Influence of Heavy Truck Operating Condition on Dynamic Load Coefficient

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Abstract. The objective of this study was to evaluate influence of heavy truck operating condition on dynamic load coefficient. A three-dimensional nonlinear dynamic model of heavy with 15 DOF (degree of freedom) was established based on Zhou Changfeng model for simulation and analysis. The tire dynamic load and dynamic load coefficient (DLC) was chosen as objective function which uses Matlab/Simulink software to simulate the full vehicle dynamics model with nonlinear rubber suspension and calculate the objective function. The influence of the different operating conditions such as road surfaces, vehicle speeds, sprung mass on dynamic load coefficient was analyzed. The results show that the influence of the road surface roughness, vehicle speed and vehicle sprung mass on the DLC values of wheel at 3rd axle as well as road friendliness is very obvious. Especially, this study proposes that the speed limits for AD250 articulated dump truck are $v_{max} \leq 30$ km/h for the road surface condition of the ISO level D, $v_{max} \leq 20$ km/h for the road surface condition of the ISO level E.

Keywords: Heavy vehicle · Rubber spring · Operating condition Dynamic load coefficient

1 Introduction

Road surface quality plays a key role in ensuring safety, the comfort, reliability, drivability and longevity of the vehicle. In order to reduce the negative impact on the road surface, the optimum concept to design "road-friendly" vehicles with the recognition of pavement loads as a primary objective function of vehicle suspension design are presented by Sun [1]. The minimization of the probability of peak value of the tire load exceeding a given value was proposed as an objective function. Using the direct update method, optimization was carried out when tire loads was taken as the objective function of suspension design and the optimal results of the suspension parameters has greatly improved road surface friendliness. The 3D nonlinear dynamic model of a typical heavy truck is developed by Quynh et al. [2]. The impact factors of dynamic tire loads are used to evaluate the dynamic interaction between heavy vehicles. The study results provide both the warning limits of road surface roughness and the limits of corresponding dynamic parameters for the 5-axle heavy truck. The geometric structural parameters of the vehicle system and the nonlinear characteristics of

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shock absorber and leaf springs were precisely described by Lu et al. [3] and the nonlinear virtual prototype model of heavy duty vehicle (DFL1250A9) was established based on multi-body dynamics theory. The vehicle speed, load, road surface roughness and tire stiffness were selected to analyze the effects on tire dynamic load and dynamic load coefficient (DLC). The effects of driving conditions and suspension parameters on dynamic load-sharing and road-friendliness of the semi-trailer were analyzed by Chen [4]. The road-friendliness metric-DLC (dynamic load coefficient) and the load-sharing metric-DLSC (dynamic load-sharing coefficient) was taken as the objective functions. The effect of employing larger air lines and connectors on the DLSC optimization ratio gives varying results as road roughness in-creases and as driving speed increases. The DLC value of the tire forces of the quarter-truck fitted with a steel suspension was found to be more than twice that of the truck fitted with an air suspension was proposed by Buhari et al. [3]. Tire forces of the one-third laden truck were more aggressive than any other loading condition, due to the uncertain body-bounce generated by the truck, which was strongly dependent on surface irregularities. At low speed, the DLC greatly decreased if the load increased.

In this study, the three-dimensional nonlinear dynamic model of heavy with rubber spring suspension systems is established based on Zhou Changfeng model for simulation and analysis. The influence of the different operating conditions on road friendliness which includes road surfaces, vehicle speeds, vehicle loads are discussed respectively based on dynamic load coefficient (DLC).

2 Vehicle Dynamic Model

2.1 Full Vehicle Dynamic Model

An AD250 articulated dump truck with the rubber suspension systems [6] are selected for the consideration of road-friendliness. A three-dimensional nonlinear dynamic model with 15 degrees of freedom is established for analyzing the influence of the heavy vehicle operating conditions on road-friendliness, as shown in Fig. 1.

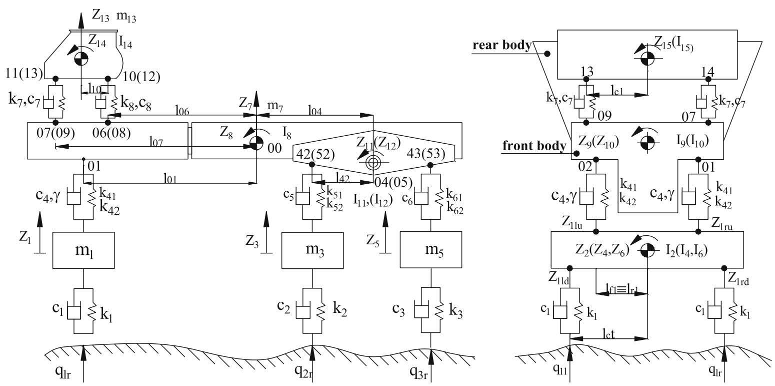


Fig. 1. 3-D dynamic model for AD250 articulated dump truck [6]

Figure 1, k_i, k_{41}, k_{42}, k_{51}, k_{52}, k_{61}, k_{62}, k_7, k_8 are the stiffness coefficients of tires, vehicle suspension systems and cab's suspension systems, respectively; c_i, c_{41}, c_{42}, c_{51}, c_{52}, c_{61}, c_{62}, c_7, c_8 are the damping coefficients of tires, suspension systems and cab's suspension systems, respectively; l_{01}, l_{04}, l_{42}, l_{43},… are the distances; m_1, m_3, m_5,… are the mass; I and I_2, I_4, I_6, I_{11}, I_{12}, are the moments of inertia of the mass, respectively; z_n, z_{11}, z_{12}, z_{13}, z_{14},… are the vertical displacements; q_{im} are the road surface roughness; γ is the ratio of compression to tensile damping (i = 1, 2, 3, k = 1 ÷ 6 and n = 1 ÷ 5 and m = left, right).

In order to facilitate the describing of vehicle dynamic systems using computer simulation, a combined method known as the multi-body system theory and D'Alembert's principle is chosen in this study. The multi-body theory is used to separate the system into subsystems which are linked by the force and moment equations. D'Alembert's principle is used to set up force and moment equations to describe vehicle dynamic subsystems.

The vertical nonlinear force of the front suspension system [6] is determined by

$$\begin{aligned} F_{01} = -G_{01} - \left(k_{41}(z_{01} - z_{1ru} + s_{4r})\right) + k_{42}\left(z_{01} - z_{1ru} + s_{4r}\right)^3\Big) \\ - c_4(\dot{z}_{01} - \dot{z}_{1ru})\left(\frac{1 + \mathrm{sgn}(\dot{z}_{01} - \dot{z}_{1ru})}{2}\right) \\ - c_4\gamma(\dot{z}_{01} - \dot{z}_{1ru})\left(\frac{1 + \mathrm{sgn}(\dot{z}_{01} - \dot{z}_{1ru})}{2}\right) \end{aligned} \tag{1}$$

The general dynamic differential equation for the 5-axle heavy truck is given by the following matrix form:

$$M\ddot{z} + C\dot{z} + Kz = C_t\dot{q} + K_t q \tag{2}$$

where, M is the mass matrix; C is the damping matrix of the suspension system; K is the stiffness matrix of the suspension system; C_t is the damping matrix of the wheel system; K_t is the stiffness matrix of the wheel system; z is the vector of displacement; q is the vector of excitation of road surface.

2.2 Road Surface Roughness

Road surface roughness plays an important role in analyzing driver ride comfort. The random excitation of road surface roughness can be represented with a periodic modulated random process. The general form of the displacement PSD of the road surface roughness is determined by the experimental formula [7]:

$$S_q(n) = S_q(n_0)\left(\frac{n}{n_0}\right)^{-\omega} \tag{3}$$

where, space frequency n is the reciprocal of the wavelength λ. It means wave numbers in a meter. n_0 is reference space frequency, it's defined as $0.1\ \mathrm{m}^{-1}$. $S_q(n)$ is PSD of road surface under the reference space frequency $S_q(n_0)$ known as the road surface roughness coefficient and ω the frequency index which decides the frequency configuration of PSD of road surface ω = 2.

The road surface roughness is assumed to be a zero-mean stationary Gaussian random process. It can be generated through an inverse Fourier transformation:

$$q(t) = \sum_{i=1}^{N} \sqrt{2S_q(n_i)\Delta n} \cos(2\pi n_k t + \phi_i) \tag{4}$$

where, ϕ_i is random phase uniformly distributed from 0 to 2π.

In this study, typical road surface roughness is adopted according to the standard ISO 8068 [8] and the simulation results of the typical road surface roughness are shown in Fig. 2.

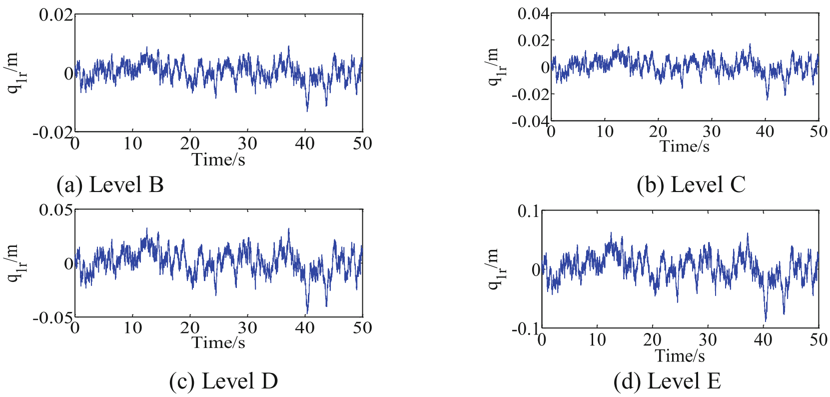


Fig. 2. Typical road surface roughness according to the standard ISO 8068

3 Dynamic Load Coefficient (DLC)

This study aims to predict the dynamic load coefficient (DLC) of tire forces from heavy truck axles and its influence on road surface friendliness. The most of the civil engineering literature uses static vehicle load for design of road surfaces. They have achieved mixed success due to the complex nature of the road damage problem. But the role of vehicle dynamic loads in the road surface design is still not completely known. Some of the major performance criteria considering road damage are based on fourth power law of American Association of State Highway Officials (AASHO) in 1960. Subsequently, other criterias were established in terms of AASHO, such as EC criteria in 1992 and Australia criteria in 1999 [9]. In this study, in order to analyze the influence of heavy vehicle operating conditions on road dynamic load coefficient (DLC) is chosen as objective function which is defined by a ratio of the root mean square of the vertical dynamic tire force over static load [5, 9], as follows:

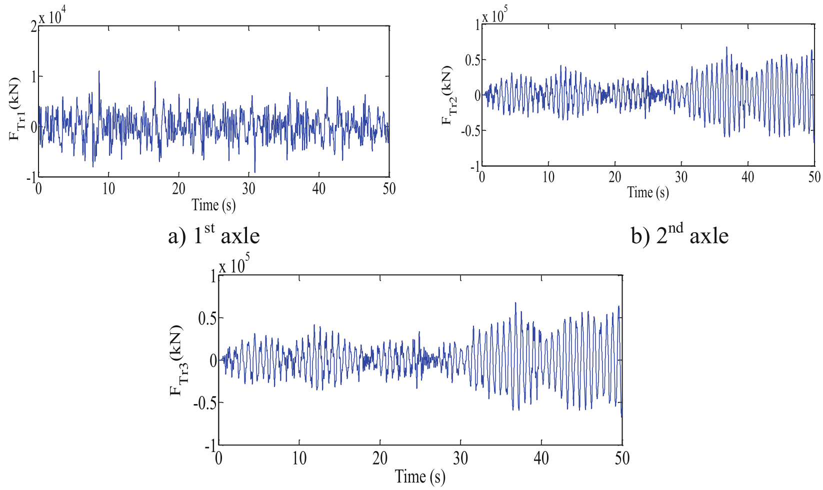
$$DLC = F_{T,RMS}/F_s \tag{5}$$

where, $F_{T,RMS}$ is the root mean square of the vertical dynamic tire force and F_S is static tire force.

The DLC's value is in range of 0.05 to 0.3 under normal operating conditions. It may reach to the zezo when the wheels is moving on a special smooth road or increase up to 0.4 when the tires of the axles spends a significant proportion of their time disconnecting the road surface [5].

4 Simulation and Analysis Results

In order to solve the general dynamic differential equation for AD250 articulated dump truck which presented in Sect. 2.1 for analyzing the influence of the vehicle operating conditions on road friendliness. Matlab/Simulink software is used with a specific set of parameters of vehicle [6] to simulate and evaluate. The simulations are carried out to analyze the influence of the vehicle operating conditions on dynamic load coefficient. For example, a simulation result of the dynamic left tire loads at 1st, 2nd and 3rd axles acting on road surface when vehicle moves on the ISO level C road surface at v = 40 km/h with fully loaded, is shown in Fig. 3.



a) 1st axle b) 2nd axle c) 3rd axle

Fig. 3. Dynamic left tire loads acting on road surface at 1st, 2nd and 3rd axles

Figure 3 could be determined the values of the root mean square of the vertical dynamic left tire forces and dynamic load coefficients (DLC) at 1st axle, 2nd axle and 3rd axle, the values such as $F_{T11,RMS}$ = 2617.4 N and DLC_{T11} = 0.073; $F_{T21,RMS}$ = 23423 N and DLC_{T21} = 0.788 $F_{T31,RMS}$ = 23471 N and DLC_{T31} = 0.789. $F_{T31,RMS}$ and the DLC_{T31} values of the left wheels at 3rd axle have the greatest value which can greatly affect road surface and DLC_{T31} values are selected to analyze in this study. In order to analyze the influence of the vehicle operating conditions road surfaces, vehicle speeds, sprung mass on dynamic load coefficient, we will continue to discuss in the following section.

4.1 Effect of Road Surface Roughness

In order to analyze the influence of the road surface roughness on dynamic load coefficient and road -friendliness, five road surface conditions from level A (very good) to level E (very poor) in ISO/TC 80686 have been considered as inputs to the vehicle-road coupled model when vehicle moves with the velocity of 30 km/h, 40 km/h, 50 km/h and fully loaded. The values of the left tire dynamic load coefficients at 3rd axle when vehicle moves on five different road surface conditions are shown in Fig. 4. From Fig. 4 shows that the DLC values of the left wheel at 3rd axle increase quickly when vehicle moves on the poor road surface conditions and the negative effects on the road surface. When vehicle moves on from the average road surface condition (level C) to poor road surface condition (level D) and then to very poor road surface condition (level E), the DLC values of the left wheel at 3rd axle increase from 164%, and 209%. To improve the safety of movement and reduce the negative impact on the road surface, this study proposes that the speed limits for AD250 articulated dump truck are $v_{max} \leq$ 30 km/h for the road surface condition of the ISO level D, $v_{max} \leq$ 20 km/h for the road surface condition of the ISO level E.

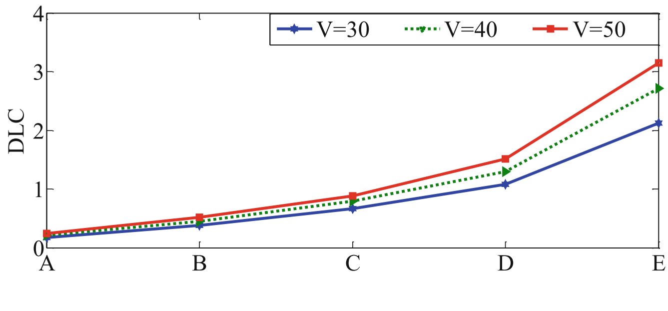


Fig. 4. Effect of road surface roughness on the DLC values of the left wheel at 3rd axle

4.2 Effect of Vehicle Speed

The vehicle speeds of 5 m/s, 7.5 m/s, 10 m/s, 12.5 m/s, 15 m/s, 17.5 m/s and 20 m/s were considered to analyze the influence of vehicle speed on the dynamic load coefficient and road friendliness when vehicle moves on three road surface conditions such as ISO level C, ISO level D, ISO level E and full loaded. The values of DLC_{T31} when vehicle moves on the different vehicle speeds are shown in Fig. 5.

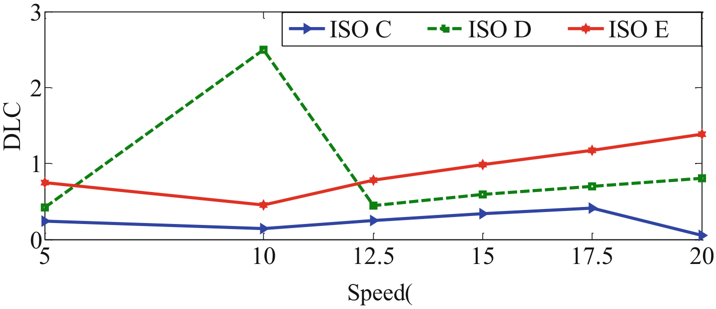


Fig. 5. Effect of vehicle speed on the DLC values of the left wheel at 3rd axle

Figure 6 shows that when vehicle speed value is v $\geq$ 12.5 m/s, the DLC_{T31} values increase the most quickly in the direction of the un-friendly road surface. Therefore, the vehicle speed values v $\leq$ 12.5 m/s is chosen as the road-friendly limit of driving speed for AD250 articulated dump truck when vehicle moves on the good road conditions and full loaded.

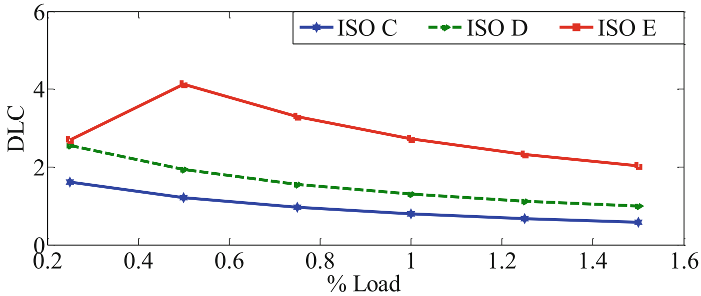


Fig. 6. Effect of sprung mass m_7 on DLC values of the left wheel at 3rd axle

4.3 Effect of Sprung Mass M_7

In order to evaluate the influence of the sprung mass m_7 on road surface damage, the load values of AD250 articulated dump truck which include 25% m_7, 50% m_7, 75% m_7, 100% m_7, 125% m_7, 150% m_7 are discussed when vehicle moves on four road surface conditions such as ISO level C, ISO level D and ISO level E and a velocity of 40 km/h. The effects of sprung mass m_7 on DLC values of the left wheel at 3rd axle are shown in Fig. 6. As discussed in Fig. 6, the values of DLC_{T31} increase most quickly when vehicle operates under less than *75% m_7* conditions. And it has impact negatively on road surface and has no benefit to the durability of the part of vehicle and the safe movement of vehicle.

5 Conclusions

From the analysis results of the influence of the different operating conditions of heavy vehicle such as road surfaces, vehicle speeds, sprung mass on dynamic load coefficient (DLC) in this study, several conclusions may be drawn as follows:

(1) The influence of the road surface roughness and vehicle sprung mass m_{-7} on the DLC values of the left wheel at 3^{rd} axle as well as road friendliness is very obvious. Especially, the DLC values of the left wheel at 3^{rd} axle increase from 164%, and 209% when vehicle moves on from the average road surface condition (level C) to poor road surface condition (level D) and then to very poor road surface condition (level E).

(2) From the analytical results, the road-friendly limits of driving speeds of vehicle were proposed when vehicle operates under different conditions. Especially, the speed limit for AD250 articulated dump truck is $v_{max} \leq 30$ km/h for the road surface condition of the ISO level D, $v_{max} \leq 20$ km/h for the road surface condition of the ISO level E.

References

1. Sun, L.: Optimum design of "road-friendly" vehicle suspension systems subjected to rough pavement surfaces. Appl. Math. Model. **26**, 635–652 (2002)
2. Van Quynh, L., Jianrun, Z., Xiaobo, L., Yuan, W.: Nonlinear dynamics model and analysis of interaction between vehicle and road surfaces for 5-axle heavy truck. J. Southeast Univ. **27**(4), 452–457 (2011)
3. Yongjie, L., Shaopu, Y., et al.: Numerical and experimental investigation on stochastic dynamic load of a heavy duty vehicle. Appl. Math. Model. **34**(1), 2698–2710 (2010)
4. Yikai, C., Jie, H., Mark, K., et al.: Effect of driving conditions and suspension parameters on dynamic load-sharing of longitudinal-connected air suspensions. Sci. China Technol. Sc. **56** (3), 666–676 (2013)
5. Buhari, R., Rohani, M.M., et al.: Dynamic load coefficient of tyre forces from truck axles. Appl. Mech. and Mater. **405**(408), 1900–1911 (2013)
6. Changfeng, Z.: Dynamic modeling, optimization and experimental research of rubber suspension system of off-road vehicle. A Dissertation Submitted to Southeast University for the Academic Degree of Doctor of Engineering (2007)
7. Dodds, C.J., Robson, J.D.: The description of road surface roughness. J. Sound Vib. **31**(2), 175–183 (1973)
8. Mechanical vibration—Road surface profiles— Reporting of measured data (1995)
9. Cole, D.J., Cebon, D.: Truck suspension design to minimize road damage. J. Autom. Eng. **210**, 95–107 (1996)