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The Effect of Tire Deformation on the Critical Speed of the Vehicles on Wet Roads

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Abstract

In this research many tire and environmental parameters had been studied and their effect on the maximum critical speed was monitored during driving on a wet road. These parameters are tire deformation tire width, tire radius, wheel load, number of grooves, groove depth, groove width and the (Aspect Ratio). And external parameters, such as water layer thickness, and the dynamic viscosity of the water. The region of the tire road contact is considered as a convergence surfaces, therefore the same mathematical model that used in the conventional bearing, had been implemented, hence Reynolds equation have been solved numerically using the finite difference technique and the results afterward are obtained for the pressure value at each point in the contact region. The results show that increasing the tire deformation, tire width, tire radius, the thickness of the water layer on the road surface, and dynamic viscosity of water, have a negative effect on the critical speed of the vehicle (decreasing). While increasing of the wheel load, numbers of grooves, groove depth, groove width and the aspect ratio, have a positive effect on the critical speed of the vehicle (increasing).Generally speaking, the tires with small deformation have a better driving performance for the vehicles compared with that of large deformation during driving the vehicle on wet roads.

1. Introduction

When the vehicle is driven with high speed on a wet road, its tires would be lifted from the road surface by a water film of high pressure. And this would cause lost the control on the vehicle, and this many cause accident (Suzuki and Fujikawa, 2001). In order to overcome this problem grooved tyres are used which lead to a safe driving with high speed without slipping (Horne and Dreher, 1963; Gallaway et al., 1979). Tire slipping and analyzing it mathematically is a complicated mater especially with the consideration of the tire deformation and the road surface roughness parameters (Bukhin, 1988; Pakalins, 2000; Bohm, 1996).

2. Aquaplaning on vehicle

The vehicles depend on friction in accelerating, decelerating and breaking, but the existence of the water layer between the tires and the road surface may cause the vehicle note to meet the previous requirements. The contact zone between the tire and the road surface may be divided into three regions as shown in Fig. 1.

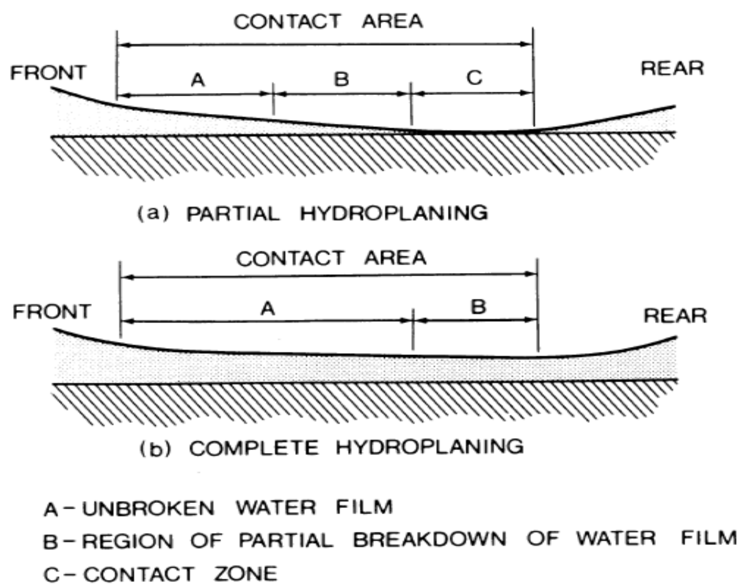

Fig. 1. Tyre road contact zone

These regions are:

(A) Front region which meet the unbroken layer of water.
(B) Middle region which meet the partially broken layer of water.
(C) Back dry region.

3. Tire Geometry

Referring to Fig. 2 the tire geometry (smooth and grooved) through driving on a wet road h is the water film thickness (without considering the tire deformation). And R is the tire radius, while δh is the tire deformation due to the water film pressure, T is the water film depth Table 2 Consists the tire dimensions specifications and the driving parameters.

Table 2: Tire dimensions specifications and the driving parameters

Parameters	Details	Units	Parameters	Details	Units
Specifications of used tire	smooth, grooved	-	No. of grooves	0-8	-
road Specifications	Asphalt plane road and smooth	-	D_g	0-8	mm
WL	350-600	Kg	L_g	2-10	mm
R	280-360	mm	*AR %*	50-70	-
L	140-220	mm	μ	0.00044-0.00124	Pa.s
T	10-50	mm	*ET*	11	MPa

3.1. Water film thickness equation

Referring to Fig. 2a

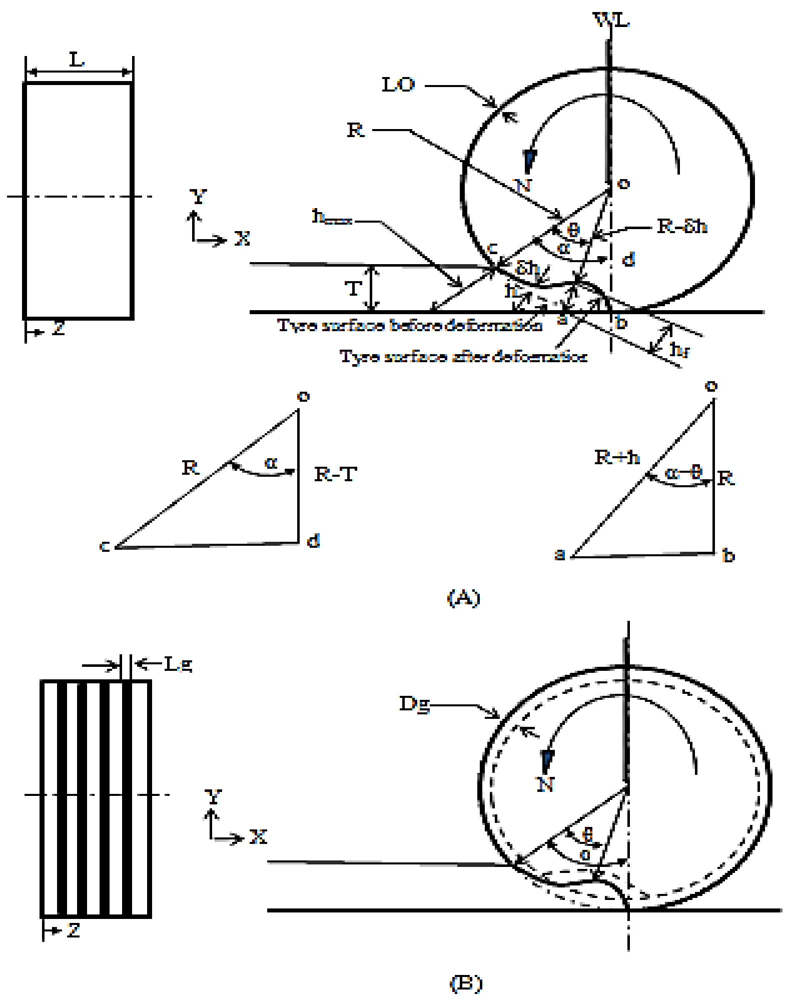

Fig. 2. Tyre geometry (A) smooth, (B) groove

Δ ocd

$$\cos(\alpha) = \frac{R - T}{R} \tag{1}$$

$$\alpha = \cos^{-1}\left(\frac{R - T}{R}\right) \tag{2}$$

Δoab

$$\cos\left(\alpha - \frac{X}{R}\right) = \frac{R}{R - \delta h + h_f} \tag{3}$$

Where $\theta = \frac{X}{R}$

$$R + h = \frac{R}{\cos\left(\alpha - \frac{X}{R}\right)} \tag{4}$$

But,

$$h_f = h + \delta h \ \ and\ h = h_f - \delta h$$

Therefor

$$R - \delta h + h_f = \frac{R}{\cos\left(\alpha - \frac{X}{R}\right)} \tag{5}$$

$$h_f = \frac{R}{\cos\left(\alpha - \frac{X}{R}\right)} - R + \delta h \tag{6}$$

Where δh is the total tire deformation, which consists two parts. These parts are, δr is the tire rubber deformation and δa is the contraction of the air column inside the tire. Hence:

$$\delta h = \delta r + \delta a \tag{7}$$

δr is computed as follow(Singer and Pytel, 1980):

$$\delta r = P(i,j) * \frac{LO}{ET} \tag{8}$$

Where ET= 11 Mpa (Callister, 2000)

And δa is computed using the following equation (Eastop and Mcc, 1969):

$$\delta a = R - LO - R_w - \frac{3V_2}{a + a_w + \sqrt{a * a_w}} \quad (9)$$

Differentiating Eq. 6 with respect to *x* gives.

$$(\frac{\partial h_f}{\partial x})_{i,j} = \frac{h_{f(i+1,j)} - h_{f(i-1,j)}}{2\Delta X} \quad (10)$$

3.2. Solving Reynolds Equation

After knowing the relative speed between the tire and the road surface, tire dimensions and the water layer viscosity, then the water film pressure can be counted using Reynolds equation (Cameron, 1979).

$$\frac{\partial}{\partial x}\left(\frac{h^3}{\mu}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{h^3}{\mu}\frac{\partial P}{\partial z}\right) = 6(U_1 + U_2)\frac{\partial h}{\partial x} \quad (11)$$

Where

$$U_1 = U = 2\pi RN \quad (12)$$

Also

$$U_2 = U = 2\pi RN \quad (13)$$

Since

U2=U1, therefor Eq. 11 becomes:

$$\frac{\partial}{\partial x}\left(\frac{h^3}{\mu}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{h^3}{\mu}\frac{\partial P}{\partial z}\right) = 12U\frac{\partial h}{\partial x} \quad (14)$$

Expanding eq. (14) gives:

$$\left(h^3\frac{\partial^2 P}{\partial x^2}\right) + \left(3h^2\frac{\partial h}{\partial x}\frac{\partial P}{\partial x}\right) + \left(h^3\frac{\partial^2 P}{\partial z^2}\right) + \left(3h^2\frac{\partial h}{\partial z}\frac{\partial P}{\partial z}\right) = 12U\mu\frac{\partial h}{\partial x} \quad (15)$$

But $\frac{\partial P}{\partial z} = 0$ (no misalignment), therefore, the previous equation becomes:

$$\frac{\partial^2 P}{\partial x^2} + \frac{3}{h}\frac{\partial h}{\partial x}\frac{\partial P}{\partial x} + \frac{\partial^2 P}{\partial z^2} = \frac{12U\mu}{h^3}\frac{\partial h}{\partial x} \quad (16)$$

Then the finite difference technique of five nodes scheme was used in order to solve Reynolds equation numerically (Amir and John, 1986).

By applying the finite difference technique, the 1^{st}& 2^{nd} derivatives of the water film pressure annually and axially are derived. Then by substituting those derivatives in Eq.16, gives:

$$\frac{1}{(\Delta X)^2}\left(P_{i+1,j}-2P_{i,j}+P_{i-1,j}\right)+\frac{3}{2h*\Delta X}\frac{\partial h_f}{\partial X}\left(P_{i+1,j}-P_{i-1,j}\right)+\frac{1}{(\Delta Z)^2}\left(P_{i,j+1}-2P_{i,j}+P_{i,j-1}\right)=\frac{12\mu U}{h^3}\frac{\partial h_f}{\partial X} \quad (17)$$

From the previous equation gives:

$$P_{i,j}=B_1P_{i+1,j}+B_2P_{i-1,j}+B_3P_{i,j+1}+B_3P_{i,j-1}-B_4 \quad (18)$$

Then using the following boundary conditions for the pressure;

Annually

P = 0 at X = 0 or θ = 0

P = 0 at X = αR or θ = α

Axially

P = 0 at Z = 0

P = 0 at Z = L

$\frac{\partial P}{\partial Z}=0$ at Z = L/2

And using the following convergence criteria to control iteration;

$$\left|\frac{(P_{i,j})_k-(P_{i,j})_{k-1}}{(P_{i,j})_k}\right|\leq 10^{-3} \quad (19)$$

Then pressure value at each node would be obtained and counting the vertical components of the water film forces is calculated.

The water film pressure on each node produces a normal force on the external surface of the tire. These nodes forces reanalyzed into two components, parallel and perpendicular to the road surface. When the summation of the normal components becomes equal to the wheel load, this would cause aquaplaning of the vehicle and this would be called critical speed of the vehicle.

And the sum of those normal components are counted as follow

The area of each element is (a) , which counted as follow:

$$a=\Delta X*\Delta Z \quad (20)$$

Then the summation of the normal components (F_N) is counted as follow:

$$F_N=\sum_{j=1}^{j=n}\sum_{i=1}^{i=m}P_{i,j}*a*\cos\left(\alpha-\frac{X}{R}\right) \quad (21)$$

4. Result

The results that obtained using a FORTRAN program that prepared for this purpose, these results are used to draw the following relationships. Fig.3 shows distribution of the water film thickness around the tire showing the effect of the tire deformation on it. While Figs. 4 and 5 shows the water film pressure distribution annually and axially. These Figs. show the effect of the tire deformation on it (increase it) which effect the critical speed of the vehicle negatively (decrease it).

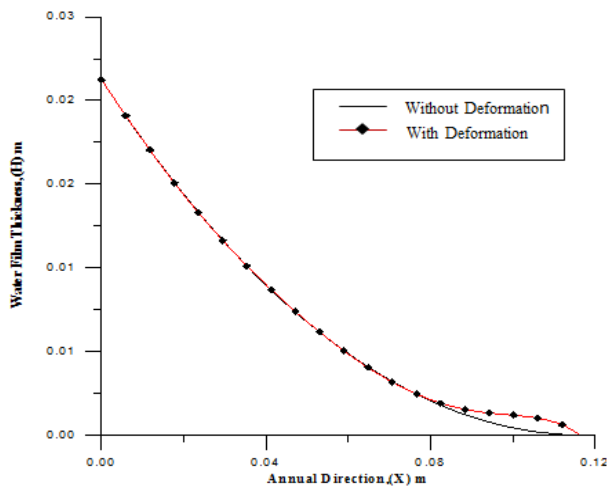

Fig. 3. Variation of the oil filmthickness $h_f$annually

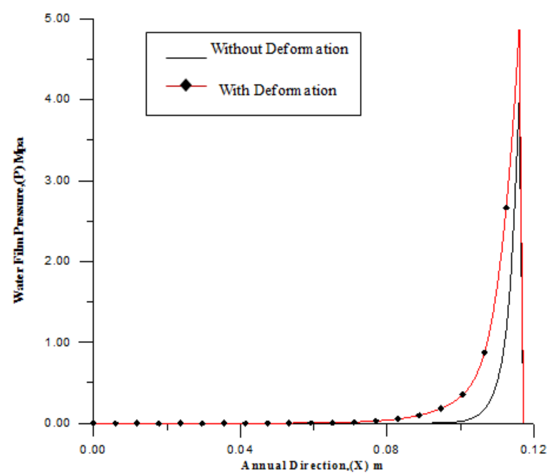

Fig. 4. Pressure *P* distribution annually

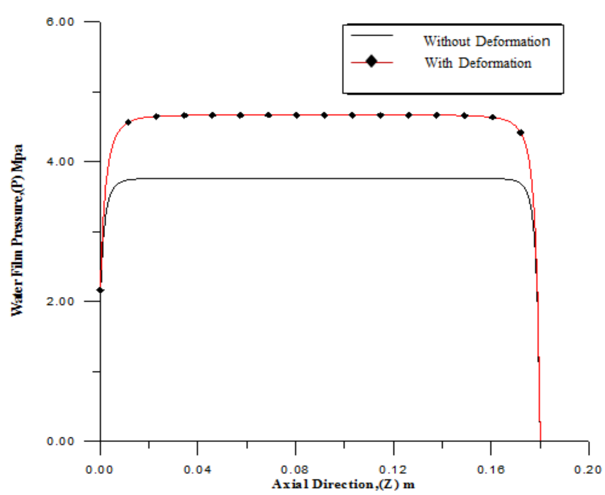

Fig. 5. Pressure *P*distribution axially*L*

Figs. 6-23 shows the relationship between the critical speed and the tire width, tire radius, water layer depth, vehicle load, groove width and aspect ratio respectively with varying the other parameters, with considering the tire deformation or not. From these figures it could be deduced that:

1) Increasing the tire width, tire radius, water layer depth and the water viscosity have a negative effect on the critical speed (decreasing it).
2) Increasing the vehicle load, number of grooves, grooves width, grooved depth and the aspect ratio have a positive influence on the critical speed of the vehicle (increasing it).
3) The tire deformation has a negative influence on the critical speed (decrease it) of the vehicle. Thus for driving on wet roads using tires made of hard tough rubber and full the tires with a high pressure this would give a safe driving.
4) These results are in satisfying agreement with that of references (McHenry, 2003; Kumar, 2009; Kakkalis and Panagouli, 1998; Kumar, 2009; Cao, 2010; Koutny, 2007).

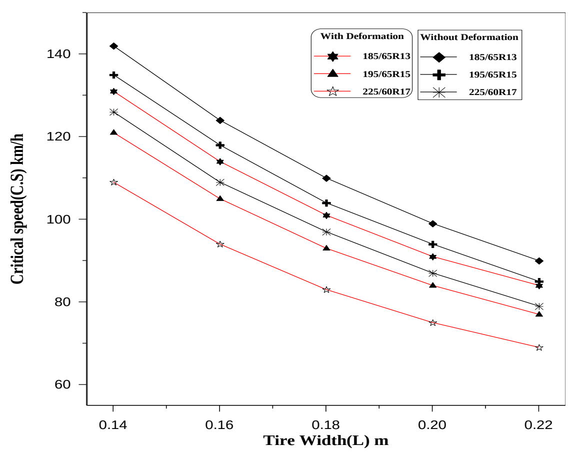

Fig. 6. The relation between *C.S.* and for different tyre radius

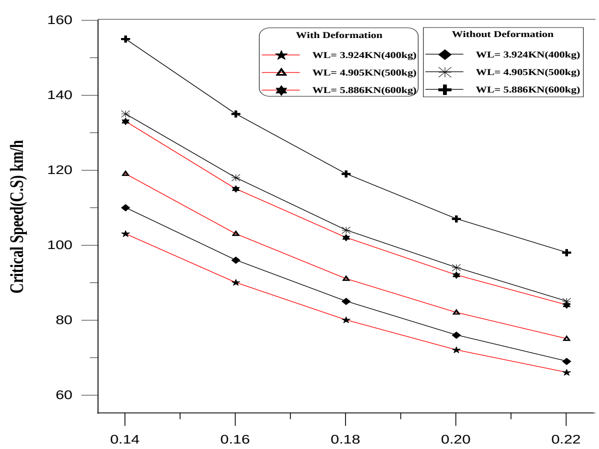

Fig. 7. The relation between *C.S.* and*L* for different wheel loads

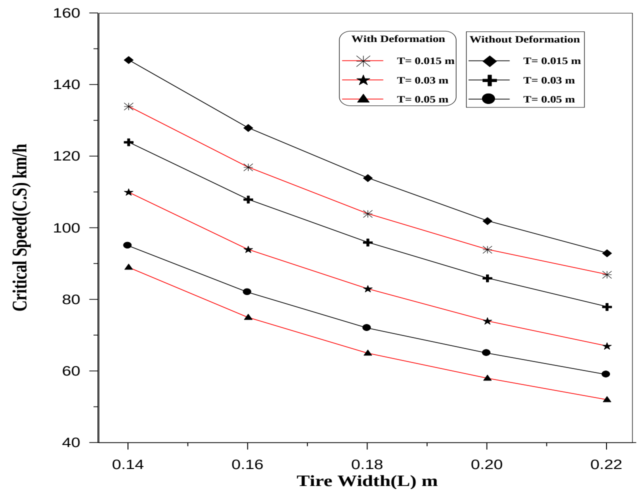

Fig. 8. The relation between *C.S.* and*L* for different water layer depth

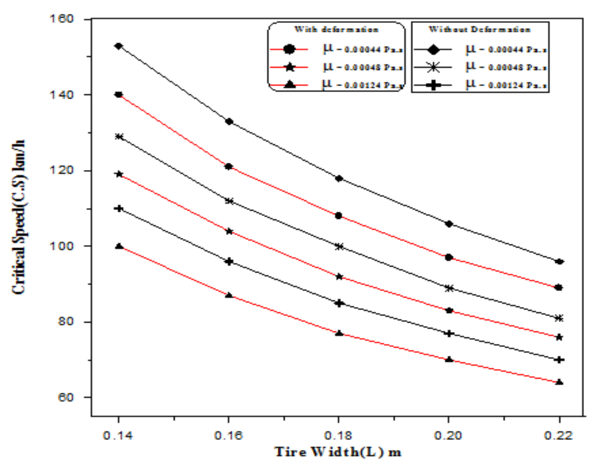

Fig. 9. The relation between *C.S.* and *L*fordifferent value of water viscosity

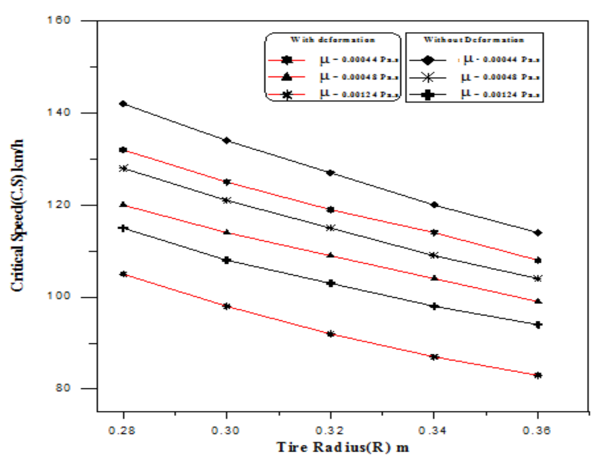

Fig. 10. The relation between *C.S.* and*R*fordifferent value of water viscosity

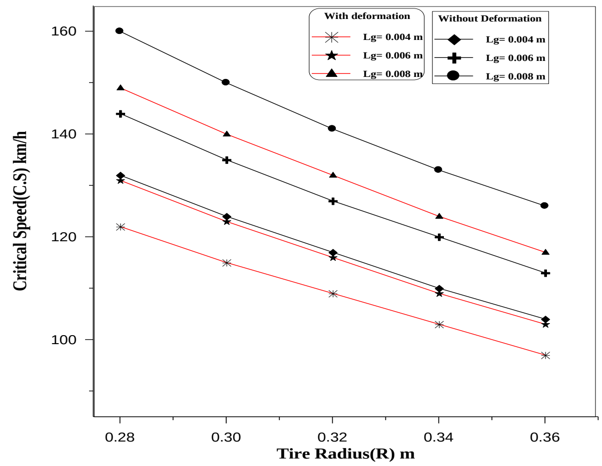

Fig. 11. The relation between *C.S.* and *R*for different values of groove width

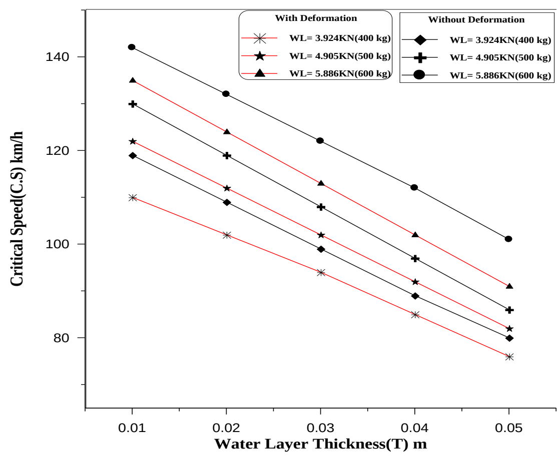

Fig. 12. The relation between *C.S.* and *T*for different wheel loads

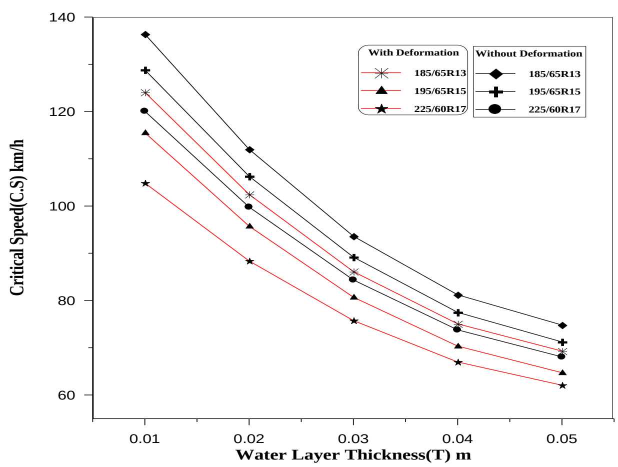

Fig. 13. The relation between *C.S.* and *T*for different values of tyre radius

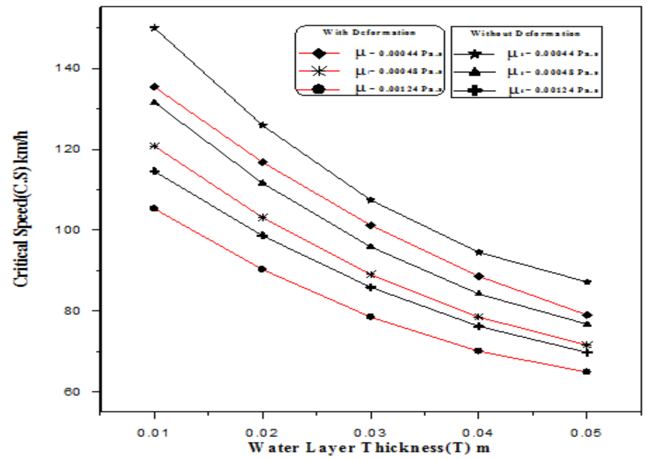

Fig. 14. The relation between *C.S.* and *T*for different water viscosity

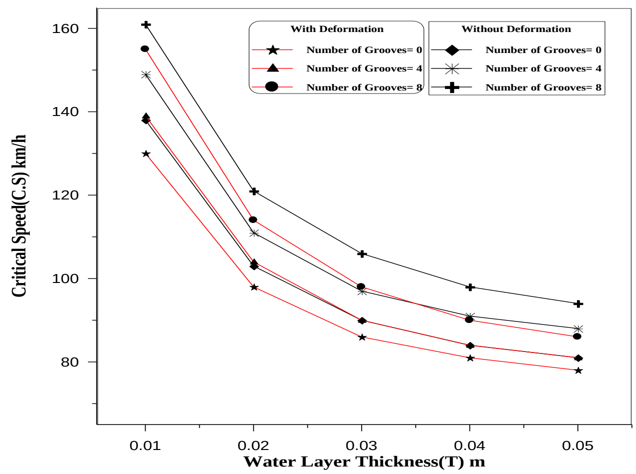

Fig. 15. The relation between *C.S.* and *T*for different number of grooves

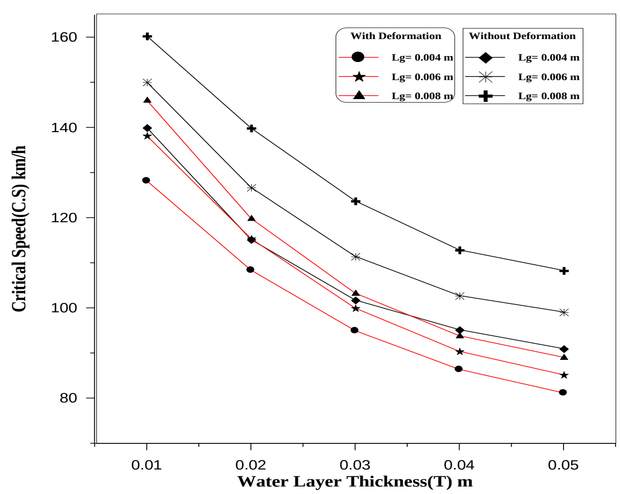

Fig. 16. The relationbetween *C.S.* and *T*for different value of groove width

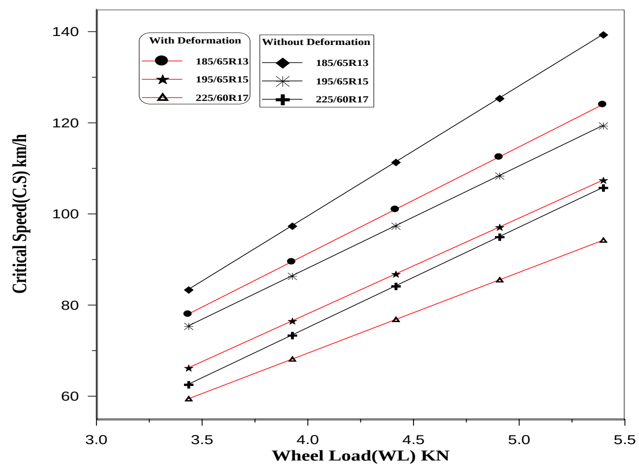

Fig. 17. The relation between*C.S.* and *WL*for different value of tyre radius

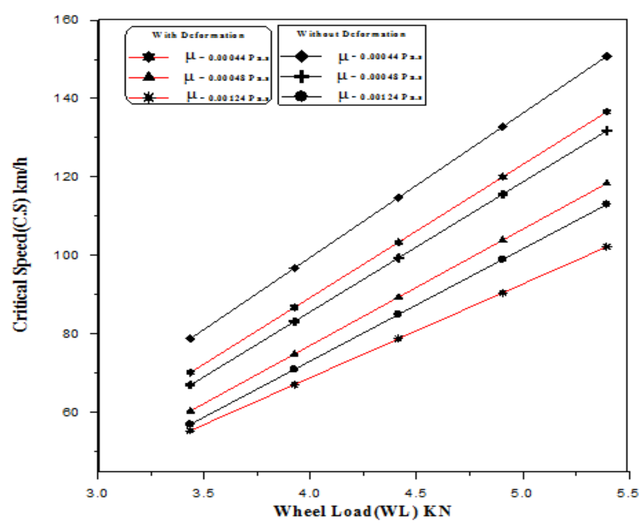

Fig. 18. The relation between *C.S.* and *WL*for different value of water viscosity

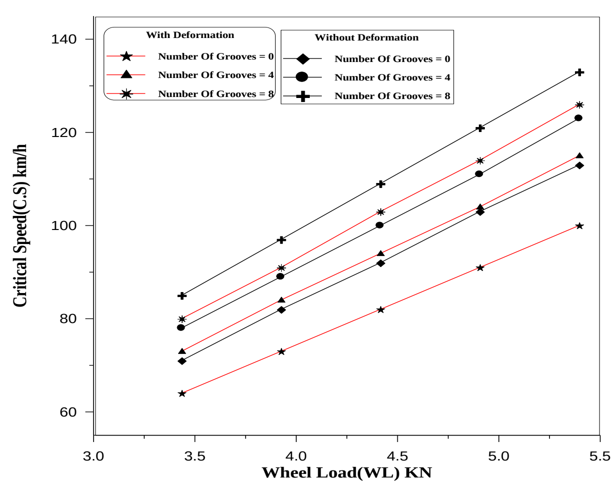

Fig. 19. The relation between *C.S.* and *WL*for different number of grooves

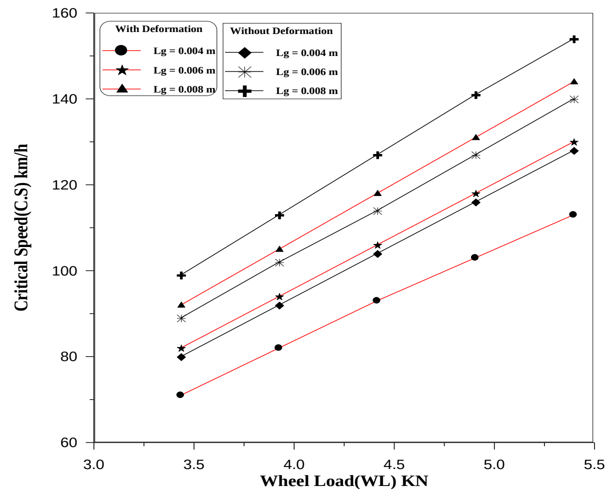

Fig. 20. The relation between *C.S.* and *WL*for different value of groove width

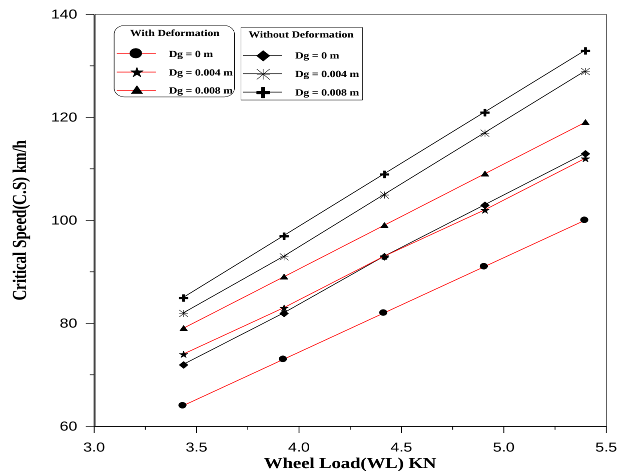

Fig. 21. The relation between*C.S* and *WL*for different value of groove depth

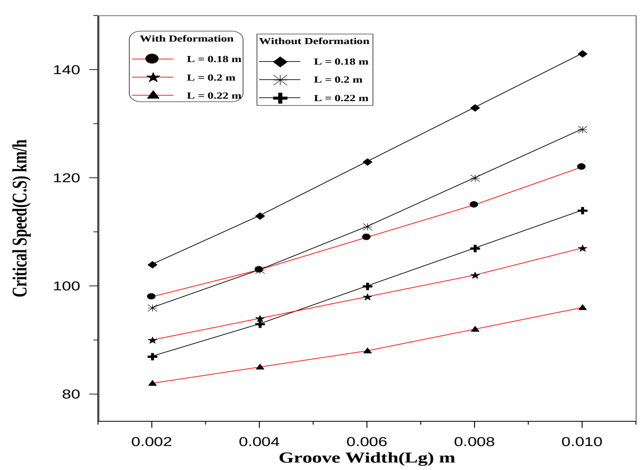

Fig. 22. The relation between *C.S.* and $L_g$for different value of tyre width

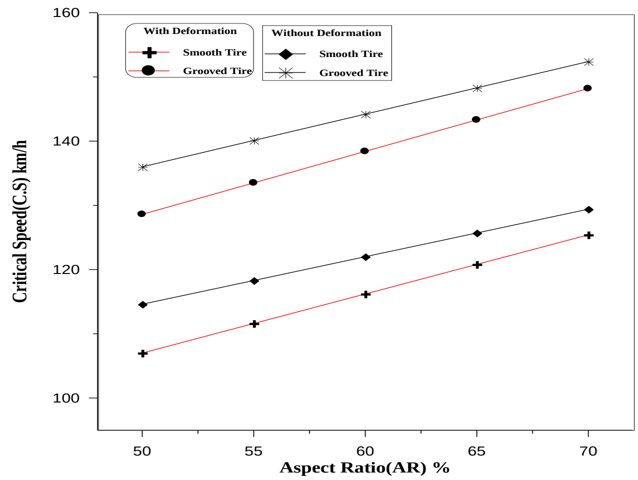

Fig.23. The relation between *C.S.* and *AR*

5. Nomenclature

a	element area on the external tyre surface (m^2)
AR	aspect ratio
$a\delta$	air contraction value (m)
$B1, B_2$	Coefficients
C.S	critical speed (m sec^{-1})
D_g	groove depth (m)
ET	modulus of elasticity of the tyre material (MPa)
F_N	resultant of force perpendicular on the road surface (N)
h_f	final value of the water film thickness (m)
$h\delta$	total deformation of the tyre (m)
k	number of iteration
L	tyre width (m)
L_g	groove width (m)
LO	tyre wall thickness (m)
p	water film pressure (N m^{-2})
R	tyre radius (m)
T	water layer depth on the road (m)
U_1	linear velocity for any point on the external tyre surface (m sec^{-1})
U_2	linear displacement, horizontal velocity of the tyre center (m sec^{-1})
V_2	column volume of air after compression (m^3)
WL	wheel load (N)
X	annual coordinate on the external tyre surface (m)
Z	axial coordinate on the external tyre surface
Greek symbols	

μ	dynamic viscosity of the water (Pa sec)
θ	annual angle for each point on the tyre surface (rad)
$r\delta$	deformation value of the tyre material (m)
Δx	element length in the annual direction (m)
Δz	element length in the axial direction (m)

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