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# Comparative Analysis of Damage between Load Spectra Generated based on Pavement Grade and Load Spectra of Actual Test Site Pavement

Bin Wang, Ruoyu Zhao, Guoru He*

China Automotive Research Institute Automobile Inspection Center (Tianjin) Co., Ltd. Tianjin 300000, China

## Abstract

**With the continuous improvement of vehicle performance, the demand for accurate simulation and damage assessment of pavement load spectra is increasing. This paper aims to evaluate the consistency and difference between the load spectra generated based on pavement grade and the load spectra of the actual test site in vehicle damage simulation. The study first reviews the characterization methods of pavement roughness, especially the concept of spatial power spectral density (PSD) and its application in pavement grade classification. Subsequently, the corresponding load spectrum time domain model was constructed according to the pavement grade specified by the national standard using Matlab/Simulink software , and the actual pavement load spectrum was obtained based on the correlation of the four-wheel load of the whole vehicle. In addition , the actual pavement load spectrum was generated by pavement load data collected in the actual test site. By analyzing the time domain, frequency domain and statistics of the two load spectra , their similarities and differences in the simulation of vehicle driving were compared. The research results show that the load spectrum generated based on the pavement grade is similar to the actual pavement load spectrum in statistical characteristics. Although there are some differences in details, these differences have little effect on the damage assessment of the vehicle , which provides a basis for establishing a bench load spectrum directly based on the pavement grade.**

## Keywords

**Pavement Load Spectrum; Vehicle Response Damage; Matlab/Simulink; Spatial Power Spectrum Density; Test Site.**

## 1. Introduction

When a vehicle is driving on an actual road, the damage to the vehicle structure caused by the dynamic load caused by the unevenness of the road surface is a complex problem with multiple factors. An accurate load spectrum can provide important input conditions for vehicle design, durability analysis, and suspension system optimization. In the vehicle virtual simulation stage, the load spectrum calculation method based on the road surface grade is generally used , while the load spectrum of the actual test site road surface is directly derived from the actual vehicle test. There may be significant differences in the damage effects of the two in the simulated vehicle driving process.

Road roughness is a key factor affecting vehicle ride comfort and structural durability . As a statistical tool to describe road roughness, spatial power spectral density (PSD) has been widely used in load spectrum generation and vehicle dynamic response analysis. However, the expression and parameter selection of PSD are usually based on specific road conditions and vehicle types, which may not fully capture the complexity of actual roads.

Although some studies have established load spectrum models based on road surface grade through simulation software such as Matlab/Simulink, the models are only used for vehicle performance simulation analysis and have not been used for actual measurement and analysis based on the test bench. In addition, the consistency between the load spectrum in the model and the actual road conditions remains to be verified. Therefore, this study processed the load spectrum model used in the simulation and compared it with the response signal obtained from the test site, so as to analyze the similarities and differences between the load spectrum obtained based on the road surface grade and the load on the test site.

In view of this, this study aims to evaluate the consistency and difference between the load spectra generated based on the pavement grade and the load spectra of the actual test site in simulating vehicle damage effects by comparing and analyzing the load spectra generated based on the pavement grade. This study constructed the load spectra based on different pavement grades through simulation using Matlab/Simulink software, directly applied them to the whole wheel coupling test bench, and collected the vehicle response signals . Subsequently, the actual pavement load spectrum was generated through the pavement load data collected at the actual test site. Through the time domain analysis , frequency domain analysis, statistical analysis and damage analysis of the vehicle response signals under the two load spectra, this study revealed the effectiveness of the load spectrum based on pavement grade in practical applications and proposed its effective application range.

This study not only provides a more accurate load spectrum for vehicle damage assessment, but also provides a new perspective and theoretical support for the generation method of load spectrum and the pre-verification of vehicle suspension system.

## 2. Basic Theory

### 2.1. Spatial Power Spectral Density

Power Spectral Density (PSD) is a statistic that describes the spatial distribution characteristics of road surface roughness. It is usually used to characterize the energy distribution of road surface roughness in the spatial frequency domain. Spatial frequency refers to the number of times the road surface roughness changes within a unit length, while spatial power spectral density represents the energy content of road surface roughness per unit spatial frequency.

In vehicle engineering, spatial power spectral density is an important parameter because it directly affects the excitation force to which the vehicle is subjected when driving. [1] The roughness of the road surface can be regarded as a random process, and its statistical characteristics can be described by the spatial power spectral density. A typical spatial power spectral density function usually has the following form:

$$G_q(n) = G_q(n_0)(\frac{n}{n_0})^{-w} \tag{1}$$

Among them, $G_q(n_0)$is the pavement power spectrum density value at the reference spatial frequency $n_0$, also known as the pavement roughness coefficient; $n$is the spatial frequency, which is the reciprocal of the wavelength; $w$is the frequency index, which determines the rate at which the pavement power spectrum density changes with the spatial frequency.

The filtered white noise method regards the single-wheel road excitation $q(t)$as the response of a first-order linear system excited by unit white noise $w(t)$. Considering the road cutoff frequency, the frequency response function of the system is:

$$H_{q\sim w}(w) = \frac{2\pi n_0\sqrt{G_q(n_0)u}}{jw+2\pi n_{00}u} \tag{2}$$

Where: $w$is the original frequency; $u$is the speed of the car; $n_{00}$is the spatial cutoff frequency of the road surface

Equation (2) is converted into a differential equation expression, and $q(t)$the time domain model of single-wheel road excitation is:

$$q(\dot{t}) = -2\pi n_{00} u \cdot q(t) + 2\pi n_0 \sqrt{G_q(n_0)u} \cdot w(t) \tag{3}$$

## 2.2. Coherence Function Mathematical Model

In vehicle dynamics, the coherence function is used to analyze the correlation between the left and right wheel track road excitations, which is crucial for understanding and predicting the dynamic response of the vehicle on uneven roads. In practical applications, the coherence function can be approximated by a parameterized model. The coherence between the time-domain road excitation of the left front wheel of the vehicle and the time-domain road excitation of the right front wheel is related to parameters such as the road excitation frequency, vehicle wheelbase and vehicle speed. At present, scholars at home and abroad have established a variety of mathematical models of coherence functions based on the actual measured road roughness data. Pazooki and Liu et al . both gave a mathematical model that uses piecewise linear functions to fit the coherence function. Lu Fan gave a constrained objective function optimization method to solve the frequency response function coefficients, and used this to establish a mathematical model of the coherence function. [2,3,4,5,6] This paper adopts the mathematical model of the coherence function given by Lu Fan and Bogsjo that takes into account the road excitation frequency and vehicle wheelbase. The model is quite close to the measured curve, and the structure is simple and easy to calculate.

$$coh_{LR}(w) = e^{-\frac{\rho L_{lr}}{\pi v} w} \tag{4}$$

Where: $\rho$is the fitting coefficient, $L_{lr}$is the left and right wheelbase of the vehicle.

## 2.3. Time Domain Relationship between Front and Rear Axle Road Excitation

Assuming that the front and rear wheel tracks of the car are the same and the car is traveling in a straight line at a constant speed, the road excitation of the rear wheel lags behind the front wheel excitation for a period of time in the same wheel track:

$$\tau = \mathrm{L_{fr}}/u \tag{5}$$

The front and rear wheel road excitation is related to:

$$q_r(t) = q_f(t - \tau) \tag{6}$$

Where: $\mathrm{L_{fr}}$is the wheelbase of the front and rear wheels, and $q_f(t-\tau)$and $q_r(t)$are the road excitations of the front and rear wheels respectively.

## 2.4. Theoretical Basis of Four-column Stand

Since the four-column road simulation test bench is not an absolute linear system, there is a certain amplitude and phase difference between the command signal and the actual displacement of the actuator. Therefore, it is necessary to use the sweep frequency excitation signal as the target and the actuator drive signal as the response signal. The system error is eliminated through the iteration principle so that the actuator drive signal is consistent with the target excitation signal. [5]

The iteration first needs to use a specific white powder noise signal as the driving signal, collect the corresponding response signal, and obtain the system transfer function. The transfer function is generally represented by the frequency domain, so it is also called the frequency response function (Frequency Response Function, abbreviated as FRF). For the whole vehicle hydraulic vibration system, the transfer function must be approximated as a linear system. Only a linear system will have a specific transfer function. According to a specific input, the corresponding system output can be obtained. It is the ratio of the system 's response signal to the driving signal.

In RPC , the output is generally known (i.e., various signals of the vehicle body and axle head obtained through data collection in the test field). In order to reproduce the working conditions of the test field in the test room, it is necessary to obtain the corresponding input signal of the actuator based on the known output signal. The input signal can be obtained by convolution calculation, that is, the inverse multiplication of the target signal and the transfer function. Compared with the time domain calculation, the convolution calculation in the frequency domain is simpler and faster, so the frequency domain is generally used for convolution calculation.

Of course, this is just a simplified description. The actual calculation uses the following formula:

$$H(f) = \frac{Y}{X} = \frac{X*Y}{X*X} = \frac{CSD}{ASD} \tag{7}$$

CSD( Cross-spectral Density ) represents the cross-power spectral density of the driving signal and the response signal, which is obtained by calculating the convolution of the two signals. ASD( Auto-spectral Density ) represents the auto-power spectral density of the driving signal, which is obtained by calculating the convolution of the driving signal itself. The transfer function is the ratio of the above two power spectral densities, which will not be elaborated here.

In this paper, a sinusoidal swept frequency signal is used as the target signal. The initial driving signal of the system is obtained by calculating the transfer function. After several iterations, the error between the final displacement response signal of the actuator and the known target signal is minimized.

## 3. Test Verification

### 3.1. Time Domain Signal Modeling based on Road Surface Grade

Modeling based on road surface grade requires determining vehicle track width, wheelbase, driving speed, road surface grade, and road surface fitting parameters. The parameter list is as follows:

**Table 1.** Vehicle time-domain road simulation parameters

| Simulation parameters | Value | Unit |
|---|---|---|
| Vehicle wheelbase | 1660 | mm |
| Vehicle wheelbase | 2915 | mm |
| Vehicle speed | 40 | Km/h |
| Road surface grade | C | |
| Road surface fitting parameters | 3.4 | |

Use MATLAB/Simulink software to generate signals. The program framework is as follows:

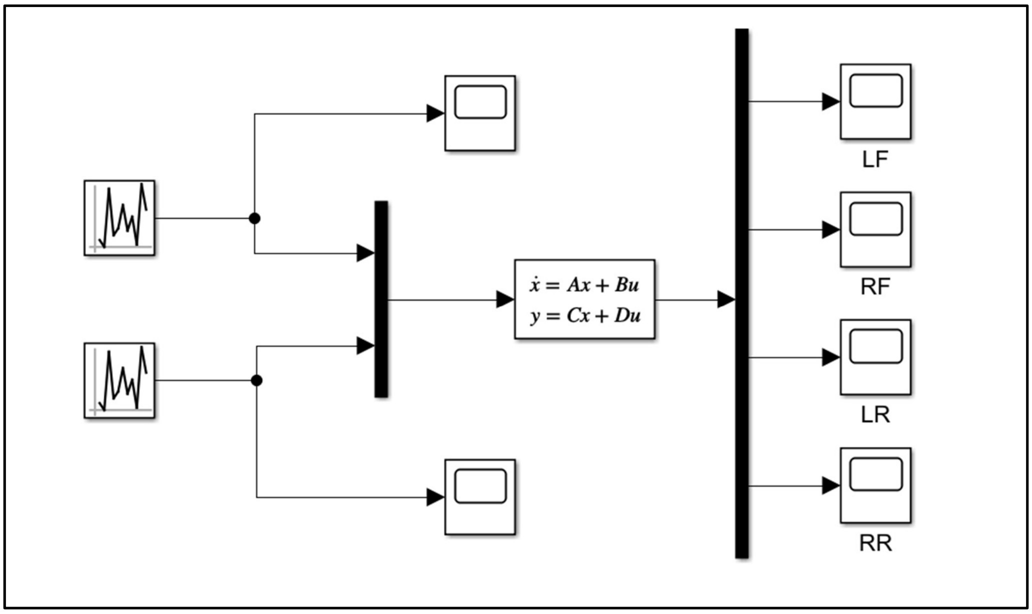

**Figure 1.** Simulink program block diagram

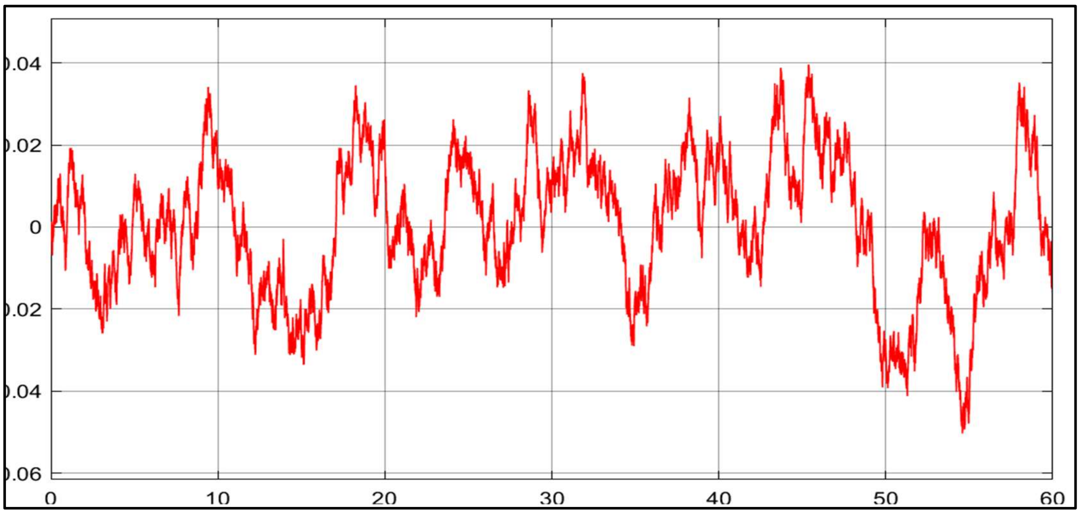

**Figure 2.** Example of generating a single channel signal

## 3.2. Four-column Bench Test

The verification work of this study was carried out on a four-column test bench. Relative damage is an effective way to quantify and analyze signals [7,8]. First, the acceleration sensor needs to be installed at the axle head position of the vehicle, and the corresponding signal collected at the test site is used as the target. The drive signal of the four-column test bench actuator is obtained through iteration, and the drive signal is compared with the random excitation time domain signal generated based on the road surface grade. The drive signal of the test bench obtained by iteration based on the response signal actually collected at the test site is compared with the random signal generated based on the road surface grade. It can be intuitively seen that the statistics of most amplitudes are consistent, and only some small-amplitude loads are statistically inconsistent. Therefore, it is necessary to further quantify the difference between the two from the response end or other analysis.

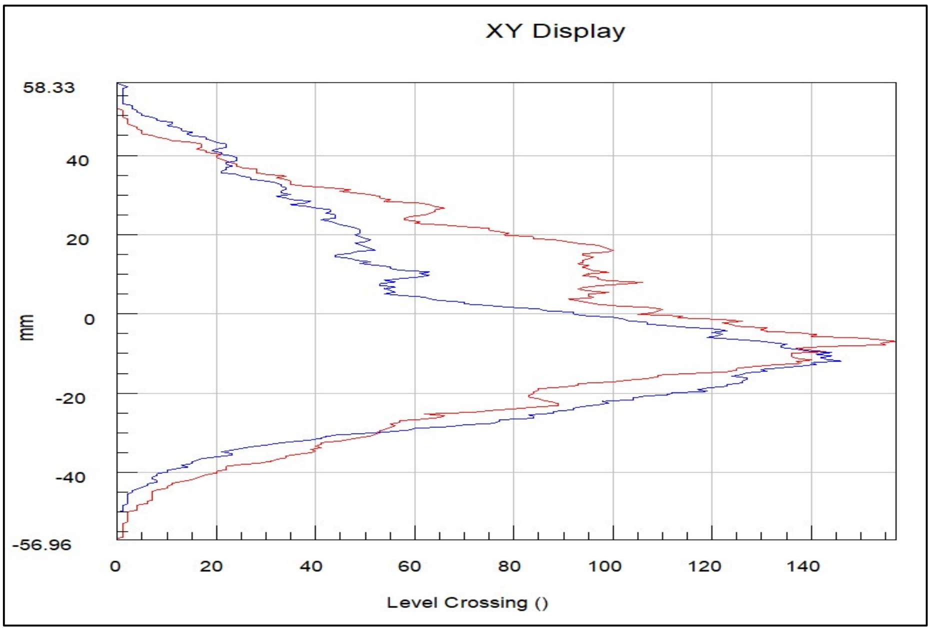

**Figure 3.** Comparison of the crossover counts of two drive signals

The two driving signals are reproduced in turn on the four-column test bench, the shaft head acceleration signal is measured, and the difference in the driving signals obtained by the two methods on the durability of the whole vehicle is analyzed from the perspectives of time domain, frequency domain, and damage.

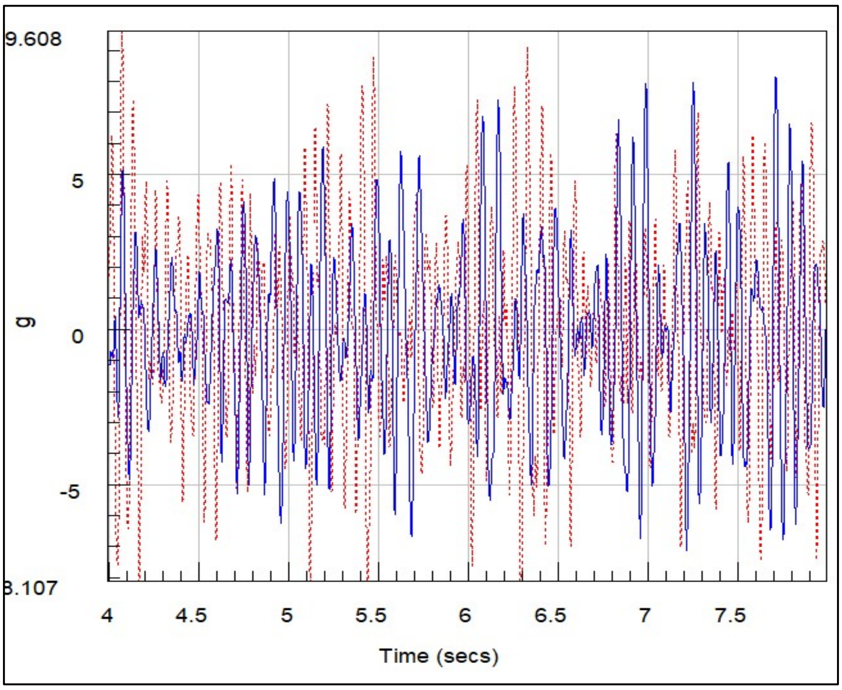

**Figure 4.** Time domain analysis of shaft head acceleration with different drive signals

From the overall analysis of the time domain signal, it can be concluded that the root mean square values of the acceleration of the two are 3.329 and 3.586 respectively, with a difference of 7.7%, which is not a big difference. Of course, other data are needed as auxiliary verification.

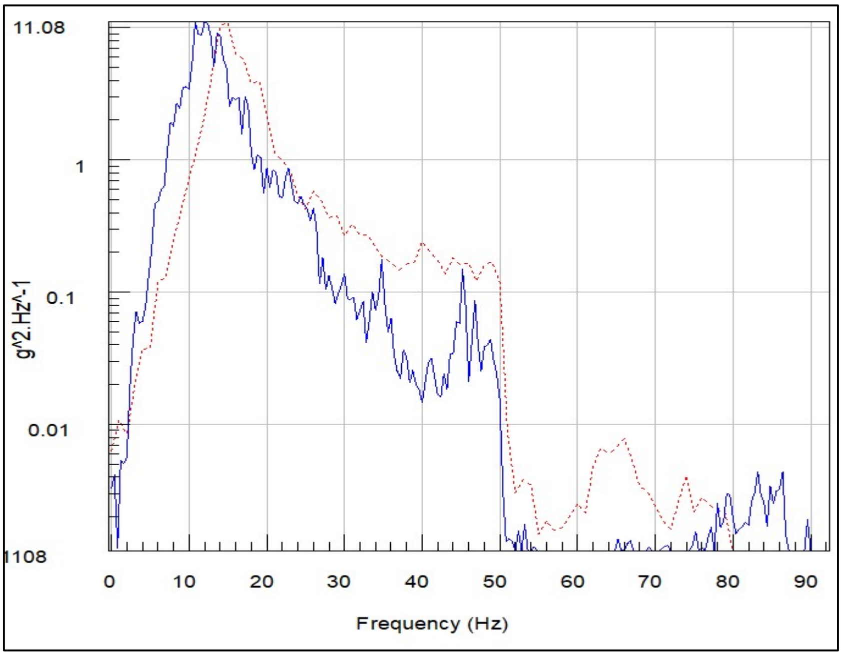

**Figure 5.** Frequency domain analysis of shaft head acceleration with different drive signals

From the frequency domain, we can see that the main frequency range of the two data is basically the same, both around 5-30Hz, and the amplitudes of other frequency bands are small and have no reference value. Therefore, from the frequency domain, the data consistency of the two is good.

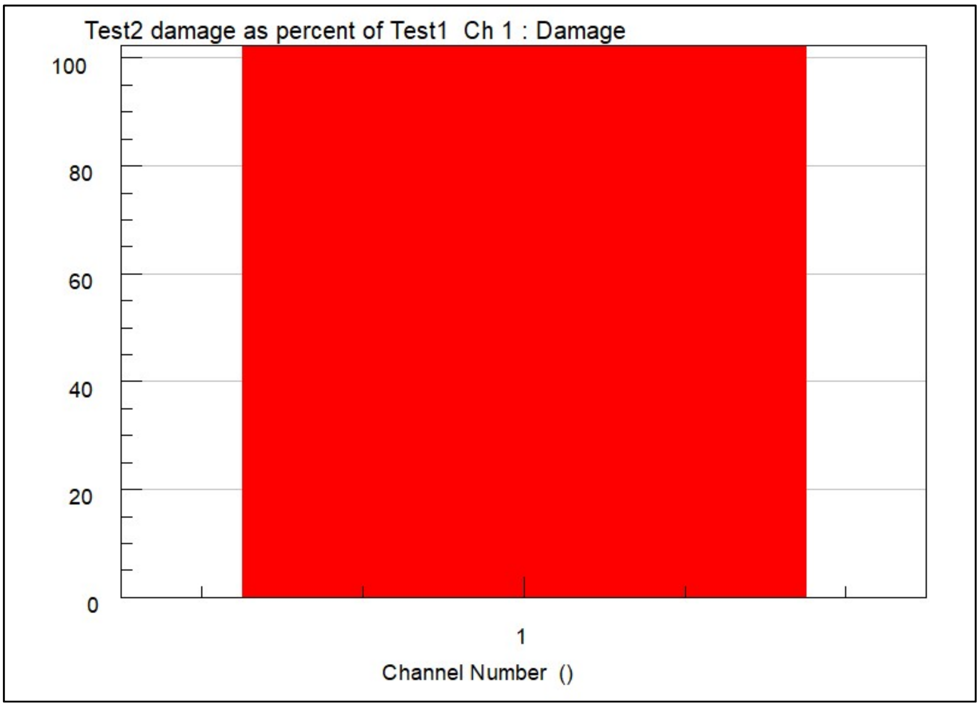

**Figure 6.** Analysis of shaft head acceleration damage under different drive signals

The damage results are the measured Belgian road surface and the vehicle axle head response signal obtained based on the driving signal at a speed of 40kM/h on a Class C road. The damage ratio is 102, and it can be seen that the damage of the two is basically the same.

## 4. Conclusion

Based on the road surface grade, this paper generates the road surface roughness of a Class C road at a speed of 40 km/h, reproduces it on a test bench, and verifies it with a real vehicle. In this way, the differences between the durable road surface model generated based on the road surface grade and the test site road surface are compared and analyzed, and the conclusions are as follows:

(1) A vehicle durability excitation signal model can be established based on the road surface grade, and the generated excitation signal can be used as a four-post test bench input.

(2) The durability excitation signal established based on the road surface grade is statistically comparable to the driving signal obtained through iteration of the actual vehicle.

(3) By properly adjusting the parameters, a real vehicle excitation model consistent with the real vehicle field can be obtained based on the road surface grade, providing a test basis for providing a standard spectrum for the four-post test bench .

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