A Study of the Impact of Asphalt Pavement Unevenness on Environmental and User Costs

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***Abstract*—This study constructs a Generalized International Roughness Index (IRI_{Eu}) for B-level standard pavement with a fixed PSD integral based on the pavement roughness power spectral density (PSD) and the International Roughness Index (IRI), along with a corresponding driving model for any uniform vehicle speed. By comparing the IRI_{Eu} values for average speed and uniform speed when the pavement roughness coefficient is the same, it is found that the relative error between the two is 13.41%, validating the model's effectiveness. For the main roads and branches of a certain city, the pavement is classified into four grades—Poor (S_0), Fair (S_1), Average (S_2), and Good (S_3)—based on the IRI_{Eu} corresponding to the average speed. Through the calculation of environmental and user costs, the following findings are observed: 1) Pavement grade is negatively correlated with cost, and for branches, both types of costs are higher than those for main roads at each grade; 2) For main roads, the increase in user costs is primarily driven by vehicle operating costs, while for branches, the increase in user costs in the S_0-S_1 grades is mainly due to relative travel costs, and in the S_2-S_3 grades, it shifts to vehicle operating costs. The results suggest that optimizing pavement grade or enhancing road functionality can reduce environmental and user costs.**

***Index Terms*—generalized IRI,pavement classification, environmental costs, user costs**

I. INTRODUCTION

WITH documents of the development of the economy, China's road infrastructure has been continuously improving, and road maintenance has become a key focus for traffic management departments. Exploring the impact of pavement roughness on environmental and user costs is crucial for determining the optimal maintenance timing, controlling expenses, and selecting the best maintenance methods. Currently, the most commonly used mathematical indicators for evaluating pavement performance in road maintenance are the International Roughness Index (IRI) and the Pavement Roughness Power Spectral Density (PSD). The Pavement Roughness Power Spectral Density (PSD) was proposed by the International Organization for Standardization (ISO) in 1982[1] as a standard for evaluating pavement roughness. The International Roughness Index (IRI) was defined in 1980 [2]by Gillespie et al. under the sponsorship of the National Cooperative Highway Research Program in the United States, using a standard 1/4 vehicle model. They introduced two roughness indicators: average corrected speed and average corrected slope. In 1982[3-4], with funding from the World Bank, Gillespie et al. used the average corrected slope (ARS) at 80 km/h to describe pavement roughness The defined it as the International Roughness Index (IRI). In 1991, Marcondes et al[5]. collected 20 measured pavement data segments and used multiple regression methods to study the relationship between IRI and PSD. In 2000, Sun et al.[6] used the theory of stochastic processes and random vibration to discuss the relationship between IRI and PSD, providing a frequency domain description of IRI while also studying a pavement classification method based on IRI. In 2005, Huang LiKui and Sheng CanHua[7-8] derived the relationship between IRI and PSD based on stochastic vibration theory. In 2007, Lou ShaoMin et al[9]. used a 1/4 vehicle model based on stochastic vibration theory to calculate the standard deviation of vertical displacement of the vehicle's spring and established a relationship between self-power spectral density and IRI. In 2012, Kalembo[10] used IRI to describe pavement roughness, collected data, and used regression analysis to derive the relationship between IRI and vehicle average speed. They used the MOVES2010a model to estimate CO_2 emissions and assess the impact of pavement roughness on CO_2 generation in vehicles. In 2019, Narh-Dometey Anita[11] used IRI to describe pavement roughness and calculated the user costs caused by rough pavements. In the same year, Zhang Zhenwei [12]extended the definition of IRI and proposed the Generalized International Roughness Index (IRI_{Eu}). In 2019, Duan Yu[13] studied the maximum off-road speed of tracked vehicles on different rough pavements and fitted curves, showing that as the pavement roughness coefficient increases, the maximum off-road speed decreases significantly before stabilizing. When vehicles travel on uneven roads, their speed is affected by pavement roughness, leading to insufficient power output from the engine in most cases. In 2024, Zhao Jingwei[16] proposed a lightweight road damage detection network based on YOLOv5. Using Ghost modules, SIoU loss functions, CARAFE upsampling modules, and CBAM attention mechanisms, the network optimized computational efficiency and detection accuracy, contributing to road maintenance from a detection technology perspective. IRI and PSD, based on pavement roughness coefficients, divide the pavement into eight grades. However, research on vehicle speed at these eight grades is limited, primarily due to two vehicle speeds for the same roughness coefficient. While the Generalized International Roughness Index (IRI_{Eu}) explores

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the theoretical relationship between pavement roughness and vehicle speed, it does not classify pavements. It still exists that multiple vehicle speeds can correspond to a single roughness coefficient, and sometimes, a vehicle speed can correspond to multiple roughness coefficients. Considering the current pavement grading systems and the research on pavement roughness and vehicle speed, it is insufficiently applicable for studying the effects of pavement roughness on environmental and user costs.

Based on the above research, this study integrates the Power Spectral Density (PSD) of pavement roughness for a single-degree-of-freedom vehicle model on B-level standard pavement in the spatial frequency domain, with the constraint of fixed power spectral area and converts CO_2 emissions into monetary costs as environmental costs. The study further investigates the impact of pavement roughness on environmental and user costs, providing a theoretical basis for road maintenance decision-making departments and contributing to reducing transportation-related carbon emissions.

II. PROPOSED MODEL

The basic conditions for constructing the Generalized International Roughness Index are PSD, IRI, and the relationship between the two above. This paper uses the Generalized International Roughness Index (IRI_{Eu}) to describe road surface roughness, combining the IRI_{Eu} of a particular city for pavement classification. It then calculates carbon emission treatment costs and user costs for the classified pavements, treating CO_2 treatment costs as environmental costs and analyzes the impact of road surface roughness on both environmental costs and user costs.

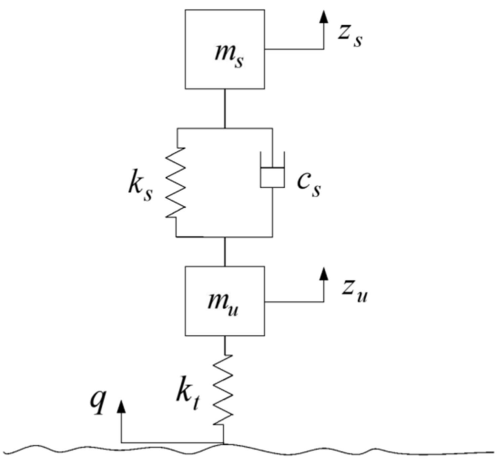

Fig. 1. 1/4 vehicle two-degree-of-freedom automobile suspension model.

This paper uses a single degree of freedom 1/4 vehicle model to simulate vehicle vibrations and makes the following assumptions about the model: 1) The vehicle travels at a constant speed. 2) The tire and road surface are in point contact, without bouncing. 3) The stiffness and damping are linear functions of displacement and velocity, respectively. 4) Vehicles with the same road surface grade have the same power, meaning that the integral of the spatial frequency power spectral density over spatial frequency is constant. As shown in Fig. 1, m_s and m_u represent the sprung and unsprung masses, k_s and k_t represent the suspension stiffness and tire stiffness, c_s is the suspension damping, z_s and z_u represent the vertical displacements of the sprung and unsprung masses, and q is the road surface roughness excitation.

$$m_s \ddot{z}_s + c_s(\dot{z}_s - \dot{z}_u) + k_s(z_s - z_u) = 0 \quad (1)$$

$$m_u \ddot{z}_u + c_s(\dot{z}_u - \dot{z}_s) + k_s(z_u - z_s) + k_t(z_u - q) = 0 \quad (2)$$

$$\mu = \frac{m_u}{m_s}, c = \frac{c_s}{m_s}, k_1 = \frac{k_t}{m_s}, k_2 = \frac{k_s}{m_s}, \quad u = u_a, f = un, \omega = 2\pi f, \dot{z} = \dot{z}_s - \dot{z}_u \quad (3)$$

Perform a Fourier transform on (1) and (2)and combine them with (3) to obtain (4), the frequency response of $\dot{z}$ concerning q.

The vehicle model in this paper is a linear system. The relationship between the spatial frequency power spectral density $G_{\dot{z}}(n)$ of the vehicle response $\dot{z}$ and the spatial frequency power spectral density $G_q(n)$ of the road surface excitation q is as follows.

$$G_{\dot{z}}(n) = |H(n)|^2_{\dot{z}} G_q(n) \quad (5)$$

Therefore, the root mean square value of $\dot{z}$ is

$$\sigma_{\dot{z}} = \sqrt{\int_{n_1}^{n_u} |H(n)|^2_{\dot{z}-q} G_q(n) d(n)} \cdot \quad (6)$$

In (6), n_1 and n_2 represent the lower and upper limits of the spatial frequency n, respectively. In vehicle engineering, the spatial frequency power spectral density $G_q(n)$ is primarily used to describe road surface roughness, as shown in (7).

$$G_q(n) = G_q(n_0)(\frac{n}{n_0})^{-W}, n_1 \le n \le n_u \quad (7)$$

In (7): n represents the spatial frequency, and m^{-1} denotes the number of wavelengths contained per meter of length. n_0 is the reference spatial frequency, set to 0.1 m^{-1}. $G_q(n_0)$ is the road surface power spectral density value n_0, referred to as the road surface roughness coefficient, with a unit of (m^2/m^{-1}), determined by the road classification. W represents the frequency index. n_u、n_1 corresponds to the upper and lower limits of the effective spatial frequency range for the road surface power spectral density.

Similarly, the vibration equation derived from the single-degree-of-freedom 1/4 vehicle model shown in Fig. 1 can obtain IRI, commonly used in road engineering to describe road surface roughness, as shown in (8). IRI refers to the cumulative absolute value of the relative vertical displacement between the sprung and unsprung masses per unit distance traveled.

$$IRI = \frac{1}{L}\int_0^T |\dot{z}_s - \dot{z}_u| dt \quad (8)$$

In (8), L and T represent the driving distance and total time of the vehicle at a speed of 80 km/h, respectively. $\dot{z}_s$ and $\dot{z}_u$ represent the vertical velocities of the sprung and unsprung masses, which are functions of the driving time t. At a speed of $u = 80km/h$, the relationship between the total distance traveled L and the total time T is as follows.

$$L = uT, u = \frac{u_a}{3.6} \quad (9)$$

Substituting the left side of (8) into (7) gives the following.

$$IRI = \frac{1}{u} E(|\dot{z}|) \quad (10)$$

$\dot{z}$ is a stationary random process following a zero-mean normal distribution. As a result, $|\dot{z}|$ follows the absolute value distribution of a zero-mean normal distribution, with its expected value given by the following equation.

$$E(|\dot{z}|) = \sqrt{\frac{2}{\pi}} \sigma_{\dot{z}} \quad (11)$$

The standard international roughness index represented by the road surface roughness power spectral density is derived from (6) and (8).

$$IRI = \frac{1}{u} \sqrt{\frac{2}{\pi}} \sqrt{\int_{n_1}^{n_u} |H(n)|^2_{\dot{z}-q} \; G_q(n) dn} \quad (12)$$

The vehicle speed is specified as 80 km/h in the definition of IRI. Considering the actual variations in vehicle speed, Zhang Zhenwei [12] extended the International Roughness Index by introducing the concept of the Generalized International Roughness Index[12] (IRI_{Eu}), with its expression given in (13).

$$IRI_{Eu} = \frac{1}{u} \sqrt{\frac{2}{\pi}} \sqrt{\int_{n_1}^{n_u} |H(n)|^2_{\dot{z}-q} \; G_q(n) dn} \quad (13)$$

Therefore, the following expression is obtained by integrating $n_1 = f_1/u, n_u = f_u/u$ over the frequency range from n_1 to n_u in (7), the following expression is obtained.

$$S_{G_q(n)} = uG_q(n_0) n_0^2 (\frac{1}{f_1} - \frac{1}{f_u}) \quad (14)$$

The vehicle operating cost adjustment factor m , described by IRI_{Eu}, as shown in (15), is used to calculate vehicle operating costs for different road surface grades.

$$m = 0.001 * [IRI_{Eu} - 0.4]^2 + 0.018 * [IRI_{Eu} - 0.4] + 0.991 \quad (15)$$

III. MODEL PARAMETERS AND VALIDATION

Fig. 1 shows the two-degree-of-freedom 1/4 vehicle model and the IRIEu model, with all parameters listed in Table I.

TABLE Ⅰ: MODEL PARAMETERS

Parameters	Numerical Value
μ	0.15
c(s^{-2})	6
k_1(s^{-2})	653
k_2(s^{-2})	63.3
Reference Spatial Frequency Power Spectral Density n_0	0.1
Frequency Index W	2
Time-frequency Upper Limit f_1 (HZ)	0.1
Time-frequency Lower Limit f_2 (HZ)	50

The selected B-grade standard urban road in this study uses the harmonic superposition method in the spatial frequency domain. The road surface roughness coefficient is 3.2×10^{-5}, the vehicle speed is $60 km/h$, and the spatial frequency domain is divided into 200 intervals with a sampling time of 10s. By substituting into (7) and performing simulations in Matlab, the power spectral density value of the random road surface roughness is obtained, as shown in Fig. 2.

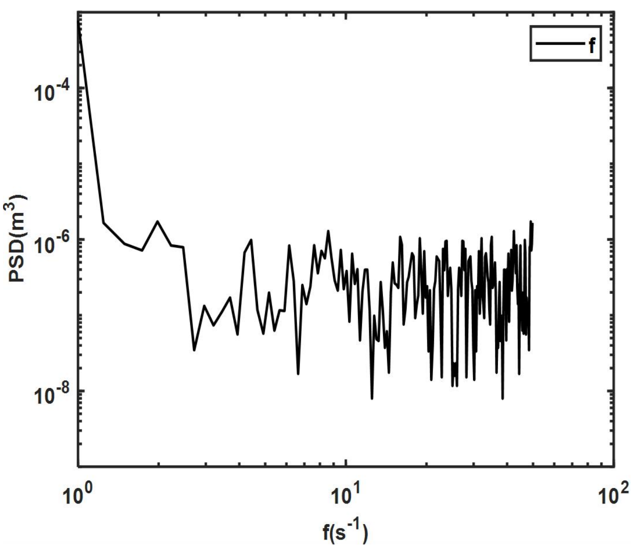

Fig. 2. Pavement power spectral density.

Applying (13), the integral value of the power spectral density for the parameters corresponding to Fig. 2 is obtained as 53.22 W, representing the power value for vehicles operating on urban roads. After determining this integral value, the speed and road surface roughness coefficient variation curve within the B-grade road range is plotted, as shown in Fig. 3. It can be observed that for vehicles operating with the same power on different road surface roughness coefficients, as the roughness coefficient increases, the vehicle's ability to maintain a uniform speed decreases, which is consistent with actual conditions. Additionally, there is a one-to-one relationship between vehicle speed and road surface roughness coefficient.

Considering that it is nearly impossible for vehicles to maintain a uniform speed while operating in an urban road network, vehicle's average speed through the section is used as an approximation for the vehicle’s uniform speed. By combining (13), the assumed conditions, and the road surface roughness coefficient corresponding to the collected section's average vehicle speed, the Generalized International Roughness Index is calculated. Other parameter values are as previously mentioned. The Generalized International Roughness Index corresponding to the section’s average and uniform speeds is then compared, as shown in Table II.Full names of authors are preferred in the author field but are not required. Put a space between the authors’ initials.

The Generalized International Roughness Index values corresponding to the section’s average speed and uniform speed obtained from the model are similar, with a relative error of only 13.41%, which is within an acceptable range. Therefore, the model based on road surface roughness and vehicle uniform speed variation is reliable.

TABLE Ⅱ: UNIFORM AND AVERAGE VELOCITIES CORRESPONDING TO THE GENERALIZED INTERNATIONAL UNEVENNESS INDEX

Methodologies	Value of The Generalized International Inequality Index	Relative Error
Uniform Velocity	9.4090	
Average Speed	8.1472	13.41%

The Generalized International Roughness Index calculation model in this paper is derived based on the Standard International Roughness Index theory.

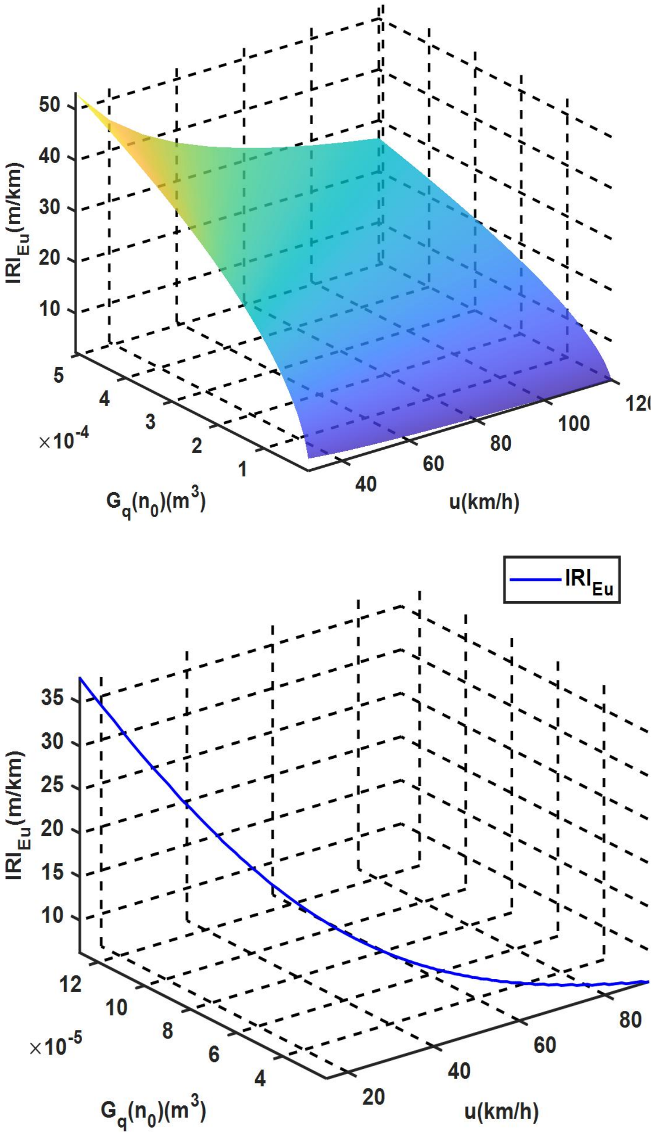

Fig. 3 .Vehicle speed variation curve with road surface unevenness coefficient.

Therefore, the constrained Generalized International Roughness Index obtained from the model is compared with the Standard International Roughness Index, as shown in Fig. 4.

Within the B-grade road range, when the vehicle speed is 80 km/h, the Standard International Roughness Index and the Generalized International Roughness Index are equal, 7.06 m/km. A vehicle speed of 80 km/h is the threshold for the two types of roughness. When the vehicle speed is less than 80 km/h, the Standard International Roughness Index is smaller than the Generalized International Roughness Index, and the difference between the two increases as the speed decreases.

When the vehicle speed exceeds 80 km/h, the Standard International Roughness Index becomes larger than the Generalized International Roughness Index, and the difference between the two increases as speed increases. Therefore, the Standard International Roughness Index does not adapt well to varying vehicle speeds and also affects the calculation of road surface roughness's impact on vehicle carbon emissions and user costs. In contrast, the Generalized International Roughness Index adapts well. In the selected city in this study, the average vehicle speed is always less than 80 km/h.

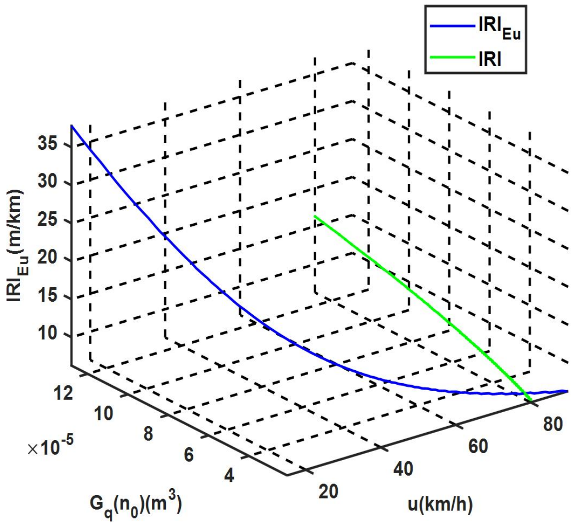

Fig. 4 . Comparison of the constrained IRI_{Eu} and IRI.

IV. CALCULATION AND ANALYSIS

The road surface is divided into eight grades based on the lower limit, geometric mean, and upper limit of the standard road surface roughness coefficient $G_q(n_0)$ .Similarly, the lower limit, average value, and upper limit of the Standard International Roughness Index can be calculated to determine the classification of road surfaces according to the Standard International Roughness Index, as shown in Table III.

As the road surface roughness coefficient increases, the Standard International Roughness Index increases accordingly, with a one-to-one correspondence between the two. The essence of both types of road classification is based on vehicle speed of 80 km/h and classification according to the road surface roughness coefficient. However, using the Generalized International Roughness Index for road surface classification would result in different uniform speeds and road surface roughness coefficients having the same Generalized International Roughness Index value, making it difficult to classify the road surfaces. Therefore, when the road surface roughness power spectral density is expressed as a power function, only by constraining the power function of the road surface roughness power spectral density and combining the road surface roughness coefficient with the vehicle's uniform speed can the Generalized International Roughness Index achieve definitiveness, all owing for a new classification of road surfaces. Traffic volume and average vehicle speed data from a certain city's road network are collected, and the average speed is substituted into (13) to calculate the Generalized International Roughness Index IRI_{Eu} corresponding to the average speed.

This paper aims to calculate environmental costs, but since environmental costs cannot be directly calculated, the MOVES2014b[14-15] model is chosen . Hereafter, MOVES2014b will be referred to as MOVES. The model simulates the vehicle carbon emissions from road surface roughness and then converts the carbon emissions into environmental costs. The MOVES model breaks down the total activity into various source groups and units, combining their distribution and emission rates to calculate the total emissions. The framework and main modules of the MOVES model are illustrated in Fig. 5. Among them, the TAG module converts parameters such as vehicle mileage, age distribution, etc., into MOVES-specific vehicle activity level parameters, such as operation hours and start-up counts. The SBDG module calculates the distribution of "source groups" defined by fuel type, year of manufacture, and standard classification. The MOVES model divides the vehicle operating conditions into several driving units based on power-to-weight ratio and speed, and the OMDG module calculates the unit distribution for various preset driving conditions. Combining the emission source group proportions calculated from the SBDG module with the driving mode proportions obtained from the OMDG module, the corrected emission rates are weighted and averaged to obtain the average emission rate in units of g/s or g/start-up. By correlating the emission rate with the activity level, the emissions of vehicles in different regions and periods can be calculated.

This paper selects the arterial and branch Road. Based on the Generalized International Roughness Index (IRI_{Eu}) corresponding to the average vehicle speed, the B-grade standard road surfaces of the secondary and main roads are classified into four categories: poor (S_0), fair (S_1), good (S_2), and very good (S_3), as shown in Table IV and V.

Four road surface grade average speeds, corresponding to a certain city's arterial and branch road, are selected. The CO_2 treatment cost is 13,400 yuan per ton, and the average traffic volume is 1,583.3 vehicles per hour. Using the MOVES [14]-[15] model, the CO_2 emissions from vehicles are simulated, and the CO_2 treatment cost is calculated, as shown in Tables IV and V. This paper considers the CO_2 treatment cost as the environmental cost.

The average income of a certain city is 257.95 yuan per hour. The road section length is set to 1 km, with the benchmark average speeds for the arterial and branch road being 51.26 km/h and 41.76 km/h, respectively. The median average speed data for different road surface grades are combined with those in Tables VI and VII. The driver's travel time, travel cost, and relative travel cost are then calculated.

The vehicle operating cost is multiplied by the vehicle operating cost adjustment factor *m* to obtain the total operating cost. This total is divided by 24,135 km to calculate the vehicle operating cost per kilometer. By multiplying this value by the traffic volume of 1,583.3 vehicles per hour, the vehicle operating costs for the arterial and branch road are obtained, as shown in Table VIII.

The sum of relative travel and vehicle operating costs is the user cost, as shown in Table IX.

For the arterial road, the emissions increase by 7 g/h/km/vehicle when the road surface changes from S_3 to S_2, and the treatment cost increases by 148.51 yuan/h/km. When the road surface changes from S_2 to S_1, emissions increase by 5 g/h/km/vehicle, and the treatment cost increases by 106.08 yuan/h/km. When the road surface changes from S_1 to S_0, emissions increase by 2 g/h/km/vehicle, and the treatment cost increases by 42.43 yuan/h/km. For the branch road in the city, when the road surface changes from S_3 to S_2, emissions increase by 4.2 g/h/km/vehicle, and the treatment cost increases by 89.1 yuan/h/km. When the road surface changes from S_2 to S_1, emissions increase by 2.1 g/h/km/vehicle, and the treatment cost increases by 44.56 yuan/h/km. When the road surface changes from S_1 to S_0, emissions increase by 3.2 g/h/km/vehicle, and the treatment cost increases by 67.89 yuan/h/km.

The worse the road surface condition, the lower the average vehicle speed and the greater the CO_2 emissions. On the arterial road, from S_2 to S_1, the CO_2 increase rate is the fastest, and the carbon treatment cost increases at the highest rate. From S_2 to S_1, the CO_2 increase rate is the slowest for the branch road, and the carbon treatment cost increase rate is also the slowest. The CO_2 emissions for each grade of the branch road are higher than those for the arterial road. Road maintenance or improving road functionality helps reduce vehicle carbon emissions and lower carbon treatment costs.

As the road surface condition worsens, the CO_2 treatment cost increases. The CO_2 treatment costs for each grade of the branch road are greater than those for the arterial road. Changing the road grade or improving road functionality helps reduce carbon treatment costs.

The relative travel costs for the arterial and branch road increase progressively from S_3 to S_0. The smallest cost increase from S_2 to S_1 is 1,070.11 yuan/h/km for the main road and 3,223.27 yuan/h/km for the Branch Road.

The vehicle operating costs for the arterial and branch road increase progressively from S_3 to S_0. The vehicle operating cost increases the most from S_1 to S_0, with the largest increase being 428.76 yuan/h/km for the arterial road and 1,225.15 yuan/h/km for the branch road . The smallest increase in vehicle operating costs from S_2 to S_1 is 358.62 yuan/h/km for the arterial road and 915.55 yuan/h/km for the branch road.

The primary factor influencing user costs on the arterial road is the proportion of vehicle operating costs, which accounts for more than 50%. For the branch road, the main factor affecting user costs for S_0 and S_1 is the proportion of relative travel costs, which also exceeds 50%. For the branch road, the primary factor for S_2 and S_3 is the proportion of vehicle operating costs, which accounts for more than 50%. From S_1 to S_0, the user costs increase the most, with the highest increase being 3,052.29 yuan/h/km for the arterial and 4,733.85 yuan/h/km for the branch road. The user costs from S_3 to S_0 on both the arterial and branch road increase progressively. For the arterial road , the smallest increase in user cost from S_2 to S_1 is 1,463.79 yuan/h/km, while for the branch road, the smallest increase from S_3 to S_2 is 4,191.62 yuan/h/km.

The worse the road surface, the higher the user cost. The user cost of a branch road is higher than that of a arterial road.Improving the surface condition of arterial road or enhancing their functionality will significantly reduce user costs.

For the arterial road, reducing vehicle operating costs is the most effective way to reduce user costs. For the branch road, reducing relative travel costs for S_0 and S_1 will most significantly reduce user costs, In contrast , for S_2 and S_3, reducing vehicle operating costs will be the most effective way to lower user costs.

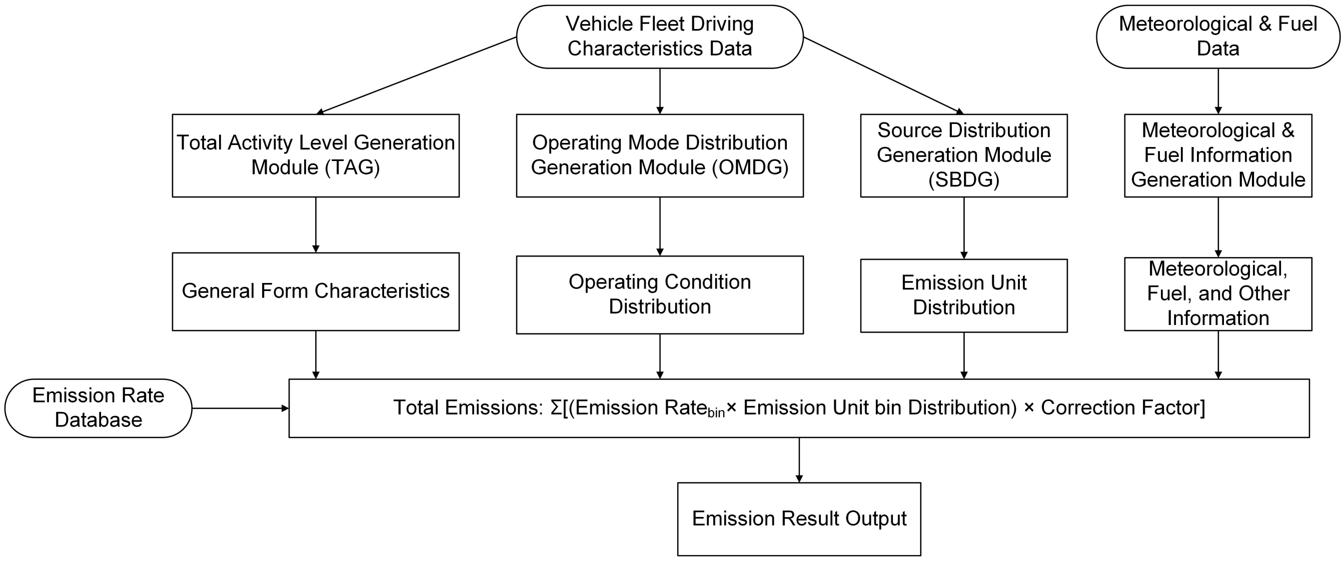

Fig. 5. Schematic diagram of the main modules and functions of the MOVES model.

$$H(n)_{\dot{z}-q} = \frac{jk_1(2\pi un)^3}{\mu(2\pi un)^4 - [k_1 + k_2(1+\mu)(2\pi un)^2] + k_1k_2 + j(2\pi un)c[k_1 - (1+\mu)(2\pi un)^2]} \tag{4}$$

TABLE III : CLASSIFICATION OF TWO ROAD SURFACE GRADES

Pavement Grading	$G_q(n_0)/10^{-6}m^3$			IRI（m/km）		
	Lower Limit	Geometric Mean	Upper Limit	Lower Limit	Geometric Mean	Upper Limit
A	--	16	32	--	2.2182	3.1370
B	32	64	128	3.1370	4.4364	6.2740
C	128	256	512	6.2740	8.8728	12.5481
D	512	1,024	2,048	12.5481	17.7457	25.0962
E	2,048	4,096	8,192	25.0962	35.4914	50.1924
F	8,192	16,138	32,768	50.1924	70.9827	100.3847
G	32,768	65,536	131,072	100.3847	141.9654	200.7694
H	13,1072	26,2144	--	200.7694	283.9309	--

TABLE IV : ENVIRONMENTAL COSTS OF ARTERIAL ROADWAY CLASSES OF PAVEMENT

IRI_{Eu} (m/km)	Pavement Grading	Pavement States	Average Velocity in Value (km/h)	CO_2 Emissions (g/h/km/vehicle)	CO_2 Treatment Fee (CNY/h/km)
$17.32 \le IRI_{Eu} < 19.44$	Poor	S_0	29.39	245	5,197.97
$15.20 \le IRI_{Eu} < 17.32$	Fair	S_1	36.23	243	5,155.54
$13.08 \le IRI_{Eu} < 15.20$	Average	S_2	40.03	238	5,049.46
$10.96 \le IRI_{Eu} < 13.08$	Good	S_3	47.28	231	4,900.95

TABLE V: ENVIRONMENTAL COSTS OF SPUR ROADS BY CLASS OF PAVEMENT

IRI_{Eu} (m/km)	Pavement Grading	Pavement States	Average Velocity in Value (km/h)	CO_2 Emissions (g/h/km/vehicle)	CO_2 Treatment Fee (CNY/h/km)
$26.97 \le IRI_{Eu} < 31.47$	Poor	S_0	19.40	251.5	5,335.88
$22.46 \le IRI_{Eu} < 26.97$	Fair	S_1	23.28	248.3	5,267.99
$17.95 \le IRI_{Eu} < 22.46$	Average	S_2	28.52	246.2	5,223.43
$13.44 \le IRI_{Eu} < 17.95$	Good	S_3	36.98	242	5,134.33

TABLE VI :RELATIVE TRAVEL COSTS ON ARTERIALS

IRI_{Eu} (m/km)	Pavement Grading	Median Average Speed (km/h)	Travel Time (h/km)	Time Cost (CNY)	Total Time Cost (CNY/h)	Relative Travel Costs (CNY/h)
$17.32 \le IRI_{Eu} < 19.44$	Poor	29.39	0.0340	8.78	13,896.30	5,928.83
$15.20 \le IRI_{Eu} < 17.32$	Fair	36.23	0.0276	7.12	11,272.76	3,305.30
$13.08 \le IRI_{Eu} < 15.20$	Average	40.03	0.0250	6.44	10,202.65	2,235.19
$10.96 \le IRI_{Eu} < 13.08$	Good	47.28	0.0212	5.46	8,638.16	670.70
	Standard	51.26	0.0195	5.03	7,967.46	

TABLE VII : RELATIVE TRAVEL COSTS FOR BRANCH ROADS

IRI_{Eu} (m/km)	Pavement Grading	Median Average Speed (km/h)	Travel Time (h/km)	Time Cost (CNY)	Total Time Cost (CNY/h)	Relative Travel Costs (CNY/h)
$26.97 \le IRI_{Eu} < 31.47$	Poor	19.40	0.0515	13.30	2,1052.18	1,1272.19
$22.46 \le IRI_{Eu} < 26.97$	Fair	23.28	0.0430	11.08	1,7543.48	7,763.49
$17.95 \le IRI_{Eu} < 22.46$	Average	28.52	0.0351	9.04	1,4320.20	4,540.22
$13.44 \le IRI_{Eu} < 17.95$	Good	36.98	0.0270	6.98	1,1044.14	1,264.15
	Standard	41.76	0.0239	6.18	9,779.99	

TABLE VIII : VEHICLE OPERATING COSTS

Pavement Grading	IRI_{Eu} (m/km)	Arterial Road (CNY/h/km)	IRI_{Eu} (m/km)	Branch Road (CNY/h/km)
Poor	$17.32 \le IRI_{Eu} < 19.44$	6,390.00	$26.97 \le IRI_{Eu} < 31.47$	8,947.29
Fair	$15.20 \le IRI_{Eu} < 17.32$	5,961.24	$22.46 \le IRI_{Eu} < 26.97$	7,722.14
Average	$13.08 \le IRI_{Eu} < 15.20$	5,567.56	$17.95 \le IRI_{Eu} < 22.46$	6,651.07
Good	$10.96 \le IRI_{Eu} < 13.08$	5,208.94	$13.44 \le IRI_{Eu} < 17.95$	5,735.52

TABLE IX : TABLE OF USER COSTS

Pavement Grading	IRI_{Eu} (m/km)	Arterial Road (CNY/h/km)	IRI_{Eu} (m/km)	Branch Road (CNY/h/km)
Poor	$17.32 \le IRI_{Eu} < 19.44$	1,2318.83	$26.97 \le IRI_{Eu} < 31.47$	2,0219.48
Fair	$15.20 \le IRI_{Eu} < 17.32$	9,266.54	$22.46 \le IRI_{Eu} < 26.97$	1,5485.63
Average	$13.08 \le IRI_{Eu} < 15.20$	7,802.75	$17.95 \le IRI_{Eu} < 22.46$	1,1191.29
Good	$10.96 \le IRI_{Eu} < 13.08$	5,879.63	$13.44 \le IRI_{Eu} < 17.95$	6,999.67

V. CONCLUSIONS AND OUTLOOK

Based on PSD and IRI, a model for the Generalized International Roughness Index and vehicle speed variations is established. This paper verifies the rationality and reliability of the model by calculating the Generalized International Roughness Index for the average and uniform vehicle speeds corresponding to the same road surface roughness coefficient.

Based on this model, the city's B-grade road surfaces, including Arterial and Branch Road, are classified into four grades according to the size of the Generalized International Roughness Index. The MOVES2014b model is then used to simulate the CO_2 emissions of roads at each grade.

Environmental and user costs are calculated for each road surface condition, and the influence of road surface grade on these costs is analyzed. The results show that as the road surface grade deteriorates, both environmental costs and user costs increase. The environmental and user costs for the Branch Roadare higher than those for the Arterial Road. Improving road surface grades or enhancing road functionality helps reduce these two costs. Reducing vehicle operating costs on the Arterial Road has the most significant effect on lowering user costs, In contrast,on the Branch Road , reducing relative travel costs for S_0 and S_1 has the most noticeable effect, and reducing vehicle operating costs for S_2 and S_3 most effectively lowers user costs.

This paper has simplified the road surface degradation issue when establishing the model for the Generalized International Roughness Index and vehicle speed variations. Whether the road surface roughness coefficient before and after vehicle compaction is the same requires further analysis. Therefore, future research on this topic should consider these aspects in more depth.

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