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Research Paper

Development of stability indicators for dynamic Phase I overturn of conventional farm tractors with front axle pivot

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Tractor overturns are serious potential hazards for operators. While rollover protective structures (ROPS) protect operators passively, greater protection can be achieved through theoretical prediction of a potential overturn. Given effective warning, an operator can act to correct a tractor's motion when a tyre is about to lose contact with the ground. Such a loss of contact is associated with the initiation of a Phase I tractor overturn. However, it remains unclear how the initiation of tractor overturn is influenced by certain factors. Furthermore, the current mathematical models for tractors should be further extended for general utilisation. This study was conducted to develop stability indicators based on a more general model for dynamic Phase I tractor overturn. We considered practical tractor configurations and motion characteristics in a three-dimensional (3D) reference frame in formulating the mathematical model. Tractor stability indicators for overturn and sideslip were derived from force calculations. A parametric study was conducted using an example tractor. The tractor speed and slope angle were found to affect the overturning stability significantly. The coefficient of maximum static friction was found to be the main factor contributing to tractor sideslip. Critical tractor speeds for various ground conditions were identified by considering the zero values of the tractor stability indicators. The critical tractor speed was determined as a function of the maximum static friction and the slope angle. By providing a display device based on ergonomics principles, the results of this study can be further implemented in the form of guidance to operators.

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Nomenclature

Symbols

α	lateral slope angle [rad]
θ	pitch angle in local coordinates [rad]
θ_1	initial angle between the horizontal line and the line connecting the COG_r and the front axle pivot, from side view [rad]
θ_2	initial angle between the horizontal line and the line connecting the COG_r and a modelled rear tyre (spring–damper unit), from side view [rad]
μ	coefficient of maximum static friction between the tyre and the ground in a direction parallel to the rotational axis of the tyre [–]
π	circumference ratio, Pi [–]
Φ	roll angle in global coordinates [rad]
φ_1	initial angle between the front axle and the line connecting the front axle pivot and a modelled front tyre (spring–damper unit), from back view [rad]
φ_2	initial angle between the horizontal line and the line connecting the COG_r and a modelled rear tyre, from back view [rad]
φ_f	roll angle of the tractor anterior part in local coordinates [rad]
φ_r	roll angle of the tractor posterior part in local coordinates [rad]
ψ	yaw angle in local coordinates [rad]
ω_X	component of tractor angular velocity about the X axis [rad s^{-1}]
ω_Y	component of tractor angular velocity about the Y axis [rad s^{-1}]
ω_Z	component of tractor angular velocity about the Z axis [rad s^{-1}]
A	coordinate transformation matrix from local to global coordinates [–]
A^T	transpose of the matrix A [–]
A_X	transformation matrix due to rotation about the X axis [–]
A_Y	transformation matrix due to rotation about the Y axis [–]
A_Z	transformation matrix due to rotation about the Z axis [–]
c_i	vertical viscous damping coefficient of tyre i [N s m^{-1}]
D	height of the obstacle [m]
e_{fy}	lateral distance between the COG_f and the pivot axis [m]
e_{fz}	vertical distance between the COG_f and the pivot axis [m]
e_G	vertical distance between the COG and the pivot axis [m]
e_{ry}	lateral distance between the COG_r and the pivot axis [m]
e_{rz}	vertical distance between the COG_r and the pivot axis [m]
f_f	lateral friction force acting on the front tyres in the Y direction [N]
f_{f_limit}	maximum static friction force acting on the front tyres in the Y direction [N]
F_{py}	reaction force between the two main tractor parts in the Y direction [N]
F_{pz}	reaction force between the two main tractor parts in the Z direction [N]
f_r	lateral friction force acting on the rear tyres in the Y direction [N]
f_{r_limit}	maximum static friction force acting on the rear tyres in the Y direction [N]
F_{si}	static ground supporting force on tyre i in the Z direction for non-sloping conditions [N]
F_{zi}	dynamic ground supporting force on tyre i in the Z direction [N]
g	acceleration due to gravity [m s^{-2}]
H_f	height of the COG_f [m]
h_f	length of the line segment between the COG_r and the tractor front axle pivot, from side view [m]
H_r	height of the COG_r [m]
h_r	length of the line segment between the COG_r and the point connecting the tractor main body (rear end) and a modelled rear tyre, from side view [m]
i_o	tractor stability indicator against overturn [–]
i_s	tractor stability indicator against sideslip [–]
I_{xf}	tractor moment of inertia about the x_f axis, i.e., the longitudinal axis of the front end of a tractor [kg m^2]
I_{xr}	tractor moment of inertia about the x_r axis, i.e., the longitudinal axis of the main body (rear end) of a tractor [kg m^2]
I_{yr}	tractor moment of inertia about the y_r axis, i.e., the axis transversal to the motion direction of a tractor, passing through the COG of its main (rear) end [kg m^2]
j_f	perpendicular distance from the point connecting the tractor front end and a modelled front tyre to the longitudinal axis through the front axle pivot [m]
j_r	perpendicular distance from the point connecting the tractor main body and a modelled rear tyre to the longitudinal axis through the front axle pivot [m]
k_i	vertical spring constant of tyre i [N m^{-1}]
L	length of the obstacle [m]
L_1	effective obstacle length during the obstacle-surmounting passage of the front wheel(s) [m]
L_2	effective obstacle length during the obstacle-surmounting passage of the rear wheel(s) [m]
L_f	horizontal distance between the COG and the front wheel [m]
l_f	horizontal distance between the COG_r and the front wheel [m]
L_r	horizontal distance between the COG and the rear wheel [m]
l_r	horizontal distance between the COG_r and the rear wheel [m]
m	total mass of the tractor [kg]
m_f	mass of the tractor front end [kg]