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Highway life-cycle cost analysis under the autonomous vehicles scenario

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Abstract: This article introduces a model designed to assess the lifecycle maintenance costs associated with asphalt pavement, taking into account various distribution patterns influenced by autonomous vehicles. The primary objective is to establish a robust framework for managing mixed traffic flows and to facilitate the adoption of technologies pertinent to autonomous driving. The model employs lifecycle maintenance costs as the key evaluative metric, incorporating considerations such as maintenance, fuel consumption, and environmental impact to analyze the effects of autonomous vehicles on pavement maintenance expenditures. The results indicate that the integration of autonomous vehicles can lead to a substantial decrease in the overall maintenance costs of asphalt pavement. This cost reduction is primarily attributed to the more consistent driving patterns exhibited by autonomous vehicles, which diminish the frequency of necessary repairs and maintenance. By estimating the lifecycle maintenance costs of asphalt pavement under various distribution scenarios resulting from autonomous vehicles, this research demonstrates that an optimal distribution of these vehicles can significantly postpone the formation of ruts, potentially reducing maintenance costs by as much as 69.5%. Conversely, the maintenance costs associated with asphalt pavement under a zero distribution scenario are found to increase by 13.7%.

Keywords: road engineering; life-cycle analysis; autonomous vehicle; finite element method; lateral distribution

1 Introduction

Autonomous driving technology is an integrated system that combines various functions such as environmental perception, planning and decision-making, and automatic driving. It has received widespread attention from governments and enterprises worldwide as an important means of solving traffic safety and road congestion problems[1-2]. The advantage of autonomous driving technology lies in its ability to improve traffic safety and reduce accident rates. At the same time, autonomous driving systems can effectively alleviate road congestion and reduce the problems of time waste and environmental pollution caused by road congestion[3]. Based on current research results, the emergence of autonomous driving technology will have an impact on the design of road infrastructure. For example, autonomous vehicle (AV) may require additional infrastructure investments, such as dedicated lanes or parking facility[3-4]. In addition, the geometric design of the road may also undergo corresponding changes, which may raise higher demands on the geometric design of the road[5].

The application of autonomous driving technology can potentially reduce wear and tear on highways, as vehicles can operate more efficiently, avoid accidents, and minimize damage to road surfaces. Multiple studies have confirmed that the reasonable use of autonomous vehicles can effectively prolong the service life of road infrastructure and improve economic benefits[6-8]. To accurately evaluate the impact of autonomous driving technology on the cost and benefit of transportation infrastructure projects, this paper introduces the life-cycle cost analysis (LCCA) model[9]. LCCA is an evaluation tool used to assess project costs and support investment decisions. The lifecycle cost items typically covered by LCCA include agency costs (such as materials, labor, equipment ownership and operation, and transportation), road user costs (such as travel delays, fuel, and safety), and other relevant social costs (such as noise and equity).

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This article takes new energy vehicles as an example to analyze the damages of AVs to roads under different lateral distribution patterns, and constructs a life cycle cost analysis model for mixed traffic flow backgrounds to quantitatively evaluate the operational and maintenance costs of roads under different scenarios. This provides a basis for the practical application of autonomous driving technology.

2 Lateral distribution of vehicles

2.1 Lateral distribution of human-driving vehicles

The lateral distribution pattern of human-driving vehicle (HV) is affected by factors such as the driving preferences of the operator, vehicle handling stability, and road grades[10-11]. Currently, many researchers have observed and demonstrated that the lateral distribution of HVs follows a normal distribution pattern with a standard deviation of 25 cm[12-13] (Figure 1). Additionally, assuming that there is no lane-changing behavior during the vehicle's travel, the probability density function of the lateral distribution of autonomous vehicles can be expressed as follows:

$$f_{\mathrm{h}}(x) = \frac{1}{\sqrt{2\pi}\,\sigma}\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right], \tag{1}$$

where, $f_{\mathrm{h}}(x)$ is the probability density function of the lateral distribution of HVs; x is the deviation between the vehicle's centerline and the lane centerline; σ is the standard deviation with a value of 25; μ is the mean.

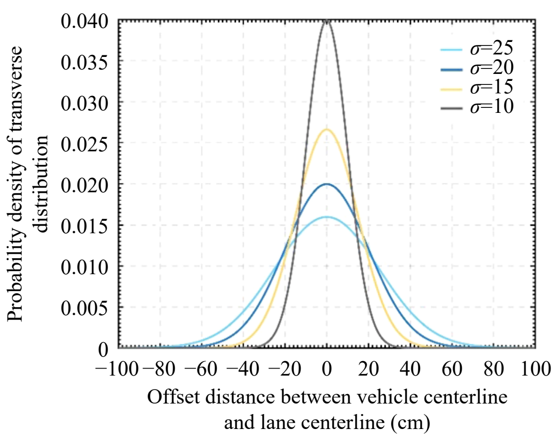

Fig. 1 The lateral distributions of HVs under different standard deviations.

2.2 Lateral distribution of autonomous vehicles

In previous studies, it has been demonstrated that AVs can overcome many of the limitations of human driving, resulting in different behavior patterns compared to manually driven vehicles[14]. Due to the close relationship between the lateral distribution of vehicles and the lifespan of roads, controlling the lateral distribution of vehicles to prolong road life has become one of the current research priorities. The lateral displacement of AVs is constrained by the dynamic control system, and they can drift laterally along a predetermined trajectory, which causes differences in lateral distribution with manually driven vehicles within the lane. This paper establishes three lateral drifting models for AVs based on previous research: zero distribution, normal distribution, and uniform distribution[6, 8, 15].

The zero distribution pattern refers to the scenario where a vehicle maintains its position at the center of the lane throughout the driving process without any lateral deviation. This represents an extreme case, which is defined as Pattern 1. Additionally, vehicles can simulate the distribution pattern of manually driven vehicles during their travel by moving within the previously mentioned lateral drift area according to a normal distribution model. This scenario is referred to as Pattern 2. Due to the precise control ability of autonomous vehicles, their lateral position can cover the entire drift area uniformly, resulting in a more balanced utilization of the road surface and reduced impact on the road. This scenario is represented by Pattern 3.

2.3 Lateral distribution of mixed traffic flow

Currently, autonomous driving technology has begun to gradually commercialize, and a small number of vehicles with autonomous driving capabilities have been put into use. It can be predicted that more and more HVs will gradually be replaced by AVs. In the future traffic flow, AVs and HVs will coexist in a certain proportion, known as mixed traffic flow. Based on the above analysis, we can obtain the composite function of the horizontal distribution of mixed traffic flow under different proportions of AVs.

$$h_{ij}(x) = w_j f_{\mathrm{a}i}(x) + (1-w_j) f_{\mathrm{h}}(x) \tag{2}$$

where, $h_{ij}(x)$ is the composite distribution of mixed traffic flow under different proportions of AVs; w_j is the proportion of autonomous vehicles with a value between 0 and 1.

3 Pavement damage assessment

3.1 Finite element model parameters

Taking Shanghai-Nanjing Expressway as an example, the typical pavement structure is illustrated in Figure 2. The upper layer consists of 4 cm thick SMA-13, the middle layer comprises 6 cm thick SUP-20, and the lower layer contains 8 cm thick SUP-25. Beneath the three asphalt layers, there are 40 cm cement stabilized crushed stone and 20 cm subgrade made of mixture of silt and sand.

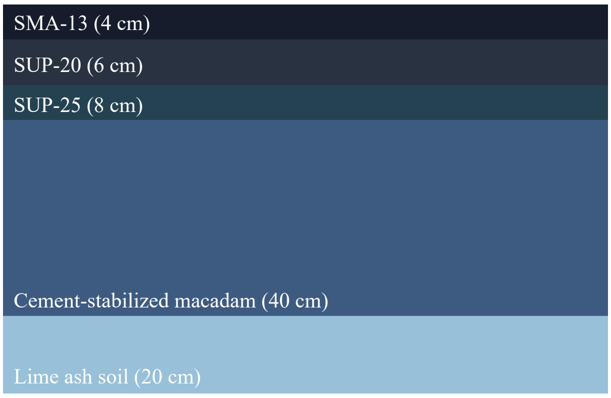

Fig. 2 Schematic diagram of typical pavement structure

This paper utilizes the large-scale general finite element software Abaqus to establish a permanent deformation simulation model for a typical pavement structure. The element type, computational model width, and depth of the model are set as follows: the horizontal width of the model is 3.90 m and the thickness is 3.0 m, in order to reduce the influence of the boundary stress reflecting wave on the results. The mesh for the area subjected to wheel load is refined locally to better capture the mechanical response under wheel load. The boundary conditions are set as lateral horizontal displacement, no horizontal or vertical displacement at the bottom, and full contact between layers[16].

3.2 Material parameters

When using the creep model in ABAQUS to simulate the rutting deformation of asphalt concrete, the Bailey-Norton law is generally adopted to analyze the material deformation, which is expressed as[17]:

$$\varepsilon_{\mathrm{c}} = A\sigma^{m}t^{n}, \tag{3}$$

where, ε_c is the strain rate; σ is axial shear stress; t is cumulative loading time; A, m and n are creep parameters related to the material properties that depend on temperature and stress levels.

To ensure the rationality of the results in finite element analysis, it is necessary to determine the relevant parameters of the materials in each layer. By referring to relevant research findings, the material parameters of each layer at different temperatures are obtained as shown in Table 1[18].

3.3 Load parameters

This paper employs the form of dual-wheel evenly distributed loads, with specific parameters shown in Table 2. During finite element analysis, the dual-wheel group is converted into two square load application areas with dimensions of 189 mm × 189 mm and a tire-ground contact pressure of 0.7 MPa. The time step for the analysis in the model, i.e., the calculation formula for cumulative loading time, is as follows:

$$t = \frac{0.36NP}{n_{\mathrm{w}}pBv}, \tag{4}$$

Table 1 Material characteristic parameters of different layers

Layers	Temp. (℃)	A	n	m	Elastic modulus (MPa)	Poisson's ratio
SMA-13	20	6.536×10^{-11}	0.937	−0.592	870	0.25
	30	3.325×10^{-9}	0.862	−0.587	620	0.30
	40	1.446×10^{-8}	0.792	−0.577	554	0.35
SUP-20	20	4.580×10^{-11}	0.944	−0.596	910	0.25
	30	2.461×10^{-9}	0.796	−0.585	752	0.30
	40	3.673×10^{-8}	0.773	−0.570	600	0.35
SUP-25	20	4.590×10^{-11}	0.922	−0.581	1 031	0.25
	30	3.461×10^{-9}	0.859	−0.576	900	0.30
	40	1.956×10^{-8}	0.830	−0.562	710	0.35

Table 2 The parameters of standard axle load

Standard Axial Load (kN)	Tire Contact Pressure (MPa)	The Center Distance Between Two Wheels (cm)	One Wheel's Equivalent Circular Diameter (cm)
100	0.7	31.95	21.30

where, t is the cumulative operating time of wheel loading, s; N is the number of wheels loading times; P is the axle load of the vehicle, kN; n_w is the number of wheels per single axle; p is the tire pressure, MPa; B is the tire contact width, cm; v is the driving speed, km/h.

3.4 Finite element analysis results

In the simulation analysis, assuming a loading cycle of 2 million times, the rutting depths under three distribution patterns were obtained for different proportions of autonomous vehicles, as shown in Table 3.

4 Life-cycle cost analysis

4.1 Maintenance cost analysis

In conducting cost-benefit analysis for maintenance, it is important to focus on the service life of asphalt pavement and the timing of repair and maintenance, as ruts are the main cause of discomfort and safety hazards for drivers. According to relevant studies on the Shanghai-Nanjing Expressway, the development of ruts on this expressway over the past 13 years since its opening is shown in Table 4[18].

In the 13th year of its operation, the Shanghai-Nanjing Expressway adopted milling and repaving maintenance measures. Based on the above finite element analysis results, the equivalent service life under different proportions of autonomous driving vehicles and lateral distribution patterns was obtained by interpolation, as shown in Table 5.

The Shanghai-Nanjing Expressway is a bidirectional eight-lane expressway. In conducting maintenance analysis, a 1 km distance is selected as the basic unit, and the various maintenance costs are shown in Table 6.

Based on the maintenance costs mentioned above, the hybrid traffic flow road maintenance cost model is obtained as follows:

$$C_m = y(C_{m,p} + C_{m,e} + C_{m,l} + C_{m,m}), \tag{5}$$

where, C_m is maintenance cost, CNY; y is equivalent service life; $C_{m,p}$ is the preventive maintenance cost, CNY; $C_{m,e}$ is the equipment usage cost, CNY; $C_{m,l}$ is the labor cost, CNY; $C_{m,m}$ is the material cost, CNY.

Table 3 The rutting depths under three distribution patterns (unit: mm)

Mode	The proportion of autonomous vehicles w_j										
	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0
Mode 1	7.851	7.694	7.536	7.379	7.221	7.064	6.907	6.749	6.592	6.434	6.277
Mode 2	4.106	4.323	4.540	4.757	4.974	5.191	5.409	5.626	5.843	6.060	6.277
Mode 3	3.533	3.807	4.082	4.356	4.631	4.905	5.179	5.454	5.728	6.002	6.277

Table 4 Rutting depth of shanghai-nanjing expressway

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
Rutting Depth(mm)	2.975	3.228	3.764	4.427	5.236	5.533	5.986	6.097	6.816	8.234	8.397	8.441	9.762

Table 5 The equivalent service life under differentpropor-tions of autonomous driving vehicles (unit: year)

Mode	The proportion of autonomous vehicles w_j										
	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0
Mode1	9.73	9.62	9.51	9.4	9.29	9.17	9.06	8.91	8.69	8.47	8.25
Mode2	3.52	3.84	4.17	4.41	4.68	4.94	5.58	6.21	6.68	7.67	8.25
Mode3	2.57	3.06	3.48	3.89	4.25	4.59	4.93	5.73	6.43	7.14	8.25

Table 6 The maintenance cost of asphalt pavement

Expense Item	Expense Details
Preventive maintenance cost $C_{m,p}$	Preventive maintenance with fog seal technology for an area of 30,000 square metres at a unit cost of CNY 11.5 per square metre per year, totally CNY 345,000.
Equipment usage cost $C_{m,e}$	The unit price for milling and demolition is CNY 9.6 per square metre and CNY 21,600 for the use and maintenance of machinery, totally CNY 309,600.
Labor cost $C_{m,l}$	The labor cost for substrate sweeping, paving, etc. is CNY 2.2 per square metre, totally CNY 66,000.
Material cost $C_{m,m}$	Based on the average market price, the material cost of asphalt for milling and resurfacing is approximately CNY 98.9 per square metre, totally CNY 2,967,000.

4.2 Fuel consumption analysis

Due to the high proportion of fuel consumption in travel costs for vehicles, many countries and regions currently prioritize research on vehicle fuel consumption as an important aspect of vehicle travel costs. Assuming two types of vehicles are considered in this study, manually driven vehicles are all fueled cars, while AVs are all electric cars. To analyze the cost of fuel consumption for the fueled cars, the widely used fuel consumption model based on actual data constructed by the World Bank is adopted. This model is based on vehicle kinematics and considers indicators such as vehicle speed and road surface smoothness. Through multiple experiments, a model that can be applied to different regions has been established. The calculation formula for the model is as follows[19]:

$$F_{\mathrm{f}} = a + \frac{b}{v} + cV^2 + dI_{\mathrm{RI}} + eI, \tag{6}$$

where, F_{f} is vehicle fuel consumption of fuel cars, L/100 km; V is vehicle speed, 100 km/h; I_{RI} is international roughness index, 5.448 m/km; I is the slope, 0%; a is 10.532; b is −108.170; c is 0.000; d is −0.260; e is 0.398.

Based on the aforementioned vehicle fuel consumption model, the unit fuel consumption of the vehicle can be calculated. A vehicle fuel consumption cost calculation model is established according to the travel characteristic data of the target city as follows:

$$C_{\mathrm{car,f}} = F_{\mathrm{f}} n_{\mathrm{pc}} l_{\mathrm{pc}} S_{\mathrm{f}}, \tag{7}$$

where, $C_{\mathrm{car,f}}$ is fuel consumption cost of fuel cars, CNY; n_{pc} is number of vehicle trips; l_{pc} is the single trip distance, km; S_{f} is average fuel price, 7.68 CNY/L.

In order to investigate the relationship between the weight of electric vehicles and greenhouse gas emissions, Ha used regression analysis to demonstrate that for every 100 kg increase in vehicle weight, electric vehicles' energy consumption demand would increase by 0.005, 1 (kW·h)/km[20]. Based on this, the following fuel consumption cost calculation model for electric vehicles can be established:

$$C_{\mathrm{car,e}} = E n_{\mathrm{pc}} l_{\mathrm{pc}} S_{\mathrm{e}}, \tag{8}$$

where, $C_{\mathrm{car,e}}$ is fuel consumption cost of fuel cars, CNY; E is Electric energy consumption of vehicles, 13.71 (kW·h)/(100 km); S_{e} is average fuel price, 0.528 3 CNY/(kW·h).

Combining the aforementioned horizontal distribution model of mixed traffic flow, we obtain an analytical model for fuel costs under different proportions of AVs.

$$C_f = w_j C_{\mathrm{car,e}} + (1 - w_j) C_{\mathrm{car,f}}. \tag{9}$$

4.3 Environmental cost analysis

The carbon emission calculation method used in this article adopts the CO_2 conversion method specified in GB/T 37 340—2019 *Method for Energy Consumption Conversion of Electric Vehicle*. This method converts the electricity consumption of electric vehicles into CO_2 emissions generated during the power generation stage, by comparing it with the CO_2 produced by the combustion of traditional fuel vehicles. The specific conversion method is as follows[21]:

$$F_f = E F_C, \tag{10}$$

where, F_{f} is vehicle fuel consumption of fuel cars, L/100 km; E is Electric energy consumption of vehicles, 13.71 (kW·h)/(100 km); F_C is the CO_2 conversion factor, 0.27 L/(kW·h).

Combining the aforementioned model, the environmental cost analysis model for mixed traffic flow can be derived as follows[22]:

$$C_e = \left[F_f(1-w_j)+0.27Ew_j\right]\times F_i p_i c n_{pc} l_{pc}/1\,000, \quad (11)$$

$$F_i = C_i \alpha_i \rho, \quad (12)$$

where, C_e is the environmental cost, CNY; F_i is the emission factor of fuel, 3.10 kgCO_2/kg; p_i is the density of fuel, 0.737 kg/L; c is carbon trading unit price, 57 CNY/t. C_i is the carbon content per unit calorific value, tC/TJ; α_i is carbonization rate; ρ is the molecular weight ratio of carbon dioxide to carbon, 44/12.

4.4 Results of life-cycle cost analysis

Based on the previous analysis of the cost model for maintaining asphalt pavements, the calculation formula for the full-life maintenance cycle cost analysis model of asphalt pavements can be derived.

$$C = C_m + C_f + C_e. \quad (13)$$

Based on the parameters mentioned above, the life-cycle maintenance cost of asphalt pavement under different distribution patterns is shown in Table 7.

Table 7 The life-cycle maintenance cost of asphalt pavement underdiffer-ent distribution patterns (unit: CNY)

Mode	The proportion of autonomous vehicles w_j										
	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0
Mode 1	3 609	3 579	3 550	3 520	3 491	3 458	3 428	3 384	3 314	3 244	3 174
Mode 2	1 319	1 448	1 581	1 680	1 791	1 898	2 145	2 388	2 573	2 949	3 174
Mode 3	968	1 160	1 326	1 488	1 632	1 769	1905	2 211	2 480	2 753	3 174

According to Table 7, under zero distribution mode, the increase in the proportion of autonomous vehicles significantly affects the maintenance cost of asphalt pavement, with cost increments of about 4.4%, 8.0%, 10.0%, 11.8%, and 13.7% for autonomous vehicle proportions of 20%, 40%, 60%, 80%, and 100%, respectively. When using normal distribution mode, the presence of autonomous vehicles is advantageous in reducing the maintenance cost of asphalt pavement. Under proportions of 20%, 40%, 60%, 80%, and 100%, the maintenance cost of asphalt pavement will be reduced by 18.9%, 32.4%, 43.6%, 50.2%, and 58.5%, respectively. In addition, the maintenance cost of asphalt pavement under uniform distribution mode can be reduced by up to 69.5%.

5 Conclusions

In this paper, a vehicle lateral distribution model was constructed under mixed traffic flow, and the impact of different lateral distribution patterns on the rut depth of asphalt pavement was simulated using ABAQUS finite element simulation technology. Based on this, a full life cycle cost maintenance analysis model considering different types of energy vehicles was established. The impact of autonomous vehicle lateral distribution patterns and proportions on the maintenance cost of asphalt pavement was calculated, and the following conclusions were drawn.

(1) The lateral distribution pattern of autonomous vehicles significantly affects the formation of asphalt pavement ruts, whereby rut depth develops most rapidly under a zero distribution pattern. However, both uniform and normal distribution patterns can provide some relief from rut formation, while the smallest rut depths are observed under the normal distribution pattern.

(2) When all vehicles in the traffic flow are manually driven, the equivalent service life of the pavement is 6.777 years. When the proportion of autonomous vehicles in a mixed traffic flow reaches 100%, the maximum equivalent service life is 7.851 years. However, if autonomous vehicles are evenly distributed throughout the entire pavement, the equivalent service life is 3.553 years.

(3) Under the zero distribution mode, the maintenance cost of asphalt pavement increases with the proportion of autonomous vehicles and can increase by a maximum of 13.7%. However, the application of the even distribution mode significantly reduces the maintenance cost of asphalt pavement, with a potential maximum reduction of 69.5%.

The established lifecycle maintenance cost analysis model in this article can effectively evaluate the impact of autonomous vehicles on asphalt pavement maintenance costs under different distribution patterns, providing reliable basis for the management of mixed traffic flow in the future. It also further promotes the implementation of related technologies in autonomous driving.

Declaration of competing interest

The author has no competing interests to declare that are relevant to the content of this article.

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