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Creep model to determine rut development by autonomous truck axles on pavement

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ABSTRACT

Impacts of autonomous truck's passes on pavement have been analyzed in this research. Two types of lateral positioning namely zero wander and uniform wander along with a super single wide tire and a dual tire have been analyzed with variable traffic speeds in ABQUS. The study concludes with the results in favor of usage of a super single wide tire under a uniform wander mode. The highest amount of pavement damage in terms of maximum rut depth is caused by the dual wheel assembly moving under a zero-wander mode. The magnitude of rut depth increases by a factor of two when a dual tire assembly is used instead of a wide tire assembly. At a uniform wander mode, rut depth increases by 0.2 mm for every 10 km/h decrease in traffic speed within 90 km/h to 70 km/h range.

KEYWORDS

autonomous trucks, lateral wander, rutting, ABAQUS

1. INTRODUCTION

Autonomous trucks are bound to bring new challenges to the current transport infrastructure.

Transverse wheel wander can affect the shape of transverse profiles of pavements during deformation. Application of wheel wander can reduce the load magnitude at a given point in the pavement. Human-driven vehicles tend to position themselves laterally in a normally distributed path [1–3]. Buiter et al. [4] reported that the wheel wander of vehicles is highly dependent on vehicle types, driving habits, wind speed, mechanical alignment of trailers and pavement condition. Lennie et al. [5] identified that the lateral wandering of vehicles is highly dependent on overtaking vehicles, lane widths, shoulder widths, shoulder types, the effect of line markings, and a class of vehicle. The amount of wander is described using a certain value of standard deviation SD [6, 7]. Effect of wheel wander is more significant for thinner pavements [8].

White et al. [1] incorporated the use of wheel wander as normal distribution and a decrease in rut depth was reported for normally distributed loading.

The latest form of research in terms of understanding of impacts of autonomous trucks on pavement performance is conducted by Chen et al. [9] and Noorvand et al. [3], it was investigated the repeated passes of trucks along with the same positions and integrated the autonomous trucks in the existing human-driven truck traffic, results showed that effect of the lateral wandering of autonomous trucks is significant only if more than 50% of autonomous trucks are used in existing human-driven truck traffic.

3D and 2D Finite Element Methods (FEMs) have been used to predict rutting of asphalt pavements. Sadeghnejad et al. [10] has used 2D FE modeling by incorporating the creep model developed by Hua 2000 [11], to predict the rutting behavior of glasphalt mixtures and the effect of temperature and stress on these mixtures. 3D and 2D FE modeling can be used to predict rutting of asphalt layers. 3D FEM, however, is expensive in terms of computational

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time [12]. Comparison of results for 2D and 3D FE modeling was done by Hua 2000 [11]. The difference in rut depths for two methods was 2%, which is not significant in terms of rutting prediction of asphalt pavements.

Since asphalt is a rheological material, hence creep model can be used to determine deflection in asphalt layers with inputs such as modulus of elasticity [13]. Dynamic creep test was utilized to study permanent deformation if foamed asphalt mixtures and reported that resulting creep strains accumulations are good indicators of permanent deformations in pavements [14].

Creep power law model in ABAQUS, in Eq. (1), has been successfully employed to investigate the permanent deformation in forms of rutting for various asphalt mixtures in finite element analysis [10, 15, 16]. Power law model is simple yet suitable for determining the rutting behavior of asphalt mixtures [10]. In power law model, the time hardening version is used in this research,

$$\varepsilon = A\sigma^n t^m, \tag{1}$$

where, ε is the creep strain rate; σ is the deviatoric stress; t is the total time; A, n, m are creep parameters, where $A>0$, $n>0$, $-1<m<0$.

However, the mode of loading is cyclic or continuous, it is going have a same effect on predicted strain rate since the whole loading time is the same if time hardening version is used to describe material's behavior [10, 11].

Method introduced by Uzarowski 2006 [2], in which the number of wheel passes are converted into step loading time fits perfectly with application of creep power law model [17, 18]. As it is shown in Eq. (2), using the equation given in MEPDG code [19], the time of loading can be calculated as follows:

$$t = \frac{L_{eff}}{17.6V_s}, \tag{2}$$

where t is the time of loading; L_{eff} is the effective length; V_s is the vehicle speed.

2. RESEARCH METHODOLOGY

Since the majority of rut depth occurs in the surface layer of pavements and the effect of wheel wander is significant in thinner asphalt pavements [8, 12]. Hence in this study an asphalt layer of 63 mm resting on a rigid surface (Portland Cement Concrete (PCC) foundation) is considered for modeling purposes. Lane width for the truck axle is kept at 3.5 m. Figures 1 and 2 show the illustrations of a dual tire and a super single wide tire assembly respectively.

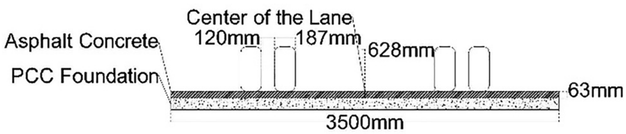

Fig. 1. Illustration of a dual tire assembly on the pavement

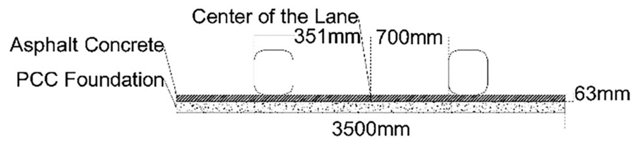

Fig. 2. Illustration of a super single wide tire assembly

2.1. Wheel loading and configurations

An axle load of 75.6 kN with a nominal tire pressure of 720 kPa has been considered in this study. Two different tire types, a super single wide base tire 455/55R22.5 developed by Michelin and a conventional dual tire G159A-11R22.5 developed by Goodyear are shown in Figs 3 and 4 respectively.

Since the tire contact pressure is not uniformly distributed [2, 14, 20], therefore the effects of varying tire pressure is included to help understand the process of permanent deformation.

As it can be observed from Figs 5 and 6, the magnitude of contact pressure in a wide base tire is less and is distributed in a wider area as compared to that of a dual tire. High concentration of contact stresses would occur as a result of usage of dual tire assembly.

Fig. 3. Digital tire footprint of a super single wide tire

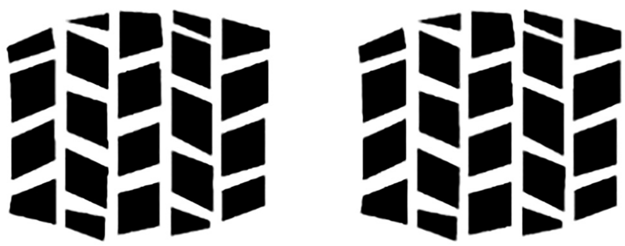

Fig. 4. Digital tire footprint of a dual tire

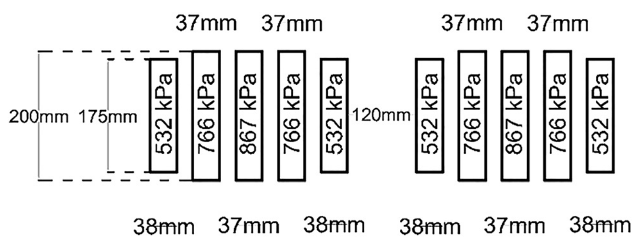

Fig. 5. Footprint details of a Goodyear G159A-11R22.5 dual tire used in simulations

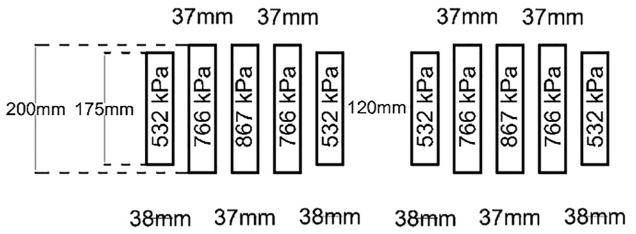

Fig. 6. Footprint details of a Michelin455/55r22.5 super single wide tire used in simulations

2.2. Data preparation for ABAQUS

Following parameters are needed in ABAQUS to perform creep analysis using the power law model as it is shown in Table 1. Uzarowski [3] has developed the modified creep parameters hence the validated elastic and creep parameters are used.

Total traffic volume is assumed to be 30 million tire passes for a period of 20 years. Vehicle speed used in this study is the nominal speed of heavy goods vehicles, weighing greater than 12 tons can be 90, 80, 60 and 50 km/h.

While considering the zero-wander mode, for an outside tread's footprint length of 175 mm, the time of loading for the first step is 118,000 s as calculated from Eq. (2). The other areas in footprint are longer by 15 percent; hence for step 2, the extra loading time is 18,000 s. The total loading time for zero wander mode and uniform wander mode has been shown in Tables 2 and 3, respectively.

The total cumulative time calculated from Eq. (2), has been distributed in six steps as shown in Table 3 Steps 1 and 2 are for the first positioning of tire and further steps indicate second and third positioning.

2.3. 2D FE model

Since the tire assembly is symmetric, hence only one portion of dual and single wheel assembly is considered in FE analysis. This approach would reduce the computational time and will have no effect on results obtained by performing the analysis on uniform wander and zero wander modes. Figures 7 and 8 show the 2D model for a dual and super single tire assembly respectively.

The mesh density including the element type and size is same for both models created for dual wheel and wide base tire assembly. The model used is a quadrilateral plain strain hourglass CPE4R consisting of 4,550 linear quadrilateral elements with 4,914 nodes. A screenshot of developed mesh is shown in Fig. 9.

Table 2. Loading time for zero wander mode for a 30 million tire passes

Speed (km/h)	Loading time (s)	
	Step 1	Step 2
90	105,000	16,000
50	189,000	29,000
40	236,000	36,000
30	315,000	47,000

Figures 10 and 11 represent the boundary conditions for dual tire and super single wide tire respectively.

3. RESULTS AND DISCUSSIONS

Simulation results for a dual tire assembly under zero and uniform wander mode at 90 km/h are shown, respectively. Simulations were performed for a total traffic of 30 million tire passes over a period of 20 years as shown in Figs 12 and 13, respectively. The deflection values are obtained after 35 increments with final step time of 16,000 s and after 38 increments with final step time of 5,300 s respectively. In the analysis part, the upheaval increment is not included in rutting depth in this study.

Due to low contact pressures and wider distribution of contact stresses for a super single wide tire, the deformation at 90 km/h is 11.8 mm, which is almost half of the deformation of 6 mm caused by a dual tire assembly using a zero-wander mode as shown in Figs 14 and 15, respectively.

A significant increase in rut depth happens as the speed is reduced to 30 km/h, the increment is highly significant in case of using a dual tire in a uniform wander mode. When measured at super slow speeds of 5 km/h and 2.5 km/h, an abrupt increase in rut development can be observed as shown in Fig. 16. Permanent deformation of 9.6 mm and 11.8 mm has been accumulated at speeds of 5 km/h and 2.5 km/h respectively.

Condition of the flexible pavement starts to deteriorate once the rut depth reaches 6 mm [8, 21], therefore it is of high concern that the number of passes for each of the tire type along with a lateral mode used should be analyzed until the rut depth reaches 6 mm. Figure 16 shows abrupt increase in rutting depth at super slow speeds.

The rate of increase in rut development is much prominent at lower speeds. As it is shown in Fig. 17, the rut development rate is linear from 90 km/h to 30 km/h.

Table 1. Elastic and creep parameters

Material	Material Parameters				
	Elastic Parameters		Creep Parameters (Constant)		
HMA Layer	Elastic Modulus (kPa)	Poisson's Ratio	A ($\times 10^{-8}$)	n	m
	950,000	0.41	41	1.48	−0.63

Table 3. Loading time for uniform wander mode for 30 million passes

Speed (km/h)	Loading time (s)					
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
90	35,000	5,300	35,000	5,300	35,000	5,300
50	63,000	10,000	63,000	10,000	63,000	10,000
40	79,000	12,000	79,000	12,000	79,000	12,000
30	105,000	15,000	105,000	15,000	105,000	15,000
5	630,000	94,500	630,000	94,500	630,000	94,500
2.5	1,260,000	189,000	1,260,000	189,000	1,260,000	189,000

Fig. 7. 2D Model for dual tire assembly

Fig. 8. 2D Model for a super single wide tire assembly

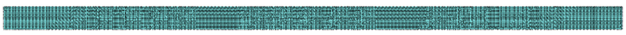

Fig. 9. Mesh formation used in FE analysis

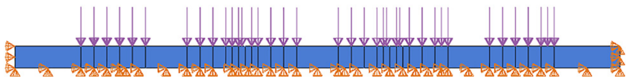

Fig. 10. Loading and boundary conditions for a dual tire assembly

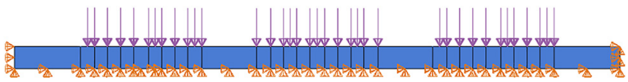

Fig. 11. Loading and boundary conditions for a super single wide tire assembly

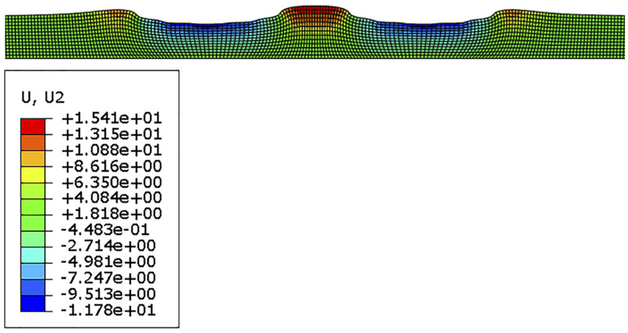

Fig. 12. Simulation result for dual wheel zero wander at 90 km/h

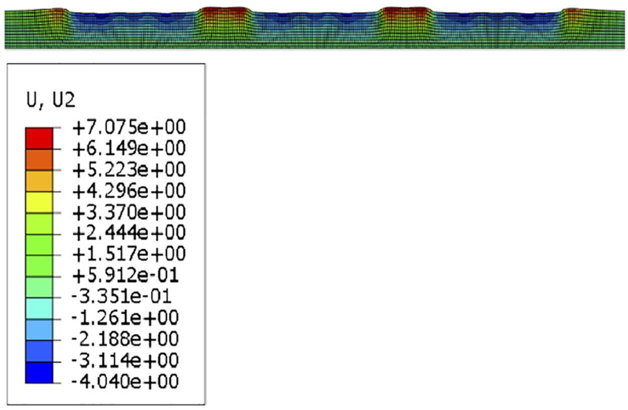

Fig. 13. Simulation result for wide wheel uniform wander at 90 km/h

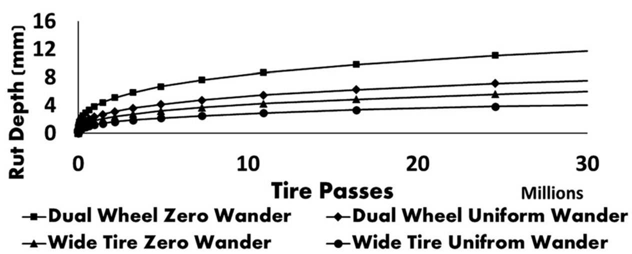

Fig. 14. Rut depth for various lateral modes and tire types at 90 km/h

4. FINDINGS AND CONCLUSIONS

The key findings in this study are mentioned below:

- Rut depth increases by a factor of 2 from wide tire to dual tire, the factor slightly increases as the speed gets down to 50 km/h;
- Effects of uniform wander and zero wander are highly significant when dual tire assembly is used;
- In case of super single tire, the rut depth decreases by an average of 2 mm if uniform wander is used instead of zero wander mode;
- The decrease in rut depth from zero wander to uniform wander increases significantly at lower speeds;
- In case of super single tire, the rut depth increases by 0.2 mm for every 10 km/h decrease in the speed;
- Wider lane width can facilitate in even more uniform distribution of lateral wander by introducing more paths at fixed distances from center line of the lane, thereby reducing the rutting potential;

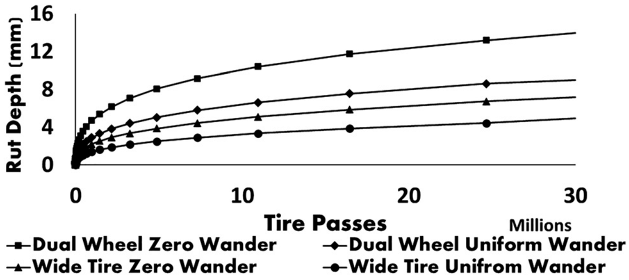

Fig. 15. Rut depth for various lateral modes and tire types at 30 km/h

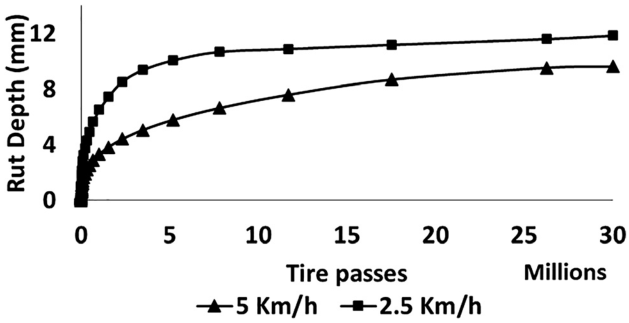

Fig. 16. Rut depth for uniform wander mode at super slow speeds

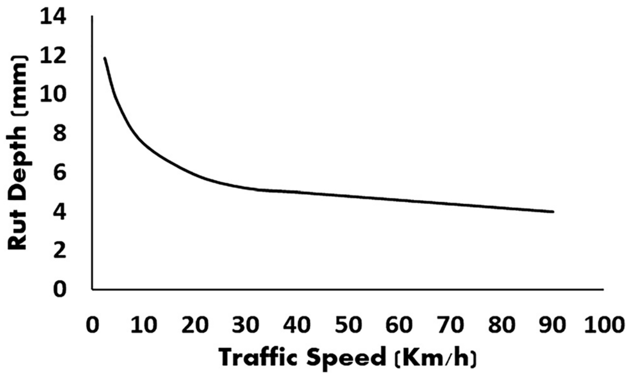

Fig. 17. Effect of traffic speed on rut depth for super single tire at uniform wander mode

- Dual tires at zero wander only require 3.23 million passes to reach a rut depth of 6 mm, on the other hand, super single tire require 30 million passes to reach a rut depth of 6 mm using zero wander mode;
- An abrupt increase in rut development start as the vehicle speed gets lower than 30 km/h and the curve tends to go vertical until the speed approaches zero;
- For a super single wide tire at uniform wander mode, rut develops at a factor of 2 mm at super speed lower than 50 km/h.

Based on the results of this study, the use of autonomous trucks will be highly beneficial only if they are only used on expressways or motorways with a minimum speed of 80 km/h. Although the difference between rut depth generated by a super single wide tire in case of a zero wander and uniform wander is quite minute, the difference increases as the vehicle speed decreases.

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