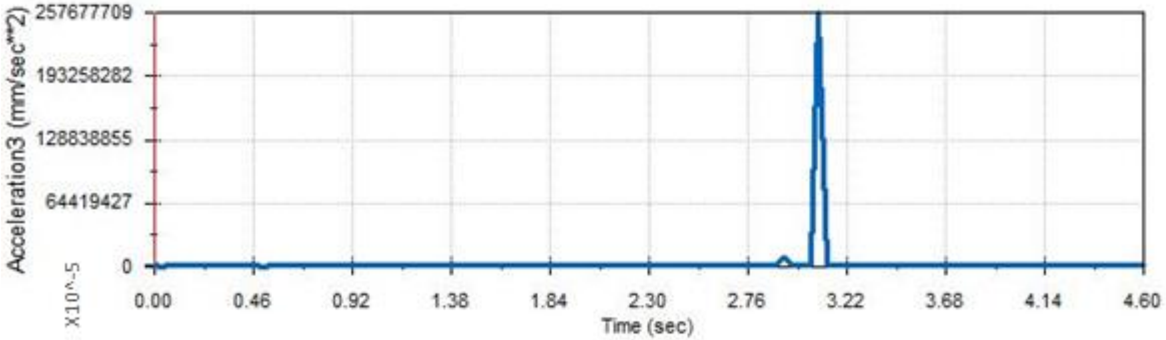
Simulations of Wheel loader on level road with slope with Obstacle.

- ❖ Operating conditions:
- ❖ Vehicle speed(m/s) : 0.3
- ❖ Slope angle(Degree) : 16.69
- ❖ Height of Slope : 300mm
- ❖ Length of Slope : 1000mm
- ❖ Obstacle dimensions: d_o=0.2m, h_o=0.05m.





Linear Velocity v/s Time Plot

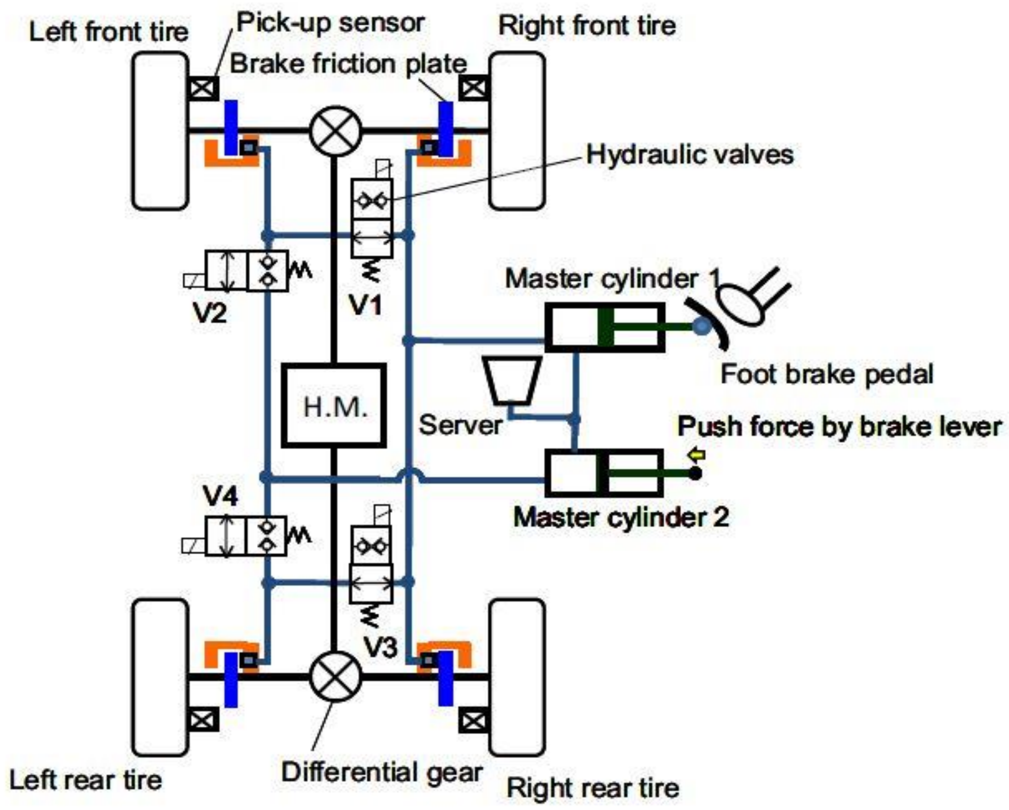


Linear Acceleration v/s Time Plot

Braking System for Direct Yaw-Moment Control

The test vehicle was modified to apply braking force on either the left or the right tires. Four hydraulic poppet valves and an auxiliary master cylinder were inserted into each hydraulic line in the brake system. These valves switch the brake system from normal mode to yaw-moment control mode. P_B is hydraulic pressure, brake piston force F_P and the braking force F_B on the tire generated by brake piston force F_P .

$$F_P = \mu_P A_P P_B$$



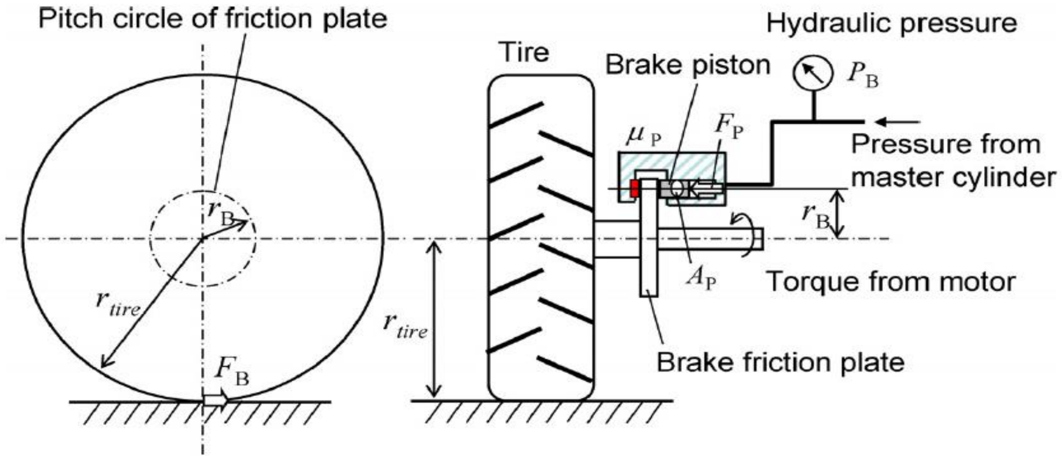
Braking System for Direct Yaw-Moment Control

$$F_P = \mu_P A_P P_B$$

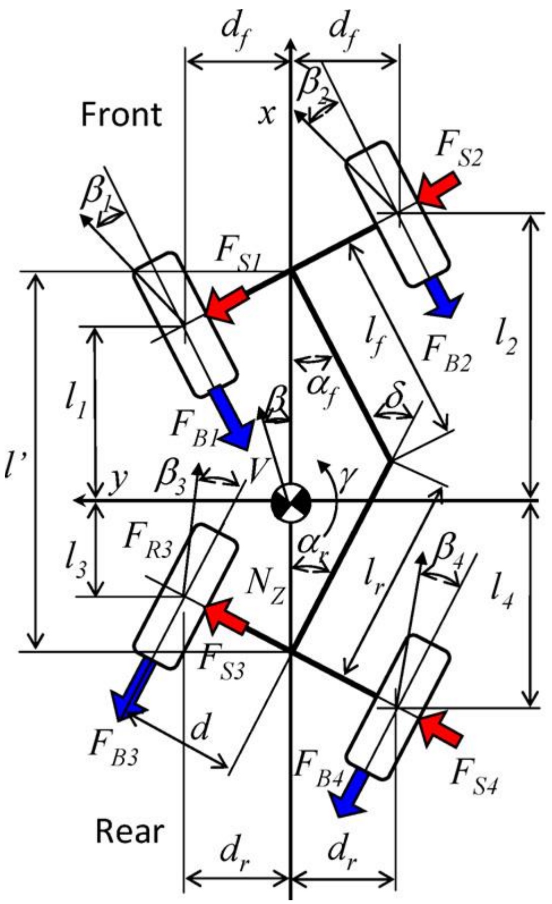
$$F_B = \frac{2 r_B F_P}{r_{tire}}$$

$$F_B = \frac{2 \mu_P r_B A_P P_B}{r_{tire}}$$

Where A_P is the cross-sectional area of the front or rear brake piston, and μ_P is the friction coefficient of the brake friction plate. And r_{tire} is the radius of the tire. The factor of 2 indicates that F_P acts both sides of the friction plate.



Equations of Motion



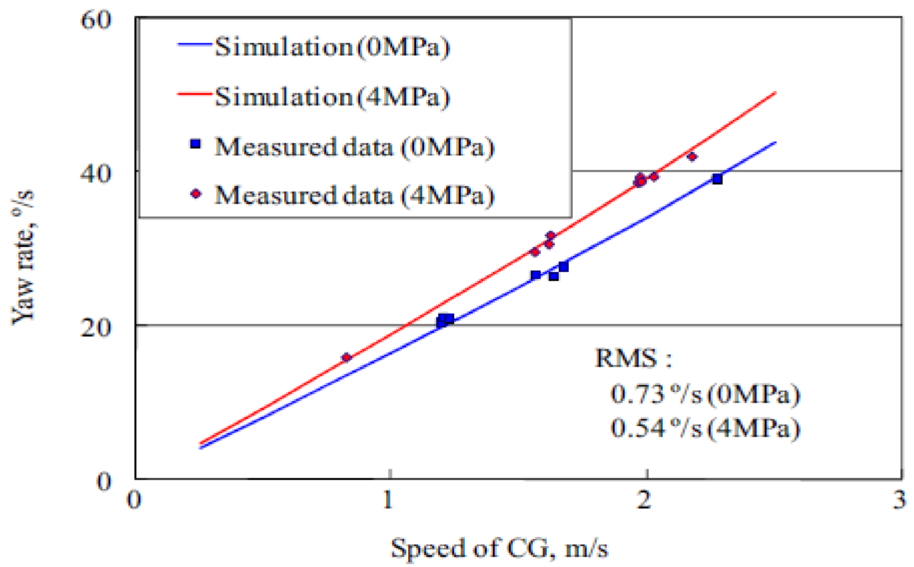
The equation of motion in the y-direction is:

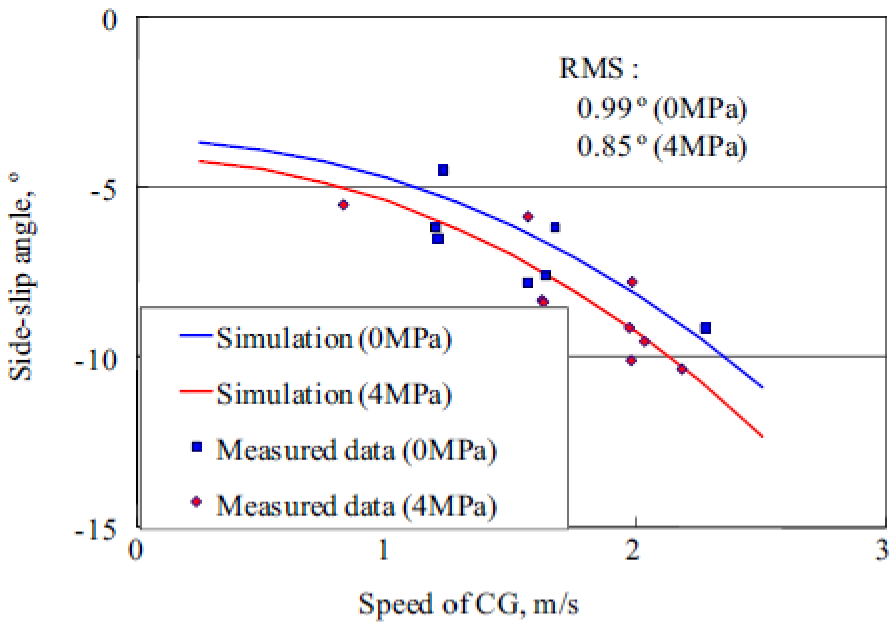
$$mV\left(\frac{d\beta}{dt}+\gamma\right)=(F_{S1}+F_{S2})\ \cos\alpha_f+(F_{S3}+F_{S4})\cos\alpha_r.$$

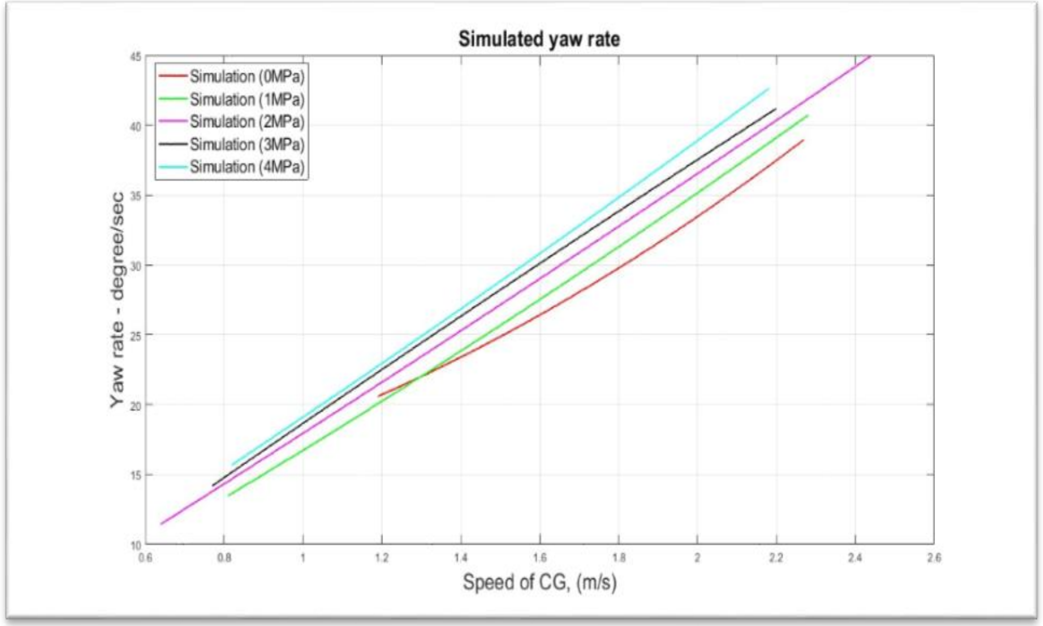
The yawing motion is:

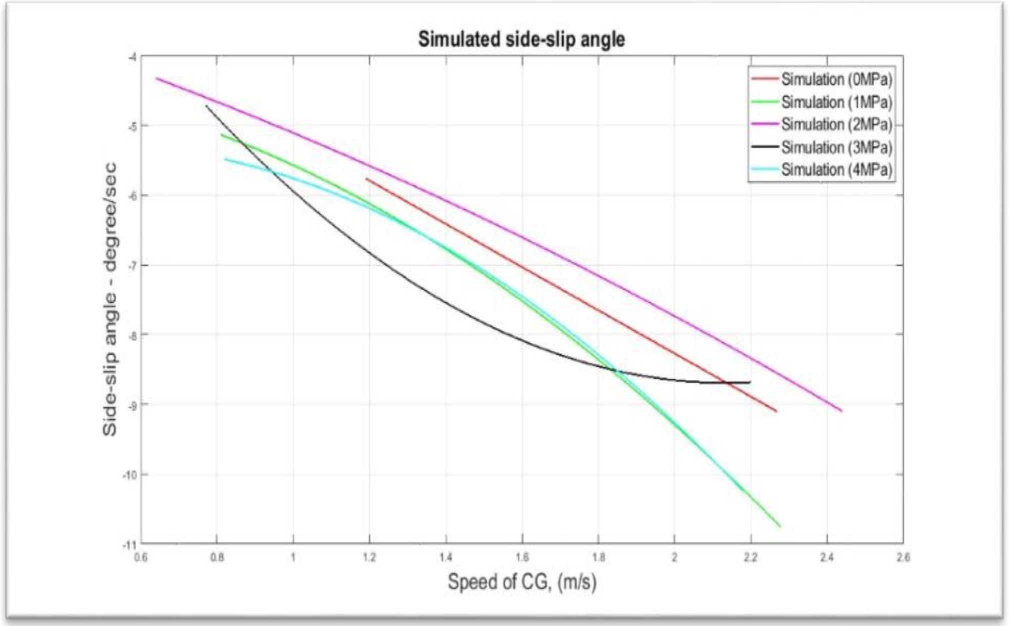
$$I\frac{d\gamma}{dt}=(l_1F_{S1}+l_2F_{S2})\cos\alpha_f+d_f(F_{S1}-F_{S2})\sin\alpha_f$$
$$-(l_3F_{S3}+l_4F_{S4})\cos\alpha_r-d_r(F_{S3}-F_{S4})\sin\alpha_r+N_Z.$$

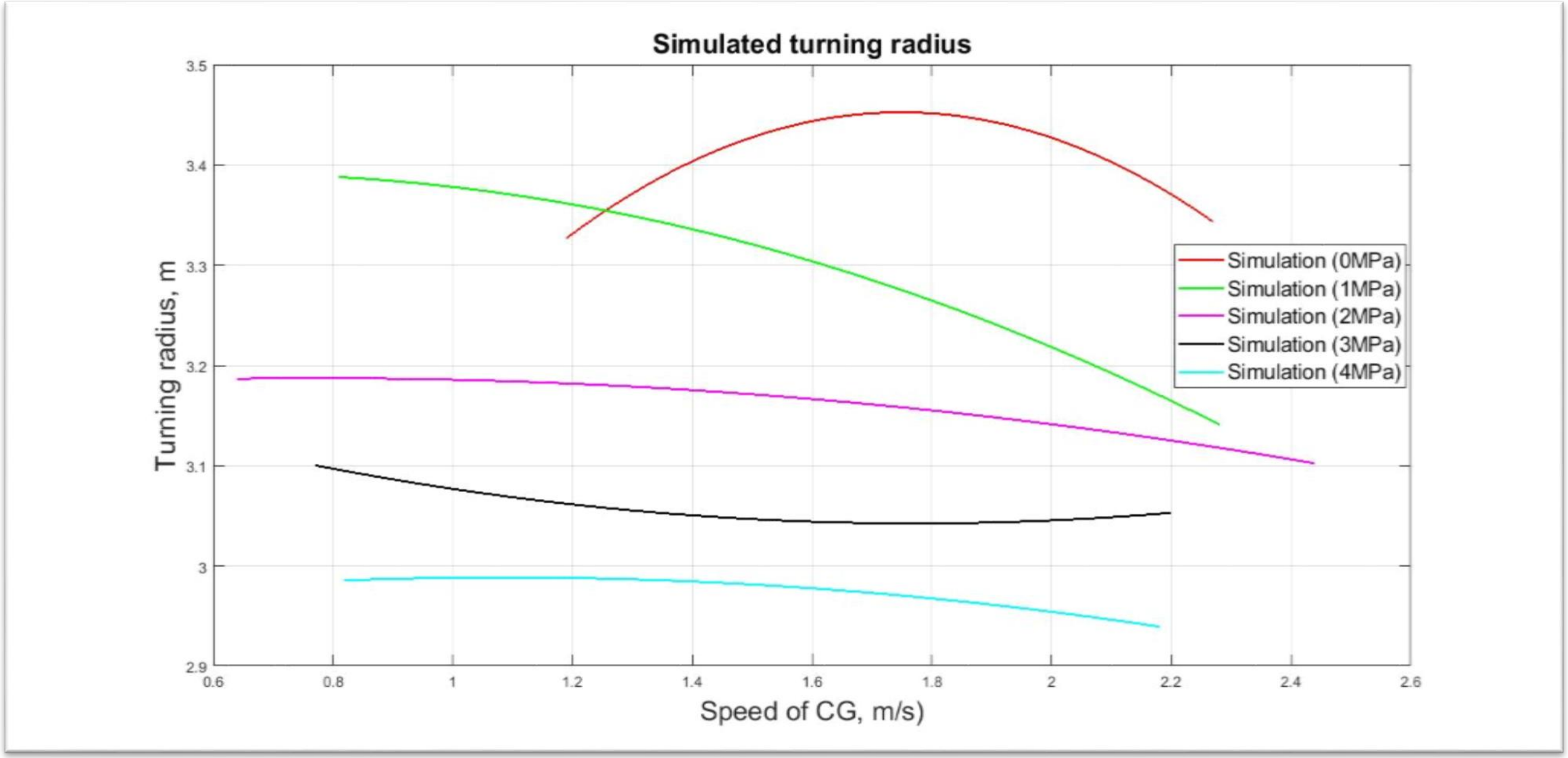
$$F_{S1}=-K_C\beta_1,\quad F_{S2}=-K_C\beta_2,$$
$$F_{S3}=-K_C\beta_3,\quad F_{S4}=-K_C\beta_4,$$


Simulation (0MPa)
Simulation (4MPa)
Measured data (0MPa)
Measured data (4MPa)
RMS :
0.73 °/s (0MPa)
0.54 °/s (4MPa)
Yaw rate, °/s
Speed of CG, m/s


RMS :
0.99 ° (0MPa)
0.85 ° (4MPa)
Simulation (0MPa)
Simulation (4MPa)
Measured data (0MPa)
Measured data (4MPa)
Side-slip angle, °
Speed of CG, m/s


Simulated yaw rate
Simulation (0MPa)
Simulation (1MPa)
Simulation (2MPa)
Simulation (3MPa)
Simulation (4MPa)
Yaw rate - degree/sec
Speed of CG, (m/s)

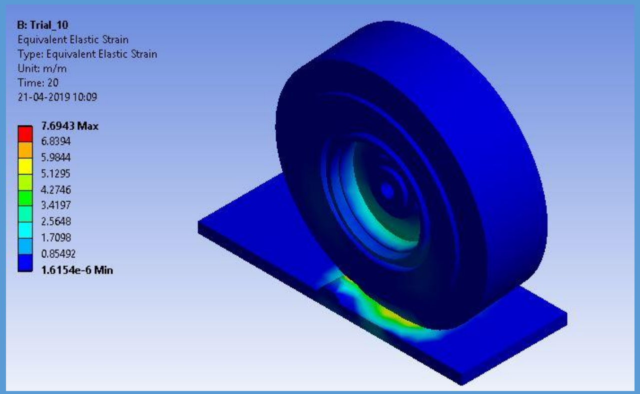

Simulated side-slip angle
Simulation (0MPa)
Simulation (1MPa)
Simulation (2MPa)
Simulation (3MPa)
Simulation (4MPa)
Side-slip angle - degree/sec
Speed of CG, (m/s)



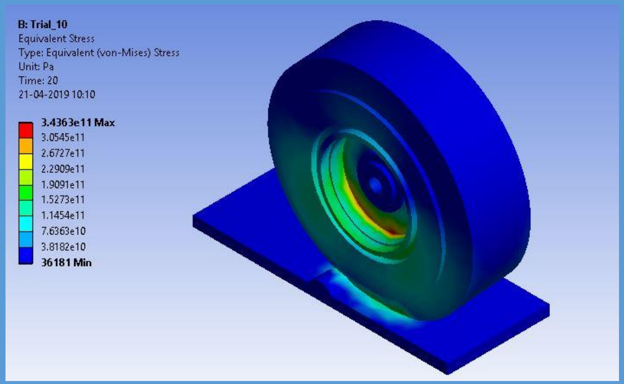
Simulated turning radius
Turning radius, m
Speed of CG, m/s
3.5
3.4
3.3
3.2
3.1
3
2.9
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
Simulation (0MPa)
Simulation (1MPa)
Simulation (2MPa)
Simulation (3MPa)
Simulation (4MPa)

Tire Analysis with Considering Lateral Force as Dominance over the Longitudinal Force

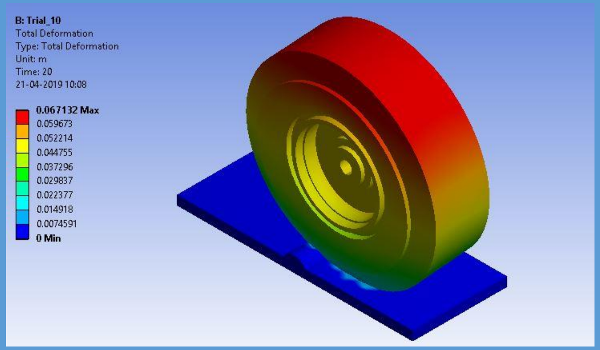
a) Strains at interface of wheel and ground



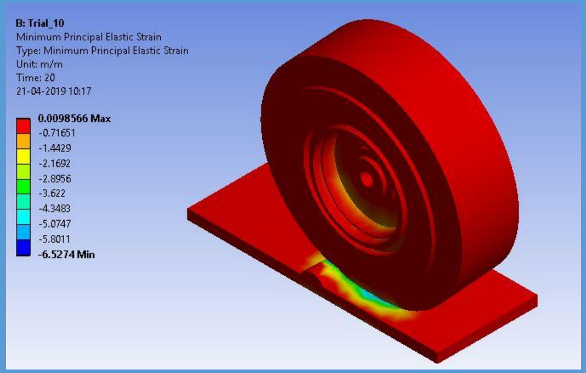
b) Stresses at interface of tire and ground

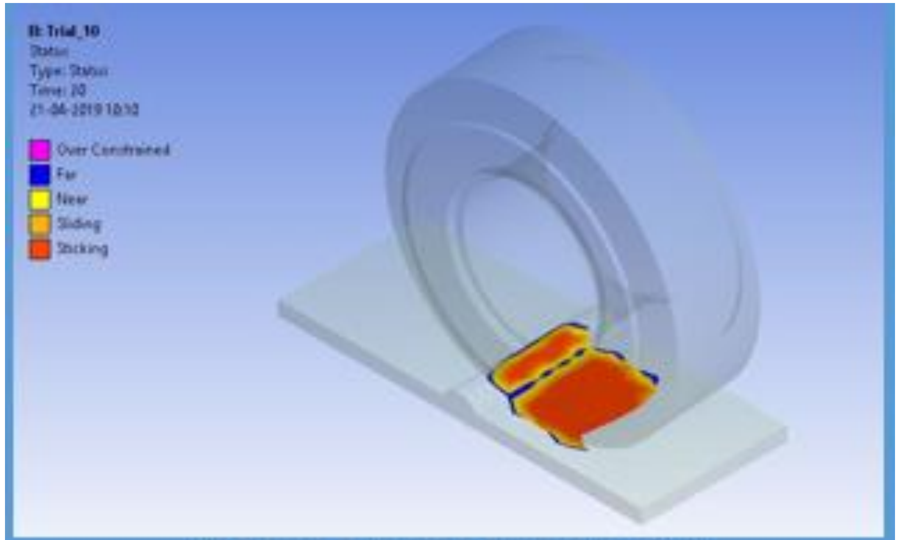


c) Total Deformation

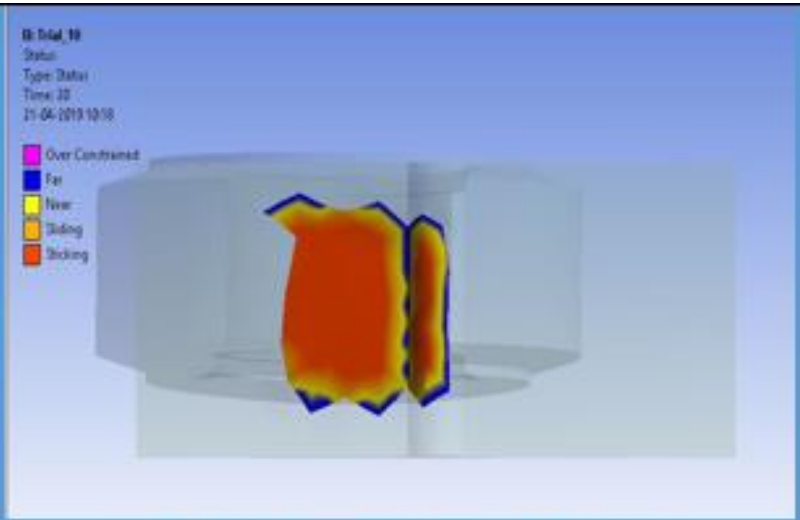


d) Minimum principle elastic strain

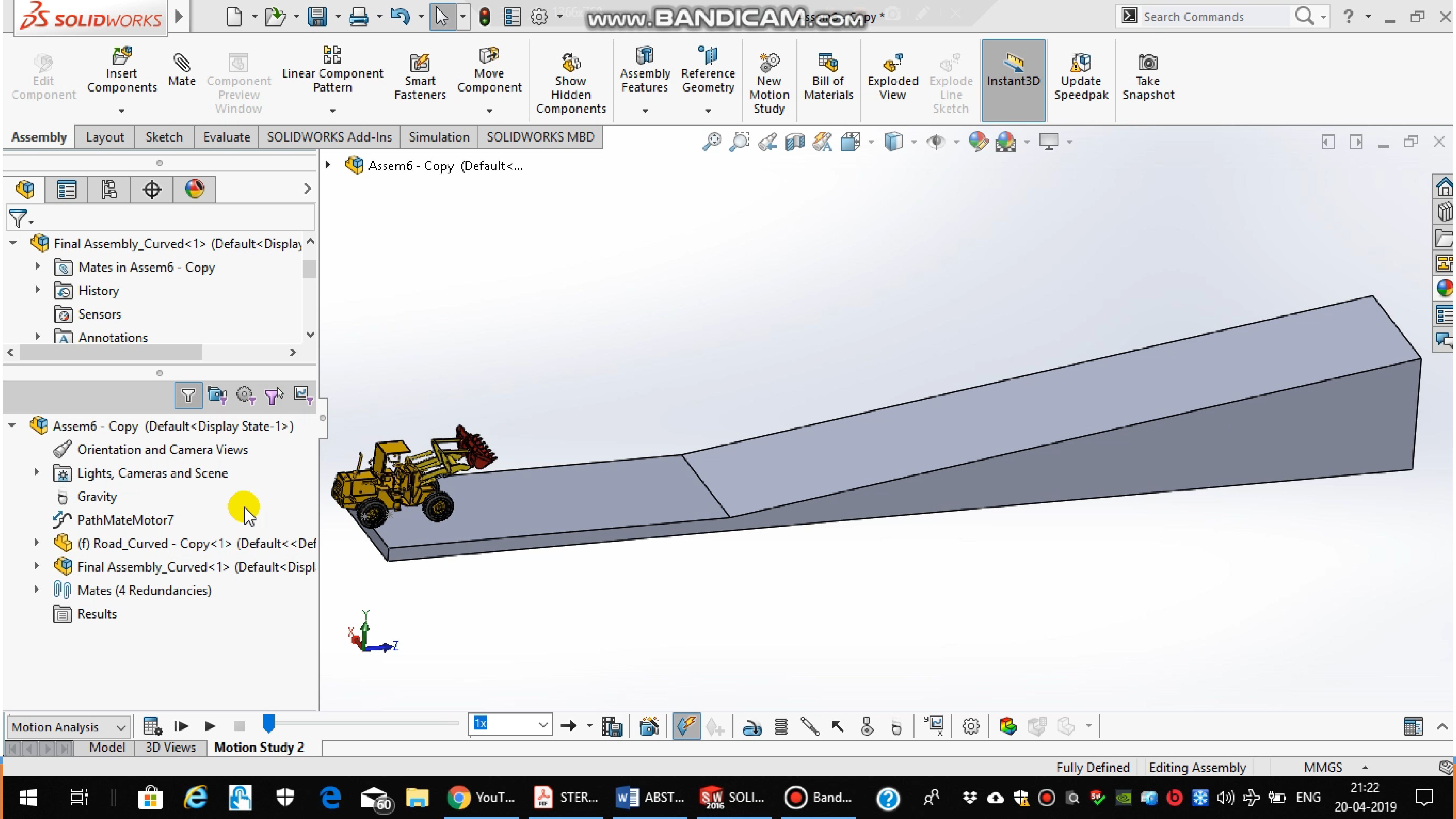




k) Contact Area in isometric view



l) Contact area from the bottom view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Update Speedpak
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Assem6 - Copy (Default<...
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History
Sensors
Annotations
Assem6 - Copy (Default<Display State-1>)
Orientation and Camera Views
Lights, Cameras and Scene
Gravity
PathMateMotor7
(f) Road_Curved - Copy<1> (Default<<Def
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Mates (4 Redundancies)
Results
Motion Analysis
1x
Model
3D Views
Motion Study 2
Fully Defined
Editing Assembly
MMGS
YouT...
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ABST...
SOLI...
Band...
ENG
21:22
20-04-2019

Recent Advancements in wheel loader

Electric Compact Wheel Loader:

- The electric compact wheel loader delivers zero emissions, significantly lower noise levels, improved efficiency and reduced operational costs, compared to its conventional counterparts.
- Combustion engine is replaced with a lithium ion battery. This stores enough electric energy to operate the machine for eight hours in its most common applications, such as light infrastructure construction and landscaping. The wheel Loader also incorporates two dedicated electric motors, one for the drivetrain and one for the hydraulics. Decoupling the subsystems gives higher efficiency in both the systems and the entire machine.

Hybrid Powertrain:

- In this innovation, the power is delivered from the Engine to the wheels and other components through two paths, a hydrostatic and mechanical path. The power delivery paths can be alternated depending upon the type of requirement, either high speed-low torque or low speed-high torque applications.

Electric Wheel Loader

Hybrid Powertrain

References

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- https://www.youtube.com/watch?v=OMSxkoV3pBs&t=1s
- https://en.wikipedia.org/wiki/Articulated_vehicle


Thank You