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CO_2 Emissions and Highway User Costs in Pavement Service Life Cycle

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Abstract

This paper proposes a methodology for estimating Carbon Dioxide (CO2) emissions and highway user costs in the pavement service life cycle where the traveling public experiences normal traffic conditions and work zones caused by construction, maintenance, and rehabilitation work activities. The primary highway user cost components include costs of vehicle operations, travel time, and CO2 emissions. The work zone related CO2 emissions comprise three components, which are CO2 emissions from highway mainline traffic, detoured traffic, and contractor's work activities such as material processing and handling, to-site transportation, and on-site work operations. A computational study is conducted for methodology application using data on traffic and work activities associated with the service lifespan of Xi'an-Hanzhong freeway corridor in Shaanxi Province, China. The results indicate that approximately 20% of total CO2 emissions is associated with work zones and 70% of highway user costs is attributable to travel time. The proposed methodology could be adopted by transportation agencies to quantify CO2 emissions and highway user costs in the pavement service life cycle and assist in developing environmental-friendly and cost-effective strategies aimed to minimize CO2 emissions and user costs in life-cycle management of highway pavements.

Keywords: Life-cycle cost analysis; Highway pavement; Carbon dioxide emissions; User costs; Initial construction; Maintenance and repair

Introduction

Background

The increasing global concerns of economic and environmental sustainability have exerted pressure on transportation agencies to systematically develop cost-effective and environmental-friendly strategies for management of pavements owing to extensive agency costs of construction, maintenance, and repair treatments, and use costs accrued in their useful service life cycles [1-6]. For example, a $91 billion annual capital investment is estimated to maintain U.S. highway pavements and the annual budget estimated to maintain U.S. Interstate highways is even as high as $101 billion from 2008-2028 [7,8]. Recent studies indicate that pavement management decisions also have significant impacts on life-cycle environmental impacts besides the economic issues [9]. For instance, Jullien et al. [10] have revealed that emissions generated by processing and production of materials for pavement preservation, to-site transportation, on-site work activities, and other interventions in pavement service life cycle even make up 5%-25% of total Carbon Dioxide (CO_2) emissions in the transportation industry. According to U.S. Federal Highway Administration (FHWA), fuel consumption and vehicle air emissions of roughly 253 million registered vehicles in the U.S. are affected by driving on pavements with varying riding quality [4]. Some researchers argue that an environmentally advantageous solution may not be preferred over others in terms of economic competitiveness [8]. To improve the overall performance of both environmental impacts and economic costs, sound methods need to be developed for analysis [7,11].

Related work

In the context of environmental impacts analysis, Life cycle assessment (LCA) has been introduced by International Organization for Standardization (ISO) to identify flow of energy or materials in a sequence of activities [12]. For instance, Stripple [13] conducted a study on a complete assessment on life-cycle CO_2 emissions of a highway project covering a verity of activities such as excavation of raw materials, production of construction materials, on-site construction activities, maintenance and operation interventions, and final disposal or reuse of materials from demolished highways. Huang et al. [14,15] developed a life-cycle environment assessment model for pavement construction and maintenance which accommodates traffic delay and recycled use. Zhang et al. [16] analyzed environmental sustainability performance of engineered cementitious composite materials in highway pavement lifespan. Yu et al. [17] presented an environmental implication of three pavement overlay alternatives through life-cycle environment analysis. Celauro et al. [18] assessed environmental impacts of different construction techniques and maintenance activities for local roads. Liu et al. [19] estimated magnitude of life-cycle CO_2 emissions associated with highway earthwork and pavement structure construction. Further, LCA-based software tools have been developed to quantify CO_2 emissions from road construction and maintenance interventions. Notables include CMS RIPT [20] and PALATE model [21].

In support of cost-effective treatments and strategies for pavement management, various approach for life-cycle cost analysis (LCCA) have been developed in recent decades. Specifically, FHWA created a policy to promote LCCA for transportation investment decisions after issuance of Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 and also published Life-Cycle Cost Analysis Primer in 2002 to promote the use of LCCA method for evaluating transportation investment alternatives and supporting sound decisions [22]. Besides, FHWA developed a pavement design LCCA software tool named RealCost Version 2.1 to perform LCCA for choosing cost-effective pavement design options [23]. More recently, Swei et al. [24] performed a review of some LCCA application studies. Labi & Sinha [1], Labi et al. [2], and Li & Madanu [25] introduced a new highway project-level LCCA method considering input factors under mixed cases of certainty, risk, and uncertainty. Further, the LCCA method was extended for evaluating highway safety hardware improvement projects [26,27]. In the same period, computer-aided LCCA procedures based on software tools of CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) and RealCost were proposed for designs of pavement rehabilitation treatments [28]. Mandapaka et al. [29] created an integrated model of LCCA and California Mechanistic-Empirical design procedure that could help select an optimal maintenance and repair strategy for flexible pavements. In addition, new LCCA methods were developed to incorporate user cost considerations in pavement useful service life cycle [6,30,31].

In recent years, some researchers have begun to jointly consider environmental impacts and economic costs in pavement management. Lidicker et al. [9] analyzed both greenhouse gas (GHG) with CO_2 emissions as the main contributor and costs associated with agencies and users for pavement resurfacing budget allocation via integration of LCA and LCCA. Yu et al. [7] introduced environmental damage cost (EDC) to combine LCA and LCCA for optimal pavement maintenance planning. Batouli et al. [4] conducted study on joint use of LCA and LCCA to investigate sustainability of different pavement design alternatives using data from Florida. Santos et al. [5] developed a comprehensive model for joint use of pavement LCCA and LCA by simultaneous considerations of agency costs, user costs, and GHG emissions.

Motivation

The current study is intended to provide a practical method for estimating environmental and economic impacts of highway users and work activities in the pavement service lifespan. In particular, this study will develop an improved method for quantifying CO_2 emissions and highway user costs associated with highway users in normal traffic operation and work zone conditions that explicitly include CO_2 emissions and user costs related to: i) highway users traversing through work zones, ii) travelers being detoured, and iii) contractor's work activities from material processing and production, to-site transportation, and on-site work. Moreover, this study will apply the proposed method in a real-world computational study for validation.

Proposed Methodology

General

Figure 1 illustrates the overall framework of the proposed method for life-cycle based analysis of CO_2 emissions and user costs by highway users and contractor's work activities in pavement service lifespan. It generally follows guide of ISO14040 [12] and U.S. Federal Highway Administration (FHWA) guide to pavement design [22]. The ISO 14040 provides a systematic process to assess environmental impacts by identifying flows of energy and materials in a sequence of activities. In this study, the pavement service life cycle is defined as the time interval between two consecutive construction interventions, including the events of initial construction, repetitive preventive and corrective maintenance, and rehabilitation treatments. In the analysis process, CO_2 emissions and user costs are estimated for normal traffic operation and work zone conditions, respectively. The CO_2 emissions in normal traffic conditions refer to the tailpipe CO_2 emissions due to vehicles fuel combustion. The work zone related CO_2 emissions comprise those of: i) highway users traveling through the work zone, ii) highway users being detoured, and iii) contractor's work activities concerning material processing and production, to-site transportation, and on-site activities. For normal traffic or work zone conditions, highway user costs mainly include costs of vehicle operations, travel time, and CO_2 emissions, namely three components: vehicle operating costs (VOC), travel time costs (TTC), and CO_2 emission costs (EC). Particular to EC in work zone conditions, it comprises cost component of vehicular emissions by highway users travelling through the work zone and being detoured, and work activity related CO_2 emissions. Detail descriptions and computations of CO_2 emissions and highway user costs are provided in the subsequent sections.

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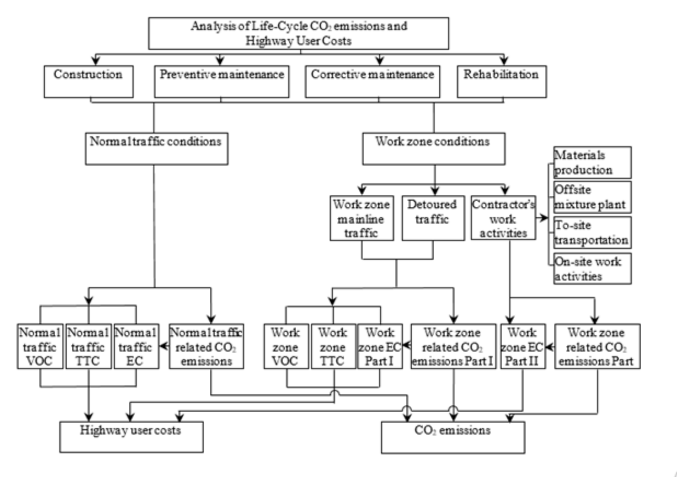

Figure 1: Overall framework of life-cycle analysis of co$_2$ emissions and highway user costs.

Estimation of CO$_2$ emissions

The total CO$_2$ emissions in the pavement service life cycle consist of CO$_2$ emissions of vehicles operating in normal traffic and work zone conditions. For work zone related CO$_2$ emissions, they comprise three portions: i) CO$_2$ emissions from work zone mainline traffic; ii) CO$_2$ emissions from detoured traffic; and iii) additional CO$_2$emissions from contractor's work activities. The individual components are computed as below:

a. Vehicular CO$_2$ emissions in normal traffic conditions. The vehicular CO$_2$ emissions in normal traffic conditions could be computed by Equation (1):

$$E^{veh}_{normal}=\Sigma^2_{i=1}\left(ER^{N_i}_{CO_2}\times VKT^{N_i}\right) \quad (1)$$

where, E^{veh}_{normal} is the CO$_2$ emissions of vehicles in normal traffic conditions;" i " is vehicle types, and value of "1" and "2" represent light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs), respectively; $ER^{N_i}_{CO_2}$ is CO$_2$ emission rate of vehicle type " i " in g/VKT in normal traffic conditions; VKT^{N_i} is total vehicle kilometers of travel (VKT) of vehicle type " i " in normal traffic conditions, depending on traffic volume, project length, and analysis period.

In Equation (1), $ER^{N_i}_{CO_2}$ is determined based on the mesoscopic traffic flow model where emission rate is assessed as a function of average vehicle speed [32]. In this study, the mesoscopic models for estimating CO$_2$emissions by LDVs and HDVs developed by Song et al. [33] are employed, which are of the following specifications:

$$ER^{LDV}_{CO_2}=4.78\times10^3\times V^{-1}\times1.11\times10^2\times-1.24\times V+2.37\times10^{-2}\times V^2 \quad (2)$$

$$ER^{HDV}_{CO_2}=3.67\times10^3\times V^{-1}\times5.34\times10^2\times-7.90\times V+5.43\times10^{-2}\times V^2 \quad (3)$$

where, $ER^{LDV}_{CO_2}$ and $ER^{HDV}_{CO_2}$ are emission rates for LDVs and HDVs in g/VMT; and V is the vehicle speed in km/h.

b. Vehicular CO$_2$ emissions of work zone mainline and detoured traffic. The CO$_2$ emissions related to vehicles travelling through the work zone and being detoured could be computed by Equation (4):

$$E^{veh}_{wz}=\begin{cases}\Sigma^2_{i=1}\left(ER^{C_i}_{CO_2}\times t^{c_i}\times n^{c_i}+ER^{R^i_w}_{CO_2}\times VKTR^i_w+ER^{D_i}_{CO_2}\times VKT^{D_i}\right) & \text{no queue}\\ \Sigma^2_{i=1}\left(ER^{C_i}_{CO_2}\times t^{c_i}\times n^{c_i}+ER^{R^i_w}_{CO_2}\times VKTR^i_w+ER^{R^i_q}_{CO_2}\times VKT^{R^i_q}+ER^{D_i}_{CO_2}\times VKT^{D_i}\right) & \text{queue}\end{cases} \quad (4)$$

Where, E^{veh}_{wz} is the CO$_2$ emissions by vehicles travelling through the work zone and being detoured; "i" is vehicle types, and the value of "1" and "2" represent LDVs and HDVs, respectively; $ER^{C_i}_{CO_2}$ is the speed change-related CO$_2$ emission rate of vehicle type " i " in g/sec; t^{c_i} is the speed change time duration per vehicle of vehicle type " i " in sec, depending on the normal operating speed and speed in work zone or queue; n^{c_i} is the number of affected vehicles of vehicle type " i " ; $ER^{R^i_w}_{CO_2}$ is the speed reduction-related CO2 emission rate of vehicle type "i" in g/VKT when driving through a work zone; $VKTR^i_w$ is the total VKT of affected vehicles of vehicle type "i" driving through the work zone, depending on vehicle volume, work zone length, and duration of work zone with speed reductions; $ER^{D_i}_{CO_2}$ is detour-specific CO$_2$ emission rate of vehicle type " i " in g/VKT; VKT^{D_i} is total VKT of vehicles of vehicle type " i " being detoured, depending on the detoured vehicle volume, detour length, and duration of detour usage; $ER^{R^i_q}_{CO_2}$ is speed reduction-related CO$_2$ emissions rate of vehicle type " i " in g/VKT when driving through a queue; $KT^{R^i_q}$ is total VKT of affected vehicles of vehicle type " i " driving through a queue. In the above expressions, $ER^{C_i}_{CO_2}$ can be estimated using microscopic vehicle-based model to account for vehicle speed change cycles, and acceleration and deceleration patterns under various speed dynamics. Specifically, the microscopic vehicle-based Comprehensive Modal Emissions Model (CMEM) calibrated using data on freeway segments in presence of work zones by Zhang et al. [34] is employed for the current study to estimate CO$_2$ emissions by LDVs and HDVs traversing through work zones and on detours. The above mesoscopic vehicle-based model is further utilized to calculate $ER_{CO_2}^{N_i}$, $ER_{CO_2}^{R_w^i}$, $ER_{CO_2}^{D_i}$, and $ER_{CO_2}^{R_q^i}$.

c. Contractor's work activity related CO2 emissions. Apart from estimating CO_2 emissions produced by vehicles of highway users traveling in normal and work zone conditions, there exists additional CO_2 emissions generated by contractor's work activities including material processing and production, to-site transportation, and on-site work operations that could be calculated by Equation (5): $E_{contractor}=E_{materials}+E_{off\text{-}site}+E_{to\text{-}site}+E_{on\text{-}site}$ (5)

where, $E_{contractor}$ is additional CO_2 emissions by contractor's work activities; $E_{materials}$, $E_{off\text{-}site}$, $E_{to\text{-}site}$, and $E_{on\text{-}site}$ are CO_2 emissions associated with material processing and production, off-site mixing plant, to-site transportation, and on-site work operations, respectively.

The CO_2 emissions from material processing and production refer to cradle-to-gate embodied emissions. The related CO_2 emissions in work zone conditions are the aggregation of emissions from different types of materials consumed in construction, preventive and corrective maintenance, and repair activities accrued during the pavement service life cycle. For each type of materials, the concerning emissions could be quantified by multiplying its total quantity in the physical unit and cradle-to-gate emission factor per physical unit. The CO_2 emissions from off-site mixture plant, to-site material transportation, and on-site work activities are mainly associated with fuel or energy consumption by construction machinery, equipment and material/waste hauling vehicles. In this study, the pump-to-wheel cycle method is employed to quantify CO_2 emissions by construction machinery, equipment, and hauling vehicle operations. Similar to CO_2 emissions of material processing and production, CO_2 emissions of these three parts are the sum of CO_2 emissions from different types of machinery, equipment, and vehicles involved in construction, preventive and corrective maintenance, and repair activities during the pavement service lifespan. For each type of machinery, equipment, and vehicles, the concerning CO_2 emissions could be obtained by multiplying its total fuel or energy consumption in a physical unit and the pump-to-wheel emission factor per physical unit. In the current study, the methods introduced by Liu et al. [19,35] and China Ministry of Transport (CMOT) [36,37] for computing $E_{materials}$, $E_{off\text{-}site}$, $E_{to\text{-}site}$, and $E_{on\text{-}site}$ are adopted. The cradle-to-gate emission factors of various materials and pump-to-wheel emission factors of different types of energy and fuels are extracted from references of Ou et al. [38], Gong & Zhang [39], and IKOE [40].

Calculation of highway user costs

The key components of user costs in the pavement useful service life cycle considered in the current study include vehicle operating costs (VOC), travel time costs (TTC), and air emission costs (EC). The amounts of each cost component are estimated for normal traffic operation and work zone conditions, respectively.

a. Vehicle operating costs. Vehicle operating costs depend on time of the day, travel distance, and condition of the road where each vehicle travels, as well as types of vehicles. They are separately calculated for normal traffic operation and work zone conditions as follows:

$$VOC_{normal}=\sum_{i=1}^{2}\left(R_{VOC}^{N_i}\times VKT^{N_i}\right)$$

$$VOC_{wz}=\begin{cases}\sum_{i=1}^{2}\left(R_{VOC}^{C_i}\times t^{c_i}\times n^{c_i}+R_{VOC}^{R_w^i}\times VKT^{R_w^i}+R_{VOC}^{D_i}\times VKT^{D_i}\right) & \text{no queue}\\ \sum_{i=1}^{2}\left(R_{VOC}^{C_i}\times t^{c_i}\times n^{c_i}+R_{VOC}^{R_w^i}\times VKT^{R_w^i}+R_{VOC}^{R_q^i}\times VKT^{R_q^i}+R_{VOC}^{D_i}\times VKT^{D_i}\right) & \text{queue}\end{cases}\quad(7)$$

where, VOC_{normal} is the VOC in normal traffic operation conditions; VOC_{wz} is the VOC in work zone conditions; $R_{VOC}^{N_i}$ is VOC rate of vehicle type " i " in \$/VKT in normal traffic operation conditions; VKT^{N_i} is total VKT of type " i " vehicles in normal traffic operation conditions; $R_{VOC}^{C_i}$ is the speed change related VOC rate of type " i " vehicles in \$/sec; t^{c_i} is the time duration of speed change per type " i " vehicle in seconds; n^{c_i} is the number of type " i " vehicles experiencing speed changes; $R_{VOC}^{R_w^i}$ is the speed reduction related VOC rate of type " i " vehicles in \$/VKT when driving through a work zone in a certain day as compared to normal traffic conditions; $VKT^{R_w^i}$ is the total VKT of type " i " vehicles experiencing speed reductions owing to the work zone; $R_{VOC}^{D_i}$ is the detour related VOC rate of type " i " vehicles in \$/VKT when being detoured as compared to traveling the equivalent distance in normal traffic conditions; VKT^{D_i} is total VKT of numbers of type " i " vehicles using the detour. For VOC computation in a queue, $R_{VOC}^{R_q^i}$ is the speed reduction related VOC rate of vehicle type " i " in \$/VKT when driving through a queue in a certain day as compared to normal traffic operation conditions; $VKT^{R_q^i}$ is total VKT of type " i " vehicles experiencing speed reductions caused by queues; " i " refers to vehicle type with 1 for LDVs and 2 and HDVs.

In Equation (7), VOC rates for the type " i " vehicle related to speed changes, normal traffic operations, work-zone related speed reductions, queue-induced speed reductions, and detours, $R_{VOC}^{C_i}$, $R_{VOC}^{N_i}$, $R_{VOC}^{R_w^i}$, $R_{VOC}^{R_q^i}$, and $R_{VOC}^{D_i}$ are calculated using corresponding fuel consumption rates of type "i" vehicles, $R_{f_j}^{C_i}$, $R_{f_j}^{N_i}$, $R_{f_j}^{R_w^i}$, $R_{f_j}^{R_q^i}$, and $R_{f_j}^{D}$, in g/sec multiplied by fuel price P_{fuel}^{j} in \$/g, where i represents vehicle type with 1 for LDVs and 2 for HDVs; and j denotes fuel type with 1 for gasoline and 2 for diesel. Specifically, $R_{f_j}^{C_i}$ is determined based on the microscopic vehicle-based model of Zhang et al. [34]; and the total of $R_{f_j}^{N_i}$, $R_{f_j}^{R_w^i}$, and $R_{f_j}^{D_i}$, are calculated using the mesoscopic traffic flow model of Song et al. [33] as below:

$$R_{f_j}^{LDV_s}=1.56\times10^{2}\times V^{-1}+3.54-3.88\times10^{-2}\times V+7.76\times10^{-4}\times V^{2}\quad(8)$$

$$R_{f_j}^{HDV_s}=1.19\times10\times V^{-1}+1.69\times10^{-2}-2.50\times V+1.72\times10^{-2}\times V^{2}\quad(9)$$

where, $R_{f_j}^{LDV_s}$ and $R_{f_j}^{HDV_s}$ are fuel consumption rates for LDVs and HDVs, respectively; and "V" is the vehicle operating speed.

b. Travel time costs. Travel time costs are estimated for normal traffic operation and work zone conditions as follows:

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$$\mathrm{TTC_{normal}}=\Sigma_{i=1}^{4}\left(\mathrm{R_{TTC}^{N_i}}\times\mathrm{n^{N_i}}\right) \quad (10)$$

$$TTC_{wz}=\begin{cases}\sum_{i=1}^{4}\left(R_{TTC}^{C_i}\times n^{C_i}+R_{TTC}^{R_w^i}\times n^{R_w^i}+R_{TTC}^{D_i}\times n^{D_i}\right) & \text{no queue}\\ \sum_{i=1}^{4}\left(R_{TTC}^{C_i}\times n^{C_i}+R_{TTC}^{R_w^i}\times n^{R_w^i}+R_{TTC}^{R_q}\times n^{R_q^i}+R_{TTC}^{D_i}\times n^{D_i}\right) & \text{queue}\end{cases} \quad (11)$$

where, $\mathrm{TTC_{normal}}$ is the TTC in normal traffic operation conditions; TTC_{wz} is the TTC in work zone conditions; $\mathrm{R_{TTC}^{N_i}}$ is the TTC rate of type "i" vehicles in $/vehicle for normal traffic conditions; $\mathrm{n^{N_i}}$ is the number of type "i" vehicles in normal operation conditions; $R_{TTC}^{C_i}$ is speed change related TTC rate of type "i" vehicles in $/vehicle; n^{C_i} is the number of type "i" vehicles experiencing speed changes; $R_{TTC}^{R_w^i}$ is speed reduction related TTC rate of type "i" vehicles in $/vehicle when they drive through a work zone; $n^{R_w^i}$ is the number of type "i" vehicles experiencing speed reductions in presence of a work zone; $R_{TTC}^{D_i}$ is detour related TTC rate of type "i" vehicles in $/vehicle when they are detoured; n^{D_i} is the number of type "i" vehicles using the detour; $R_{TTC}^{R_q^i}$ is speed reduction related TTC rate of type "i" vehicles in $/vehicle when they drive through a queue; $n^{R_q^i}$ is the number of type "i" vehicles experiencing speed reductions caused by queues; and "i" represents vehicle types with 1 to 4 representing passenger cars, buses, light-duty trucks, and heavy-duty trucks, respectively.

In Equations (10) and (11), $R_{TTC}^{N_i}$, $R_{TTC}^{C_i}$, $R_{TTC}^{R_w^i}$, $R_{TTC}^{R_q^i}$, and $R_{TTC}^{D_i}$ are estimated based on vehicle speeds in normal traffic conditions, acceleration/deceleration rates, speeds in work zones or queues, speeds on detour, and work zone, queue, and detour lengths. Apart from estimates of travel time rates, value of time (VOT) is a key factor of TTC estimation. This study proposes a region based VOT model that incorporates time of year and trip purpose considerations for VOT estimation in the following:

$$\mathrm{VOT_y=VOT_y^b\times\theta+VOT_y^r\times(1\text{-}\theta)} \quad (12)$$

where, $\mathrm{VOT_y}$ is VOT of a traveler in year y; $\mathrm{VOT_y^b}$ is VOT for business trips in year y; $\mathrm{VOT_y^r}$ is VOT for recreation trips in year y; "è" is time utilization ratio for a traveler. In this study, $\mathrm{VOT_y^b}$ is determined by considering the gross labor productivity. $\mathrm{VOT_y^r}$ is established using weighted average per capita disposable income from urban and rural net income and the recreation expenditure ratio of weighted average per capita disposable income. $\mathrm{VOT_y^b}$ and $\mathrm{VOT_y^r}$ are estimated based on 40 working hours per week and 50 weeks per year. è and the recreation expenditure ratio are determined based on findings of Wang et al. [41].

c. Vehicle emission costs. Vehicle emissions costs comprise vehicular CO_2 emissions for normal traffic operation and work zone conditions. These costs are quantified according to CO_2 emission quantities associated with normal traffic operation and work zone conditions multiplied by unit price of CO_2 emissions in dollar per gram. The work zone related CO_2 emission quantities consist of those caused by vehicles traversing through work zones and being detoured, as well as additional CO_2 emissions from contractor's work activities. The emission costs are calculated as below:

$$\mathrm{EC_{normal}=E_{normal}\times p_{co_2}} \quad (13)$$

$$\mathrm{EC_{wz}=\left(E_{veh\_wz}+E_{cont\_wz}\right)\times p_{co_2}} \quad (14)$$

where, $\mathrm{EC_{normal}}$ and $\mathrm{EC_{wz}}$ are emission costs for normal traffic and work zone conditions; $\mathrm{EC_{normal}}$, $\mathrm{E_{veh\_wz}}$, and $\mathrm{E_{cont\_wz}}$ are emission quantities for normal traffic and work zone conditions where the work zone related emissions contain those generated by vehicles traveling through work zones and using detours, as well as contractor's work activities; and $\mathrm{p_{co_2}}$ are unit rates of CO_2 emissions. In the current study, the unit rates of CO_2 emissions of the U.S. Environmental Protection Agency (EPA) are adopted [42].

Analysis of life-cycle user benefits

In general, two sets of life cycle user cost profiles can be created. The first life-cycle user cost profile comprises annual user costs estimated according to the base-case typical pavement life-cycle activity profile where the needed maintenance and repair treatments are timely implemented according to the design specification [25]. In real world situations, the needed pavement maintenance and repair treatments may not be properly implemented owing to budget limitations or management deficiency. As such, an alternative life-cycle user cost profile with annual user costs occurred in accordance with the actual pavement life-cycle activity profile could be established. The annualized user cost amount associated with the typical profile is likely to be lower. Relying on the two sets of annualized user cost amounts and annual travel quantities corresponding to typical and actual profiles, the concept of change in consumer surplus can be employed to calculate equivalent uniform annualized user benefits in the pavement service lifespan with the base-case typical pavement life-cycle activity profile used as the benchmark [6].

Figure 2 depicts different components of annualized user benefits and schematic diagrams of three cases of typical and alternative pavement life-cycle activity profiles considered for the analysis. The three cases of profiles are classified into highway mainline without work zone (M-NWZ) and mainline with work zone (M-WZ), which are further divided into two cases of mainline with work zone and without detour (M-WZ-ND) and mainline with both work zone and detour (M-WZ-D). As such, there are nine possible combinations between the typical and alternative profiles. For itemized user benefits as reductions in itemized user costs concerning vehicle operations, travel time, and CO2 emissions, UUC0 and UUC1 are itemized unit user costs (UUC) associated with typical and alternative pavement life-cycle activity profiles, while VKT0 and VKT1 are vehicle kilometers of travel corresponding to typical and alternative pavement life-cycle activity profiles. For the itemized user costs, the annual user benefits can be calculated as changes in consumer surplus showing as hashed areas. With traffic volumes extrapolated for future years of the pavement service lifespan, the itemized user benefits in the pavement service lifespan can be computed and expressed in equivalent uniform annualized benefits.

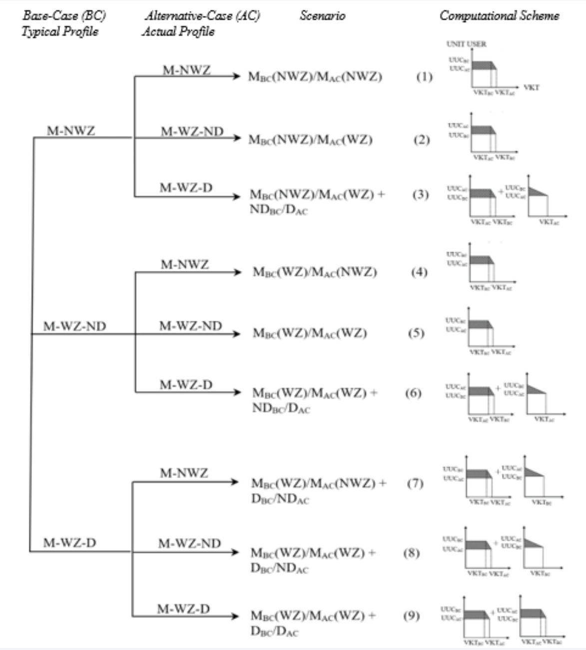

Figure 2: Illustration of life-cycle user benefit calculation computational study.

Computational Experiment

Data preparation and analysis

a. Data collection and processing. A computational experiment is conducted for the proposed methodology application and validation using data on Xi'an-Hanzhong Freeway that connects city of Xi'an with city of Hanzhong in Shaanxi province, China. The 4-lane freeway is 258.65 km long with an alignment traversing through the Qinling Mountain range in central China opened to traffic in October 2007. The design speed limits are 80 km/h for rolling sections and 60 km/h for mountainous sections. By early 2019, the highest annual average daily traffic (AADT) along the expressway has exceeded 40,000 vehicles per day. In consideration of data availability and completeness, a 41.25-km long segment of the expressway is selected for the computational study. In particular, flexible pavements are designed for the segment with an expected service life expectancy of 15 years. A discounted rate of 5.5% is used to compute the equivalent uniform annualized amounts of itemized user costs and benefits.

b. Pavement life-cycle activity profiles. For creating the base-case typical pavement life-cycle activity profile, the agency and user cost rates established according to Technical Specifications for Highway Maintenance issued by China Ministry of Transportation [43,44] and related guidelines developed by China Ministry of Housing and Urban-Rural Development (CMOHURD) [45] are adopted. The highway user costs associated with the typical pavement life-cycle activity profile are estimated accordingly. Figure 3 illustrates base- and alternative case actual pavement life-cycle activity profiles.

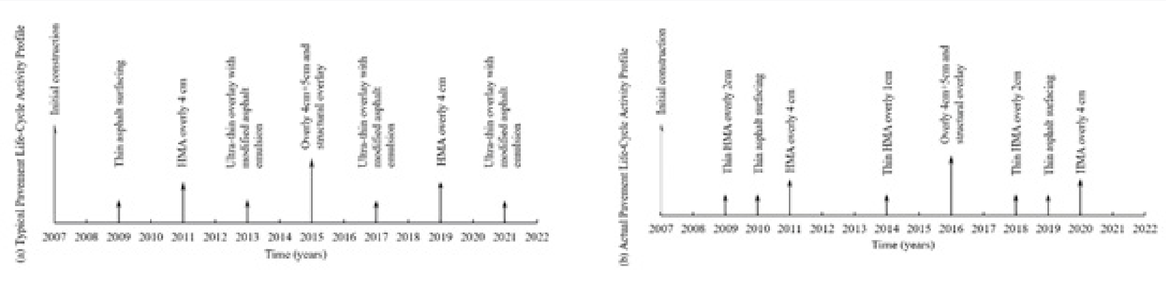

Figure 3: Illustration of typical and actual pavement life-cycle activity profiles.

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c. Work zone characteristics. With costs of vehicle operations, travel time, and air emissions considered as three primary items of user costs, the user costs in the pavement service lifespan comprise annual amounts of those itemized user costs for normal traffic operation and work zone conditions. In presence of work zones related to pavement maintenance and repair activities, the itemized user costs consist of those generated by highway users traversing through work zones and being detoured, as well as additional user costs caused by contractor's work activities. To facilitate reliably estimating the above user costs, work zone details including work zone length, duration, daily vehicle volume, composition, and distribution by time of the day, highway capacities in absence and presence of work zones, and work zone traffic management strategies such as time of work activities, posted speed limits, lane closure, and travel lane configuration need to be collected for individual work zones.

According to safe operation standards of highway maintenance by China MOT [46], contractors are warranted to work from Monday to Sunday, 8:00am to 18:00pm for preventive and corrective maintenance, and rehabilitation work. For maintenance of the freeway main alignment, a single-lane closure up to 5-kilometer in length is allowed. For rehabilitation of the freeway main alignment, closure

of one or more travel lanes in one direction up to 15-kilometer long is permitted. No truck can travel through any work zone. Detour distances can be estimated using Google map provided with information on work zone lane closures and access points. Work zone posted speed limit is typically set at 40 km/h. Except for winter months from November to April of the subsequent year along the Xi'an-Hanzhong expressway alignment, contractor's work schedules of pavement maintenance and repair treatments are largely flexible. Preventive pavement maintenance is usually scheduled for 15 to 20 days in July to September of a given year and corrective pavement maintenance is primarily arranged for 15 to 30 days in May to June of the subsequent year. Pavement repair work typically lasts for 45 to 60 days, which is scheduled to begin in July and August and must be completed by mid-September to avoid excessive traffic disruptions prior to the China National Day of October 1st in each year. The 2010 Highway Capacity Manual [47] developed by the U.S. Transportation Research Board (TRB) is used as the main reference to determine highway capacities in absence and presence of work zones along the freeway section. Table 1 summarizes work zone characteristics.

Table 1: Summary of work zone characteristics.

Designation	Preventive Maint.	Corrective Maint.	Rehabilitation
Work zone length (km)	≤ 5	≤ 5	≤ 15
Work zone duration (days)	15- 20	15- 30	45- 60
Work activity schedule	July-September of a given year	May-June of the subsequent year	begins in July- August and ends in Mid-September
Contractor's operation schedule	8:00 am-18:00 pm	8:00 am-18:00 pm	8:00 am-18:00 pm
	Monday to Sunday	Monday to Sunday	Monday to Sunday
Speed limit (km/h)	40	40	40
Lane closure	One lane closure	One lane closure, with no truck in lane closure direction	Two-lane closure, with two-way traffic opened and no truck in both directions
Detour distance		Southbound to Hanzhong (142.5 km)	Northbound to Xi'an (258.3 km)

d. Traffic conditions. Historical traffic data from 2007 to 2016 is obtained from traffic countingstations installed along the freeway alignment. The raw data contains details of 24-hour directional hourly vehicle volumes and compositions on the 5th, 15th and 25th days of each month of a given year. The types of vehicles are classified into passenger cars, buses, light-duty trucks, and heavy-duty trucks with typical lengths of 4.5, 12, 7, and 11 meters, respectively. In 2008 when the freeway began the first year of service, AADT reached 5,790 vehicles comprised of 39.4%, 5.9%, 19.7%, and 35% of passenger cars, buses, light-duty trucks, and heavy-duty trucks. The corresponding vehicle occupancies were 2.3, 47, 2, and 2 riders. Field traffic data is available till 2016. For traffic projections beyond 2016 in the pavement service lifespan, historical traffic data from 2008 to 2016 is used to develop two S-shape non-truck and truck traffic growth curves.

Results

a. CO_2 emissions. Table 2 presents CO_2 emissions during the 15-year pavement service lifespan. The total CO_2 emissions are 6,160.36 tons/lane-km for the 15-year typical pavement life-cycle

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activity profile and are 6,197.11 tons/lane-km for the alternative life-cycle activity profile. This reveals that 36.76 tons/lane-km of CO_2 emissions could be reduced if the needed maintenance and repair treatments in the pavement service lifespan are timely implemented by the highway agency.

Table 2: CO_2 emissions estimated by typical and actual life-cycle profiles (ton/lane-km).

Year	CO_2 Emissions by								Total CO_2 Emissions		
	Normal Traffic		Work Zone Traffic		Detoured Traffic		Contractor's Work				
	Typical	Actual	Typical	Actual	Typical	Actual	Typical	Actual	Typical	Actual	DIFF[1]
2007	-	-	-	-	-	-	517.78	517.78	517.78	517.78	0
2008	139.05	139.05	0	0	0	0	0	0	139.05	139.05	0
2009	208.51	208.51	11.76	11.76	0	0	3.31	4.38	223.58	224.66	1.07
2010	223.56	189.1	0	37.36	0	0	0	5.93	223.56	232.39	8.83
2011	218.71	218.71	8.8	8.8	56.35	56.35	29.13	29.13	312.99	312.99	0
2012	273.23	273.23	0	0	0	0	0	0	273.23	273.23	0
2013	312.62	329.02	17.66	0	0	0	9.28	0	339.57	329.02	-10.55
2014	331.07	314.57	0	17.87	0	0	0	3.31	331.07	335.75	4.68
2015	366.81	400.17	11.99	0	249.86	0	63.67	0	692.33	400.17	-292.16
2016	413	378.57	0	22.95	0	271.93	0	63.67	413	737.13	324.13
2017	398.43	419.32	24.48	0	0	0	9.28	0	432.19	419.32	-12.87
2018	422.76	401.7	0	24.81	0	0	0	9.28	422.76	435.79	13.03
2019	401.45	403.73	19	25.02	94.35	0	29.13	9.28	543.94	438.03	-105.91
2020	426.37	402.84	0	19.07	0	95.01	0	29.13	426.37	546.05	119.68
2021	406.16	427.46	25.19	0	0	0	9.28	0	440.63	427.46	-13.17
2022	428.29	428.29	0	0	0	0	0	0	428.29	428.29	0
Total	4,970.03	4,934.28	118.89	167.64	400.55	423.28	670.88	671.91	6,160.36	6,197.11	36.76
% Total	80.70%	79.60%	1.90%	2.70%	6.50%	6.80%	10.90%	10.80%	100%	100%	
% DIFF		-0.70%		41%		5.60%		0.20%			0.60%

[1] DIFF= Difference between the CO_2 emissions estimated using typical and actual activity profiles, respectively.

For CO_2 emissions attributable to normal traffic, work zone mainline traffic, work zone detoured traffic, and contractor's work activities in pavement service lifespan, their shares are 79.6-80.7%, 1.9-2.7%, 6.5-6.8%, and 10.8-10.9% for the quantities estimated according to typical and actual life-cycle activity profiles. This finding indicates that work zone contributes to approximately 19.3-20.4% of total CO2 emissions and about 53-57% of work zone related CO_2 emissions is attributable to contactor's work activities. This finding suggests that work zone induced CO_2 emissions should be incorporated into estimation of total CO_2 emissions. Further, in presence of a major rehabilitation work in 2015 for the typical pavement life-cycle activity profile or in 2016 for the actual pavement life-cycle activity profile, the share of CO_2 emissions associated with work zone mainline traffic, work zone detour traffic, and contractor's work activities could increase drastically from 20% combined to (692.33- 366.81)/ 692.33= 47% or (737.13- 378.57)/ 737.13= 48.6%, respectively.

For CO_2 emissions computed using typical and actual pavement life-cycle activity profiles, the total quantities of CO_2 emissions produced by normal traffic and for contractor's work activities in pavement service lifespan are quite identical. For CO_2 emissions produced by normal traffic that amount to approximately 80% of total CO_2 emissions, the annual CO_2 emissions steadily increase from approximately 139 tons/lane-km in the first year to 428 tons/lane-km in the last year of the lifespan. Conversely, the quantities of CO_2 emissions by work zone mainline traffic and detoured traffic in presence of work zones estimated based on the actual pavement life-cycle activity profile are higher than those of the typical pavement life-cycle activity profile by 41% and 5.6%, respectively. Table 3 summarizes CO_2 emissions directly associated with initial construction, preventive and corrective maintenance, and rehabilitation work in pavement service lifespan. For each type of work, they are further categorized into CO_2 emissions from work zone mainline traffic, detoured traffic in presence of work zones, and contractor's work activities. In total, work zones related to construction, maintenance, and rehabilitation work activities contribute to about 19-20% of total CO_2 emissions in pavement service lifespan. Of all types of work, initial construction accounts for 41% of work zone related total CO_2 emissions, followed by rehabilitation work at 28.4%, corrective maintenance work at 18.8%, and preventive maintenance at 11.8%. Specifically, 78.4% of CO_2emissions of preventive maintenance is caused by work zone mainline traffic, 63.7% of CO_2 emissions of corrective maintenance work is caused by detoured traffic, and 75.8% of CO_2 emissions of rehabilitation work is caused by detoured traffic.

Table 3: Work zone-related co$_2$ emissions caused by construction, maintenance, and repair treatments according to actual pavement service life cycle profile.

Category of CO_2 emissions (tons/lane-km)	Initial Construction	Preventive Maint.	Corrective Maint.	Rehabilitation	Work Zone Total	
a. CO_2 emissions from work zone mainline traffic	-	116.82	27.87	22.95	167.64	13.30%
b. CO_2 emissions from detoured traffic in presence of work zones	-	-	151.35	271.93	423.28	33.50%
c. CO_2 emissions from contractor's work	517.78	32.19	58.27	63.67	671.91	53.20%
Work zone total	517.78	149.01	237.49	358.55	1,262.83	100%
	41.00%	11.80%	18.80%	28.40%	100%	
% life-cycle total (6,197.11 tons/lane-km)	8.40%	2.40%	3.80%	5.80%	20.40%	

b. Highway user costs. Table 4 summarizes key inputs for estimating user benefits in terms of savings of vehicle operating costs, reductions in travel time costs, and cutbacks of CO_2 emission costs if needed pavement maintenance and repair treatments are timely implemented according to the typical pavement service life activity profile. These inputs are associated with traffic characteristics, vehicle fuel consumption and unit rates, value of time, CO_2 emission and unit rates, pavement useful service life, and discount rate. Table 5 presents results of life-cycle highway user costs of vehicle operations, travel time, and air emissions estimated based on typical and actual pavement life-cycle activity profiles, respectively. For both cases, the total life-cycle highway user costs are similar, which amount to approximately 4,478,360 and 4,481,050 dollars per lane-km, respectively. The total user cost savings from the typical pavement life-cycle activity profile are 2,690 dollars per lane-km. Of which, travel time contributes to 68.7-68.8% of the total highway user costs, followed by vehicle operations at 29.7-29.8% and vehicle air emissions at 1.5%. For annual user costs of vehicle operations, travel time, and air emissions, the vehicle emission costs tend to remain stable in the pavement service lifespan. However, steady growths of annual user costs are observed for vehicle operations and travel time from \$37,360/lane-km and \$34,630/lane-km in the first year to \$93,640/lane-km and \$245,880/lane-km in the last year of pavement service life cycle, respectively. Therefore, a much fast pace of growth is revealed for travel time costs as opposed to vehicle operating costs.

Table 4: Key input data for user benefit calculation.

Category	Input Value						
Traffic characteristics	Monthly factor	May	June	July	August	September	
		1.16	1.21	1.1	1.02	1.01	
	Weekly factor	Monday	Tuesday-Thursday		Friday	Saturday	Sunday
		0.83	1.05		1.07	1.03	0.98
Fuel consumption (kg/VKT)	Speed (km/h)	Normal (65)		Work zone (40)		Detoured (80)	
	LDV	0.07		0.07		0.07	
	HDV	0.1		0.13		0.09	

CO_2 emissions rate (kg/VKT)	Speed (km/h)	Normal (65)		Work zone (40)	Detoured (80)
	LDV	0.2		0.22	0.22
	HDV	0.31		0.4	0.3
Fuel price from year 2008 to year 2022 ($/kg)	Gasoline	0.89-1.63			
	Diesel	0.88-1.40			
Value of time from 2008 to 2022 ($/hour)		0.95-3.41			
CO_2 emissions price ($/ton)		20			
Pavement service life (year)		15			
Discount rate		5.50%			

Note: VKT= Vehicle kilometers of travel; LDV= Light-duty vehicle; and HDV= Heavy-duty vehicle.

Table 5: Estimated highway user costs and benefits using typical and actual pavement life-cycle activity profiles ($1,000/lane-km, in 2007 constant dollars).

Year		Highway User Costs							Million VKT		Benefits			
	VOC		TTC		EC		Total				VOC	TTC	EC	Total
	Typical	Actual	Typical	Actual	Typical	Actual	Typical	Actual	Typical	Actual				
2008	37.36	37.36	34.63	34.63	2.56	2.56	74.55	74.55	43.68	43.68	0	0	0	0
2009	64.88	64.88	50.06	50.06	3.84	3.84	118.78	118.78	67.07	67.07	0	0	0	0
2010	70.78	72.13	59.91	60.69	3.69	3.74	134.39	136.57	68.85	68.85	0.38	0.68	0.02	1.08
2011	95.35	95.35	110.95	110.95	4.45	4.45	210.75	210.75	77.1	77.1	0	0	0	0
2012	88.57	88.57	141.82	141.82	4.06	4.06	234.45	234.45	87.73	87.73	0	0	0	0
2013	104.93	104.39	199.59	198.64	4.65	4.63	309.17	307.66	108.55	108.55	-0.87	-0.37	-0.02	-1.26
2014	92.05	92.58	217.77	218.94	4.42	4.43	314.24	315.95	110.09	110.09	1.16	0.57	0.02	1.76
2015	149.31	97.18	297.45	285.03	8.07	5.06	454.84	387.26	185.5	134.96	-19.15	-2.88	-0.14	-22.17
2016	86.34	134.89	302.98	317.23	4.95	8.07	394.27	460.19	139.55	191	23.24	2.8	0.14	26.18
2017	75.46	74.62	306.03	300.94	4.8	4.76	386.3	380.33	141.7	141.7	-4.78	-0.36	-0.03	-5.17
2018	81.29	82.19	293.22	298.23	4.55	4.59	379.06	385.01	142.8	142.8	4.16	0.73	0.03	4.92
2019	104	87.94	284.76	288.12	5.25	4.38	394.02	380.44	147.93	143.44	3.39	0.16	0.01	3.56
2020	91.74	110.13	270.69	272.76	4.12	5	366.55	387.89	143.87	148.39	1.22	0.4	0.01	1.63
2021	96.9	95.78	262.9	258.29	3.96	3.92	363.75	357.99	144.17	144.17	-3.73	-0.9	-0.03	-4.66
2022	93.64	93.64	245.88	245.88	3.72	3.72	343.25	343.25	144.4	144.4	0	0	0	0
Total	1,332.63	1,331.63	3,078.64	3,082.21	67.09	67.21	4,478.36	4,481.05	1,752.98	1,753.93	5.02	0.83	0.02	5.87
(%)	29.80%	29.70%	68.70%	68.80%	1.50%	1.50%	100%	100%			85.50%	14.10%	0.30%	100%

Summary and Conclusion

This paper has proposed a methodology for estimation of CO_2 emissions and highway user costs in the pavement service life cycle. The analysis considers traffic operations in normal and work zone conditions, respectively. The CO_2 emissions in pavement service life cycle are classified into CO_2 emissions caused by normal traffic, work zone mainline traffic, detoured traffic owing to work zone control, and contractor's work activities related with material processing and handling, to-site transportation, and on-site work operations. For normal and work zone traffic induced CO_2 emissions, they are quantified by emission factors and vehicle kilometers of travel associated with light- and heavy-duty vehicles.

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For contractor related CO_2 emissions, they are estimated by cradle-to-gate the method and the pump-to-wheel cycle method. The highway user cost components mainly include costs of vehicle operations, travel time, and CO_2 emissions for normal and work zone traffic conditions according to respective unit cost rates and vehicle kilometers of travel for light-duty and heavy-duty vehicles.

A computational experiment is carried out using data on geometric design, traffic operations, and records of construction, maintenance, and repair work in the 15-year service lifespan of Xi'an-Hanzhong freeway corridor in Shaanxi Province, China. The CO_2 emissions in pavement service life cycle is approximately 6,197 tons per lane-km with 80/10/10 split attributable to normal traffic, work zone-related traffic, and contractor's work activities. The highway user costs in pavement service life cycle are approximately $4,481,000 per lane-km in 2007 constant dollars with 69% attributable to travel time. In addition, about 37 tons per lane-km of CO_2 emissions and $5,870 per lane-km of highway user costs could be saved if the needed maintenance and repair treatments could be timely implemented.

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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