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Tyre Safety Performance on Asphalt Pavement in Malaysia Climate – Analysis through Finite Element Method

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Abstract – *Interaction characteristics between tyre and asphalt pavement surface are one of the important aspects that need to be taken into consideration in maintaining the safety of driving through increasing the effectiveness of tyre and optimizing the possibility of skidding, especially during hydroplaning conditions. Lower quality of tyres in terms of tyre life, bad tyre rethreading, low tyre material quality plus lack of awareness by road users can be considered the main factors in occurrence of car accidents in Malaysia. The study is done on the contact performance between tyre surface and asphalt pavement in hot and humid Malaysia climate, with the application of Finite-Element Method. In maintaining or increasing the safety features of tyre, several parameters such as rotational speed, vehicle weight, tyre-road contact friction will be studied through computer simulation. It is estimated that increment of loading, surface contact between tyre and road pavement will increase, thus increasing the frictional contact. It is shown that effective frictional characteristic is needed, where traction, braking, life of tyre can be optimized.*

Keywords: Tyre-road interaction, traction performance, contact friction, finite element method

1.0 INTRODUCTION

Statistically, the number of car crashes incident increases each year, as shown in Figure 1, where it is reported by the Ministry of Transport Malaysia and the media that, 521,466 cases of road crashes, which resulted in 7,152 road deaths in 2016 (Malaysian Institute of Road Safety Research, n.d.). A large number strategies and action had been proposed and taken into action to reduce the number of road crash incident such as improvement of road infrastructure, penalty over road usage misconduct and implementation of Road Safety

Education (RSE) in schools (Malaysian Institute of Road Safety Research, n.d.). However, the successfulness of these strategies is still based on the awareness and morality of the road users themselves. Application of faulty tyres can be one of the road users' bad behaviours, where it is assumed that lack of tyre maintenance, poor inflation and worn tyre threads decrease the safety performance of tyres (Abdul Khalid et al., 2018), supported a statistic that 41.3% from 15,100 objects obtained from the North-South Expressway was tyre debris (Bajuri, n.d.).

Technically, the vehicle is moved by the pull-push action (the tyre is pulling the car while pushing the road) called traction (Oh & Lee, 2014; Naranjo et al., 2014, Wu et al., 2014; Aguilar-Martínez & Alvarez-Icaza, 2015; Gray et al., 2016). However, whenever the car brakes in sudden (emergency braking), the existence of inertial force is always becoming a risk for the vehicle to slip, especially for the car without the ABS (Anti-lock Braking System) being equipped and application of faulty tyres (Oh & Lee, 2014). This will lead to vehicle crash and danger to the car user himself, as well as other road users too, who might actually abide the road safety measures and law, but being exposed to other road users' misconduct (Oh & Lee, 2014; Naranjo et al., 2014, Wu et al., 2014; Aguilar-Martínez & Alvarez-Icaza, 2015; Gray et al., 2016).

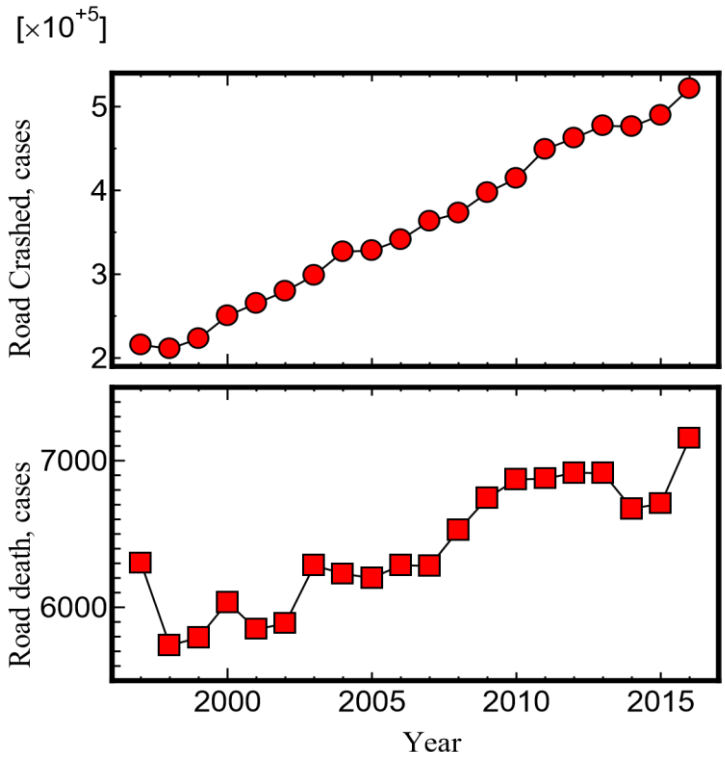

Figure 1: Statistic of the road crashed and road death cases from 1996 to 2016 (Malaysian Institute of Road Safety Research, n.d.)

As an assessment of tyres safety performance, one of the characteristics that need to be studied is the tyre traction mechanism (Oh & Lee, 2014; Naranjo et al., 2014, Wu et al., 2014; Aguilar-Martínez & Alvarez-Icaza, 2015; Gray et al., 2016; Ozaki & Kondo, 2016). Understanding on the traction mechanism will leads to knowing how to design effective tyre thread for any road circumstances, such as traction for Malaysia hot and humid asphalt pavement or rainy season wet pavement applications (Bhoopalam & Sandu, 2014; Zhao &

Zhang, 2014; Schjønning et al., 2015; Ueckermann et al., 2015; Ozaki & Kondo, 2016; Savitski et al, 2017; Chen et al., 2018). Tyre thread deformation during normal and emergency braking; and tyre slipping conditions can become one of the main criteria for the tyre thread designing process. Plus, this will help in explaining the danger of using low-quality tyres, illegal rethreaded tyres or worn tyres (Bajuri, n.d.).

Several studies had been done on modelling the tyre performances on the road using Finite Element Method (Wei & Olatunbosun, 2014; Sharp et al., 2016; Smith & Uddin, 2016; Nishiyama et al., 2017; Zhao & Zhang, 2017; Nishiyama et al., 2018). A finite element method is a powerful tool in analysing any engineering, safety and costing related topics and phenomena. In the case of tyre performances, it can be considered as hard to model realistic frictional behavior of thread traction and sliding rubbers on rough asphalt pavement. Prediction on tyre performance and safety accuracy with Finite Element Method (FEM) is majorly effected by practical boundary conditions such as vehicle loading, frictional coefficient, geometry of tyre and its thread and temperature during road-pavement interaction (Wei & Olatunbosun, 2014; Sharp et al., 2016; Smith & Uddin, 2016; Nishiyama et al., 2017; Zhao & Zhang, 2017; Nishiyama et al., 2018).

In the present study, the effect of friction between tyres and pavement contact will be analysed through the application of Finite Element Method (FEM). An effective model of tyre-road interaction is modelled. The contact quality of thread and pavement is translated into friction coefficient for various situations, assuming lower to higher frictional contact. The heat transfer between pavement and tyre will be observed to indicate tyre softening behavior. Additionally, start-stop analysis will be analysed to simulate tyre slipping, where this knowledge can be applied to estimate braking time.

2.0 METHODOLOGY

In this paper, commercially available tyre geometry for domestic use (175/65 R14) is simplified into a practical FEM model, as shown in Figure 2. Simulating the dynamic loading onto one single tyre is complex, thus it is simplified by estimating the area of contact between tyre and pavement for any loading condition for the model (Figure 3) and explain through Equation (1) to Equation (7).

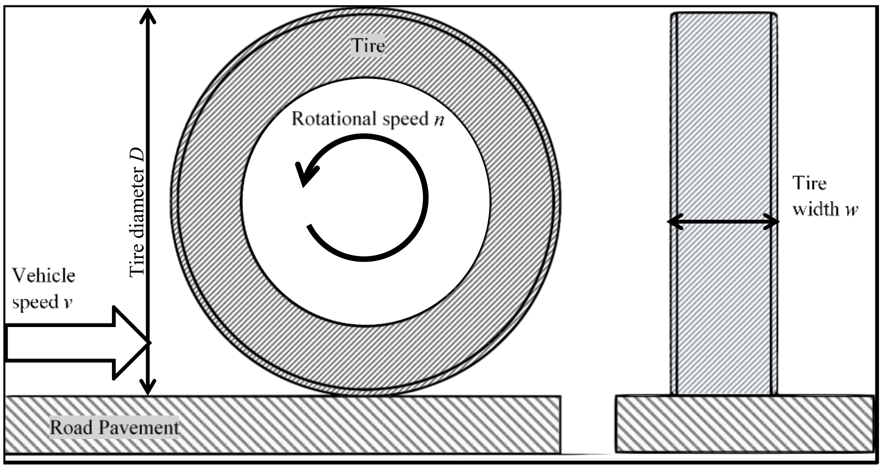

Figure 2: Simplified tyre and pavement model

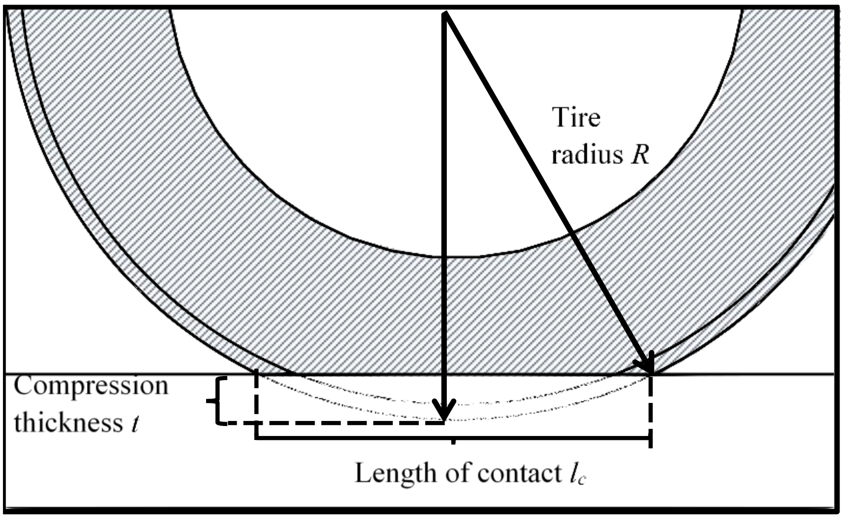

Figure 3: Estimating the relationship between loading and contact area

Based on Figure 3, as the radius of tyre *R*, the length of contact between tyre and pavement can be shown as l_c, the compression thickness due to loading *F* as *t*, tyre material elastic modulus as *E* and width of tyre as *w*, it can be estimated that

$$\text{Length of contact, } l_c = 2\sqrt{(R^2 - (R-t)^2)} \quad (1)$$

While the area of contact between tyre and pavement *A* can be shown as Equation (2),

$$\text{Area of contact, } A = l_c w \quad (2)$$

thus,

$$A = 2w\sqrt{(R^2 - (R-t)^2)} \quad (3)$$

and,

$$\text{Material stress, } \sigma = \frac{F}{A} = \frac{F}{A = 2w\sqrt{(R^2-(R-t)^2)}} \quad (4)$$

Since,

$$\text{Material stress, } \sigma = Et \quad (5)$$

by replacing (4) into (5)

$$\frac{F}{2w\sqrt{(R^2 - (R-t)^2)}} = Et \quad (6)$$

thus, the final equation can be obtained as,

$$F = 2Etw\sqrt{(R^2 - (R-t)^2)} \quad (7)$$

However, Equation (7) shows a very complex equation to estimate tyre compression thickness t from loading F, thus it is easier to obtain the relationship by numerically calculated each possible relationship between those parameters and will be presented in the following chapter. Meanwhile, the rotational speed of the tyre in [rad/s] can be estimated by Equation (8), where this is needed as an input parameter for the model. Taken into consideration that Malaysia vehicle speed v unit is in [km/h],

$$\text{Tyre rotational speed, } n = v.\frac{10^6}{3600R}\left[{rad}/{sec}\right] \tag{8}$$

Additionally, the tyre is modelled under elastic-plastic deformation conditions, while the tyre is designed under rigid deformation conditions in FEM. In the study, the tyre model is rotated on the moving pavement model. The traction of the tyre is designed in terms of speed ratio between tyres rotation and pavement, e.g. when tyres are rotated, but pavement is not moved, traction = 0, and pavement is moving with the same speed with tyres, traction = 1. This is to ease the analysis of the effect of interface friction using simplified tyre design. The tyre specification and analysis conditions are shown in Table 1 and Table 2.

Table 1: Tyre specifications

Variable	Specification
Tyre model	175/65 R14
Tyre diameter D[mm]	566
Tyre width w [mm]	175
Material elastic modulus E [kPa]	7500 (Control), 10000, 15000 (Control)
Thermal conductivity k [kW/mK]	0.14

Table 2: Simulation conditions

Variable	Condition
Vehicle speed v [km/h]	100.00
Rotational speed n [rad/s]	100.00
Frictional coefficient μ	0.2~0.6
Traction ratio r	0.4~1.0

3.0 RESULTS AND DISCUSSION

Figure 4 shows the relationship between compression thickness t with loading F and tyre pavement contact area A estimated numerically from Equation (3) and Equation (7). It can be observed from the figure that, for different tyre material elastic modulus, the tyre-pavement area of contact A for a particular loading is different for a similar tyre model. For similar loading F of 3,368.75 [N] per tyre (vehicle curb weight: 1,075 [kg], four passengers with 75 [kg] in weight for each person) condition, tyre with 7.5 [MPa], 10 [MPa] and 15 [MPa] shows tyre-pavement area of contact A as 14,576 [mm^2], 13,248 [mm^2], and 11,575 [mm^2], respectively. It can be assumed that weaker (lower elastic modulus) tyre material will increase the frictional contact area between tyre and road, while tougher tyre material will decrease the frictional contact area between tyre and road.

Although it is still complex to explain the relationship between tyre friction, traction and safety, it is still can be understood that weaker tyre material (lower elastic modulus) might be safer for short term applications due to higher stability due to higher contact surface. However, after a certain period of usage, the tyre may show a higher worn surface and higher risk of tyre failure. Meanwhile, for tougher tyre material (higher elastic modulus), possibility to slip is higher due to lesser contact area.

Additionally, the estimated tyre compression thickness for material B is chosen as general rubber tyre material properties. Based on the load conditions applied in the study (3,368.75 [N]), tyre compression thickness *t* of 2.54 [mm] is chosen to study the effect of friction and traction onto the performance of the tyre. Figure 5 shows the stress distribution on tyre for driving speed of 100 [km/h] with frictional coefficient of 0.2 and traction ratio of 1.0. It can be observed from Figure 5 that the tyre stress is peak at the zone contacted with the pavement, as the tyre experienced loading from the vehicle weight as well as frictional contact.

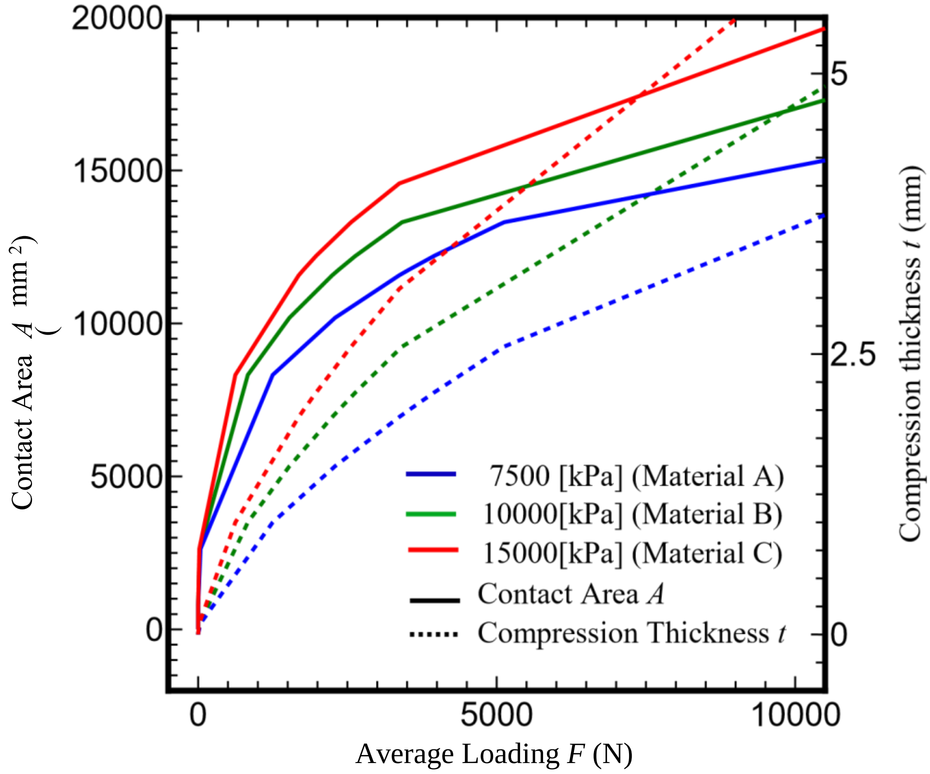

Figure 4: The relationship between compression thickness *t* with loading *F* and tyre-pavement contact area *A*

Meanwhile, Figure 6 shows the lateral and vertical loading experienced by tyre estimated by FEM for various frictional coefficient for 100 [km/h] driving speed. Although experimental validation is required for the estimated data, it can be observed that vertical loading is almost constant for various frictional coefficients, but lateral loading is increasing with the increasing frictional coefficient. It can be assumed that the tyre may experience adhesive like contact onto pavement, thus decrease the effective life of the tyre when the frictional coefficient is too high. Meanwhile, in the case of extremely low frictional coefficient, the braking and traction performance of the tyre will decrease, leading to crashes and dangers as this kind of tyre being utilized.

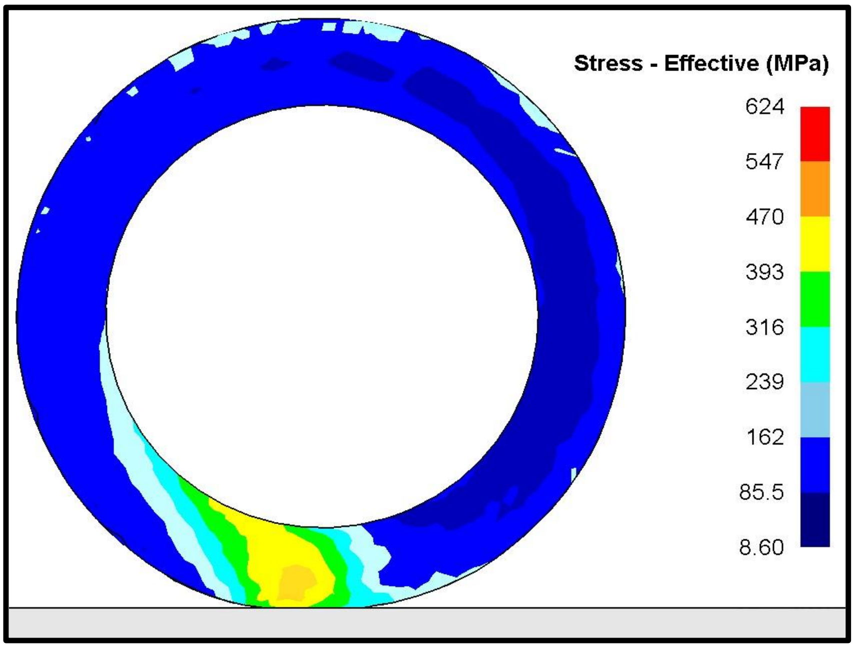

Figure 5: Stress distribution for tyre for 100 km/h driving speed

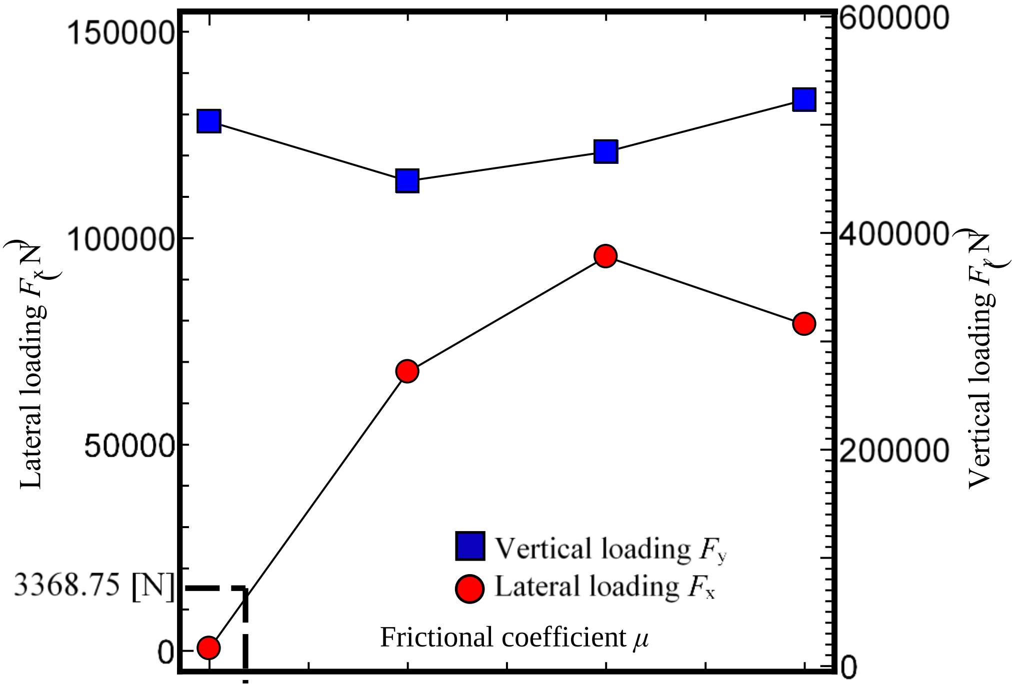

Figure 6: Effect of friction coefficient onto lateral and vertical loading for 100 km/h driving speed

Additionally, in current study, the tyre is modelled without thread, and a maximum surface contact area can be assumed. Thus, it can be easily estimated that, for current simulation case of vehicle plus passengers weight situation (3,368.75 [N] per tyre vertical loading), and based on Figure 6, the best frictional coefficient required from 100% traction for non-threaded tyre is assumed to be 0.01425 (current simulation model) and this frictional value will be optimized based on the tyre thread design, where effective tyre contact area varies based on thread design, thus frictional condition between tyre and pavement can be optimized.

4.0 CONCLUSION

The paper had discussed the modelling of tyre and its performance estimation with the application of Finite Element Method. Several parameters had been taken into consideration, such as tyre material properties, tyre-pavement interface condition and temperature conditions to suits the study for safety road applications in Malaysia. Several conclusions can be made as follows:

1. A tyre with lower elastic modulus has higher contact area, thus improve the stability but the effect of friction is becoming higher.

2. A tyre with a higher elastic modulus has lower contact area, thus might decrease the frictional contact.

3. A higher tyre-pavement interface friction coefficient will increase the lateral loading experience on the tyre.

4. Lower tyre-pavement interface friction coefficient will decrease the lateral loading experience on the tyre, thus decrease the traction and braking performance of the tyre.

As for future recommendations, it is suggested to take into consideration the design and contact area of actual tyre thread. It is needed to verify the finding in this paper with the actual tyre pavement contact test, and improve the understanding of the mechanism of tyre and its safety performance.

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