

Research Article

The Influence of Work Zone Management on User Carbon Dioxide Emissions in Life Cycle Assessment on Highway Pavement Maintenance

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The higher contribution of traffic delay to environmental impacts is urging the highway agencies to take work zone management into the maintenance schemes decision-making. Aiming to understand the role of work zone management in user CO₂ emissions reduction, this paper firstly developed a practical methodological framework of traffic delay-related CO₂ emissions caused by highway maintenance based on a popular life cycle user cost analysis approach in regard of the microscopic vehicle operation analysis. The method was applied in an actual freeway flexible pavement with 15-year design life in Shaanxi Province, China, covering three types of preventive maintenance, correction maintenance, and rehabilitation. In addition, the impacts of key inputs of proposed method on work zone user CO₂ emissions results were checked. The results show that traffic delay attributes to 29.4% of total CO₂ emissions of the life cycle of highway pavement maintenance, and 51.8% of work zone user CO₂ emissions result from preventive maintenance, especially from micro vehicle operations including speed change and queue near work zone (62% of total work zone user CO₂ emissions). The work zone management alternative strategies related to less traffic volume or higher highway capacity including vehicle type limitation and the limited work zone speed have an advantage in reducing the work zone CO₂ emissions over changing work zone length or work zone timing. The findings in this paper may present a useful tool and reference for robustly supporting the decision-making on highway maintenance carbon mitigation in work zone traffic.

1. Introduction

The increasing global concern on climate change has exerted pressure on the highway agencies of all nations as there are considerable interferences between highway maintenance & rehabilitation (M&R) with intensive consumption of resources and fuels (e.g., asphalt, cement, diesel, and gasoline) [1–4] and thus with substantial carbon dioxide (CO₂) emissions [5, 6]. It is found that the total CO₂ from highway rehabilitation and reconstruction is 787.19 and 1,383.28 MT per lane per mile associated with materials production, fuels usage (e.g., diesel, gasoline, and electricity) of the on-site machine, and transportation vehicle operation [7].

For M&R phase, the CO₂ emissions related to maintenance construction work and the mitigation technologies have been the main concern in previous studies [8–11]. Ma et al. [11] analyzed the CO₂ emissions of sixteen asphalt pavement maintenance technologies and claimed that microsurface and fog seal have the lowest GHG emissions. In addition, the existence of the work zone will also affect the operation of passing vehicles and generate additional carbon emissions. The findings in previous studies indicate that construction-related traffic delay was even the greatest contributor to environmental impacts throughout the whole highway pavement life cycle [12, 13]. Most of these few studies on traffic delay CO₂ emissions (also called as user

CO₂ emissions) associated with work zone in pavement maintenance using life cycle assessment (LCA) were mainly conducted by the direct combination of traffic simulation software (e.g., VISSIM, AIMSUN, and Quickzone) and emission software (e.g., MOVES, CMEM), for one thing, to obtain the value or share of work zone-related traffic delay on total environmental impact, and for another thing, to explore the importance of work zone management on the total work zone emissions produced by highway maintenance. Huang et al. [12] explored the impact of delivery speed of the roadwork on carbon emissions of a pavement rehabilitation. Kang et al. [14] and Galatioto et al. [15] studied the influence of road maintenance construction road closure and construction time on carbon emissions from maintenance activities. Liu et al. [16] carried out a comparative LCA analysis on the carbon emission of three preventive and corrective maintenance schemes with different time reopened to the traffic.

However, due to the complexity and uncertainty of the speed change, as well as acceleration/deceleration of vehicles travelling through the highway maintenance work zone, the work zone related user CO₂ emissions are generally assumed which have little contribution to the total CO₂ emissions for a highway maintenance, especially for the maintenance that happened at night with the lower traffic volume [17]. Consequently, the part of work zone is rarely taken into the system boundary of LCA on highways [18]. But there still are strong supporters who stress the importance of the traffic delay on total LCA results and tried to develop the computation method of user CO₂ emissions. For example, in situations where there is only a small amount of data available, Yu and Lu [19] and Chong and Wang [20] roughly estimated the extra CO₂ emissions produced from traffic delay by a VKT-based approach based on average speed/vehicle miles travelled data and constant emission factor, without considering queue and speed change near the work zone. Lizasoain-Arteaga et al. [21] evaluated the performance of macrosimulation method and microsimulation method for estimation of work zone traffic delay-related 6 pollutants (CO₂, CO, NO_x, CH₄, C₆H₆, NH₃, VOC, and PM_{2.5}). The findings show that macrosimulation could be used for rough calculations, but it should be noted that there is a significant deviation of the emissions results when the highway presents “A” level of service and “C” level of service.

On one hand, limited by the financial budget, the highway agencies face the challenge of looking for the cost-effective M&R options for keeping highway infrastructure in good functional condition. The influence of traffic congestion on road users in the United States was \$121 billion in 2011, as a result of 5.5 billion hours of delay and 2.9 billion gallons of wasted fuel [22]. Thus, highway authorities are desperate for highway maintenance management policies which simultaneously account for CO₂ emissions and costs of both agency and users over the whole highway pavement service life. More recently, integration of life-cycle cost analysis (LCCA) and LCA has been recognized as an effective management method for comprehensive maintenance schemes decision considering the balance of the cost and environmental impact. In the comprehensive analysis of LCA and LCCA, pavement

condition-related greenhouse gases (GHG_s) have been considered to have a significant impact on the balance of user cost and user environmental emissions over the overlay or resurfacing period, as the pavement roughness and smoothness have a significant impact on the change of fuel and then affect the user cost and GHGs [23–26]. With the inclusion of traffic delay in highway pavement LCA in recent decade, it has been found that some studies began to try to take the traffic-delay user CO₂ emissions and user cost into consideration simultaneously [17, 27, 28].

Despite this background, the few existing researches on calculation method of emissions associated with traffic delay caused by pavement maintenance are mainly focused on obtaining the emission value itself and its contribution on total LCA results, not aiming to service for the analysis on the impact of work zone management on total emissions saving. In addition, even it is an important contributor to the total highway LCA emissions, the user emissions associated with traffic delay caused by work zone are relatively simplified compared to user cost consideration in the integration of LCCA and LCA. The lack of the consistent, accurate, and comparable calculating method and system boundary of traffic delay analysis makes that even little research could make a better integration of LCA and LCCA [29, 30].

On the other hand, with the end of large-scale road initial construction, maintenance gradually becomes the top priority of highway asset management. The longer life cycle of highways and the frequent maintenance activities make that the carbon emissions of life cycle maintenance activities cannot be ignored. Work zone is a critical area for maintenance activities and involving work zone management into life cycle assessment on highway maintenance should be an important content of maintenance plan decision-making. But it is still immature since there are gaps in the knowledge and lack of practical guidelines and methodologies on work zone CO₂ emissions calculation.

Thus, this study tried to propose a new and practical calculation method of work zone related user CO₂ emissions in regard of the microscopic vehicle operation and LCCA integration analysis. Furthermore, to verify the performance of the proposed method on work zone carbon mitigation management, an experimental application and environmental impacts analysis of several schemes (e.g., shorter work zone length, higher work zone limited speed, etc.) was conducted. In the next section of this paper, the methodology developed in this study is described in detail, followed by an introduction of materials used. Then results and discussion of experimental applications based on an actual freeway flexible pavement with 15-year design life in Shaanxi Province, China, are given. Finally, conclusions and future work are summarized.

2. Methods and Materials

2.1. Conceptual Analysis

2.1.1. Definition of Work Zone User CO₂ Emissions. In the simplest sense, the work zone user CO₂ emissions are CO₂ emissions related to the highway user over the life of the

project. The concerns of the work zone user CO₂ emissions are the differential CO₂ emissions incurred by the vehicles between normal operation and work zone operation. The normal operation means highway user CO₂ emissions related to using a facility during periods free of maintenance and rehabilitation activities. However, the work zone operation reflects highway user CO₂ emissions associated with using a facility during periods of maintenance and rehabilitation activities that restrict the capacity of the facility and disrupt normal traffic flow. Thus, work zone user CO₂ emissions are high with relation to the work zone characteristics (highway capacity, work zone length, lane closures, posted speed, etc.) and traffic characteristics (Average Annual Daily Traffic, directional hourly demand distributions, vehicle classification, etc.).

2.1.2. Components of Work Zone User CO₂ Emissions. For a work zone, its components of user CO₂ emissions are associated with two situations of base case situation and queue situation. In base case situation, traffic operates under free-flow conditions, and, in queue situation, traffic operates under forced-flow conditions (F level of service).

- (i) Under free-flow conditions, all vehicles that travel through the work zone need to slow down to the limited speed and then accelerate back to normal operating speed. This is commonly referred to as a speed change and thus results in two categories of work zone-related user CO₂ emissions including speed change delay CO₂ emissions and reduced speed delay CO₂ emissions, shown in Figure 1(a).

Speed change delay CO₂ emissions are the additional CO₂ emissions associated with decelerating from the upstream approach speed to the work zone speed and then accelerating back to the initial approach speed after traversing the work zone.

Reduced speed delay CO₂ emissions are the additional CO₂ emissions related to traversing the work zone at the lower posted speed, mainly depending on the upstream and work zone speed differential and length of the work zone.

- (ii) Under forced-flow conditions, all vehicles that travel through the work zone need to slow down to the queue speed, then speed up to the limited speed, and then accelerate back to normal operating speed. In detail, when there is no stop in queue, the vehicle needs to decelerate to the lower speed (queue speed) in Figure 1(b) from the upstream speed; then the vehicle needs to accelerate to limited speed at work zone; when the vehicle undergoes a stop and wait in queue, the vehicle needs to decelerate to stop; then the vehicle needs to accelerate to the operating speed in queue, as well as travelling the queue under a queue speed; finally the vehicle needs to accelerate to limited speed at work zone from the operating speed in queue. In short, compared to work zone user CO₂ emissions under free-flow conditions, two components of queue speed change delay CO₂ emissions

and reduced speed delay CO₂ emissions in queue are added, as shown in Figure 1(b).

Queue speed change delay CO₂ emissions are the additional CO₂ emissions associated with completing deceleration to the lower queue speed or stopping from the upstream approach speed to the work zone speed and then accelerating back to the initial approach speed after traversing the work zone.

Reduced speed delay CO₂ emissions in queue are the additional CO₂ emissions related to traversing the queue at the queue speed, mainly depending on the upstream and queue speed.

In sum, there are two components of work zone user CO₂ emissions under free-flow conditions including speed change delay CO₂ emissions, reduced speed delay CO₂ emissions, and four components of work zone user CO₂ emissions under forced-flow conditions including speed change delay CO₂ emissions, reduced speed delay CO₂ emissions, queue speed change delay CO₂ emissions, and reduced speed delay CO₂ emissions in queue.

2.2. Estimation Method of Work Zone User CO₂ Emissions

2.2.1. Computational Analysis. The conceptual analysis above in Section 2.1 indicates that the work zone user CO₂ emissions are highly associated with vehicles operation situations and work zone characteristics, which is consistent with the analysis of user costs in LCCA. In LCCA, the user costs are determined by multiplying the quantity of the individual user cost components by the unit cost for those cost components. This method is provided as a technical bulletin by Federal Highway Administration (FHWA) and has become the most popular method (represented as FHWA-UC method in this paper) adopted for analyzing work zone vehicle operating costs related to life-cycle cost analysis in pavement design [27]. The bulletin illustrated a detailed highway capacity-based approach for determining the quantity of the individual user cost components and an adaptable method for determining the various user cost rates. Considering the consistency of sources and the related influencing factors of the work zone user CO₂ emissions with work zone user costs, the FHWA-UC method was introduced and revised to estimate the work zone user CO₂ emissions. Similarly, the individual work zone user CO₂ emissions components are determined by multiplying the quantity resulting from work zone traffic delay by the unit CO₂ emissions.

2.2.2. Computational Methods

(1) *The Approach Framework.* Based on the FHWA-UC method and the computational analysis, the critical point of computing the work zone user CO₂ emissions is to determine the quantity of each work zone user CO₂ emissions component and the related unit CO₂ emissions. Thus, this paper firstly proposed the approach framework for

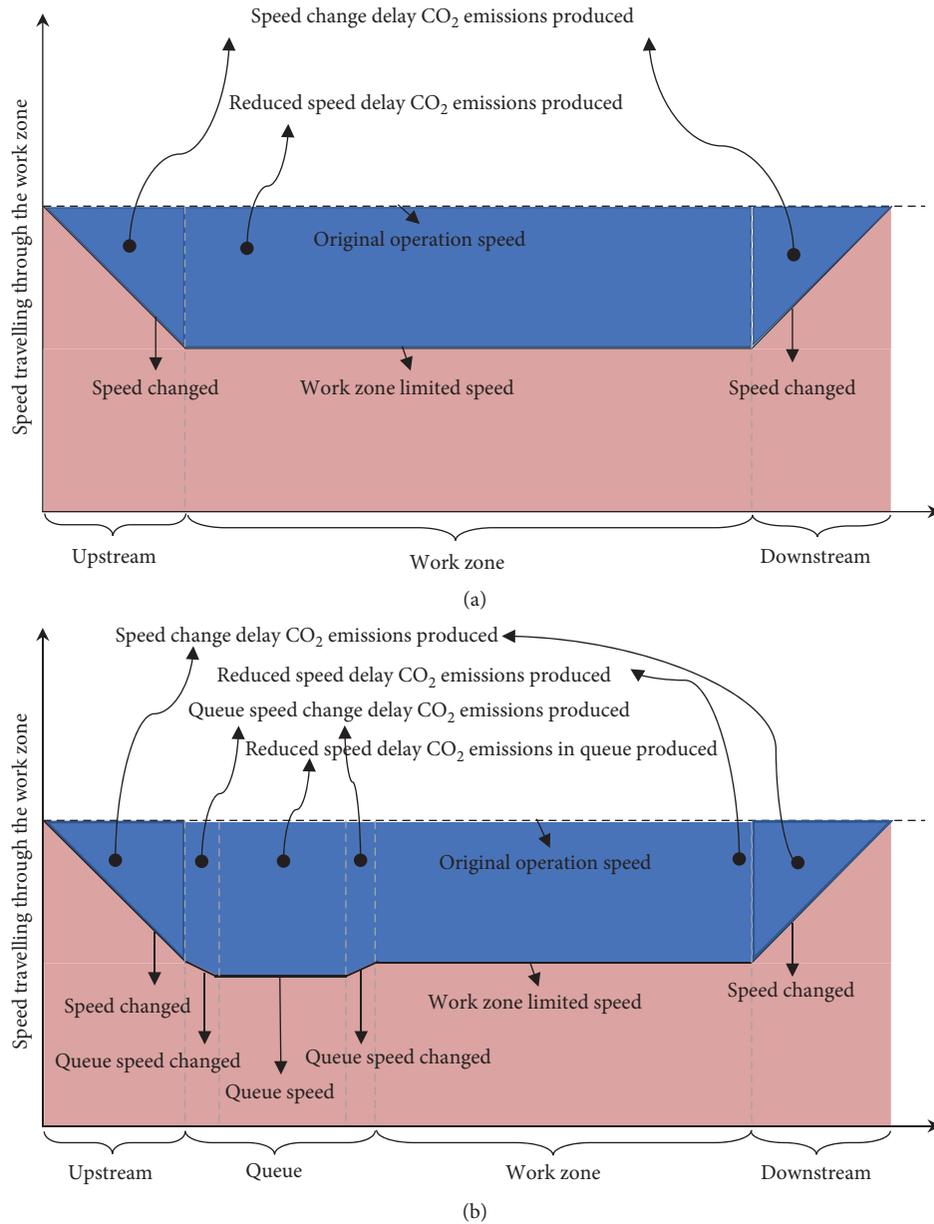


FIGURE 1: Vehicle operation and CO₂ emissions produced: (a) under free-flow conditions and (b) under forced-flow conditions.

calculating the work zone user CO₂ emissions including ten steps as illustrated in Figure 2.

(2) *The Computational Methods.* As mentioned above, the bulletin proposed by FHWA has provided a detailed and step-by-step highway capacity-based approach for determining the quantity of the individual user cost components, which can be used for determining the quantity of the individual user CO₂ components directly in this study. For more information on highway capacity-based method, view the bulletin of “Life-Cycle Cost Analysis in Pavement Design” [31]. Different from the method for determining the various user cost rates in LCCA, the user CO₂ emissions rates are more complicated, especially for the speed change-related user CO₂ emissions

components. Thus, this paper focuses on the computational methods of CO₂ emission rates.

- (i) In terms of speed reduced-related CO₂ emissions including reduced speed delay CO₂ emissions and reduced speed delay CO₂ emissions in queue, the unit CO₂ emissions are highly related to the original upstream speed and work zone posted speed or queue speed. A meso-fleet-based model with advantages in CO₂ emissions estimation on an average level is introduced in this study. This model represents a function of emission rates versus average speed because emission rates in a steady-state operation are highly dependent on speed [32]. Therefore, the unit speed reduced-related CO₂

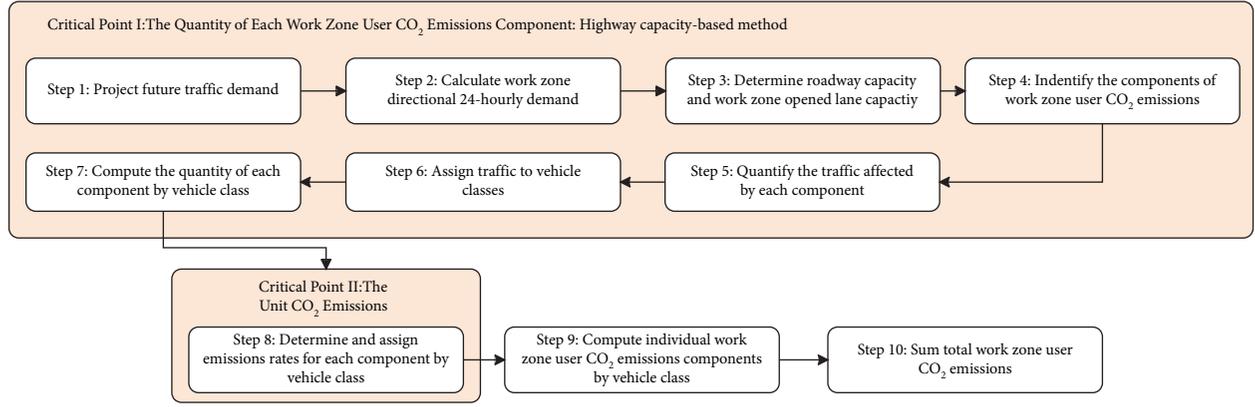


FIGURE 2: The framework of work zone user CO₂ emissions computation approach.

emissions could be expressed as in the following equation:

$$EF_{CO_2}(\Delta v) = EF_{CO_2}(V_1) - EF_{CO_2}(V_0). \quad (1)$$

In the above equation, $EF_{CO_2}(\Delta v)$ represents the unit speed reduced-related CO₂ emissions, $EF_{CO_2}(V_1)$ represents the unit CO₂ emissions of speed V_1 (work zone posted speed or queue speed in this study), and

$EF_{CO_2}(V_0)$ represents the unit CO₂ emissions of speed V_0 (the original upstream speed in this study).

In this study, mesoscopic vehicle CO₂ emission models for light duty vehicles (LDVs) and heavy duty vehicles (HDVs) based on the real-world vehicle operation and emission data conducted by Song et al. [33] are adopted as in the two following equations:

$$EF_{CO_2}^{LDVs}(v) = 4.78 \times 10^3 \times V^{-1} + 1.11 \times 10^2 - 1.24 \times V + 2.37 \times 10^{-2} \times V^2, \quad (2)$$

$$EF_{CO_2}^{HDVs}(v) = 3.67 \times 10^3 \times V^{-1} + 5.34 \times 10^2 - 7.90 \times V + 5.43 \times 10^{-2} \times V^2. \quad (3)$$

- (ii) In terms of speed change-related CO₂ emissions, such as speed change delay CO₂ emissions and queue speed change delay CO₂ emissions, the unit CO₂ emissions are not only related to the original upstream speed and work zone posted speed or queue speed but also associated with the accelerating and decelerating performance. A microvehicle-based model is introduced in this study. The model provides a better way to estimate the vehicle fuel consumption and emissions in vehicle speed change condition with its ability to consider emissions caused by the acceleration and deceleration patterns under various speeds [34]. The unit speed change-related CO₂ emissions could be expressed as in the following equation:

$$EF_{CO_2}(\sim \Delta v) = \int_{v_0}^{v_1} f(a, d, v) dv. \quad (4)$$

In the above equation, $EF_{CO_2}(\sim \Delta v)$ represents the unit speed change-related CO₂ emissions. $f(a, d, v)$ represents the unit CO₂ emissions by a response surface function of acceleration a , deceleration d , and speed v . v_1 represents the end speed after speed change. v_0 represents the original speed before speed change.

The microvehicle-based model conducted by Zhang et al. [35] is used in this paper to obtain the relationships between CO₂ emissions rate and acceleration or deceleration patterns under various speeds. This specific model is developed by a combination of field experiments and the Comprehensive Modal Emissions Model (CMEM). Field experiments collected second-by-second vehicle speed and acceleration data along a freeway segment on rush hour and work zone time, and then the CMEM generated second-by-second emissions for LDVs and HDVs. For more information on this method, view the publication of [35].

2.3. Case Study and Data Source

2.3.1. Brief Background. To test this methodology and analyze the impact of work zone management on CO₂ emissions saving, a real case study was conducted using real work zones on a segment of freeway from Xi'an city to Hanzhong city, China. The length of the case project is 41.251 kilometers and the length of pavement part is 20.55 kilometers. The entire freeway is four-lane double way, totally closed and interchanged. Limited by the terrain, geology, and technical standards of freeway maintenance, the design speed is limited to 60 kilometers per hour (km/h)

or 80 kilometers per hour. The analysis period of the flexible pavement is 15 years.

The project maintenance record files noted that five maintenance events were conducted until 2016 from 2007 when it opened to the traffic. The five maintenance events are (i) thin hot mix asphalt (HMA) overlay 2 cm in 2009, (ii) thin asphalt surfacing in 2010, (iii) HMA overlay 4 cm in 2011, (iv) thin HMA overlay 1 cm in 2014, and (v) overlay 4 cm + 5 cm structural overlay. Combining the historical data with the data collection results from official highway pavement maintenance reports, M&R archives of China freeways from highway administration authority, and interviews on experienced pavement manager, the maintenance events in the future after 2016 until 2022 are predicted. They are (i) thin HMA overlay 2 cm in 2018, (ii) thin asphalt surfacing in 2019, and (iii) HMA overlay 4 cm in 2020.

It should be noted that, for better understanding the impact of work zone user CO₂ emissions on the total CO₂ emissions for pavement maintenance activities, this study calculated the CO₂ emissions associated with the maintenance construction work activities including materials production, on-site and off-site machinery/equipment work, and transportation. More information on the detailed calculation methods can be found in previous publications by the same authors of this paper [36, 37].

2.3.2. Components Quantity-Related Data Source

(1) *Work Zone Characteristics.* The work zone length, limited speed, construction traffic organization scheme, and other work zone characteristic data are mainly obtained from engineering files, field investigations, and the “Highway Maintenance Safety Operation Rules” standard (JTJG H30-2015) [38]. The capacity analysis of highway work zone mainly refers to “Road Capacity Manual 2010” [39]. In this case study, 5-kilometer-long single-directional lane is closed from 8 a.m. until 18 p.m. for preventive maintenance and corrective maintenance. As for the rehabilitation, 15-kilometer-long single-directional lanes are closed from 8 a.m. until 18 p.m. Work zone posted speed is 40 km/h. The work time of preventive maintenance is usually in place for 15 to 20 days in July to September. The work zone of corrective maintenance is usually in place for 15 to 30 days in May to June. In general, the rehabilitation occurs in July to August lasting for 45 to 65 days. For corrective maintenance, the direction with lane closure is closed to all types of trucks. But, for rehabilitation, both directions are not available for any trucks when the work zone happens.

(2) *Traffic Characteristics.* The historical traffic volume data from 2007 to 2016 were obtained from traffic count stations. Passenger cars, passenger buses, light-duty trucks, and heavy-duty trucks were classified in this study. Vehicle classification counts indicate a traffic stream mix of 87% of passenger cars for passenger vehicles, 13% of passenger bus for passenger vehicles, 36% of light-duty trucks, and 64% of heavy-duty trucks for trucks vehicles. The vehicle lengths for

the four types of vehicles are 4.5 meters, 12 meters, 7 meters, and 11 meters, respectively.

2.3.3. *The Unit CO₂ Emissions-Related Data Source.* As the work zone posted speed is 40 km/h and the upstream speed and downstream speed are statistically 65 km/h, the queue speed was calculated by the method of highway capacity-speed relationship using the maximum volume travelling through the queue. A frequently happening queue speed of 10 km/h was given here. Based on the assumption of uniform acceleration and deceleration, the average value of speed is used to calculate the carbon emission rate of the speed change in two cases of “65-40-65” (vehicles travelling through without queue) and “65-0-65” (vehicles travelling through with queue). Under uniform acceleration and deceleration, it is simplified that the change process of “65-0-10-40-65” in the queue status is equivalent to “65-0-65.” With the basis of equation (4) and CO₂ emissions consumption response surface developed by [35], the specific input parameters for model validation of four vehicle operation statuses are obtained as in Tables 1 and 2.

3. Results and Discussion

3.1. Results

3.1.1. *General CO₂ Emissions Distribution during Pavement Service Life.* During the service life of the case freeway pavement, there are five times of preventive maintenance, two times of corrective maintenance, and one time of rehabilitation. It can be observed from Figure 3 that all the maintenance events during the whole service life of the case freeway pavement produce up to 5742.36 tons of CO₂ emissions totally. In detail, the rehabilitation accounts for 47.3% of total CO₂ emissions of all the maintenance events during the service life, and the preventive maintenance is the second contributor, followed by corrective maintenance.

In addition, Figure 3 also indicates that, among CO₂ emissions sources, maintenance construction related fuel/energy usage from construction machinery or equipment/transportation is the largest contributor, followed by the materials production and work zone related traffic delay. These findings are generally consistent with previous studies in which materials production and equipment are the main emissions sources for life cycle assessment on highway pavement [7, 14]. But the findings do not accord with the conclusions of those studies that involved the traffic delay into system boundary. For example, [12, 15] claimed that the traffic delay CO₂ emissions are the first top CO₂ emission sources during pavement maintenance.

However, in this study, there is not a significant gap among CO₂ emissions contribution of three sources to the total CO₂ emissions during the service life of the pavement. In particular, there only is a 4.7% difference between CO₂ emissions from work zone user CO₂ emissions and materials production which were considered as the largest contributor to pavement CO₂ emissions sources in most previous studies. This emphasized the importance of the work zone user CO₂ emissions in the life cycle assessment on the

TABLE 1: Speed reduced CO₂ emissions rate.

Vehicle operation status	Vehicle type	CO ₂ emissions rate (g/km)		
		65 km/h	40 km/h	10 km/h
General CO ₂ emissions	Car	204.07	218.82	578.97
	Passenger bus/truck	306.38	396.63	827.43
Reduced speed status (65-40)	Car		14.75	
	Passenger bus/truck		90.25	
Reduced speed in queue status (65-10)	Car		374.9	
	Passenger bus/truck		521.05	

pavement maintenance. To understand the inconsistent findings, one cause may be accounted for by the discrepantly traffic volume, maintenance work amount. Another reason may be that, different from the previous study that focused on one time or one type of maintenance, this study considered the total work zone user CO₂ emissions from all maintenance events during the whole pavement life.

3.1.2. Distribution of CO₂ Emissions Sources in Types of Maintenance Work Activities. To further understand the share of CO₂ emissions source in each type of highway pavement maintenance, Figure 4 illustrates that rehabilitation contributes to most of the total CO₂ emissions associated with the construction machinery/equipment and transportation vehicle. This maintenance type is also the top contributor of material production related CO₂ emissions and the second contributor of work zone user CO₂ emissions. As for the preventive maintenance, it dominantly makes up for work zone user CO₂ emissions from disrupted vehicles travelling through the work zone during the whole highway service life. Meanwhile, for corrective maintenance, majority of its CO₂ emissions are associated with the maintenance construction work activities including the construction machinery/equipment and transportation vehicle and are less related to the traffic delay. This may be the result of all the truck being prohibited to travel to this route when the corrective maintenance exists; there is less traffic travelling through the work zone and it is under a better operation condition with less queue and thus less traffic delay-related CO₂ emissions. In sum, for the case freeway in this study, work zone management may be of help for preventive and rehabilitation maintenance to reduce the CO₂ emissions during the whole service life.

3.1.3. Distribution of Work Zone User CO₂ Emissions. A further analysis on the contributor of work zone user CO₂ emissions in Table 3 displays that reduced speed delay travelling the work zone accounts for the largest CO₂ emissions. This finding may explain that it is partially reasonable that previous study principally considered the additional traffic delay fuel usage CO₂ emissions directly related to speed limitation at the work zone, as it at least covers 38.84% of total work zone traffic delay-related CO₂ emissions for the whole life view. However, it also means that about 61.16% of CO₂ emissions were neglected without considering the speed change and queue near work zone. The underestimate of traffic delay CO₂ emissions may mislead the

decision-making on maintenance scheme selection, for example, the balance of the user CO₂ emissions and user costs.

In detail, among the components of the work zone user CO₂ emissions related to the speed change and queue near work zone, the reduced speed in queue status ranks at the top of CO₂ emissions sources. In terms of speed change status and queue speed change status, their sum of additional traffic delay fuel usage CO₂ emissions is up to 35.28% of the total work zone user CO₂ emissions. This means that considering the microvehicle operating situations of speed change needs to be emphasized for grasping the overall CO₂ emissions caused by work zone traffic delay.

3.2. Discussion. In this section, several key parameters in work zone user CO₂ emissions calculation are systematically analyzed as these parameters are highly related to the results of work zone user CO₂ emissions, thus influencing the work zone management strategies decision. The type of preventive maintenance is selected due to its dominant contribution to total work zone user CO₂ emissions during the life cycle of highway pavement. Detailedly, the event that happened in 2018 is checked as the base case in this study. The parameters are varied within the allowed value in work zone norms or standards and resealable value corresponds to reality. These parameters which are mainly considered in this study are work zone length, work zone limited speed, work zone duration, work zone timing, and vehicle type limitation, and their base value and discussed value in the case preventive maintenance are summarized in Table 4.

3.2.1. The Impact of Work Zone Length on Work Zone User CO₂ Emissions. Figure 5(a) displays the total work zone user CO₂ emissions and change rate compared to the base case for different work zone length. The gradual increasing bar with the increased work zone length represents that the higher the work zone length is, the greater the total work zone user CO₂ emissions are. It is worth mentioning that the computation method proposed in the present study does not take the impact of work zone length change on queue into consideration. Thus, the change of work zone length only positively influences the change of the CO₂ emissions of reduced speed delay CO₂ emissions and has no effect on the other three CO₂ emissions components.

The line in Figure 5(a) indicates that, compared to base case in which initial work zone length is 5 km, there is a linear relationship between the change of work zone length and the change of total work zone user CO₂ emissions, and the average

TABLE 2: Speed change CO₂ emissions rate.

Vehicle operation status	Vehicle type	Average change speed (km/h)	Acceleration (m/s ²) (<i>a</i>)	Deceleration (m/s ²) (<i>d</i>)	CO ₂ emissions rate (g/s) in average change speed
					<i>a</i> <i>d</i>
Speed change status (65-40-65)	Car	52.5	3.283	-3.283	10
	Passenger bus/truck	52.5	3.283	-3.283	375
Queue speed change status (65-0-65)	Car	32.5	3.283	-3.283	7
	Passenger bus/truck	32.5	3.283	-3.283	325

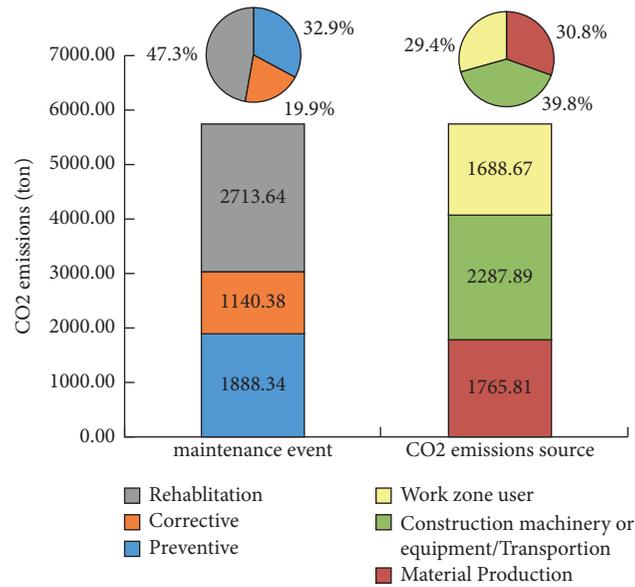


FIGURE 3: CO₂ emissions distribution of maintenance event and sources during the life cycle of highway pavement.

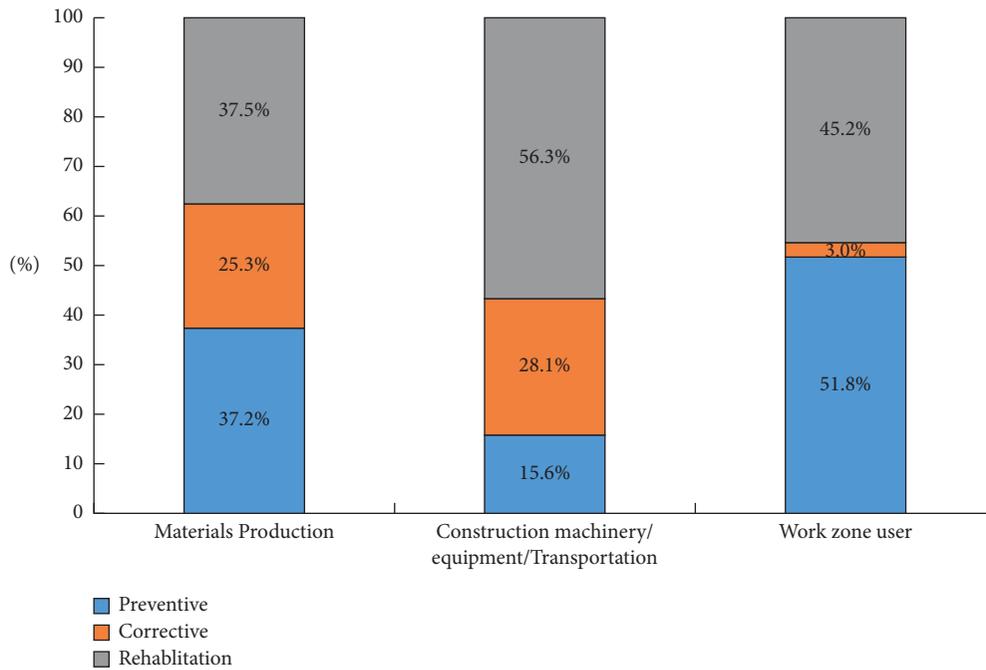


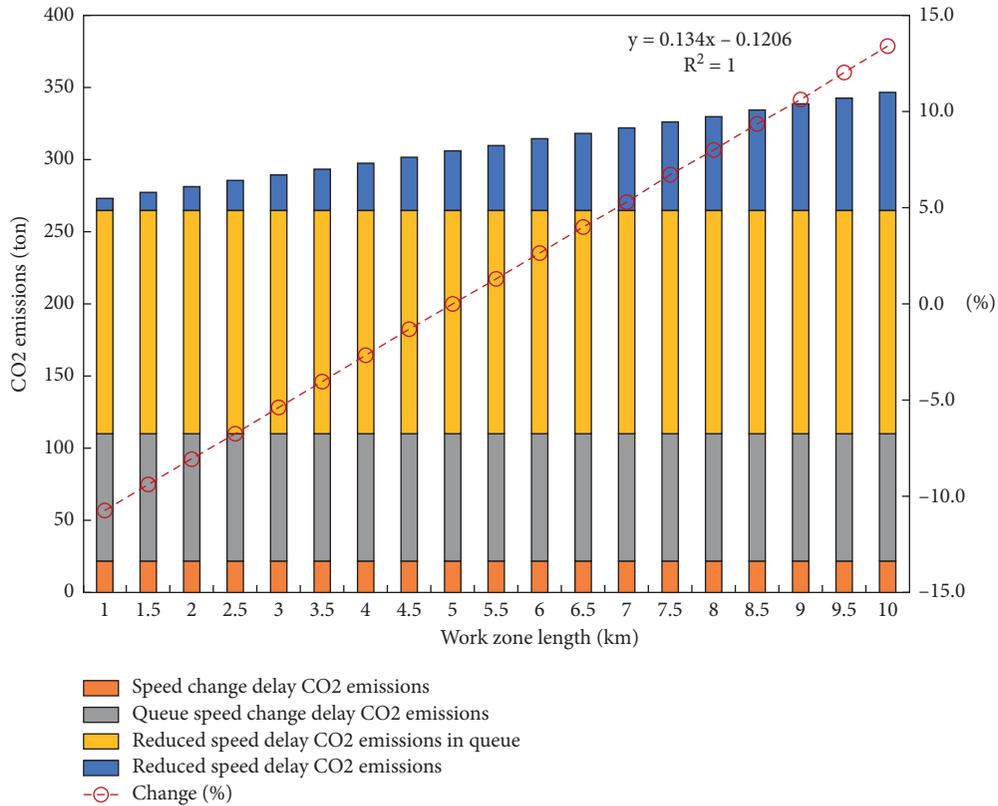
FIGURE 4: Distribution of CO₂ emissions sources in different types of maintenance event.

TABLE 3: Work zone user CO₂ emissions components of maintenance event in life cycle of case freeway pavement (from 2007 to 2022).

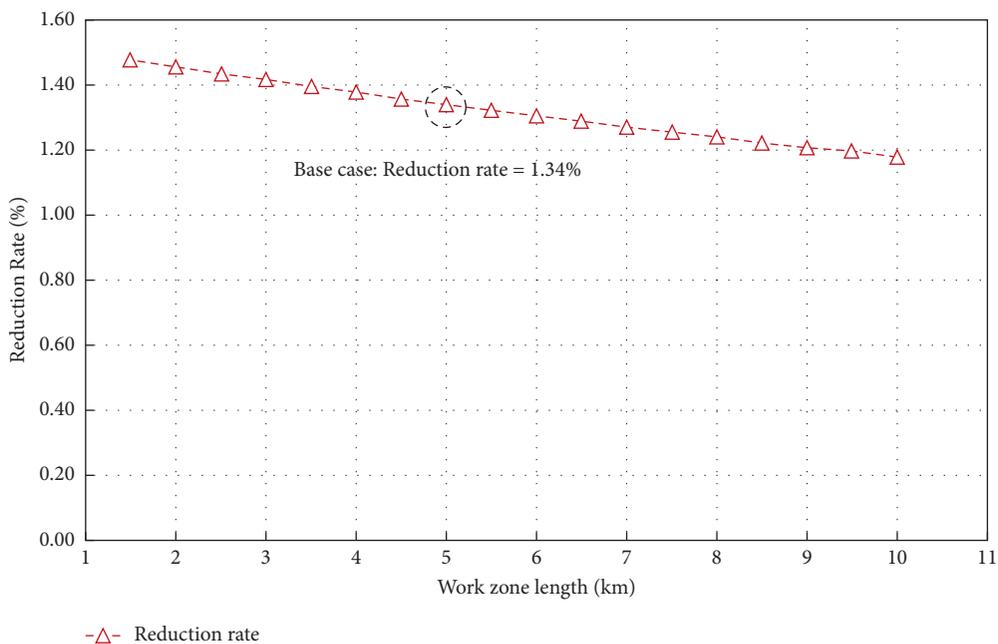
Work zone user CO ₂ emissions components	CO ₂ emissions (tons)	Percentage (%)
Speed change delay CO ₂ emissions	305.44	18.09
Reduced speed delay CO ₂ emissions	655.96	38.84
Queue speed change delay CO ₂ emissions	290.31	17.19
Reduced speed delay CO ₂ emissions in queue	436.96	25.88
Total	1688.67	100.00

TABLE 4: Base value and discussed value of key parameters in work zone user CO₂ emissions calculation (2018).

Key parameters	Work zone length (km)	Work zone duration (days)	Work timing	Work zone limited speed (km/h)	Vehicle type limitation
Base value	5	18	Monday to Sunday	40	All vehicles
Discussed value	1 to 10	7 to 30	Off-peak days with work zone duration of 18 days (Monday to Thursday, Sunday)	30, 35, 45, 50	No HDV; no HDV & LDV



(a)



(b)

FIGURE 5: (a) Total work zone user CO₂ emissions and change rate compared to base case for different work zone length; (b) reduction rate of total work zone user CO₂ emissions per 500-meter reduction for different initial work zone length.

reduction rate of total work zone user CO₂ emissions per 500-meter reduction is 1.34%. A further study on reduction rate of total work zone user CO₂ emissions per 500-meter reduction for different initial work zone length (shown as Figure 5(b)) reveals that, with the initial work zone length increase, the average reduction rate of total work zone user CO₂ emissions per 500-meter reduction decreases gradually and then decreases slowly when reaching the 1.2% level. This means that when the work zone length is relatively shorter, a small change of work zone length can produce considerable reduction of the total work zone user CO₂ emissions. However, when the work zone length is relatively longer, a significant change of work zone length is needed.

3.2.2. The Impact of Work Zone Duration on Work Zone User CO₂ Emissions. The impact of work zone duration on work zone user CO₂ emissions results is presented in Figures 6(a) and 6(b). Obviously, as shown in Figure 6(a), the longer the work zone duration is, the greater the total work zone user CO₂ emissions is. Compared to base case in which initial work zone duration is 18 days, there is a linear relationship between the change of work zone duration and the change of total work zone user CO₂ emissions, and the average reduction rate of total work zone user CO₂ emissions per day is 5.56%. In addition, the impact of work zone duration on each work zone user CO₂ emissions component is consistent with the total work zone user CO₂ emissions.

A detailed research on reduction rate of total work zone user CO₂ emissions per day saving for different initial work zone duration reveals that, with the initial work zone duration increase, the average reduction rate of total work zone user CO₂ emissions per day reduction decreases gradually (see Figure 6(b)). For example, as mentioned above, when the initial work zone duration is 18 days for base case, the total work zone user CO₂ emissions will be reduced by 5.56% with per day reduction, and when initial work zone duration is 30 days, the emissions will be reduced by 3.33% for each day. However, when initial work zone duration is 8 days, the carbon emissions will be reduced obviously by 12.5% for each day with per day reduction. This means that when the work zone duration is relatively shorter, a small change of total work zone days can help reduce considerable total work zone user CO₂ emissions. However, when the total work zone duration is relatively longer, a significant change of work zone duration is needed.

3.2.3. The Impact of Work Timing on Work Zone User CO₂ Emissions. From Figure 7(a), which provides the analysis results of the impact of work timing on work zone user CO₂ emissions, there is a 22% reduction of the total work zone user CO₂ emissions resulting from off-peak days work timing change from Monday to Sunday into Monday to Thursday, and Sunday.

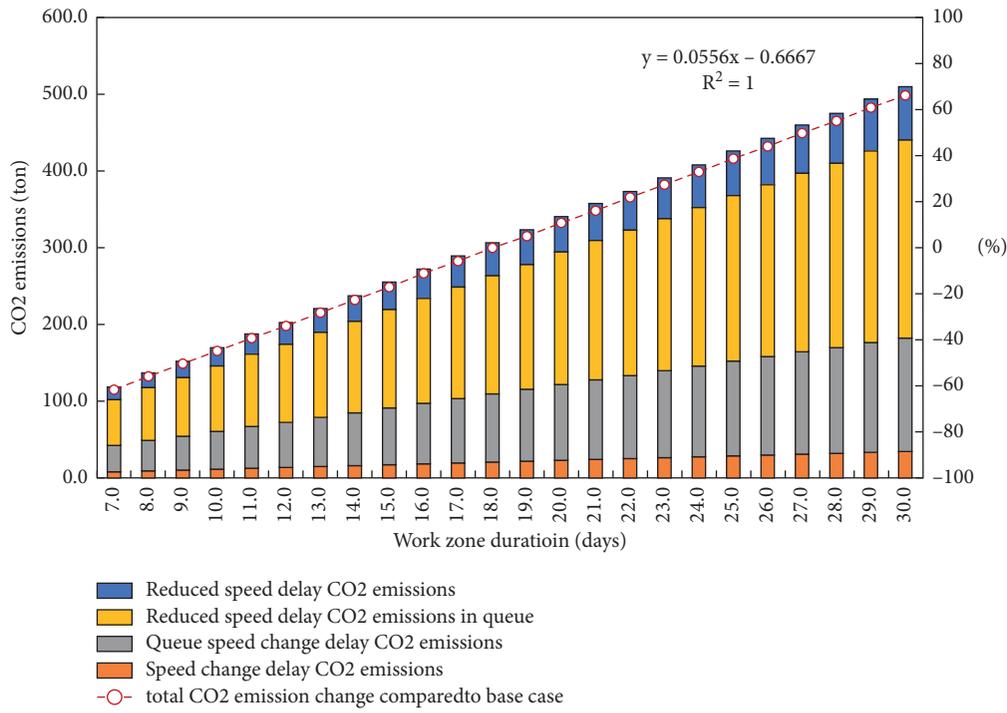
Specific to each work zone user CO₂ emissions component, presented in Figure 7(b), the work zone timing change results in CO₂ emissions reduction by 30%, 27%, 26%, and 17% for speed change delay, reduced speed delay, queue speed change delay, and reduced speed delay in queue, respectively.

The findings indicate the following: (1) off-peak days work timing has a better performance on the reduction of user CO₂ emissions related to speed change delay and reduced speed delay; (2) the absolute reduction value of queue speed change delay and reduced speed delay in queue is still critical to the saving of the total work zone user CO₂ emissions due to their predominant contribution to the total work zone user CO₂ emissions; (3) off-peak days work timing aiming for avoiding higher traffic volume does not help reduce the CO₂ emissions from reduced speed delay in queue. A plausible explanation may be that the capacity of work zone opened lane even could not match the level of the traffic volume during off-peak days. Further analysis is suggested to explore other alternative work zone management ways, especially those with less traffic volume or higher highway capacity, to reduce the top CO₂ emissions of work zone user CO₂ emissions.

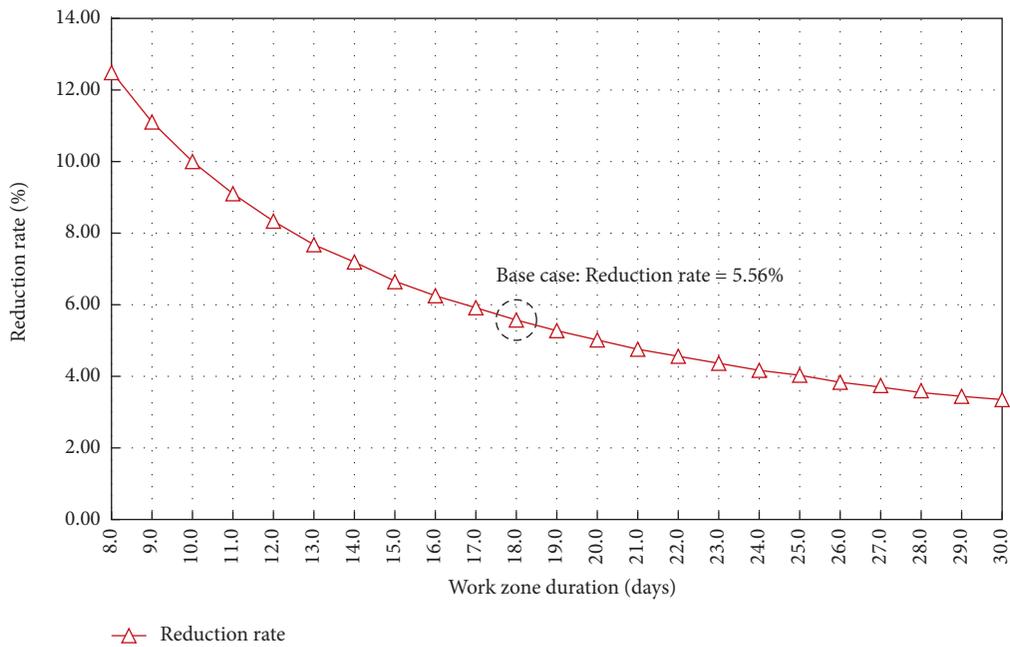
3.2.4. The Impact of Vehicle Type Limitation on Work Zone User CO₂ Emissions. Figure 8 illustrates the results of the impact of vehicle type limitation on work zone user CO₂ emissions. As shown in Figure 8(a), there are rapid 86% and 85% reductions of the total work zone user CO₂ emissions resulting from no HDV and no HDV & LDV vehicle limitation, respectively. The less difference in total work zone user CO₂ emissions reduction between no HDV and no HDV & LDV vehicle limitation may be explained by a higher proportion of HDV in the traffic stream mix of 36% of light-duty trucks and 64% of heavy-duty trucks for trucks vehicles as mentioned in Section 2 in this paper.

For each work zone user CO₂ emissions component, vehicle type limitation results in CO₂ emissions reduction in no HDV and no HDV & LDV scenario by 89%, 84% to 86%, 76% to 81%, and 76% to 77% for reduced speed delay in queue, queue speed change delay, speed change delay, and reduced speed delay, respectively (seen in Figure 8(b)). The finding reveals that vehicle type limitation has a better performance on the reduction of all user CO₂ emissions components, especially for the top CO₂ emissions from reduced speed delay in queue and queue speed change delay.

3.2.5. The Impact of Work Zone Limited Speed on Work Zone User CO₂ Emissions. The results of work zone user CO₂ emissions caused by different work zone limited speed shown in Figure 9(a) display that the higher the speed is, the less the emissions are. In detail, an increase of 5 km/h can reduce 40% to 47% of total work zone user CO₂ emissions from 30 km/h to 50 km/h. In addition, as the speed increases, the contribution of reduced speed delay CO₂ emissions in queue to total work zone user CO₂ emissions decreases rapidly, from 78% of 30 km/h to 18% of 50 km/h. Conversely, the contribution of the other three work zone user CO₂ emissions components to total work zone user CO₂ emissions grows up with the increase of work zone limited speed at different levels, from 1% to 32%, from 9% to 15%, and from 13% to 34% for speed change delay CO₂ emissions, reduced speed delay CO₂ emissions, and queue speed change delay CO₂ emissions, respectively. These findings reveal the following: (1) The growth of the limited speed can obviously



(a)



(b)

FIGURE 6: (a) Total work zone user CO₂ emissions and change rate compared to base case for different work zone duration; (b) reduction rate of total work zone user CO₂ emissions per day saving for different initial work zone duration.

help in reducing the CO₂ emissions of the top contributor of the reduced speed delay in queue. As illustrated in Figure 9(b), this indicates that changing the speed to improve the road capacity is an important way to reduce carbon emissions in work zone. (2) The key to reduce the emissions in different work zones with different limited speed is different. For work zone with lower work zone

limited speed (e.g., 30 km/h), it may be more useful to take measures to release the delay of vehicles travelling the queue. However, as for work zone with higher work zone limited speed (e.g., 50 km/h), it may be more helpful to take measures to improve the operation condition with less vehicle speed change no matter when travelling through the work zone or when travelling through the queue.

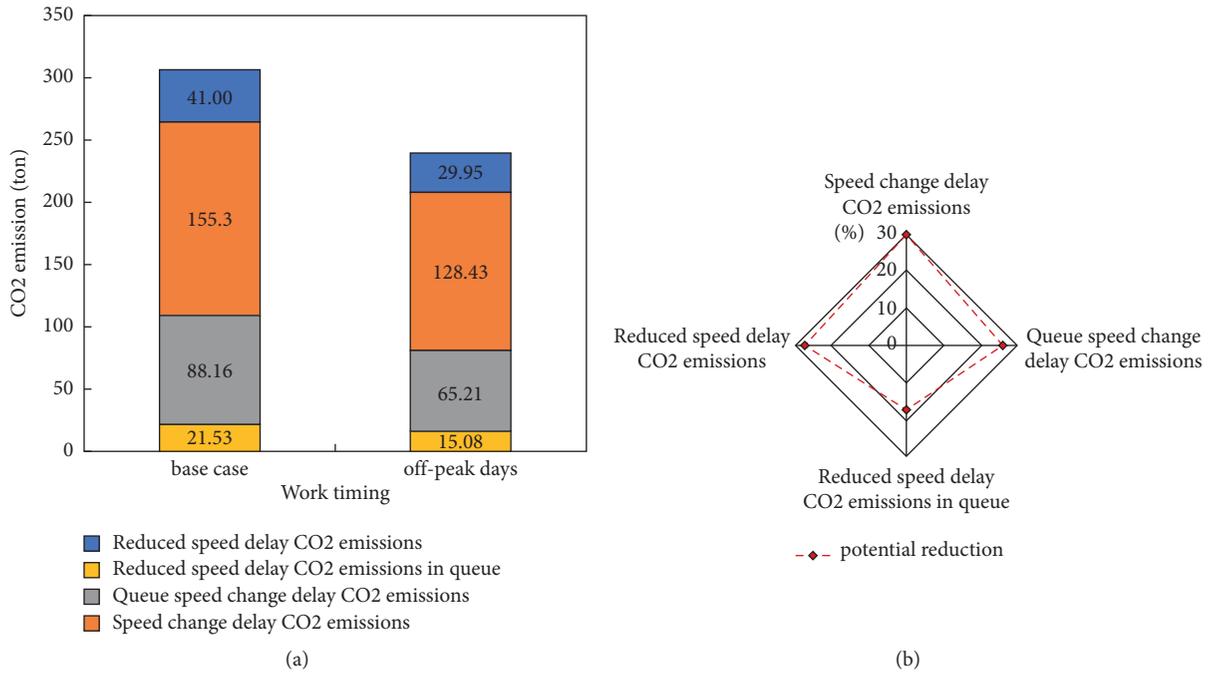


FIGURE 7: (a) Total work zone user CO₂ emissions before and after work zone timing change; (b) potential reduction regarding different work zone user CO₂ emissions component under work zone timing change.

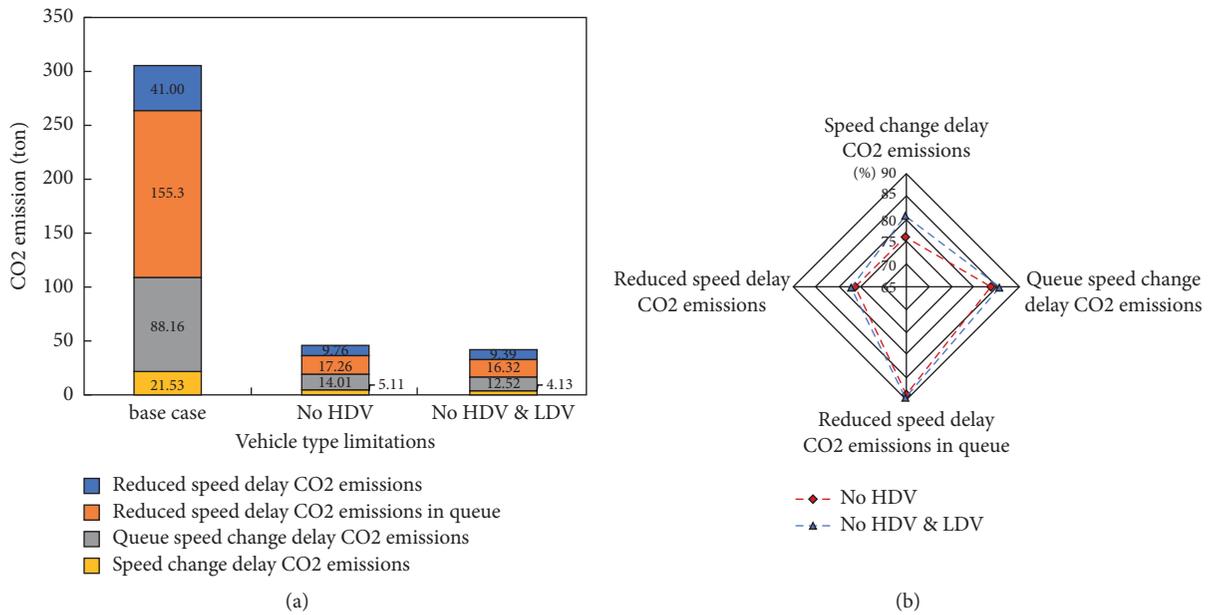
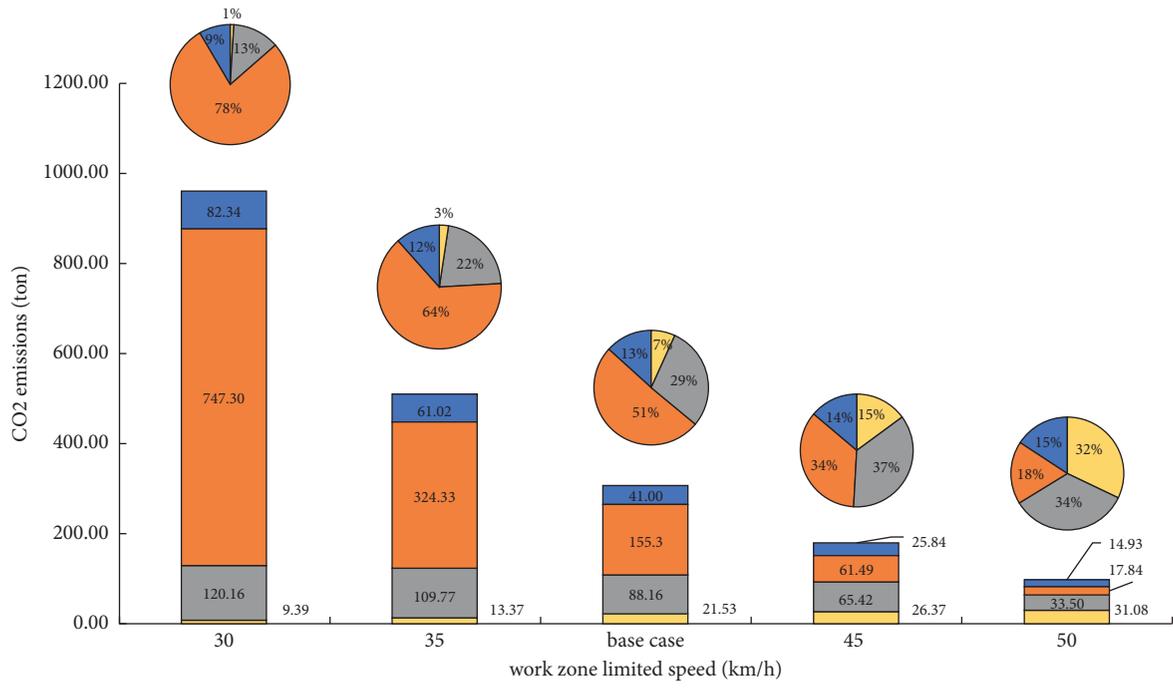
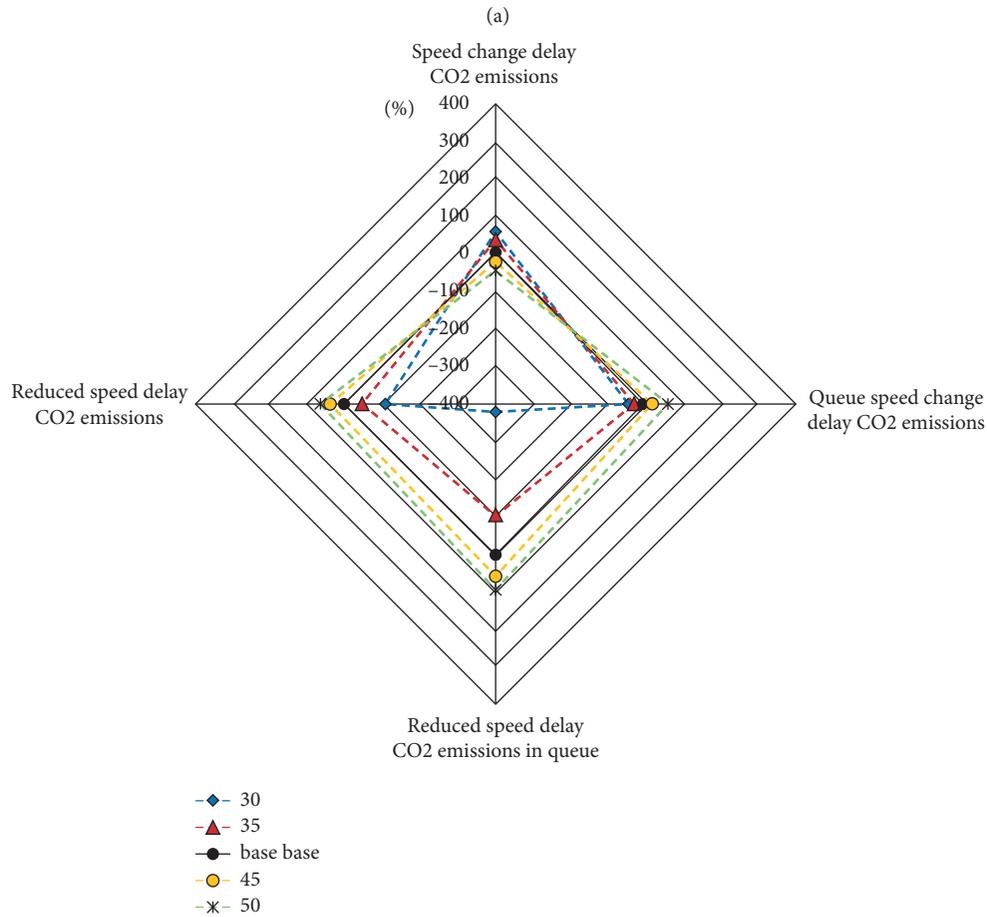


FIGURE 8: (a) Total work zone user CO₂ emissions; (b) potential reduction regarding different work zone user CO₂ emissions component under vehicle type limitation.



- Reduced speed delay CO₂ emissions
- Reduced speed delay CO₂ emissions in queue
- Queue speed change delay CO₂ emissions
- Speed change delay CO₂ emissions



(b)

FIGURE 9: (a) Total work zone user CO₂ emissions; (b) potential reduction regarding different work zone user CO₂ emissions component under work zone limited speed.

4. Conclusions

This study explored the importance of work zone management strategy on carbon dioxide saving during life cycle assessments on highway pavement maintenance. A highway capacity-based approach referred from life-cycle user cost analysis has been developed to estimate the work zone user CO₂ emissions. Then, the method was verified through a real freeway flexible pavement in Shaanxi, China, with 15-year life span and three types of maintenance schemes. In addition, the influence of work zone management strategies on the total work zone user CO₂ emissions has been explored by analyzing several key parameters in work zone user CO₂ emissions calculation including work zone length, work zone limited speed, work zone duration, work zone timing, and vehicle type limitation. This study concludes that about 61.16% of CO₂ emissions were neglected without considering the speed change and queue near work zone, indicating that the highway capacity-based calculation model proposed in this study could be used to comprehensively catch the additional vehicle CO₂ emissions interrupted by the lane closure or traffic control and management where work zone exists. Among the work zone management alternative strategies, those strategies with less traffic volume or higher highway capacity are more effective to reduce the CO₂ emissions of work zone user CO₂ emissions. In practical terms in this study, proper vehicle type limitation or the limited work zone speed is more effective in reducing the work zone CO₂ emissions than work zone management strategies like change work zone length or work zone timing. Even though, in further research, the research on the influence of mixed work zone management strategies on the work zone CO₂ emissions is suggested for the better maintenance work zone management decision-making, in addition, it is better to consider the mechanistic-empirical pavement design method, for example, the pavement deterioration model, to determine the activity profiles. The sensitivity analysis of the large input parameters still needs to be conducted in future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Yuanyuan Liu contributed to funding acquisition, conceptualization, investigation, methodology, and roles/writing—original draft. Xiaodong Zhu contributed to data support and revision suggestion. Xiaoxia Wang contributed to funding acquisition and writing—review and editing. Yuanqing Wang contributed to formal analysis, funding acquisition, and supervision. Qian Yu contributed to writing—review and editing. Shuang Han contributed to funding acquisition and revision suggestion.

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