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Integrated Life Cycle Analysis of Cost and CO_2 Emissions from Vehicles and Construction Work Activities in Highway Pavement Service Life

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Abstract: In this study, we aimed to provide a practical method to estimate the economic and environmental impact of vehicle and work activities throughout the entire service life of a pavement area to support pavement management strategies and decisions. To achieve this, we integrated two key life cycle analysis methods, life cycle assessment (LCA)) and life cycle cost analysis (LCCA). The integrated model not only considers CO_2 emissions associated with the four main modules—the materials module, the work activities module, the work zone module and the usage module—mentioned in LCA, it also considers agency costs and user costs related to highway usage, work activities, work zone traffic delays and detours in the LCCA process. We used detailed and integrated methods to compute CO_2 emissions and costs based on the four modules and two components of agency and users mentioned above. A case study based on a real freeway project in China was used to verify the applicability of the integrated model. The results of the application of the integrated LCA-LCCA model indicate that maintaining the typical activity profile could be beneficial in terms of both CO_2 emissions and cost, with savings of 36.8 ton/lane/km of CO_2 emissions and 10,530 USD/lane/km (in 2007 dollars) representing the total benefits during the pavement's service life. This means that timely maintenance could help to achieve savings in terms of financial costs and CO_2 emissions simultaneously.

Keywords: life cycle assessment; life cycle cost analysis; highway pavement; CO_2 emissions; China

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1. Introduction

As an important consumer of high-carbon-density building materials and fossil-fuel-driven construction machinery, the highway construction sector has attracted the attention of transportation agencies in all nations in the pursuit of cost-effective and environmental-friendly management strategies [1,2]. Taking China as an example, an estimated 2.60 trillion-yuan capital investment was made in 2021 to construct new highway infrastructure and maintain existing highways, accounting for 71% of the transportation sector [3]. According to the Intergovernmental Panel on Climate Change (IPCC), the carbon emissions from highways contribute to about 69% of total emissions from the transport sector [4]. Some practical studies have claimed that the emissions from the extraction and production road materials, to-site transportation, on-site construction machinery and other phases during the life cycle of a road, including road construction, maintenance and recycling of road materials make up 50% of the total CO_2 emissions from the transport sector [5]. In the future, the total mileage of highways will continue to increase and the number of maintenance projects will increase further. Therefore, the rapid increase in carbon emissions from highway construction will obviously conflict with the goal of achieving a carbon peak and even carbon neutrality in the transportation sector.

On the other hand, a solution which is found to be environmentally advantageous in a pavement assessment might not be preferable over other solutions in terms of economic competitiveness [6]. Resolving the contradiction between increasing road performance requirements and insufficient maintenance funds has always been a problem for highway management. The addition of carbon emission targets has made it more difficult to make decisions in relation to highway maintenance schemes. Thus, the relationship between environmental issues and economic problems in pavement management needs to be considered.

Life cycle cost analysis (LCCA) has been recognized as a useful methodology to estimate long-term alternative investment options and to select pavement asset management strategies. Since the Intermodal Surface Transportation Equity Act of 1991, the Federal Highway Administration (FHWA) has pursued a policy of promoting LCCA, publishing the detailed *Life-Cycle Cost Analysis Primer* in 2002 and developing a pavement design LCCA software tool named RealCost, which deepened the understanding of LCCA among transportation officials and finally enabled them to make economically sound decisions [7,8]. With the gradual and wide application of LCCA and the improvement of its methods, various categories of costs associated with highway agencies and road users in every phase of the pavement life cycle have attracted the attention of scholars [6]. Pasha et al. [9] estimated work zone road user costs based on the rehabilitation strategies for different pavement types. Moreover, pavement deflection [10], skid resistance [11], the presence of platoon trucks on pavements [12] and other factors have been integrated into LCCA analysis for the selection of pavement surface treatments and the management of work zone activities.

As for environmental impact assessments, since the first comprehensive life cycle assessment (LCA) study on a road was conducted in 2001, a consensus on assessing the potential environmental burdens and impacts of alternative road options using LCA has formed. It was found that carbon emissions from highway maintenance and construction mainly come from the production of materials, conveyance vehicle transportation and construction machinery (including off-site mixing station machinery) [13–16]. Regarding pavement types, asphalt pavement has less carbon emissions than concrete pavement [17,18]. Apart from the initial road construction and maintenance work activities, recent studies have found that the carbon emissions caused by vehicle delays caused by maintenance construction activities are higher than the total carbon emissions of maintenance and construction [19]. Thus, estimations of the emissions of disrupted traffic caused by road maintenance works based on traffic micro-simulation have been added into road LCA analysis [20,21]. It was reported that lane closures, construction and maintenance time and frequency have significant impacts on the carbon emissions of maintenance activities due to the temporal changes in traffic [22,23].

To improve both economic and environmental sustainability, the development of methods and tools to assess environmental performance is necessary in order to support appropriate choices in investment activities [24]. Many studies have focused on the combination of LCA and LCCA in the optimization and analysis of maintenance schemes. Lidicker et al. [25] analyzed both the costs and GHG emissions of agencies and users in relation to single-facility optimal pavement resurfacing problems using LCA and LCCA. Yu et al. [24] applied the environmental damage cost (EDC) concept to a combined LCA–LCCA model to optimize pavement maintenance plans. With the aim of covering the pavement's entire life cycle, Santos et al. [26] developed a comprehensive and integrated pavement life cycle cost/life cycle assessment model considering agency costs, user costs and GHG emissions. Choi [27] considered environmental costs with the aim of reducing life-cycle costs and carbon dioxide emissions in road construction using a hybrid of the LCCA and life-cycle assessment methods. Reger et al. [28] explored the trade-off between costs (including user and agency costs) and greenhouse gas emissions in the pavement replacement process and found that there is a possible optimal decision-making range that reduces total emissions but does not increase total costs. France-Mensah et al. [29] proposed a mixed-integer optimization algorithm with multiple objectives such as determining the best pavement condition level, the lowest costs for road users, and the least greenhouse gas emissions, and claimed that the optimized LCA and LCCA methods could reduce emissions by 12.3% and costs by 10.2%.

An understanding of the relationship between monetary costs and greenhouse gas emissions (GHGs) has been gradually developed in recent studies, but the potential to implement strategies which can account for both concerns simultaneously remains insufficient. In addition, the previous studies have mainly concentrated on partial segments of a single type of pavement-preservative events or on the main types of future pavement-preservative events after new construction activities. Initial pavement construction or past maintenance events as part of the entire life-cycle activity profile have rarely been considered in previous studies, even though this represents a larger resource-consuming and more emissions-intensive phase [30]. Moreover, the methodology for the computation of components of the LCA method is separate from that of the corresponding components of LCCA, which can only provide the overall results regarding emissions and costs, rather providing information on contributors at a more microscopic scale.

With the aim of providing a practical method to estimate the economic and environmental impact of vehicle and work activities throughout the entire service life of an area of pavement, including rehabilitation and reconstruction, maintenance and preventative measures for pavement management strategies and decisions, in this study we attempted to integrate two key life cycle analysis methods, LCA and LCCA, to assess the CO_2 emissions of the highway transport sector and the costs for agencies and users. The specific aims of the integrated LCA-LCCA were: (1) To develop a hybrid LCA-LCCA framework considering CO_2 emissions associated with four main modules of LCA (the materials module, the work activities module, the work zone module and the usage module) and simultaneously considering agency costs and user costs related to usage, work activities, work zone traffic delays and detours in the LCCA. (2) To provide practical and detailed integrated methods for computing CO_2 emissions and costs based on the four abovementioned modules and the two components of agencies and users. (3) To verify the applicability of the integrated model based on a real freeway project.

2. Materials and Methodology

2.1. Methodology Framework

According to the LCA concept, guided by International Standardization Organization (ISO) 14040 2006, information on the related material and energy flows in each stage of each subproject during a road's service life is needed in order to estimate the CO_2 emissions of a highway. Generally, the production of materials, to-site transportation, off-site works and on-site construction are the system boundaries for highway LCA analysis. The life cycle of a road includes its initial construction, maintenance and rehabilitation. Reconstruction conducted to extend the life of the pavement and end-of-life components were not considered in this study.

As highway LCCA analysis is reported by the FHWA, agency cost and user cost were considered in this study. Agency cost refers to costs related to initial construction, maintenance and rehabilitation incurred directly by the agency over the lifetime of the project. User costs are an aggregation of three separate cost components: vehicle operating costs (VOC), travel time costs (TTC) and vehicle emission costs (VEC). Due to the limitations of the available data, crash costs were not considered in this study. In the LCCA of pavement, there are user costs associated with both normal operations and work zone operations.

With the aim of achieving greater consistency in the computation model structure and the input data from LCA and LCCA, in this study we classified road activities into four components—the materials module, the work activities module, the work zone module and the usage module—in the LCA. Furthermore, the calculation results of these four modules were divided into two broad categories in terms of agency CO_2 emissions and user CO_2 emissions. In the LCA model, the work activities module included the to-site transportation, off-site working and on-site construction. The CO_2 emissions of these three sources are related to both engine fuel combustion and the fuel production used by transportation vehicles or construction machinery. The usage module refers to the operation of vehicles after the highway opens for transportation. The work zone module mainly refers to the delayed traffic due to maintenance events. For the computation of user CO_2 emissions, we relied on the classification of user costs in the LCCA model. The inventory of materials module in the LCCA and the work activities module in the LCA were used as the inputs for agency cost calculations. For user cost calculations, the emissions from the work zone module and the usage module provided the inputs for user cost calculations.

Figure 1 shows the overall methodological framework and Figure 2 displays the details of the model proposed in this research.

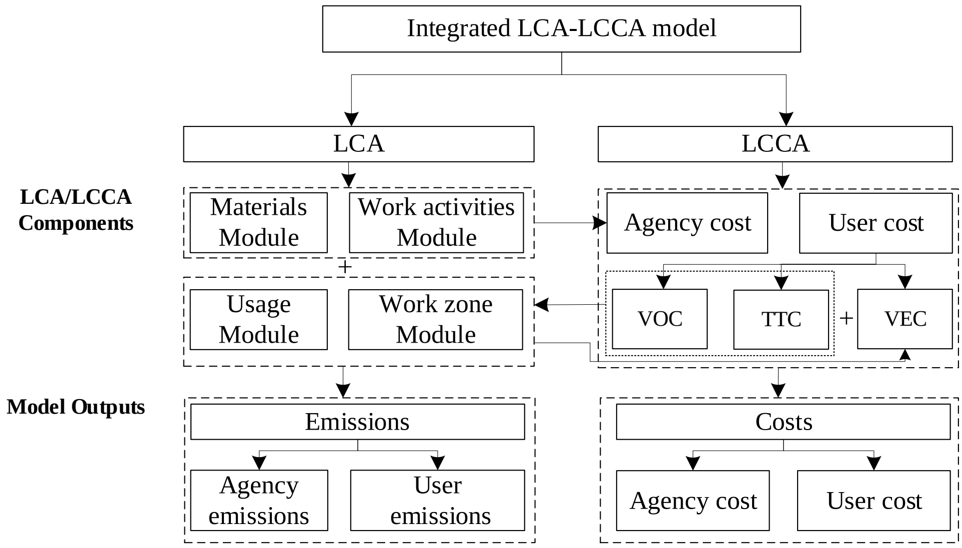


Figure 1. The overall integrated LCA-LCCA framework.

2.2. Agency CO_2 Emissions and Agency Cost

2.2.1. Agency CO_2 Emissions

Agency CO_2 emissions from the materials module refers to the "cradle-to-gate" embodied emissions associated with the production of materials. The CO_2 emissions of the materials module are an aggregation of emissions from different types of materials consumed in preventive maintenance, corrective maintenance and rehabilitation activities that occurred during the analysis period. For each type of material, its related embodied emissions was obtained by multiplying its total quantity in physical units and the "cradle-to-gate" emission factors per physical unit.

CO_2 emissions from the work activities module are mainly associated with fuel or energy consumption from construction equipment and materials/waste transport vehicles. In this study, the "Well to Wheel" fuel cycle method was applied to estimate the CO_2 emissions of the work activities module, including the "Well to Pump" cycle from the exploitation and refining of raw materials, fuel production and allocation to fuel stations and the "Pump to Wheel" cycle of fuel combustion during on-site equipment or transport vehicle operation. Similarly to the materials module, CO_2 emissions of the work activities module are the sum of emissions from different types of equipment and vehicles used in preventive maintenance, corrective maintenance and rehabilitation activities that occurred during the analysis period. For each type of equipment and vehicles, the related CO_2 emissions were obtained by multiplying the total work time in physical units and the "Well to Wheel" emission factor per physical unit.

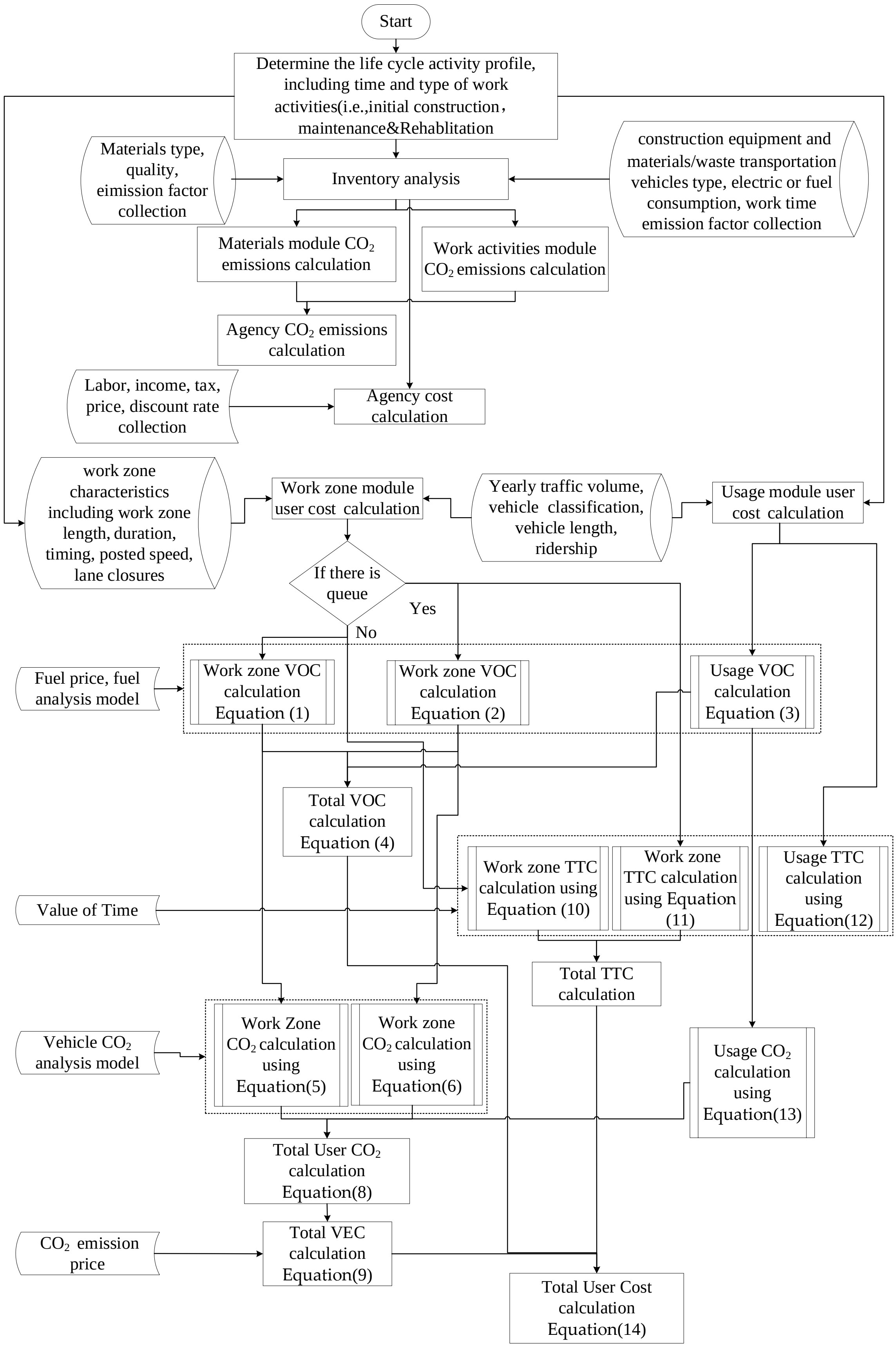


Figure 2. Detail methodology of the framework proposed in this research.

2.2.2. Agency Cost

Instead of using historical and aggregated bid prices or contract prices directly, agency costs in this study were computed by means of a process-based accounting method, guided by LCA. Multiple items of consumption resources were identified in terms of raw materials, energy or fuel, labor, equipment, transport vehicles, etc. This method shows a reasonable consistency with the calculations of agency CO_2 emissions presented in previous studies. Agency cost is an aggregation of the total cost of items. For each type of item, its related cost was estimated by multiplying its total quantity in physical units and the corresponding price per physical unit.

The data on the types of material, equipment and transportation vehicles; the amount of materials and labor; and the total work time were obtained from highway project design files, the *China Approximate Estimate Norm of Highway Project 2007* and the *China Equipment and Transport Vehicles Cost Norm*. The "cradle-to-gate" emission factors of various materials and "Well to Wheel" emission factors of different energies and fuels were referred to in the peer-reviewed literature and published research reports [15]. The prices of various materials, energies and fuels for different years in the analysis period were obtained by means of an interpolation method based on the available data on highway project budget files and official reports. The details of these concepts and CO_2 emissions computation methods for the materials module and the work activities module can be found in previous publications [5,15]. The timing and type of preventive M&R activities were estimated based on past highway pavement activity profiles and the conclusions drawn from interviews with experienced pavement managers. The analysis period was 15 years for asphalt pavement in China. The discounted rate for agency costs was 5.5%, based on values recommended by China's Ministry of Housing and Urban-Rural Development.

2.2.3. User CO_2 Emissions and User Cost

As mentioned in Section 2.1, in the LCA model, the computation of users' CO_2 emissions relied on the classification of user cost in the LCCA model. Thus, the VOC user cost calculation method is described here first.

For the work zone module, user cost included the user cost caused by work activities and user costs incurred during normal operation. Based on the FHWA report entitled "*Work Zone Road User Costs: Concepts and Applications*", in this study we provided an improved and detailed framework to estimate the VOC and TTC associated with work-activities, such as speed changes, speed reductions through the work zone areas and detours due to partial or full lane closures. Limited by the length requirement, for the present study, we list only the main computation steps and improved inputs here. The calculation formula is provided in Table 1.

VOC depends on the time, the distance and the conditions of the road on which each vehicle travels, as well as the type of vehicle. The computation methods are expressed as Equations (1)–(4) in Table 1. The speed change time is closely related to the normal operation speed and the speed in the work zone or queue. The total vehicle kilometers traveled (VKT) of affected vehicles relies on the work zone length, the traffic volume and the work event's duration. This indicates that the traffic organization and work zone optimization should be considered in these models. Detour VOC rates are associated with the normal operation speed and the speed in the detour route. Specially, the speed change VOC rate of vehicle type i was calculated based on the speed change fuel consumption rate ($R^{c_i}_{f_j}$) of vehicle type i and the fuel price (p^j_{fuel}) of type j. $R^{c_i}_{f_j}$ is determined by the acceleration and deceleration patterns under various speeds; thus, a micro-vehicle-based model which provided a better way to estimate the vehicle emissions in vehicle speed change conditions was entered into the computation as a function of acceleration or deceleration, speed and fuel consumption. In this study, a micro-vehicle-based model, determined by a combination of field experiments and the comprehensive modal emissions model (CMEM) [31], was used. The fuel consumption for light-duty trucks (LDVs) and heavy-duty truck (HDVs) was collected based on second-by-second vehicle speed and acceleration or deceleration on rush hour and work zone time in this study.

Table 1. The calculation methods of user costs and user CO_2 emissions used in this study.

Items	Sub-Components	Formula	Equation Number
VOC	$VOC_{work\ zone}$	$VOC_{work\ zone} = \sum_{i=1}^{2} (R_{voc}^{C_i} \times t^{C_i} \times n^{C_i} + R_{voc}^{R_w^i} \times vkt^{R_w^i} + R_{voc}^{D_i} \times vkt^{D_i})$ no queue	(1)
		$VOC_{work\ zone} = \sum_{i=1}^{2} (R_{voc}^{C_i} \times t^{C_i} \times n^{C_i} + R_{voc}^{R_w^i} \times vkt^{R_w^i} + R_{voc}^{R_q^i} \times vkt^{R_q^i} + R_{voc}^{D_i} \times vkt^{D_i})$ queue	(2)
	VOC_{usage}	$VOC_{usage} = \sum_{i=1}^{2} (R_{voc}^{N_i} \times vkt^{N_i})$	(3)
	VOC_{user}	$VOC_{user} = VOC_{work\ zone} + VOC_{usa\_}$	(4)
User CO_2 emissions	$E_{work\ zone}$	$E_{work\ zone} = \sum_{i=1}^{2} (R_{co_2}^{C_i} \times t^{C_i} \times n^{C_i} + R_{co_2}^{R_w^i} \times vkt^{R_w^i} + R_{co_2}^{D_i} \times vkt^{D_i})$ no queue	(5)
		$E_{work\ zone} = \sum_{i=1}^{2} (R_{co_2}^{C_i} \times t^{C_i} \times n^{C_i} + R_{co_2}^{R_w^i} \times vkt^{R_w^i} + R_{co_2}^{R_q^i} \times vkt^{R_q^i} + R_{co_2}^{D_i} \times vkt^{D_i})$ queue	(6)
	E_{usage}	$E_{usage} = \sum_{i=1}^{2} (R_{co_2}^{N_i} \times vkt^{N_i})$	(7)
	E_{user}	$E_{user} = E_{work\ zone\_} + E_{usage}$	(8)
VEC	VEC_{user}	$VEC_{user} = E_{user} \times p_{co_2}$	(9)
TTC	$TTC_{work\ zone}$	$TTC_{work\ zone} = \sum_{i=1}^{4} (R_{ttc}^{C_i} \times n^{C_i} + R_{ttc}^{R_w^i} \times n^{R_w^i} + R_{ttc}^{D_i} \times n^{D_i})$ no queue	(10)
		$TTC_{work\ zone} = \sum_{i=1}^{4} (R_{ttc}^{C_i} \times n^{C_i} + R_{ttc}^{R_w^i} \times n^{R_w^i} + R_{ttc}^{R_q^i} \times n^{R_q^i} + R_{ttc}^{D_i} \times n^{D_i})$ queue	(11)
	TTC_{usage}	$TTC_{usage} = \sum_{i=1}^{4} (R_{ttc}^{N_i} \times n^{N_i})$	(12)
	TTC_{user}	$TTC_{user} = TTC_{work\ zone} + TTC_{usage}$	(13)
Total user cost	Null	$C_{user} = VOC_{user} + VEC_{user} + TTC_{user}$	(14)

Notes: $R_{voc}^{C_i}$ is the speed-change VOC rate of vehicle type i in USD/s; t^{C_i} is the speed change time per vehicle of vehicle type i in seconds; n^{C_i} is the number of affected vehicles of type i under speed change conditions; $R_{voc}^{R_w^i}$, $R_{voc}^{D_i}$ and $R_{voc}^{N_i}$ are speed-reduction VOC rates, detour VOC rates and normal-operation VOC rates of vehicle type i in USD/VKT, respectively; $vkt^{R_w^i}$, vkt^{D_i} and vkt^{N_i} are the total VKT of the number of affected vehicles of type i under speed reduction conditions, under detour conditions and under normal operation conditions, respectively; $R_{voc}^{R_q^i}$ is the speed-reduction VOC rate of vehicle type i in USD/VKT when driving through a queue in a certain time as compared to normal conditions; $vkt^{R_q^i}$ is the total VKT of the number of affected vehicles of type i under speed reduction conditions, driving through a queue. For similar key parameters related to user CO_2 emissions, VEC and TTC calculation formulas, the differences in subscript may be helpful for understanding the meaning of these key parameters. Full and detailed parameter descriptions can be found in the Supplementary Materials.

For $R_{voc}^{R_w^i}$, $R_{voc}^{D_i}$, $R_{voc}^{R_q^i}$ and $R_{voc}^{N_i}$, the fuel consumption rates of vehicle type i were obtained based on a meso-fleet-based model with advantages in the estimation of CO_2 emissions on an average level. This model represents a function of emission rates versus average speed, as emission rates are greatly dependent on speed. In this study, mesoscopic vehicle fuel consumption models for LDVs and HDVs using real-world vehicle operation and emission data were taken from the work of Song et al. [32].

In the work zone module and the usage module, CO_2 emissions are closely related to fuel consumption, which is calculated using Equations (5)–(8) in Table 1. Maintaining the consistency with VOC calculations, the speed-change-related CO_2 emissions rate and speed-reduction-related CO_2 emissions rate were obtained from [31] and [32], respectively.

As expressed in Equation (9) in Table 1, vehicle emissions costs (VEC) were obtained by multiplying the user emissions and CO_2 price units. The CO_2 price was selected as the social cost of carbon.

For TTC computation in Equations (5)–(8), the value of time (VOT) was a critical factor. The variations in time of year and trip purposes (for work or recreation) needed to be considered. In this study, VOT was a weighting function of the VOT of travelers for work and the VOT of travelers for recreation.

2.3. Data Sources

2.3.1. Brief of Case Study

A real case study was selected to examine the ability of the proposed integrated LCA-LCCA model to estimate impacts of pavement maintenance strategies on economic and environmental sustainability. The case project was a 20.55 km length of pavement, forming part of a freeway in the western area of China. The entire freeway is a four-lane double way, which is totally closed and interchanged. Limited by the terrain, geology and technical standards of freeway maintenance, the design speed is limited to 80 km/h and in some sections the speed does not even reach 60 km/h. The analysis period of the asphalt concrete pavement was 15 years.

2.3.2. Data Collection

Life-Cycle Activity Profiles

To determine the typical activity profile, the collection of official highway pavement maintenance reports and maintenance and rehabilitation archives of Chinese freeways, stored by the related highway administration authorities, was conducted. To account for missing information, interviews with an experienced pavement manager were conducted. In a typical activity profile, preventive maintenance, corrective maintenance and rehabilitation were frequently conducted every two years, four years and eight years, respectively. Preventive maintenance refers to thin asphalt surfacing and ultra-thin overlays with a modified asphalt emulsion. Corrective maintenance refers to reactive activities, mainly including thick hot mix asphalt (HMA) overlays. Rehabilitation included restoration treatments and structural overlays.

Historical data on the case project from year 2007 (when it opened to the traffic) until 2016 were collected to construct an alternative activity profile (the actual activity profile). After 2016, the maintenance frequency and events were assumed according to the profile constructed for the period from 2007 to 2016. There were five instances of maintenance events up to 2016, including a thin HMA overlay of 2 cm in 2009, of 4 cm in 2011 and of 1cm in 2014, thin asphalt surfacing in 2010 and a 4cm + 5cm structural overlay in 2015. From 2016 until 2022, the maintenance events consisted of an HMA overlay of 2 cm in 2018 and of 4 cm in 2020, and thin asphalt surfacing in 2019.

Work Zone Characteristics

The work zone events occurring as part of a typical activity profile and as part of the alternative profile are illustrated in Figure 3. Other work zone characteristics, including work zone length, duration, timing, posted speed and lane closures, were collected from work activity archives, project completion files and safety work standards for highway maintenance. Specially, work zone capacity was obtained from highway capacity manual (HCM) 2000. Detour distances for two directions were obtained by conducting measurements using Google Maps. Detour distances in the south-bound direction and north-bound direction were 142.5 km and 258.3 km, respectively.

Traffic Characteristics

The historical traffic volume data from 2007 to 2016 were obtained from traffic counting stations. The traffic volume data after 2016 were predicted via trend extrapolation. Passenger vehicles were classified into passenger cars and passenger buses, accounting for 87% and 13%, respectively. Truck vehicles were classified into light-duty trucks and heavy-duty trucks, accounting for 87% and 13%, respectively. The vehicle lengths for passenger cars, passenger buses, light-duty trucks and heavy-duty trucks were 4.5 m, 12 m, 7 m and 11 m, respectively, according to the national standards.

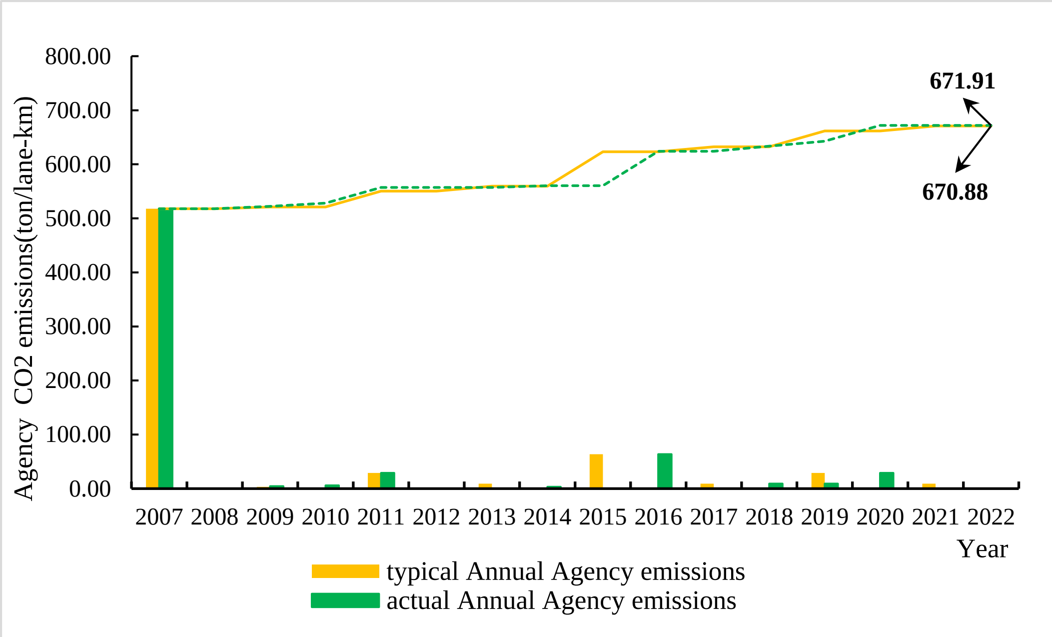


Figure 3. Life-cycle agency CO_2 emissions associated with the typical activity profiles and the actual activity profile.

3. Results

3.1. Total CO_2 Emissions and Their Distribution

As shown in Table 2, over the 15-year analysis period, the total CO_2 emissions from the typical activity profile and the actual activity profile were 6197.1 ton/lane-km and 6160.7 ton/lane-km, respectively. Namely, the total CO_2 emissions from the actual activity profile were 36.76 tons higher for one lane of one kilometer in length than that in the typical activity profile. This means that maintaining the typical activity profile could help to reduce CO_2 emissions. As depicted in in Figures 3 and 4, the total cumulative agency CO_2 emissions and user CO_2 emissions from the actual activity profile were 1.03 ton/lane-km and 35.73 ton/lane-km compared to those from the typical activity profile, respectively. We concluded that about 97.2% of CO_2 emissions in the typical activity profile were from user CO_2 emissions, compared to those in the actual activity profile.

Table 2. The total CO_2 emissions in the two activity profiles (ton/lane-km).

Items	**Typical Activity Profile (T)**		**Actual Activity Profile (A)**		**Difference (T-A)**
	ton/lane-km	**%**	**ton/lane-km**	**%**	
Agency CO_2 emissions	671.91	10.8	670.88	10.9	1.03
User CO_2 emissions	5525.55	89.2	5489.82	89.1	35.73
Total	6197.1	100	6160.7	100	36.76

As for the contributors of CO_2 emissions, user CO_2 emissions were dominant, accounting for up to 89% of the total life-cycle CO_2 emissions for both the actual activity profile and the typical activity profile, whereas about 11 % of life-cycle CO_2 emissions were related to agencies. This demonstrated that for the entire lifetime of a highway project, controlling the environmental impact caused by service traffic is critical. This finding is consistent with those of previous studies, which emphasized the importance of reducing CO_2 from the operation phase of a road, especially for roads with heavy traffic [19,20].

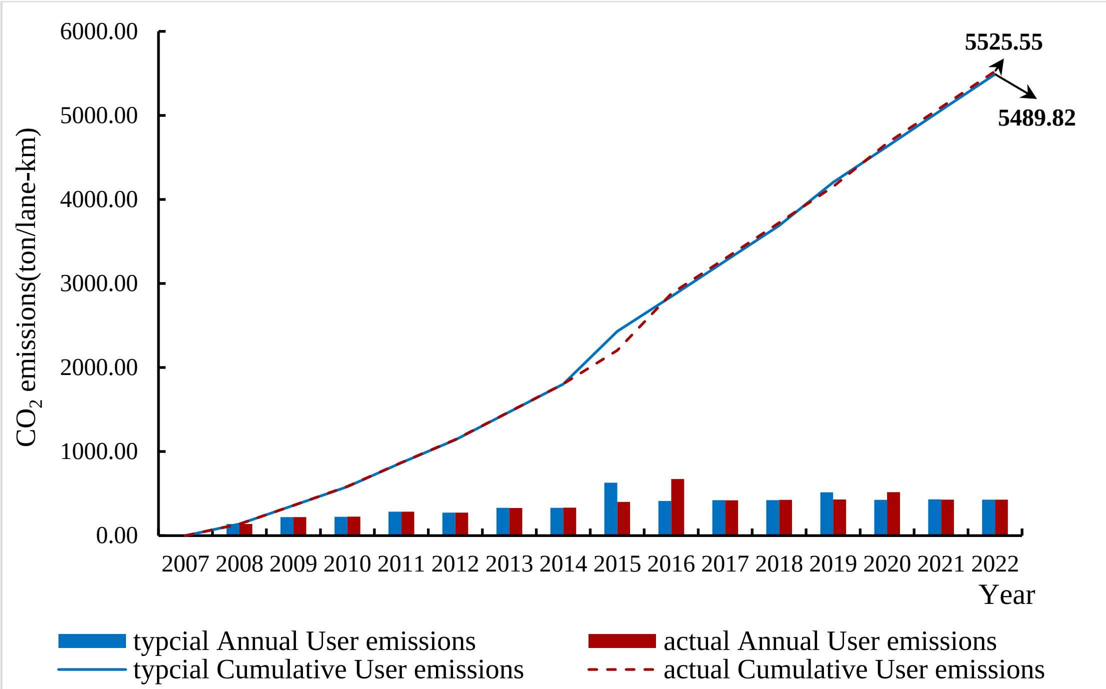


Figure 4. Life-cycle user CO_2 emissions of typical and actual activity profiles.

3.2. Total Costs and Their Distribution

Figure 5 presents the life-cycle agency costs for the typical activity profile and the actual activity profile, respectively. Obvious differences can be observed between the annual agency costs for the two activity profiles. After the normalization and processing of these values into equivalent uniform annual cost (EUAC) values, throughout the 15-year analysis period, the agency costs from the typical activity profile and the actual activity profile were 38,980 and 29,060 2007 dollars, respectively. The actual activity profile generated a 1.3-times higher agency cost than the typical activity profile. Thus, the agency savings provided by maintaining the typical activity profile are USD 9920/lane/km in 2007 dollars. That is, ensuring a typical activity profile could save 25.5% of agency costs for one lane of one kilometer in length in the pavement's service life.

Regarding the user costs for the typical activity profile and the actual activity profile, the results was displayed in Figure 6a,b, showing that the trends of annual user costs were consistent between the two activity profiles. Overall, during the life cycle of the highway's asphalt pavement, the annual user cost increased steadily with the growth of the highway's service life. Preventive maintenance activities had no significant influence on the growth trend of annual user cost, whereas the occurrence of corrective maintenance and rehabilitation maintenance activities led to significant increases in the annual user cost, especially in the case of rehabilitation activities, which led to an abrupt change in the annual user cost.

In the years in which maintenance events occurred, the interference of the work zone contributed significantly to the annual user cost, mainly due to the extra user cost of users traveling through the construction area and the users in the detour condition, especially in the years in which rehabilitation maintenance was required. For example, the user cost resulting from the truck detour caused by the rehabilitation activity in 2016 led to a significant increase in the annual user cost in the actual activity profile.

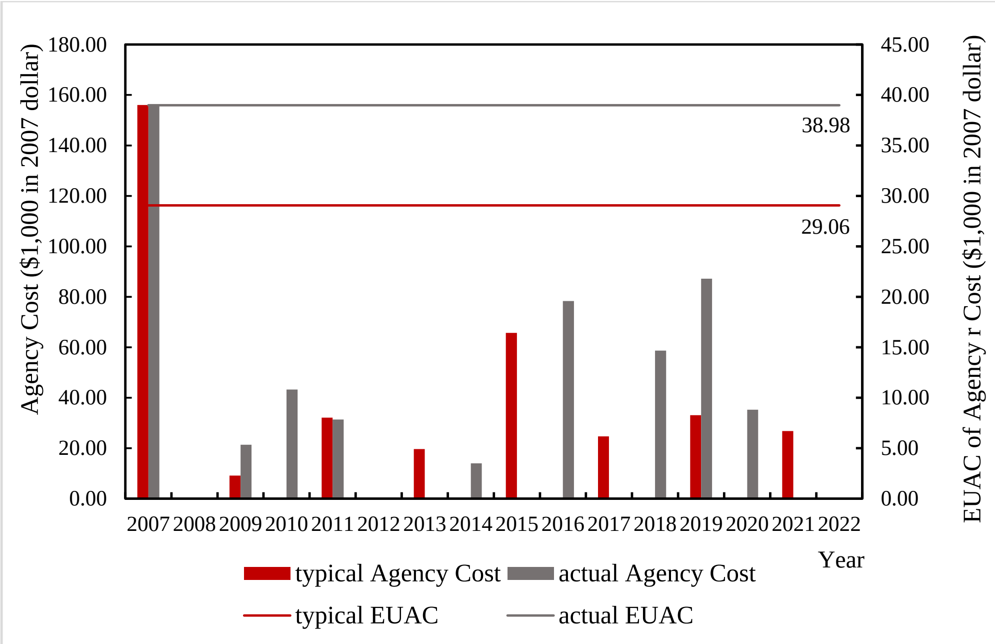
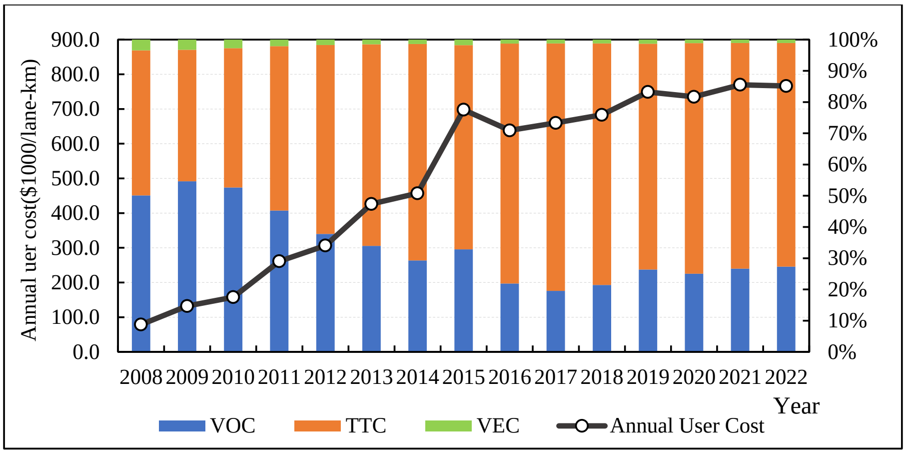
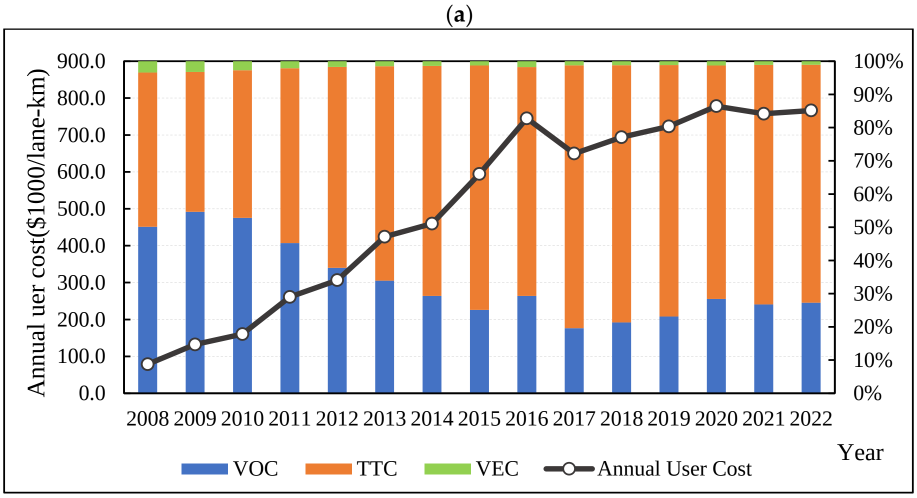


Figure 5. Annual agency costs and discounted EUAC values for the typical and actual activity profiles.



(**a**)



(**b**)

Figure 6. Annual user cost and their compositions in the typical and actual activity profiles. (**a**) Typical Activity Profile; (**b**) Actual Activity Profile.

In regard to the user cost components specifically, their contribution to the total user cost varied with the service life of the pavement. In the early stage of highway operation, the VOC was the major source of user cost, whereas with an increase in the highway's operation time, the proportion of VOC in the user cost decreased. TTC, compared to VOC, was the major source of user cost in the early stage of highway operation, with its trend going in the opposite direction. With the increase in the highway operation time, the proportion of TTC in the user cost increased. On the other hand, the contribution of VEC to the total user cost decreased over time.

In sum, VOC and TTC were the major contributors to user cost, and at the beginning of the highway's operation, the VOC and TTC were comparable, whereas the TTC made the dominant contribution to the total user cost with the growth of volume after a period of traffic operation. The VEC was a minor source of user cost, compared to the TTC and VOC.

4. Conclusions and Recommendations

In this study, we proposed an improved and detailed method to integrate life cycle assessment (LCA) and life cycle cost analysis (LCCA) to estimate the cost and CO_2 emissions of vehicle and work activities in the entire service life of an area of pavement for the development of pavement management strategies and decisions. In this framework, four main modules (the materials module, the work activities module, the work zone module and the usage module) mentioned in LCA, as well as agency costs and user costs related to usage, work activities, work zone traffic delays and detours, which are included in LCCA, were analyzed simultaneously. The applicability of the integrated model was verified by taking a real freeway project in China as a case study. The findings of our study may provide a useful tool and a reference to robustly support decision-making regarding the mitigation of carbon emissions and cost-saving measures regarding highway construction and maintenance. The main findings were as follows.

i. The integrated LCA-LCCA model was able to provide consistent outputs, such as CO_2 emissions and costs results for each component covered by the four main modules, namely, the materials module, the work activities module, the work zone module and the usage module.
ii. Maintaining the typical activity profile could help to reduce CO_2 emissions. Over the 15-year analysis period, the total CO_2 emissions from the actual activity profile were 36.76 tons higher in one lane of one kilometer in length than that from the typical activity profile, and about 97.2% of CO_2 emissions savings in the typical activity profile were from user CO_2 emissions.
iii. Maintaining the typical activity profile could help to save agency costs of USD 9920 /lane/km in 2007 dollars after normalized processing of the data into equivalent uniform annual cost (EUAC) over the 15-year analysis period.
iv. During the life cycle of highway's asphalt pavement, the annual user cost increased steadily with the increase in the highway's service life, whereas yearly significant growth was caused by the occurrence of rehabilitation and maintenance activities, mainly due to the detours of users.
v. Regarding the user cost components, VOC and TTC were the major contributors to user cost, followed by VEC. Specially, TTC was the top contributor to the total user cost when traffic volume was increasing.

Even though the proposed integrated LCA-LCCA model could provide a useful tool in helping decision-makers to develop economic and environmental sustainability pavement management strategies, we can provide several recommendations for the improvement of the model. Firstly, in the current model, we determined the activity profiles based on the pavement design manuals or related project maintenance archives from the provincial departments of highways, especially in determining future maintenance events. In further research, we suggest considering the mechanistic-empirical pavement design method, e.g., the pavement deterioration model, to determine the activity profiles. Secondly, the effects of pavement roughness on CO_2 emissions and user costs should be included in the model as a factor in the long service life of a highway project. Thirdly, the impact of the uncertainty of input parameters on the results of the integrated LCA-LCCA model needs to be examined in further research. These parameters may include discount rates, fuel costs, CO_2 emissions prices, traffic volume, etc. Finally, the model developed in this study could be extended to the regional road network level from a project level in further studies to provide more comprehensive information for maintenance strategies and decisions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14020194/s1, Table S1: The calculation methods of user cost and user CO_2 emissions in this study.

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