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DYNAMICS OF DUMPING TRUCKS

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Abstract

Two and tree dimensional modelling, simulations and animations have been worked out for the purpose of demonstrating and validating the important situations for which accidents may occur. The equations of Kane dynamic's involving mass and inertia of the various bodies and external forces have been set up using the Autolev software and simulations have been studied through graphics and animation. Medium to strong steady and gusty winds, variable terrain bearing property, transverse terrain inclination and weights transfer of loose bulk material are some of the factors which increase considerably the incidence of the vehicle's roll-over. Critical values of some parameters are addressed and some guidelines are proposed that will hopefully prevent roll-over accidents. Type and stiffness of rear axle suspension and their moment arm are addressed.

Introduction

Dump trucks, especially tractors with long Semi-Trailer, are subject to roll-over under circumstances which at first sight might look unimportant. Medium to strong steady and turbulent winds, variable terrain bearing properties, transverse terrain inclination and more or less important weight transfer of loose bulk material are factors which increase considerably the incidence of vehicle roll-over. We shall be concerned principally by the stability in roll while lifting and unloading

We have confined our investigation upon the following factors contributing to roll-over:

1) Tractor-semi-trailer in a parallel or offset configuration while dumping.

2) Terrain side inclination angle.

3) Wind forces contribution in the presence of terrain inclination

4) Some suspension factors .

Many important publications came up since the 70's which treated the roll-over problem for moving road vehicles, as for instance, Isermann, 1970, [1], Winkler and Fancher 1992, [2]. Studies are rare for problems related to dump trucks vehicles. In 1970, researchers at the TRRL [3] (Transport and Road Research Laboratory) in Great Britain carried a set of testing for different truck combinations, using a tilt table. To validate their findings, they also drove these truck combinations on circular tracks of various radius. Their results showed that for a lateral acceleration of 0.2g to 0.3g the critical inclination angle was about 6 to 7 degrees. In that study, they investigated particularly the unloading operation done with dump truck vehicles. They measured the critical roll-over angle for various dump trailer length and dump box lift angles. They found out that the critical roll-over angle was decreasing as the trailer length was longer. For a dump trailer box raised at 45 degrees, critical roll-over angle as small as 4.3 degrees were observed. A summary of their results appears in Table 1.1.

Table 1 Summary of the experimental results of the TRRL study.

Trailer length m.	Side angle (box at 0 deg)	Side angle (box at 45 deg)
6.1	13.4 deg	6.2 deg
9.1	11.2	5.2
12.2	9.5	4.3

Novak et al. [3] carried simulations with different unloading situations. Different forward velocities were considered during unloading with varying lift angles of the dump box, various terrain conditions as well as different unloading modes. The modes refer here, to the location and portion of a the stuck carried load when the box is raised to its maximum. The authors reported the following important factors related to roll-overs such as:

1) Terrain unevenness, terrain inclination angle, the presence of holes, bumps, soft-ground, etc.

2) Load: badly distributed load either in a lateral or longitudinal direction. Possible stuck load inside the box.

The accident report of the Committee for Health and Work Security in Quebec lists the type dump vehicles involved in roll-over accidents. Most of them are of the long semi-trailer type. The carried load is either earth or gravel, crushed stone and other high static friction coefficient materials.

The present paper is the outcome of a recent research study reported in [5], in a report (in French) , to the IRSST and to the ASTE. A more extended set of results is presented there with detailed discussions and conclusions going beyond this presentation.

Modelling

In the present study, a 40 feet semi-trailer, the maximum length allowed in the province of Quebec, is considered. The load consists of bulk material with a large friction angle. Three types of unloading are dealt with; uniform dumping over the whole width of the box, asymmetrical unloading, partial and full stuck bulk load. Steady wind at various velocities and orientation with respect to the trailer has been introduced into the model. The effect of gusty wind is discussed later at the end of the paper.

The dynamic equations of motion and a Fortran code were obtained, using the Autolev code, version 2, for rigid bodies. A set of fifty and more commands are available in Autolev 2 and permit the description of a 3 dimensional dynamic model with masses, mass moment of inertia, linear and angular velocities and accelerations, gravity forces, internal and external forces, such as damping and spring forces found in tyres and suspension elements. After compiling and setting up input files with parameters values and initial conditions, the execution yields files which are used for graphics and animation. Animation in two-dimensional space, were produced and were found very useful in the development stage. A listing of the Autolev commands used to generate a two dimensional simulation program is given in the appendix.

Model with pneumatic but deflated suspensions. During the unloading of bulk material from a dump trailer with deflated pneumatic suspensions, the dump box rests on the frame and the vehicle behaves as a rigid body (Fig 1). The only parameters influencing its behaviour are the terrain inclination , the wind direction and velocity and the position of its centre of gravity, bulk load included.

Model with leaf spring suspensions. This model considers a dump semi-trailer with leaf spring suspensions or still inflated pneumatic suspensions while unloading. In the presence of a lateral terrain inclination, a load transfer occurs which further increases the lateral dump box inclination . This contributes to raising the load on the suspension and tires located on the roll side. (Fig 2)

Three dimensional model. A three dimensional model of the dump semi-trailer was programme in a fashion similar to the model described in appendix B. It is much more extensive and length and the results will be presented in the form of animations. In particular, the case where the load is impacting against a blocked rear panel is impressive. When half the load is wet and stuck on one side of the dump box, the vehicle becomes suddenly out of balance and is quite prone to roll-over.

Results from the Dynamic Analysis

The Autolev dynamic simulation program was run for various initial conditions. Initially it was executed for a variety of standard input conditions in order to validate basic cases such as static equilibrium, natural frequencies, etc. In this later case, a simple small initial velocity input over U3 was sufficient to get the most important eigenvalues. The major one, in roll, was identified as 0.21 Hz in. When a steady wind is applied against the left trailer siding, the frame will assume a time varying angle and weight transfer will occurs from the left to the right suspensions, before coming to a stall or else, to a roll-over. The roll-over case is assumed to occur when the force under the left rear wheel turns out negative. At that moment during the simulation, the tire and ground stiffness and damping constants are changed to zero before the next integration step of the equations of motion. There is no convergence problem in so doing as long as we use a forward algorithm such as a Runge-Kutta, and as long as we do not intervene within the internal steps of the subroutine. Some of the interesting results are presented in table 2 below.

Table 2. Dynamic Simulation Results.

Cases	Wind V	Fp1	%	Fp2	%	Time for Roll-O	Status	Roll-Over
1-	0. m/s	203500N	100 %	203500N	100 %	∞ s	Steady st	No
2-	20.0	111700	55	298000	146	2.98 s.	min-max	No
3-	30.0	39300	19	375400	184	2.26	min-max	No
4-	40.0	0.0	0	423000	208	1.60		Yes
5- .21Hz	20.0	0.0	0	423000	208	9.0	Gusty	Yes

Case 1 is a simple steady case. When deflexions are properly specified at time zero, there is no motion from step to step integration. Case 2 ,3 and 4 are concerned with steady wind forces against the dump box side. Roll-Over occurs at 1.6 s for case 4. For case 2 and 3, some oscillations take place, since the steady wind act as a step force at time zero. What is reported here is the minimum and the maximum load under left and right wheel and their percentage with respect to the steady case 1 and the time at which this occurs. Case 5 is a gusty wind of average amplitude equal to 20 m/s assumed to be cyclic with a frequency of 0.21 hz, the principal natural frequency of the dump box in roll. The roll-over does happen here after approximately 2 cycles. It is noteworthy to say that the problem is non-linear since large amplitudes occurs around the roll-over instant.

Gusty winds, oscillating between a minimum of zero wind and a maximum velocity, has been modelled and its effect represented by a offset sinusoidal force. Gusty winds are quite efficient in producing roll-over when their gust frequency approaches the trailer roll natural frequency. Their effect may be compared to the tip-over of car and vans when being pushed sideways in phase with the rolling mode amplitude.

Other cases are presented here when the dump centre of mass is displaced laterally and when the right ground and tire stiffness k_2 is reduced, following for example a sudden terrain collapse. The ensuing angular momentum is likely to give the vehicle an important roll motion.

The following table 3 indicates that the time for roll-over is becoming shorter as one might expect. For cases 3 and 4, some special treatment will have to be done to the program since the roll-over initially taking place on the right side is reversed after the change in stiffness k_1 in the integration routine.

Table 3. Dynamic Simulations Results for payload off-centre and reduced ground stiffness.

Cases	K_2	L_3 offset	F_1	F_2	Time R-O	Remark
1	50%	0	73000	132000	Oscillate	No
			319000	315000		roll-over
2	50%	0.1	0	148000	1.95s	Roll-over
3	50%	0.25	0	222000	1.15s	“
4	50%	0.5	0	335000	1.10s	“

Results from a steady state analysis.

Simulations has been carried out for the two suspension models described above. The wind speed ranged from 0 m/s to 20m/s (72 km/h) with an incidence angle ranging from 0° to 90°. The trailer was either in line with or at 90° to its tractor. Linearised equations for static equilibrium as obtained from **appendix A** are utilised in this case. The results, giving the maximum permitted sideways terrain angle as a function of wind incidence angle and wind velocity, are shown on the Figures 3 to 6.

Figure 3: Maximum lateral terrain inclination angle versus wind velocity U and wind incidence angle for a loaded ,fully raised dump semi-trailer and a deflated suspension.

Figure 4: Maximum lateral terrain inclination angle versus wind velocity U and wind incidence angle. The semi-trailer is at 90 deg. to the tractor, fully loaded , in a raised position and with a deflated suspension .

Figure 5: Maximum lateral terrain inclination angle versus wind velocity U and wind incidence angle for a loaded dump semi-trailer in a fully raised position, and with a leaf spring suspension. (span L_2 = 0.75m.)

Figure 6: Maximum lateral terrain inclination angle versus wind velocity U and wind incidence angle for a loaded dump semi-trailer in a fully raised position, and with a leaf spring suspension. (span L_2 = 0.65m.

In the preceding 4 figures, the points of special interest are the those on the right vertical axis where the wind incidence angle is normal to the dump box and points for which the ground inclination angle is zero. As it may be seen from Figure 3 and 4, the tractor semi-trailer is a very stable system when having a pneumatic suspension which is deflated. When the fully loaded dump box is in its downward position, it could sustain a strong side wind without any risk of roll-over up to a maximum lateral terrain inclination of 23 deg . Under similar conditions, with a raised box and half the bulk load stuck in the upper part of the box, the maximum inclination drops down to 11 deg. according to figure 3. When the tractor is set at 90 deg. to the semi-trailer, and for the same conditions as those of figures 3, an important reduction occurs in the maximum permitted lateral terrain inclination. Figures 4 is the counterparts of figure 3. This may seems to be a paradox. When the tractor is set at 90 deg, it looks as if the area for static stability has increased considerably, due to the fact that one side of this triangle is equal to the tractor length. But the fifth wheel degrees of freedom in rotation are removing a great deal of the roll restraint on the trailer when set at 90 deg to the tractor. Therefore the static area for stability is reduced significantly. When a dump trailer is equipped with a leaf spring suspension, the risk of roll-over is quite increased . The box may now oscillate or rotate around the frame longitudinal axis. Figure 5 relates to conditions similar to those of figure 3 except again for a leaf spring suspension. Comparing Figure 3 and 5, permitted lateral terrain inclination angles drop from 13 to 4.3 deg under no wind conditions and from 11 deg to zero deg. under heavy wind conditions so that roll-over is possible at full wind side velocity for a level terrain. An interesting observation comes out when comparing the last figures , where the half-span Tr has been reduced from 0.75m on figure 5 to 0.65 m on figure 6. This half span Tr is the distance between the frame longitudinal central plane and the longitudinal plane going through either left or right leaf spring suspension. This distance is not standard and may be found to be between 0.5m and 0.75m. The comparison of the results of those two figures show that a decrease in the parameter Tr, while unloading, is accompanied by a similar decrease in the vehicle stability. Figure 6 in particular, shows that the maximum permitted lateral terrain inclination angle cannot exceed 1 deg even with no wind. With a moderate wind, the roll-over is unavoidable. Other simulations, not reported here, also show a great risk of roll-over for tractor semi-trailer combinations set at 90 deg., even in the absence of any wind.

Conclusion

Some dynamic simulations have shown that roll-over may take place due to inertia effects and momentum and should be preferred to purely static cases. A semi-trailer should always be set in line with the tractor longitudinal axis. Large offset angle should be avoided. Position at 90 deg. must definitely be avoided. A vehicle with fixed leaf spring suspensions is more prone to roll-over than one with pneumatic suspensions deflated prior to unloading. The half span L_2 for leaf spring suspensions should be increased as much as possible when designing dumping trailers. Minimal width for such span should be imposed for bulk dumping vehicles. Pneumatic suspensions are to be preferred as long as the attendant deflates them prior to lifting its dump box. Often, this is not the case. Dumping should not proceed when carrying bulk material with a high friction coefficient, specially when this material has been soaked with rain, and other conditions prevail such as uneven terrain, leaf spring suspensions, presence of steady or gusty winds. Operators should inspect the loaded material for evenness and dry conditions before raising their box.

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Acknowledgement

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APPENDIX A

Steady state equilibrium. Maximum transverse terrain inclination for a semi-trailer box on suspensions.

Calling R = rpn, the wheel radius, F_1 =Fp1,the force under the left wheel, F_2 =Fp2, the force under the right wheel, α = q5i,the terrain inclination angle, β = q4, the frame rotation with respect to the axle, F_w the amplitude of the wind force, m_2 the combined mass ($m_b + m_c$) the moment equilibrium equation over the axle yields, for small angles approximations, the following equation

$$-(m_2 g L_1 + 2k_3 L_2^2 \beta -- m_2 g R \beta + 2 L_1 F_1 + m_a g L_1 - m_a g R \alpha = 0 \qquad (1)$$

F_1 is set to zero for impending roll-over.

Free body diagram for the frame and dump box body yields the following equation.

$$\beta = 1/\mathrm{den}\,[\,(m_2 g L_4 - F_w L_3)\,\alpha + (F_w L_4 + m_2 g L_4)] \qquad (2)$$

where $\mathrm{den} = 2 k_3 L_2^2 + F_w L_3 - m_2 g L_4$

Solving for (1) and (2), with F1 = 0. yields expressions for α and β in terms of the geometrical and physical parameters. Graphics such as figure 3 to 6 are obtained through such procedures.

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Appendix B

Autolev Commands for the Two dimensional Roll Over Simulation Program

All angles are in radians.

```
DOF(4)
FRAMES(A,B,C)
mass(a,ma,b,mb,c,mc)
PRINCIPAL(A,B,C)
!R7 is a point where wind resultant force is applied.
POINTS(O,R1,R2,R3,R4,R5,R6,r7,r8,r11,r22)
!R11 and R22 are road contact points below R1 and R2 at radius RPN
!Ls3 is the initial suspension length from R3 to R5 and from R4 to R6
MASSLESS(O,R1,R2,R3,R4,R5,R6,r7,r8,r11,r22)
CONST(RHO,CD,S,uv,L1,L2,L3,L4,L5,L6)
CONST(G,K1,K2,K3,K4,ls3,AM1,AM2,AM3,AM4,ab,rpn,f,q5i,q6i,kh)
specified(q5,q6)
!q5i is the initial transverse road angle as read in the input file
!q6i is the angle at which the box is beeing raised.(rad)
q5=q5i
q6=q6i
SIMPROT(N,A,3,(Q3-Q5))
SIMPROT(A,B,3,Q4)
DIRCOS(N,B)
SIMPROT(B,C,1,Q6)
DIRCOS(N,C)
DIRCOS(A,C)
WAN=U3*A3
WBA=U4*B3
WBN=ADD(WAN,WBA)
EXPRESS(WBN,N)
WCN=ADD(WAN,WBA)
EXPRESS(WCN,C)
Q1'=U1
Q2'=U2
Q3'=U3
Q4'=U4
ALFAN=DERIV(WAN,T,N)
ALFBN=DERIV(WBN,T,N)
```

```
ALFCN=DERIV(WCN,T,N)
!Point O is a fixed reference origin in the Newtonian Frame.
PON=0*N1+0*N2
VON=0.0*N1+0.0*N2
POASTAR=Q1*N1+Q2*N2
VASTARN=U1*N1+U2*N2
!R1 and R2 are axle points where equivalent tires loads are applied.
PASTARR1=-L1*A1
PASTARR2=L1*A1
!R5,R6 are box application points for equivalent suspension forces.
PASTARR3=-L2*A1
PASTARR4=L2*A1
PR1R11=-RPN*A2
PR2R22=-RPN*A2
!velocities commands
V2PTS(N,A,ASTAR,R1)
V2PTS(N,A,ASTAR,R2)
V2PTS(N,A,ASTAR,R3)
V2PTS(N,A,ASTAR,R4)
V2PTS(N,A,ASTAR,R22)
V2PTS(N,A,ASTAR,R11)
!Bstar is Frame center of mass assumed to be articulated around A*
PASTARBSTAR=AB*B2
V2PTS(N,B,ASTAR,BSTAR)
! location of R5 and R6 on the chassis.
PBSTARR5=-L2*B1
PBSTARR6=L2*B1
!Cstar or C* is the box and payload center of mass.
PBSTARCSTAR=L3*B1+L4*B2
!R7 and R8 are points on the box sides for external forces (wind..)
PBSTARR7=-L5*C1+L6*C2
PBSTARR8=L5*C1+L6*C2
!vectors from fixed point O are formed for later animations.
POBSTAR=ADD(POASTAR,PASTARBSTAR)
POCSTAR=ADD(POBSTAR,PBSTARCSTAR)
EXPRESS(POCSTAR,N)
POR1=ADD(POASTAR,PASTARR1)
EXPRESS(POR1,N)
POR2=ADD(POASTAR,PASTARR2)
EXPRESS(POR2,N)
POR3=ADD(POASTAR,PASTARR3)
EXPRESS(POR3,N)
```

```
POR4=ADD(POASTAR,PASTARR4)
EXPRESS(POR4,N)
POR5=ADD(POBSTAR,PBSTARR5)
EXPRESS(POR5,N)
POR6=ADD(POBSTAR,PBSTARR6)
EXPRESS(POR6,N)
POR7=ADD(POBSTAR,PBSTARR7)
EXPRESS(POR7,N)
POR8=ADD(POBSTAR,PBSTARR8)
POR11=ADD(POR1,PR1R11)
POR22=ADD(POR2,PR2R22)
!projections of the previous vectors are needed for the animations.
XR11=DOT(POR11,N1)
YR11=DOT(POR11,N2)
XR22=DOT(POR22,N1)
YR22=DOT(POR22,N2)
XR1=DOT(POR1,N1)
YR1=DOT(POR1,N2)
XR2=DOT(POR2,N1)
YR2=DOT(POR2,N2)
XASTAR=DOT(POASTAR,N1)
YASTAR=DOT(POASTAR,N2)
XR3=DOT(POR3,N1)
YR3=DOT(POR3,N2)
XR4=DOT(POR4,N1)
YR4=DOT(POR4,N2)
XBSTAR=DOT(POBSTAR,N1)
YBSTAR=DOT(POBSTAR,N2)
XR5=DOT(POR5,N1)
YR5=DOT(POR5,N2)
XR6=DOT(POR6,N1)
YR6=DOT(POR6,N2)
XR7=DOT(POR7,N1)
YR7=DOT(POR7,N2)
XCSTAR=DOT(POCSTAR,N1)
YCSTAR=DOT(POCSTAR,N2)
XR8=DOT(POR8,N1)
YR8=DOT(POR8,N2)
!following controls yield output files for the specified variables.
CONTROLS(XR11,YR11,XR1,YR1,XR22,YR22,XR2,YR2,XASTAR,YASTAR)
CONTROLS(XR3,YR3,XR4,YR4,XBSTAR,YBSTAR,XR5,YR5,XR6,YR6)
CONTROLS(XR7,YR7,XCSTAR,YCSTAR,XR8,YR8)
```

```
!mass centers velocities and accelerations.
V2PTS(N,B,BSTAR,R5)
V2PTS(N,B,BSTAR,R6)
V2PTS(N,B,BSTAR,R7)
V2PTS(N,C,BSTAR,CSTAR)
AASTARN=DERIV(VASTARN,T,N)
ABSTARN=DERIV(VBSTARN,T,N)
ACSTARN=DERIV(VCSTARN,T,N)
!gravity forces on each mass
FORCE(ASTAR)=-G*MA*N2
FORCE(BSTAR)=-G*MB*N2
FORCE(CSTAR)=-G*MC*N2
!wind force on R7
FORCE(R7)=(1/2)*RHO*CD*S*(UV)^2*(1.-SIN(2*PI*F*T))*cos(Q3+Q4-Q5)*b1
! extr1 is the combined tire and ground deflexion under left wheel.
!Roll-over start when extr1 becomes positive.
EXTR1=DOT(POR11,N2)
!extr2 is the opposite deflexion under the right wheel.
EXTR2=DOT(POR22,N2)
!dextr1 is the deformation rate needed for damping forces.
DEXTR1=DOT(VR11N,A2)
DEXTR2=DOT(VR22N,A2)
!ground forces (elasticity and damping )
FORCE(R11)=(-K1*RIGHT(EXTR1)-AM1*RIGHT(DEXTR1))*A2
FORCE(R22)=-KH*Q1*N1+(-K2*RIGHT(EXTR2)-AM2*RIGHT(DEXTR2))*A2
PR3R5=ADD(POR5,-POR3)
!frame suspension deflexion
EXTR3=DOT(PR3R5,A2)
PR4R6=ADD(POR6,-POR4)
EXTR4=DOT(PR4R6,A2)
!suspension rates of deflexion
DEXTR3=DERIV(EXTR3,T)
DEXTR4=DERIV(EXTR4,T)
! output files are requested.
CONTROLS(EXTR1,EXTR2,EXTR3,EXTR4)
!Frame suspension forces
FORCE(R3/R5)=-K3*(RIGHT(EXTR3)-LS3)*A2-AM3*RIGHT(DEXTR3)*A2
FORCE(R4/R6)=-K3*(RIGHT(EXTR4)-LS3)*A2-AM3*RIGHT(DEXTR4)*A2
!forces on wheels
FP1=DOT(FORCE(R11),A2)
FP2=DOT(FORCE(R22),A2)
!forces from the axle to the frame
```

```
FP3=DOT(FORCE(R3/R5),A2)
FP4=DOT(FORCE(R4/R6),A2)
!Transverse forces from the wind.
FP5=DOT(FORCE(R7),b1)
!output files for the wind and suspension forces.
CONTROLS(FP1,FP2,FP3,FP4,FP5)
!Command for the generalised forces for the Kane equations.
FR
!Command for the evaluation of the Kane equations inertia forces.
FRSTAR
!Command for the symbolic expressions of the Dynamics Kane  equations
KANE
!Command for making a file containing all symbolic evaluations.
RECORD(BEN4,ALL)
!Fortran source code command.
CODE(BEN4,SUBS)
```

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Appendix C

List of parameters used in the dynamic program.

1-rh0 = 1.2	Air density kg/m^3
2-cd = 2.3	Drag coefficient
3-S = 35.1	Trailer side surface m^2
4-uv = 0, 4. - 40.0	Wind velocity m/s
5-L1 = 0.975	Distance from rear axle centre to the wheels centre.m.
6-L2 = 0.65	Distance from the rear axle centre to the suspension centre.m.
7-L3 = 0.0	Off centre side distance of the payload and dump box centre of mass m.
8-L4 = 0.914	Height of mass centre above the frame centre of mass B* m.
9-L5 = 1.19	Box half width m.
10-L6 = .915	Height at which the wind resultant will act m.
11-G = 9.81	Earth gravity constant
12-K1 = 2 E06-8E06.	Tire and ground stiffness for the left rear wheel N/m.
13-K2 = 2 E06-2E06	Tire and ground stiffness for the right rear wheel N/m.
14-k3 = “	Rear leaf spring suspension stiffness either side N/m.
15-k4 = 0. “	Standby spring stiffness N/m.
16-Ls3 = 0.87	Initial spring length for k3 and k4 m.
17-am1 = 0.0 -	Rear left tire and ground damping constant
18-am2 = 0.	Rear and right tire and ground damping constant.
19-am3 = 0.	Rear suspension damping constant over R5 and R6.

20-am4 = 0.	Standby damping constant
21-ab = 0.	Distance from mass centres A* and B*
22-rpn = 0.5	Wheel radius m.
23-f= = 0.0 - 4.	Wind gust frequency Hz.
24-q6i = 0.0	Initial dump box lift angle rad.
25-q5i = 0.0	Terrain transverse angle rad.
26-kh = 400000.	Lateral tire and ground stiffness against side motion.
27-Ma = 1200	Rear tires and axles mass with centre A* kg
28 Mb = 3650	Frame mass with centre B* kg
29 Mc = 36650	Dump box and payload mass with centre C* kg
30 Ia(1) = 2	Body A centre Moment of inertia, axis a1 Kg-m^2
31 Ia(2) = 570	“ “ “ “ “ “ kg-m^2
32 Ia(3) = 570	“ “ “ “ “ “ a3
33 Ib(1) = 27400	Body B “ “ “ “ b1
34 Ib(2) = 3470	“ “ “ “ “ “ b2
35 Ib(3) = 27400	“ “ “ “ “ “ b3
36 Ic(1) = 275150	Body C “ “ “ “ c1
37 Ic(2) = 275150	“ “ “ “ “ “ c2
38 Ic(3) = 275150	“ “ “ “ “ “ c3
39 U(1) = 0.0	generalised horizontal velocity of axle A* m/s.
40 U(2) = 0.0	“ vertical “ “ “ “ m/s.
41 U(3) = 0.0	“ angular “ “ “ “ rad/s
42 U(4) = 0.0	“ “ “ “ frame B rad/s.
43 Q1 = 0.0	“ horizontal displacement of axle A m.
44 Q2 = 0.4745	“ vertical “ “ “ m.
45 Q3 = 0.0	generalised angular coordinate for axle A rad.
46 Q4 = 0.05	“ “ “ frame B rad.

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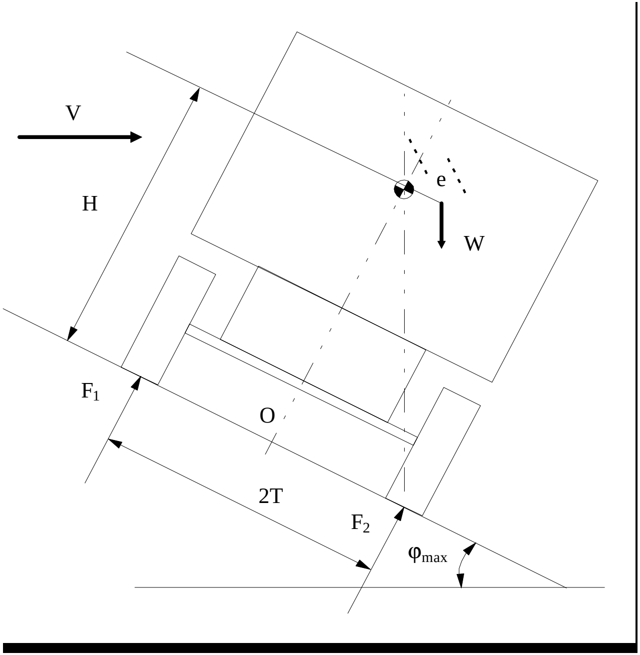

Figure 1: Vehicle model prior to roll-over with deflated suspensions

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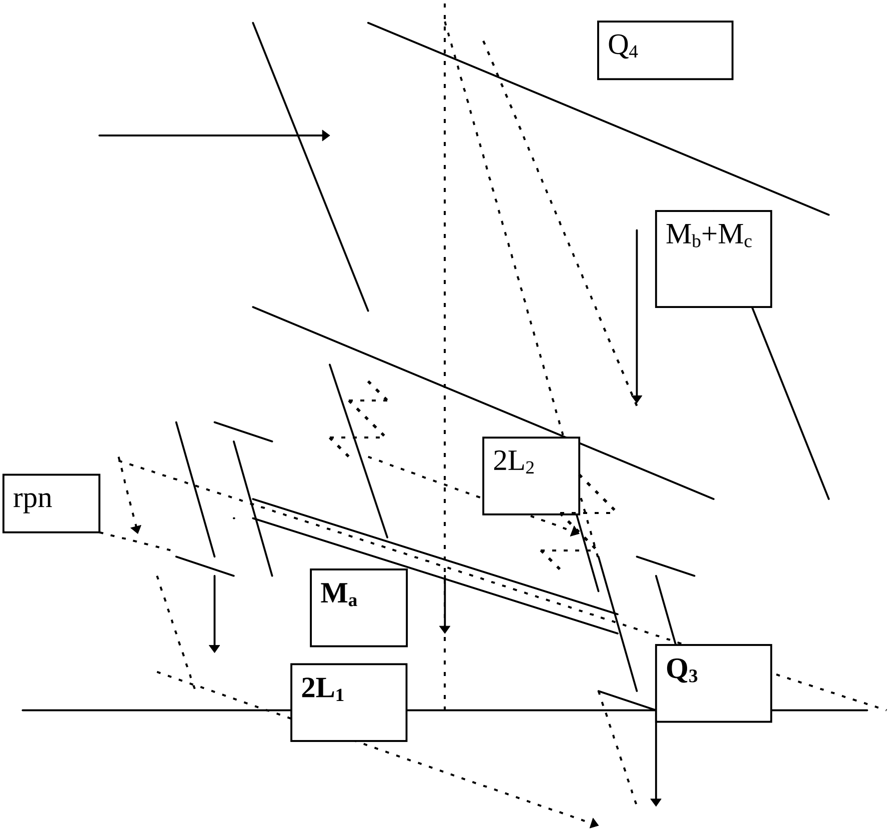

Figure 2: Dump truck model wth leaf spring suspensions.

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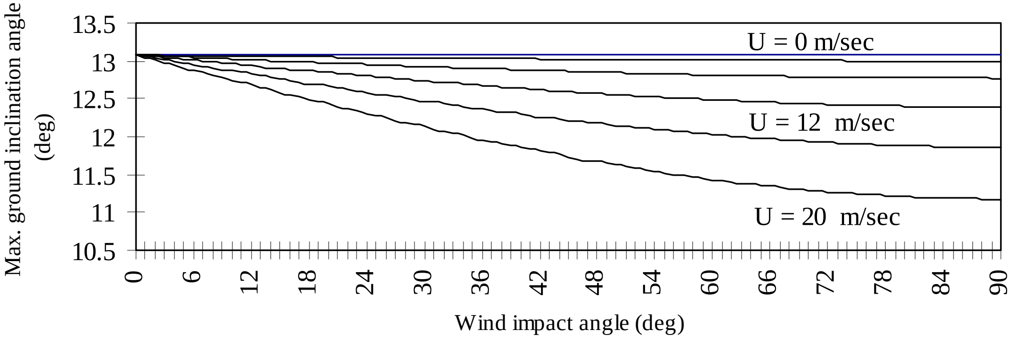

Figure 3

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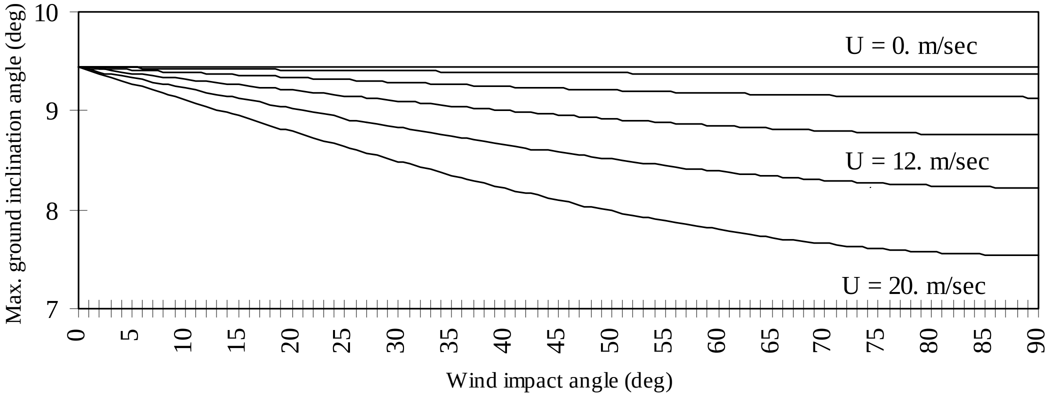

Figure 4

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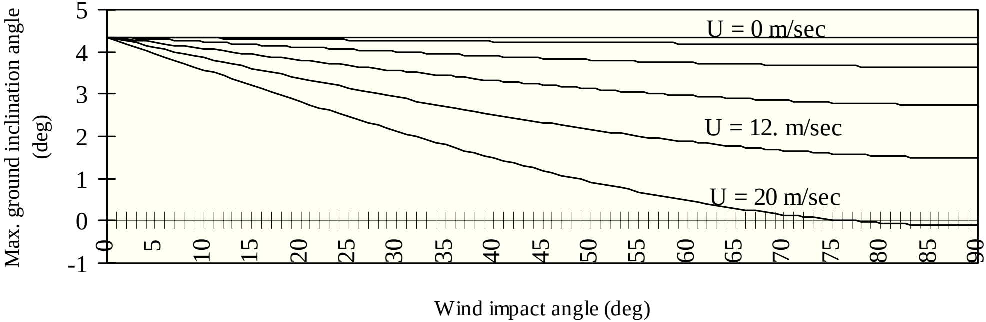

Figure 5

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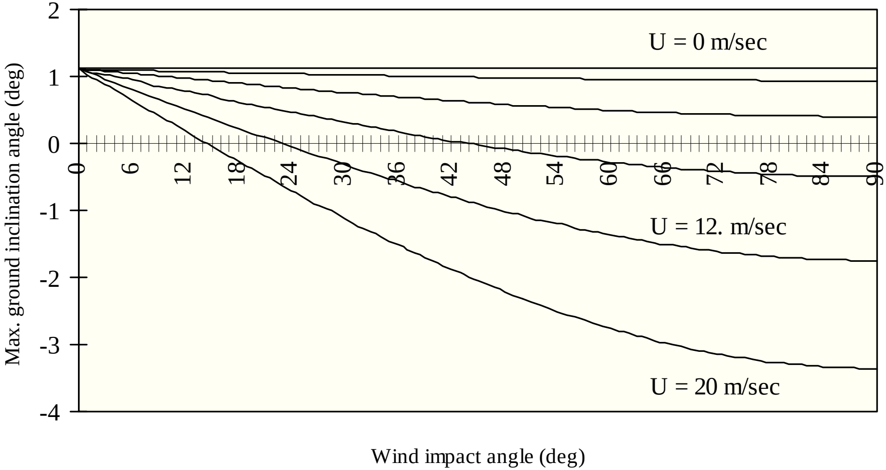

Figure 6

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