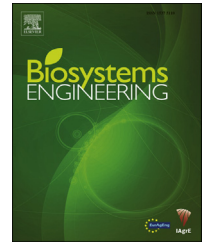


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Research Paper

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

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