Effect of Height at Gravity Center on Tractor-Trailer Rollover

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The height at the gravity center of sprung mass is a parameter that greatly affects the rollover of the tractor-trailer. The gravity center height of sprung mass depends on the type of cargo and how it is loaded on the vehicle. This article investigates the effect of gravity center height of sprung mass h2= (2÷2.5) m on the ability to rollover of the fully loaded tractor-trailer when turning the steering wheel according to the rules of steering RSM (Ramp Steer Maneuver). The survey results showed that a full-load 6-axle tractor-trailer running on a road with a friction coefficient of 0.8 without the wheels separates from the road and the vehicle loses no stability and rollover. The vehicle operates provided that the speed <40km/h, and the left steering angle LSA<5deg for a vehicle with the height at gravity center of the trailer to the road surface is h2s=25dm; V<44km/h and LSA<5.5deg for h2s=24dm; V<50km/h and LSA<6deg for h2s=23dm; V≤50km/h and LSA<7deg for h2s=22dm.

Keywords: Rollover, force distribution coefficient, lateral rollover coefficient, steering angle.

1. INTRODUCTION

Vehicle rollover includes tripped rollover and inertia rollover. Tripped rollover usually occurs on roads with low friction coefficient, the vehicle slips and collides with obstacles or potholes in the road. Inertia rollover usually occurs when the vehicle is fully loaded, has a big height at gravity center of sprung mass running at big velocity on a road with a big friction ratio, and has sudden driver actions such as turning around, changing lanes, braking, accelerating, etc. In this paper, the authors focus on studying the effect of the height at the gravity center of the trailer on the road surface on the inertia rollover when the vehicle is turning and running at different speeds.

The authors used the Force Distribution Coefficient (FDC) to determine the state of the wheels separating from the road surface and used the Lateral Rollover Coefficient (LRC) to confirm the rollover instability of the tractor-trailer as the formula (1, 2)[1÷3]:

$$FDC = \left| \frac{\sum_{i=1}^{i=6} (F_{ir} - F_{il})}{\sum_{i=1}^{i=6} (F_{ir} + F_{il})} \right| \quad (i = 1:1:6) \tag{1}$$

When FDC= 1, the wheels will separate from the road.

$$LRC = \left| \frac{\sum_{i=2}^{i=6} (F_{ir} - F_{il})}{\sum_{i=2}^{i=6} (F_{ir} + F_{il})} \right| \quad (i = 2:1:6) \tag{2}$$

When LRC=1, the tractor-trailer with six axleswill lose stability and rollover.

2. Computational model

The tractor-trailer consists of 2 vehicles, which is one tractor has 3 axles and one semi-trailer also has 3 axles connected by one turntable. The method of splitting the multiple system structure is used to build a computational model of the tractor-trailer ispresented in Figure 1.[4÷8]

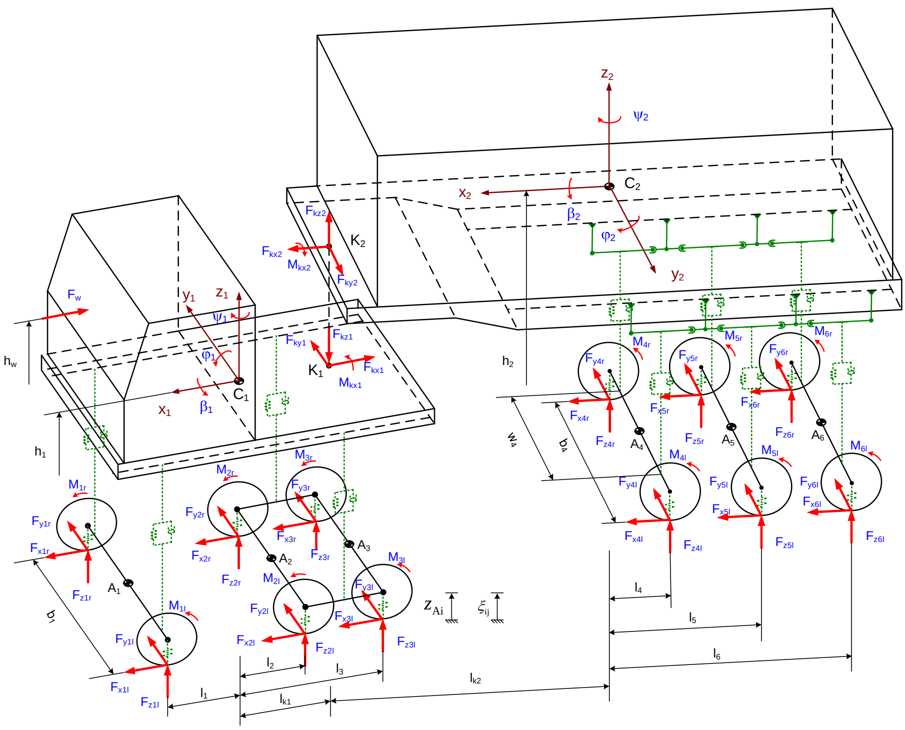

Fig.1. Computational model of the tractor-trailer with six axles

Based on Figure 1, we set up a system of dynamic equations to investigate the effect of gravity center height on the inertia rolloverof the tractor-trailer with six axlesby building equations to balance the forces and moments in a three-dimensional coordinate system using the Newton method, and at the same time building the moment equilibrium equation around the coordinate axes ox, oy, oz by the Euler method, specifically as follows:[9÷15]

$$(m_1+m_{A1}+m_{A2}+m_{A3})\ddot{x}_1=F_{x1r}cos\delta_{1r}+F_{x1l}cos\delta_{1l}-F_{y1r}\sin\delta_{1r}-F_{y1l}\sin\delta_{1l}+F_{x2l}+F_{x2r}+F_{x3l}+F_{x3r}-F_{wx}-F_{kx1} \quad (3)$$

$$(m_2+m_{A4}+m_{A5}+m_{A6})\ddot{x}_2=F_{x4l}+F_{x5l}+F_{x6l}+F_{x4r}+F_{x5r}+F_{x6r}+F_{kx2} \quad (4)$$

$$(m_1+m_{A1}+m_{A2}+m_{A2})\ddot{y}_1=F_{x1r}\sin\delta_{1r}+F_{x1l}\sin\delta_{1l}+F_{y1r}cos\delta_{1r}+F_{y1l}cos\delta_{1l}+F_{y2r}+F_{y3r}+F_{y2l}+F_{y3l}-F_{ky1} \quad (5)$$

$$(m_2+m_{A4}+m_{A5}+m_{A6})\ddot{y}_2=F_{y4r}+F_{y5r}+F_{y6r}+F_{y4l}+F_{y5l}+F_{y6l}+F_{ky2} \quad (6)$$

$$m_1\ddot{z}_1=F_{C1r}+F_{K1r}+F_{C2r}+F_{K2r}+F_{C3r}+F_{K3r}+F_{C1l}+F_{K1l}+F_{C2l}+F_{K2l}+F_{C3l}+F_{K3l}-F_{kz} \quad (7)$$

$$m_2\ddot{z}_2=F_{C4r}+F_{K4r}+F_{C5r}+F_{K5r}+F_{C6r}+F_{K6r}+F_{C4l}+F_{K4l}+F_{C5l}+F_{K5l}+F_{C6l}+F_{K6l}-F_{kz} \quad (8)$$

$$J_{x1}\ddot{\beta}_1=(F_{Cil}+F_{Kil}-F_{Cir}-F_{Kir})\frac{w_i}{2}+F_i(h_1-h_{Bi})-M_{kx1} \quad (i=1:1:3) \quad (9)$$

$$J_{x2}\ddot{\beta}_2=(F_{Cil}+F_{Kil}-F_{Cir}-F_{Kir})\frac{w_i}{2}+F_i(h_2-h_{Bi})+M_{kx2} \quad (i=4:1:6) \quad (10)$$

$$J_{y1}\ddot{\varphi}_1=-(F_{Cil}+F_{Kil}+F_{Cir}+F_{Kir})l_i+F_{xi}^{'}(h_1-r_i)+F_{kx1}(h_1-h_{k1})+F_{kz1}l_{k1}+M_{il}+M_{ir} \quad (i=1:1:3) \quad (11)$$

$$J_{y2}\ddot{\varphi}_2=-(F_{Cil}+F_{Kil}+F_{Cir}+F_{Kir})l_i+F_{xi}^{'}(h_2-r_i)+F_{kx1}(h_2-h_{k1})+F_{kz1}l_{k1}+M_{il}+M_{ir} \quad (i=4:1:6) \quad (12)$$

$$J_{z1}\ddot{\psi}_1=(F_{x1l}\sin\delta_{1l}+F_{y1l}cos\delta_{1l}+F_{x1r}\sin\delta_{1r}+F_{y1r}cos\delta_{1r})l_1+(F_{x1l}cos\delta_{1l}-F_{x1r}cos\delta_{1r})\frac{b_1}{2}+F_{ky1}l_{k1} \quad (13)$$

$$+(F_{y1r}\sin\delta_{1r}-F_{y1l}\sin\delta_{1l})\frac{b_1}{2}-(F_{y2l}+F_{y2r})l_2-(F_{y3l}+F_{y3r})l_3+(F_{x2l}-F_{x2r})\frac{b_2}{2}+(F_{x3l}-F_{x3r})\frac{b_3}{2}$$

$$J_{z2}\ddot{\psi}_2=(F_{xil}-F_{xir})\frac{b_i}{2}+F_{ky1}l_{k1}-(F_{yil}+F_{yir})l_i \quad (i=4:1:6) \quad (14)$$

$$m_{Ai}\ddot{z}_{Ai}=F_{CLil}+F_{CLir}-F_{Cil}-F_{Kil}-F_{Cir}-F_{Kir} \quad (i=1:1:6) \quad (15)$$

$$m_{Ai}\ddot{y}_{Ai}=F_i+F_{yil}+F_{yir} \quad (i=1:1:6) \quad (16)$$

$$J_{Axi}\ddot{\beta}_{Ai}=(F_{Cir}+F_{Kir}-F_{Cil}-F_{K1l})\frac{w_i}{2}+(F_{CLil}-F_{CLir})\frac{b_i}{2}-F_{yi}(r_i+\xi_{Ai})+F_i(h_{Bi}-r_i) \quad (i=1:1:6) \quad (17)$$

$$J_{Ayir}\ddot{\varphi}_{ir}=M_{Air}-M_{Bir}-F_{xir}r_{dir} \quad (i=1:1:6) \quad (18)$$

$$J_{Ayil}\ddot{\varphi}_{il}=M_{Ail}-M_{Bil}-F_{xil}r_{dil} \quad (i=1:1:6) \quad (19)$$

Table 1. Symbols and meanings

Symbols	Meanings
$i = 1:1:3$; $i = 4:1:6$	Order of axles of the tractor and semi-trailer
l, r	left side; right side
x, y, z	Vehicle motion in the 3D coordinate system
r_d	Tire rolling radius
δ_l, δ_r	Left steering angle (LSA); Right steering angle (RSA)
l_i	The length from the center of gravity to axles
h_{1s}, h_{2s}	Height at the gravity center of the tractor and trailer
b_i, w_i	Distance between left and right tires and suspensions
φ_{il}, φ_{ir}	Rotation angle of left and right i-th wheels
β_1, φ_1, ψ_1; β_2, φ_2, ψ_2	The angle of rotation of the tractor and trailer in the 3D coordinate system
m_1, m_2, m_{Ai}	Body axles mass of the tractor and trailer
J_{x1}, J_{y1}, $J_{z1;}$ J_{x2}, J_{y2}, J_{z2}	The tractor and trailer inertia moment in the 3D coordinate system
$J_{Ayil,}$ J_{Ayir}	Inertia moment of left and right wheels
F_{Cil}, $F_{Kil;}$ F_{Cir}, F_{Kir}	The elastic and damping force of left and right i-th suspensions
$F_{CLil;}$ F_{CLir}	The left and right tire elastic force
F_{xil}, F_{yil}, $F_{zil;}$ F_{xir}, F_{yir}, F_{zir}	Left and right tire forces
M_{Ail}, $M_{Bil;}$ M_{Air}, M_{Bir}	Driving and braking torque of left and right i-th wheels

3. Surveys and reviews

The authors used the RSM (Ramp Steer Maneuver) steering rule of the National Highway Traffic Safety Administration (NHTSA) to study the influence of the height at gravity center of the body on the inertia rollover of the 6-axle tractor-trailer. The steering wheel is rotated 150 degrees at a speed of 175 deg/s, corresponding to a left wheel steering angle of LSA=6deg, as shown in Figure 2 [1÷3].

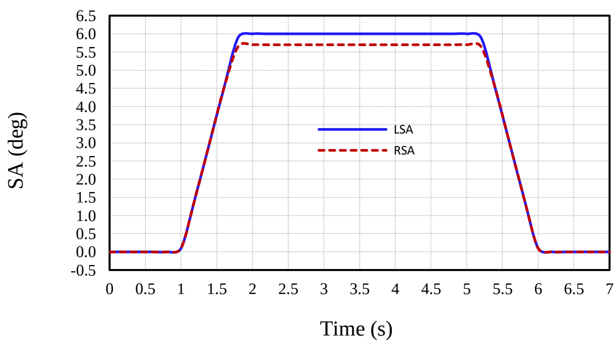

Fig.2. Rules of turning the steering wheel RSM

A full-load tractor-trailer is running on a road with a friction coefficient of 0.8, the steering wheel is rotated according to the RSM rule, and investigating the influence of the height at gravity center of the trailer on the inertia rollover of the tractor-trailer with six axleswhen the vehicle with h_{2s}=[20:1:25]dm is rotated at different speeds.

Figure 3 is a graph of the maximum Force Distribution Coefficient (FDC_{max}) of the vehicle when the steering wheel is turned to the left corresponding to the left steering angle of LSA=6deg and the vehicle is moving at a velocity of 50km/h. When the left steering angle is LSA=6deg, a vehicle with the distance from the height at gravity center of the trailer is h_{2s}=23dm will have an FDC_{max}=1 at V≥50km/h; Similarly, when h_{2s}=24dm, FDC_{max}=1at V≥44km/h;when h_{2s}=25dm, FDC_{max}=1 at V≥40km/h,the wheels will separate from the road. If the vehicle is is moving at a velocity of 50km/h, a vehicle with the distance from the center of gravity of the trailer to the road surface is h_{2s}=22dm will have an FDC_{max}=1at LSA≥7deg; Similarly, when h_{2s}=23dm, FDC_{max}=1at LSA≥6deg; when h_{2s}=24dm, FDC_{max}=1at LSA≥5.5deg; when h_{2s}=25dm, FDC_{max}=1at LSA≥5deg, the wheels will separate from the road.

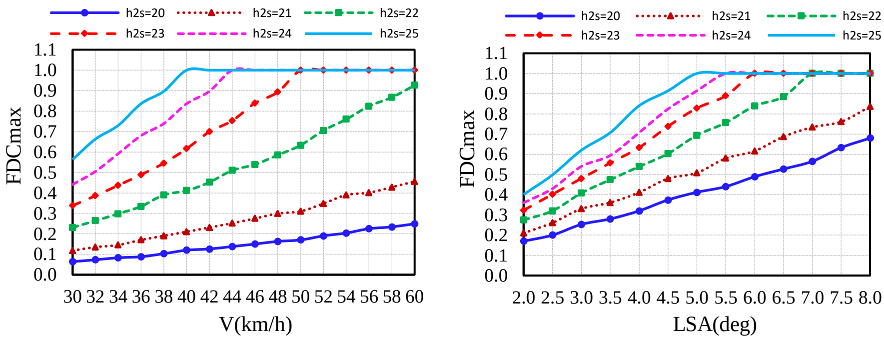

Fig.3. The maximum Force Distribution Coefficient at LSA=6deg and 50km/h

The maximum Lateral Rollover Coefficient (LRC_{max}) of the tractor-trailer at a velocity of 50km/h is performed in Figure 4. The tractor-trailer will lose stability and roll overLRC_{max}=1 when h_{2s}=25dm and LSA≥5deg or h_{2s}=24dm and LSA≥5.5deg or h_{2s}=23dm and LSA≥6deg or h_{2s}=22dm and LSA≥7deg.

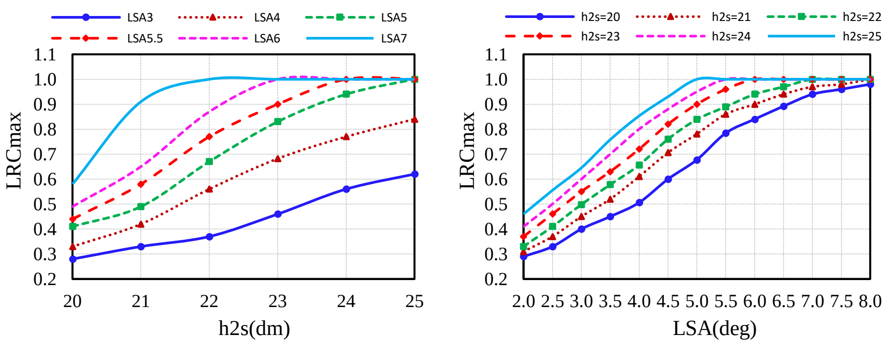

Fig.4. The maximum Lateral Rollover Coefficient of the vehicle at 50km/h

Figure 5 is a graph of the maximum acceleration in the lateral of the tractor (Y''_{1max}) and trailer (Y''_{2max}) at the left steering angle LSA=6deg.When the tractor-trailer is running at a velocity of 60km/h, the maximum lateral acceleration of the tractor Y''_{1max}=5.96m/s^2 if the height at gravity center of the trailer is h_{2s}=25dm; Likewise, Y''_{1max}=5.9m/s^2 if h_{2s}=24dm;

Y''_{1max}=5.37m/s^2 if h_{2s}=23dm; Y''_{1max}=4.08m/s^2 if h_{2s}=22dm; Y''_{1max}=2.17m/s^2 if h_{2s}=21dm; and Y''_{1max}=1.20m/s^2 if h_{2s}=20dm. The maximum acceleration in the lateralof the trailer Y''_{2max}=(1.09÷4.76)m/s^2 if the height at gravity center of the trailer is h_{2s}=(20÷25)dm.

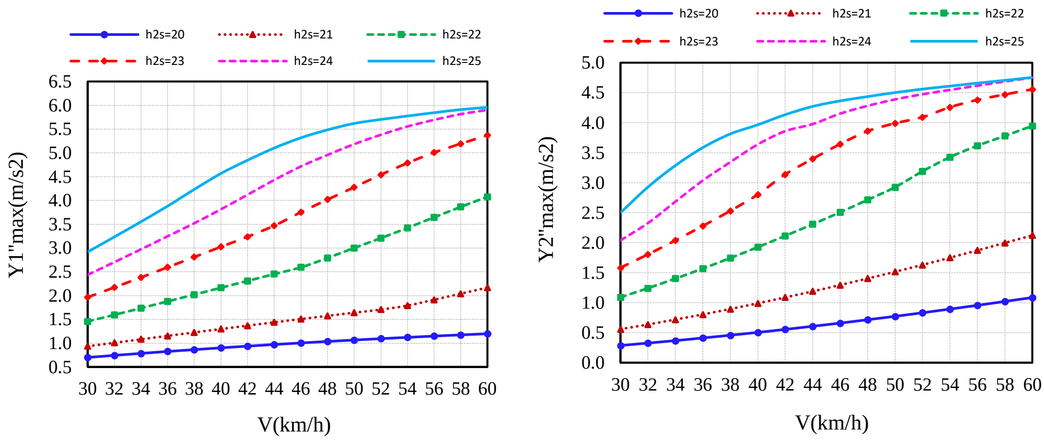

Fig.5. The maximum acceleration in the lateralof the tractor and trailer at LSA=6deg

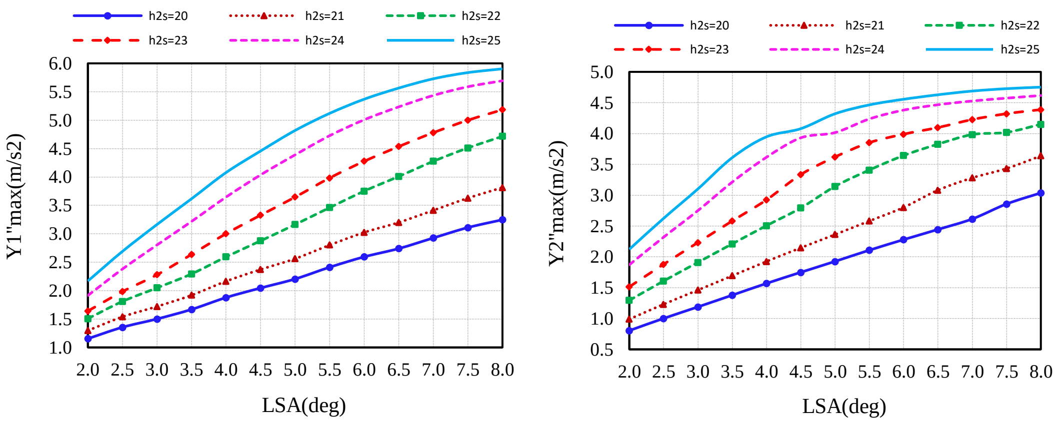

Fig.6. The maximum acceleration in the lateralof the tractor and trailer at 50km/h

The maximum acceleration in the lateral of the tractor and trailer at a speed of 50km/h is shown in Figure 6. If the tractor-trailer is running at a velocity of 50km/h and the left steering angle is LSA=8deg, the maximum acceleration in the lateral of the tractor Y''_{1max}=(3.25÷5.90)m/s^2 if the height at gravity center of the traileris h_{2s}=(20÷25)dm. Likewise, the maximum acceleration in the lateral of the trailer Y''_{2max}=(3.04÷4.75)m/s^2 if h_{2s}=(20÷25)dm.

Figure 7 is a graph ofthe rollover angle of the tractor (RA_1) and trailer (RA_2) at the left steering angle is LSA=6deg.Case the vehicle is traveling at a velocity of 60km/h and the left steering angle is LSA=6deg, then RA_1=(1.1÷9.2)deg if the height at gravity center of the traileris h_{2s}=(20÷25)dm. Likewise, RA_2=(1.1÷9.6)deg if h_{2s}=(20÷25)dm.

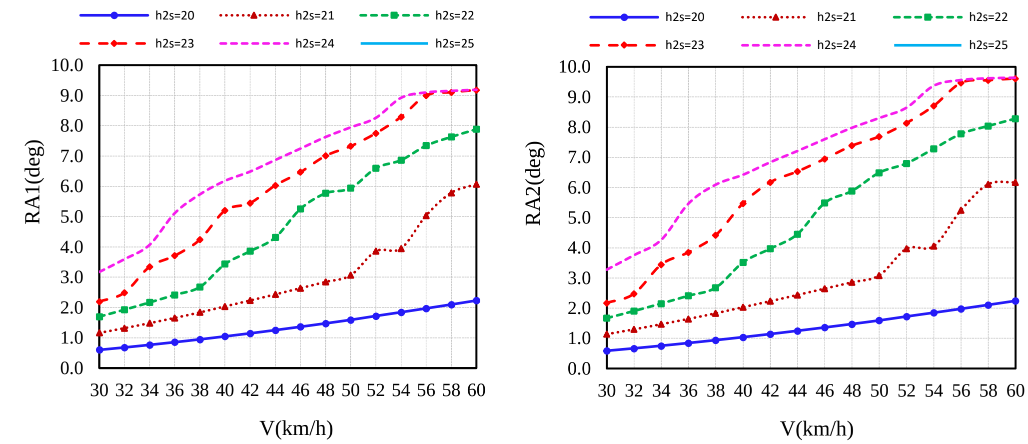

Fig.7. The rollover angle of the tractor and trailer at LSA=6deg

The rollover angle of the tractor (RA_1) and trailer (RA_2) at a velocity of 50km/h is indicated in Figure 8. Case the vehicle is traveling at a velocity of 50km/h and the left steering angle is LSA=8deg, then RA_1=(3.71÷9.18)deg if the height at gravity center of the traileris h_{2s}=(20÷25)dm. Likewise, RA_2=(3.85÷9.62)deg if h_{2s}=(20÷25)dm.

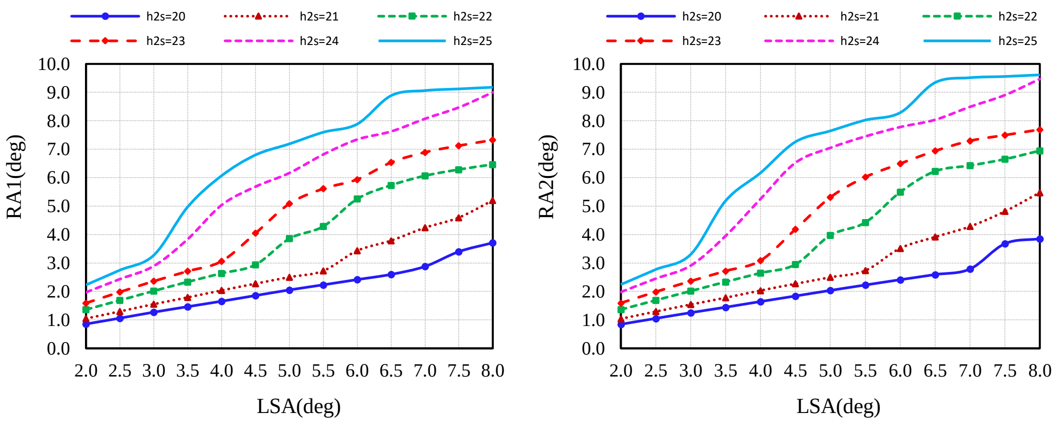

Fig.8. The rollover angle of the tractor and trailer at 50km/h

4. Conclusions

To ensure that a full-load 6-axle tractor-trailer runs on the road surface with a coefficient of adhesion of 0.8 without the wheels separating from the road, maintaining stability and preventing rollover at the maximum Force Distribution Coefficient and the maximum Lateral Rollover Coefficient $FDC_{max}=LRC_{max}=1$, the vehicle is operated provided that the vehicle speed V<40km/h and left steering angle LSA<5deg for a vehicle with the height at gravity center of the trailer is h_{2s}=25dm; V<44km/h and LSA<5.5deg for h_{2s}=24dm; V<50km/h and LSA<6deg for h_{2s}=23dm; V≤50km/h and LSA<7deg for h_{2s}=22dm.

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