

Tool for the analysis of CO₂ emissions on asphalt pavement roads: case study in Baja California, Mexico.

Herramienta para el análisis de emisiones de CO₂ en carreteras de pavimento asfáltico: caso de estudio Baja California, México.

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How to cite

J. D. Flores Ruiz, M. A. Montoya Alcaraz, L. G. García Gómez, and C. C. Martínez Lazcano, "Tool for the analysis of CO₂ emissions on asphalt pavement roads: case study in Baja California, Mexico." *Engineering: Science, Technology, and Innovation*, vol. 12, 2025.

<https://doi.org/10.26495/dx868577>

Article information

Received: 06/05/2025

Accepted: 31/08/2025

Published: 30/12/2025

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ABSTRACT: *The objective of this research was to develop and implement a tool to calculate carbon dioxide emissions generated during the use and end-of-life phases of a section of asphalt pavement, considering as a case study a section of the Mexicali-San Felipe road in Baja California, Mexico, with an analysis period of 35 years. The methodology employed consisted of applying the principles of Life Cycle Assessment (LCA) established in the ISO 14040 and 14044 standards, collecting specific data such as vehicle traffic, pavement geometry and structure, and the fuel efficiency and consumption of the machinery used to remove and transport the asphalt material. The results showed that during the study period, the use phase generated approximately 147.56 tonnes of CO₂ associated with projected vehicle traffic, reflecting a cumulative impact from the continuous use of the road, while the end-of-life phase contributed 61.33 tonnes of CO₂ generated by the removal and disposal of damaged materials (construction waste). Therefore, it is concluded that both stages contribute significantly to the total impact of the pavement and should be incorporated into future LCA studies to obtain a more accurate environmental assessment. In this sense, the proposed tool is practical, adaptable, and replicable, providing support for sustainability-oriented decision-making in the design, operation, and rehabilitation of road infrastructure.*

Keywords: Asphalt pavements, carbon footprint, life cycle assessment, environmental impact, road transport.

RESUMEN: *El objetivo de la presente investigación fue desarrollar e implementar una herramienta para calcular las emisiones de dióxido de carbono (CO₂) generadas durante las etapas de fase de uso y fin de vida de una sección de pavimento asfáltico, considerando como caso de estudio un tramo de la carretera Mexicali-San Felipe, Baja California, México, con un periodo de análisis de 35 años. La metodología empleada consistió en aplicar los principios del Análisis de Ciclo de Vida (ACV) establecidos en las normas ISO 14040 y 14044, recopilando datos específicos como el tránsito vehicular, la geometría y estructura del pavimento, el rendimiento y consumo de combustible de la maquinaria utilizada para retirar y transportar el material asfáltico. Los resultados mostraron que durante el periodo de estudio, la etapa fase de uso generó aproximadamente 147.56 toneladas de CO₂ asociadas al tráfico vehicular proyectado, lo que refleja un impacto acumulativo por el uso continuo de la carretera, mientras que la de fin de vida aportó 61.33 toneladas de CO₂ generadas por las actividades de retiro y eliminación de materiales dañados (residuos de construcción). Por lo tanto, se concluye que ambas etapas contribuyen de forma significativa al impacto total del pavimento y que se deben de incorporar en los próximos estudios de ACV para obtener una evaluación ambiental más precisa. En este sentido, la herramienta propuesta es práctica, adaptable y replicable, que representa un apoyo para la toma de decisiones orientadas a la sostenibilidad en el diseño, operación y rehabilitación de la infraestructura vial.*

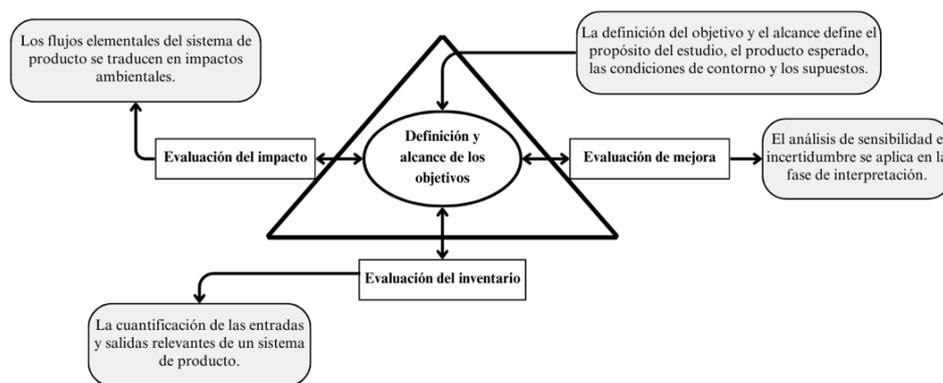
Palabras Claves: Pavimentos asfálticos, huella de carbono, análisis del ciclo de vida, impacto ambiental, transporte por carretera.

1. INTRODUCTION

The environmental impact of road infrastructure has become an area of growing interest in recent years due to the impact of greenhouse gas emissions and the depletion of natural resources. Asphalt pavements, widely used on roads worldwide, generate a significant amount of CO₂ (carbon dioxide) emissions not only during their construction and maintenance, but also during their use and at the end of their useful life. Furthermore, it has been determined that total CO₂ emissions from global energy consumption amounted to 37,079.18 million tonnes in 2023 [1]. This continuous increase in emissions has significant repercussions on public health. For example, [2] mentions that a significant relationship was found between traffic-related air pollution and hospital visits for acute bronchitis (AB) in children, particularly school-age children during cold seasons. In addition, in 2019, the World Health Organisation (WHO) estimated that 99 out of every 100 people breathe polluted air and live in places where air quality levels exceed the limits set by the WHO [3].

To address this problem, various alternatives have been devised, one of which is the implementation of Life Cycle Assessment (LCA), a methodology that provides a comprehensive and systematic assessment of the environmental impacts of products and systems throughout their life cycle, from the extraction of raw materials to their final disposal [4], [5]. The methodological approach is provided by the guidelines established in the ISO 14040 and ISO 14044 standards, which define four interrelated stages of LCA: objective and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation, as shown in Figure 1 [6], [7].

Figure 1. LCA approach according to ISO 14044.



Source: own elaboration.

Within the field of road infrastructure, the implementation of life cycle assessment in pavements is of great importance as it allows the environmental effects associated with the road sector to be assessed. This approach allows the measurement of the ecological impacts generated throughout the service life of the pavement, ranging from the extraction and production of materials to their final disposal. One of these impacts is the quantification of greenhouse gas emissions generated by the various activities that constitute each stage of the life cycle. Excessive emissions of these gases are one of the main drivers of global climate change, with carbon dioxide being the main contributor, accounting for approximately 60% of the greenhouse effect [8]. This research also analyses asphalt pavements, as they are widely used throughout the world due to their good performance on roads, easy rehabilitation and the comfortable driving conditions they offer [9].

Several studies have addressed the environmental impact of the pavement life cycle. Research such as [10] and [11] has shown that replacing virgin materials with a percentage of crushed plastic reduces CO₂ emissions by 20%, and using recycled asphalt pavement reduces emissions by 30%. In addition, recent studies have highlighted the

importance of using warm asphalt mix for the construction of the pavement wearing course, as it has a 15% lower environmental impact than hot asphalt mix. This is because the production of warm asphalt mix saves between 12% and 14% in fuel [12]. Therefore, the implementation of sustainable design strategies, together with carbon capture and storage (CCS) systems, can reduce CO₂ emissions by 10%. This requires establishing clear guidelines that prioritise environmentally friendly practices and climate change mitigation technologies [13].

The objective was to develop a tool to analyse CO₂ emissions generated during the use and end-of-life phases of asphalt pavements. It is sought to assess the environmental impact of road operation, consider the life span and determine the amount of emissions generated during pavement removal and final disposal processes. It also takes as a reference a case study located in Mexico, on the Mexicali-San Felipe highway.

2. MATERIALS AND METHODS

The method proposed to quantify CO₂ emissions from the 'use phase' and 'end-of-life' stages is through two models, which are:

- Analysis model for the Use Phase stage.
- Analysis model for the end-of-life stage.

In order to carry out the emissions analysis using the different models proposed, information must be collected first. This initial stage allows the necessary data on the inputs, processes and activities involved to be obtained, which is key to estimating the associated emissions.

2.1 Data collection

In order to carry out the analysis of the stages indicated, various data about the case study must be taken into consideration. Information about the geometry and structure of the pavement, road data and pavement maintenance strategies must be available in order to determine the service life of the road.

2.1.1 Pavement geometry and structure

The geometry of a pavement refers to the shape, design and physical characteristics of the road, taking into account the dimensions of the lanes on which vehicles travel, the horizontal and vertical orientation, the slopes and other aspects that affect traffic safety and comfort. The structure of a pavement refers to the arrangement and composition of the various layers of material that make up the road, from the subgrade to the wearing surface. The purpose of the structure is to provide strength and durability to the pavement, to withstand traffic loads and ensure user safety. For this study, data obtained from the auscultation carried out by the SICT (Secretariat of Infrastructure, Construction and Transport of Mexico) in 2022 was used. The case study has two lanes (3.5 metres wide per lane) and a hard shoulder (2 metres wide) in each direction, as well as a 7.5-metre-wide central reservation. The case study is shown in Figure 2.

Figure 2. Section of the case study.



Source: own elaboration.

In addition, the pavement structure of the case study consists of three layers: the subgrade, the granular base, and the surface layer, which is the asphalt pavement, with a total length of 7.8 km. The thickness of the asphalt pavement is 18.8 cm, the granular base is 19.4 cm, and the sub-base is 23.8 cm.

2.1.2 Road data

In Mexico, vehicles are classified into three categories: light vehicles, heavy vehicles, and special vehicles. This classification is detailed below, and Figure 3 illustrates this categorisation schematically, based on the Official Mexican Standard [14], which establishes the maximum dimensions and permitted weight for transport vehicles travelling on roads under federal jurisdiction.

Light vehicles: These are vehicles with two axles or four wheels.

Heavy vehicles: These are vehicles designed to transport cargo or passengers and have two or more axles and six or more wheels.

Special vehicles: These are intended for specific uses, such as special trucks and trailers used to transport heavy machinery, bulky loads, and agricultural and construction machinery that occasionally travel on roads.

Figure 3. General classification of vehicles.

Tipo de Vehículo	Número de ejes	Esquemas		Símbolo	
		Perfil	Planta		
Ligeros	Automóvil	2			A2
	Camionetas				A'2
Pesados	Autobuses	2			B2
		3			B3
	Camiones	2			C2
		3			C3
				T2-S1	
		5			T3-S2
		6			T3-S3
		9			T3-S2-R4
Especiales	Camiones y/o Remolques	Variables			
	Maquinaria agrícola				
	Bicicletas				
	Otros				

Source: Extracted from [14].

The road data for the case study is provided annually in the form of reports and allows for the identification of sections with higher or lower traffic volumes, as well as other important aspects such as the average annual daily traffic (AADT). Determining vehicle

traffic growth rates is essential for more accurately forecasting the estimated life of the pavement.

From the publication of Road Data by the General Directorate of Technical Services of Mexico from 2011 to 2019 and for the year 2022, omitting the years affected by the pandemic in the area (2020 and 2021), the annual growth rates and vehicle classification were obtained as described in Tables 1 and 2 below.

Table 1. Road data used for direction 1 from Mexicali to San Felipe.

Mex - San Felipe	
Year	AADT
2011	9117
2012	9066
2013	10146
2014	10293
2015	10170
2016	9972
2017	11427
2018	12254
2019	12015
2022	13475

Source: own elaboration using road data from the General Directorate of Technical Services of Mexico for the year 2023 (updated as of 1 January).

Table 2. Road data used for direction 2 from San Felipe to Mexicali.

San Felipe - Mexicali	
Year	AADT
2011	8960
2012	9140
2013	10101
2014	10224
2015	8564
2016	9926
2017	11359
2018	12021
2019	11473
2022	11237

Source: own elaboration using road data from the General Directorate of Technical Services of Mexico for 2023 (updated as of 1 January).

Table 3 shows the traffic counts, vehicle classification and AADT for the study section, information provided by the Secretariat of Communications and Transport of Mexico (SCT).

Table 3. Vehicle classification and AADT for the study section.

Mexicali - San Felipe Highway				CODE 02096		ROUTE: MEX-005				YEAR: 2022		
LOCATION	STATION			AADT	VEHICLE CLASSIFICATION IN PERCENTAGE							
	KM	TE	SC		M	A	B	C2	C3	T3S2	T3S3	T3S2R4
Direction 1	0	3	1	13475	6.40 %	78.90%	1.70%	4.20%	3.60%	3.60%	1.00%	0.60%
Direction 2	0	3	2	11237	6.70 %	79.40%	1.70%	3.70%	4.00%	3.00%	1.00%	0.50%

Source: own elaboration using road data from the General Directorate of Technical Services of Mexico for the year 2023 (updated as of 1 January).

2.2 Analysis model for the Use Phase stage

This model is based on the one proposed by Hammerstrom [15] and predicts vehicle exhaust emissions based on fuel consumption and speed.

Fuel consumption is a function of vehicle speed, which in turn depends on the characteristics of the road and the vehicle itself. The coefficients and variables mentioned in the formulas come from various studies under controlled conditions that have allowed the creation of tables with recommended values for use in the model.

Equation 1 is used to determine the amount of CO₂ emissions generated by each type of vehicle during the use phase. This equation is based on the model proposed by Hammerstrom to predict vehicle exhaust emissions.

Equation 1 is used to calculate CO₂ emissions.

$$E_{CO_2} = \frac{3.6 a_0 IFC 10^3}{vel} \quad (1)$$

Where:

E_{CO_2} = CO₂ emissions in g/vehicle per km

IFC = Instantaneous fuel consumption, in ml/m

a_0 = Model parameter

vel = Vehicle speed in km/h

On the other hand, to obtain the results, it is necessary to apply (2), which uses the CO₂ emissions generated by each type of vehicle in grams per kilometre travelled, the average annual traffic, the vehicle classification and also the total distance of the road section being analysed.

$$TEOC = (AADT * CLV)(E_{CO_2})(D) \quad (2)$$

Where:

$TEOC$ = Total emissions per road operation

$AADT$ = Average annual daily traffic

CLV = Vehicle classification

E_{CO_2} = CO₂ emissions in g/vehicle per km

D = Distance in kilometres

The above is for calculating CO₂ emissions for the year 2022 only. Therefore, to calculate emissions for subsequent years, it is necessary to know the AADT for the entire analysis period. The pavement analysis period was determined using the RevPav-5 programme, which allows us to know the expected life of an existing pavement structure, knowing its geometric and resistance parameters for each layer, such as thicknesses, CBR values, Residence Modules and Poisson's Ratio, obtaining as a result that the pavement structure needs to be rebuilt in 2057, leaving an analysis period from 2023 to 2057 [16].

Likewise, to calculate the AADT for the years after 2022, a scatter plot was created based on the AADT recorded during the period from 2011 to 2022, omitting the years 2020 and 2021 due to records affected by the COVID-19 pandemic.

The scatter plots were created using the Microsoft Excel software, with the data from Tables 1 and 2, resulting in equations (3) and (4).

$$Y = 405.07x - 80570 \quad (3)$$

$$Y = 263.87x - 521575 \quad (4)$$

Equation 3 is used to determine the AADT for the coming years from Mexicali to San Felipe, where the variable 'x' is the year to be determined. The same applies to the San Felipe - Mexicali direction with equation 4.

2.3 Analysis model for the end-of-life stage

Since the pavement was rebuilt with a new design, the material that no longer met the functionality requirements of the new pavement was removed, including the granular base layer and the asphalt surface course.

The granular base is removed using a motor grader scarifier to loosen the granular base layer and a front loader to place it in the gondola that will transport the material to the deposit site. The asphalt layer was removed using a milling machine, which cuts and lifts the pavement using rotating blades. The loader then placed the removed asphalt material in the gondola to be transported to the disposal site, located 8.1 kilometres away.

It should be noted that the materials are transported by a 30m³ capacity tipper truck, better known as a gondola truck. Transporting the material requires the use of a front loader with a capacity of 150m³/h to place the material inside the gondola truck, which has the capacity to transport 30m³ per trip, generating 1.84 kgCO₂ per kilometre travelled [17]. In addition, it is estimated that the consumption of 1 litre of diesel generates approximately 2.69 kgCO₂ [18]. The performance of the machinery and fuel consumption are shown in Table 4 and the transport route is illustrated in Figure 4.

Table 4. Performance and fuel consumption of machinery.

Machinery required	Performance	Consumption unit
Pavement milling machine	500 m ² /h	37 L/h
Front loader	150 m ³ /h	8 L/h
Motor grader	460 m ² /h	15 L/h

Source: own elaboration.

The amount of emissions generated by the machinery is determined as follows:

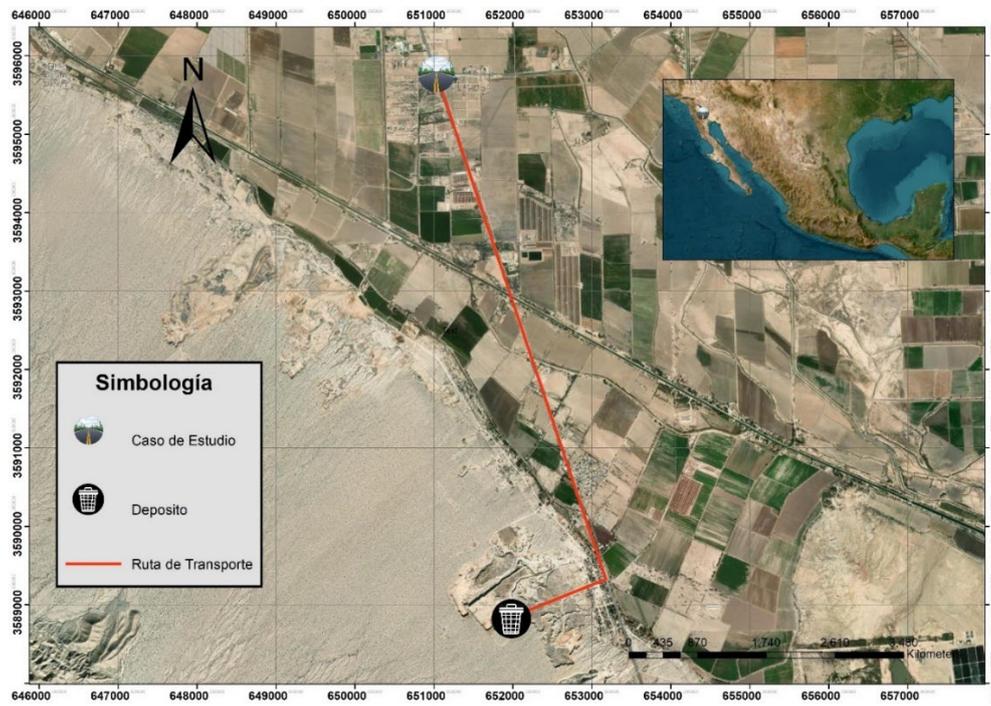
- Determination of the total work area in cubic metres for the pavement milling machine and in square metres for the motor grader.
- Calculation of the hours of operation of the machinery in relation to its performance throughout the entire period of operation to complete the removal of the material.
- Obtainment of the total litres consumed by each type of machinery in relation to the total hours of operation.
- The emissions generated by the use of the different types of machinery are obtained by multiplying the litres of diesel consumed by the factor 2.69 kg of CO₂.

To determine the emissions generated by the transport of materials, the following points are used:

- Determination of the volume of material to be transported, considering the abundance factor of 12%.
- Calculation of the working hours of the front loader with respect to its performance and the volume of material to be placed in the gondola truck.
- Obtainment of the diesel consumption (litres) for the total work to be performed to

- load the 30m³ trucks.
- Multiplication of the total litres consumed by the CO₂ emissions factor generated by consuming one litre of diesel.
- Determination of the number of trips the gondola truck must make by dividing the total amount of material to be transported by the truck's capacity.
- The total emissions generated by the truck's journey from the material bank to the disposal site are obtained by multiplying the number of trips by the distance travelled on each trip (km) and by the emissions factor generated for each kilometre travelled.

Figure 4. Transport route, case study - disposal site.



Source: own elaboration.

3. RESULTS

As part of the Life Cycle Assessment applied to the case study, the CO₂ emissions generated during the use and end-of-life stages of the pavement were evaluated. These stages are often less explored in traditional studies, even though they can represent a significant fraction of the total environmental impact of the system.

3.1 Use Phase

During the use phase, emissions associated with vehicular traffic on the analysed road section were estimated, taking into account the projected growth in Annual Average Daily Traffic (AADT) from 2023 to 2057. The estimate considers the distance of the section and the number of vehicles that travel on the road annually. Therefore, the results show a progressive increase in emissions, directly related to the growth of AADT. For example, in the Mexicali–San Felipe direction, emissions increased from 1.55 TonCO₂ in 2023 to 3.10 TonCO₂ in 2057, while in the opposite direction they went from 1.38 to 2.40 TonCO₂ during the same period, as shown in Table 5.

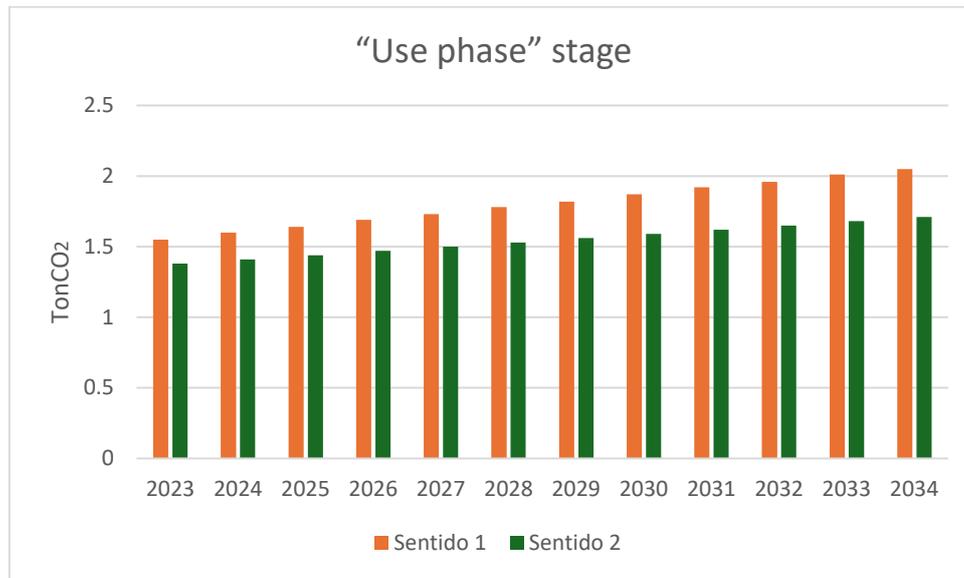
Table 5. Total emissions generated by different activities in the “use phase” stage.

Direction 1			Direction 2		
Year	AADT	TonCO ₂	Year	AADT	TonCO ₂
2023	13,756	1.55	2023	12,234	1.38
2024	14,161	1.60	2024	12,498	1.41
2025	14,566	1.64	2025	12,762	1.44
2026	14,971	1.69	2026	13,026	1.47
2027	15,376	1.73	2027	13,289	1.50
2028	15,781	1.78	2028	13,553	1.53
2029	16,186	1.82	2029	13,817	1.56
2030	16,591	1.87	2030	14,081	1.59
2031	16,996	1.92	2031	14,345	1.62
2032	17,401	1.96	2032	14,609	1.65
2033	17,806	2.01	2033	14,873	1.68
2034	18,211	2.05	2034	15,137	1.71
2035	18,616	2.10	2035	15,400	1.74
2036	19,022	2.14	2036	15,664	1.77
2037	19,427	2.19	2037	15,928	1.80
2038	19,832	2.23	2038	16,192	1.83
2039	20,237	2.28	2039	16,456	1.86
2040	20,642	2.33	2040	16,720	1.89
2041	21,047	2.37	2041	16,984	1.92
2042	21,452	2.42	2042	17,248	1.95
2043	21,857	2.46	2043	17,511	1.98
2044	22,262	2.51	2044	17,775	2.01
2045	22,667	2.55	2045	18,039	2.04
2046	23,072	2.60	2046	18,303	2.07
2047	23,477	2.65	2047	18,567	2.10
2048	23,882	2.69	2048	18,831	2.13
2049	24,287	2.74	2049	19,095	2.16
2050	24,693	2.78	2050	19,359	2.19
2051	25,098	2.83	2051	19,622	2.22
2052	25,503	2.87	2052	19,886	2.25
2053	25,908	2.92	2053	20,150	2.28
2054	26,313	2.96	2054	20,414	2.31
2055	26,718	3.01	2055	20,678	2.34
2056	27,123	3.06	2056	20,942	2.37
2057	27,528	3.10	2057	21,206	2.40
Amount of emissions		81.41	Amount of emissions		66.15

Source: own elaboration.

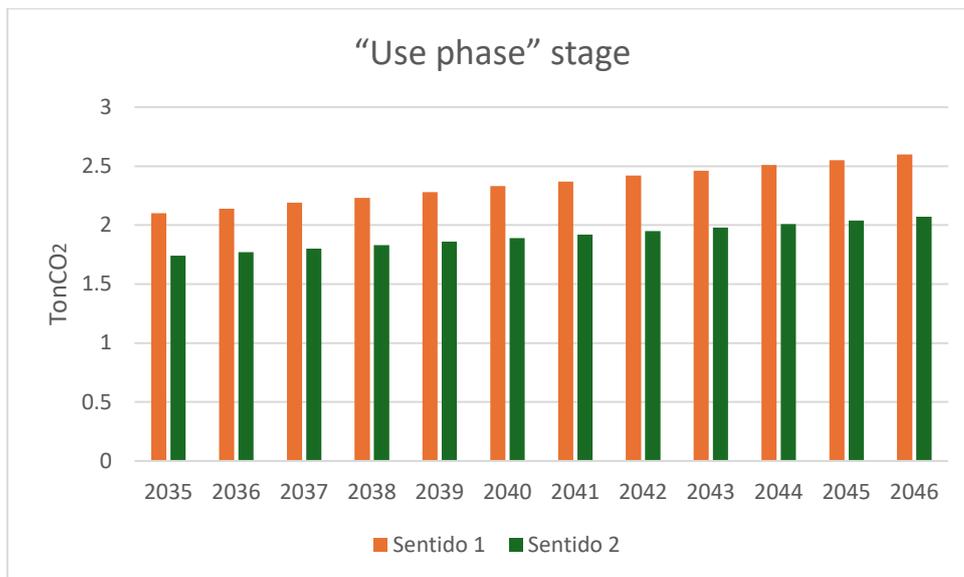
The cumulative result of emissions for both directions of traffic was 147.56 tonnes of CO₂, broken down into 81.41 tonnes of CO₂ for direction 1 and 66.15 tonnes of CO₂ for direction 2. This progressive increase in emissions over the years reflects the sustained growth in traffic and highlights the importance of considering this stage in LCA studies on road infrastructure. Figures 5, 6 and 7 also show this same data.

Figure 5. Total emissions generated in the different activities in the “use phase” stage, from 2023 to 2034.



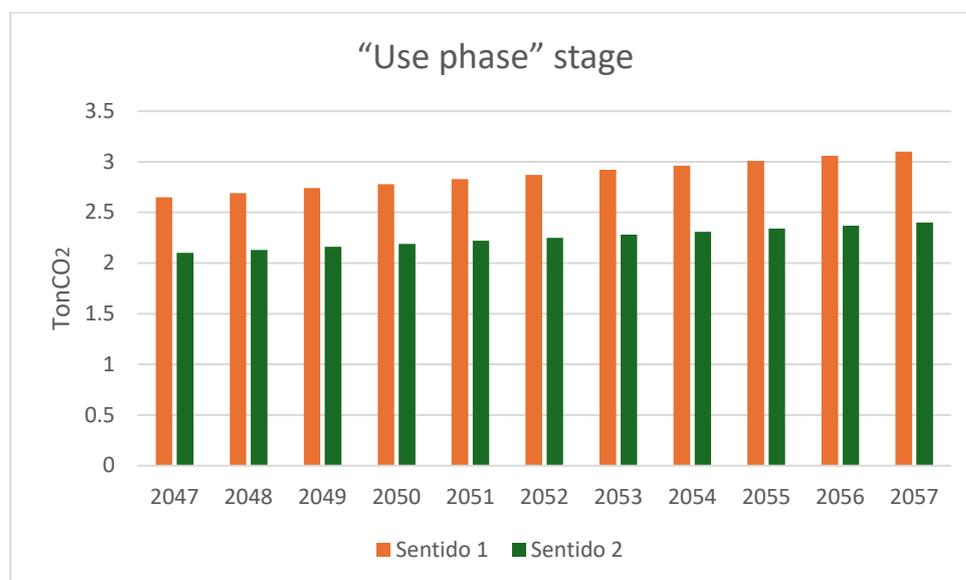
Source: own elaboration.

Figure 6. Total emissions generated in the different activities in the “use phase” stage, from 2035 to 2046.



Source: own elaboration.

Figure 7. Total emissions generated in the different activities in the “use phase” stage, from 2047 to 2057.



Source: own elaboration.

3.2 End of life

The end-of-life stage considers emissions generated by the use of machinery for the demolition of the asphalt pavement and granular base, as well as the transport of waste to the disposal site. Unlike the use phase, in this case it is a one-off event associated with the reconstruction of the pavement at the end of its service life.

- **Asphalt pavement**

The emissions generated by the use of machinery to remove the asphalt pavement are shown in Table 6, and the emissions generated by transporting the material are shown in Table 7.

Table 6. Emissions generated by the use of machinery to remove the asphalt pavement.

Machinery	Performance	Amount of work	Hours worked	Consumption unit	Litres consumed	TonCO ₂
Pavement milling machine	500 m ² /h	109,200 m ²	219	37 L/h	8,103	21.80

Source: own elaboration.

Table 7. Emissions generated by the transport of the discarded asphalt pavement from the case study to the disposal site.

Machinery	Performance	Amount of work (m ³)	Hours worked	Consumption unit	Litres consumed	KgCO ₂	TonCO ₂
Front loader	150 m ³ /h	22,993.2	153	8 L/h	1,224	3,292.6	3.29
Machinery	Performance	Amount of work (m ³)	Trips	Distance (km)	Emissions per km	KgCO ₂	TonCO ₂
Gondola	30 m ³ - trip	22,993.2	767	8.1	1.84 KgCO ₂	11,431.4	11.43

Source: own elaboration.

In the case of the asphalt layer, 21.80 TonCO₂ were accounted for by the use of machinery (milling machine) and a total of 14.72 TonCO₂ by transport activities (front loader and gondolas), adding up to a total of 36.52 TonCO₂.

- **Granular base**

The emissions generated by the use of machinery to remove the granular base are shown in Table 8, and the emissions generated by transporting the material are shown in Table 9.

Table 8. Emissions generated by the use of machinery to remove the granular base.

Machinery	Performance	Amount of work	Hours worked	Consumption unit	Litres consumed	Ton CO ₂
Motor grader	460 m ² /h	109,200 m ²	238	15 L/h	3,570	9.60

Source: own elaboration.

Table 9. Emissions generated by the transport of the discarded granular base from the case study to the disposal site.

Machinery	Performance	Amount of work (m ³)	Hours worked	Consumption unit	Litres consumed	KgCO ₂	TonCO ₂
	150 m ³ /h	23,726.9	159	8 L/h	1,272	3,421.7	3.42
Machinery	Performance	Amount of work (m ³)	Trips	Distance (km)	Emissions per km	KgCO ₂	TonCO ₂
Gondola	30 m ³ - trip	23,726.9	791	8.1	1.84 KgCO ₂	11,789.1	11.79

Source: own elaboration.

As for the granular base, emissions per machine (motor grader) were 9.60 TonCO₂, while transport generated 15.21 TonCO₂, for a total of 24.81 TonCO₂.

Therefore, the end-of-life stage of the pavement contributed 61.33 tonnes of CO₂, which represents a significant contribution to the total impact of the system evaluated.

4. DISCUSSION

4.1 Added value of the research

This study presents a new way of assessing the environmental impact of asphalt pavements by explicitly incorporating the use and end-of-life stages into the life cycle assessment. Most previous research in Mexico and internationally tends to focus more on the stages of material extraction and production, pavement construction, and maintenance and rehabilitation, ignoring the later stages. The tool developed not only allows CO₂ emissions to be quantified in these stages, but is also adaptable to different contexts and road conditions, making it a replicable resource for similar projects.

4.2 Limitations of the study

Emissions in the use phase were estimated using the model proposed by Hammerstrom in 1995, which does not consider variables such as acceleration, braking, roughness (International Roughness Index - IRI) or traffic congestion that may occur in the case study. Therefore, these variables could increase actual emissions in urban scenarios or scenarios with irregular traffic. Furthermore, the research is limited to a single case study (the Mexicali-San Felipe highway), so the conclusions should not be generalised to other regions without adaptation. Other GHGs (greenhouse gases) such as methane (CH₄) or nitrogen oxides (NO_x) were not evaluated, which could provide a more complete picture of the environmental impact.

4.3 Practical implications

The results indicate that, over a period of 35 years, the use phase generated 147.56 tonnes of CO₂ and the end-of-life phase generated 61.33 tonnes of CO₂. This suggests that those responsible for road planning and management should:

- Improve pavement geometry and structure to reduce vehicle resistance and maintain a good level of service with respect to the IRI.
- Implement traffic management policies that promote the use of vehicles with lower emissions.
- Include technologies such as electric vehicles, which, although not considered in this study, would substantially modify emissions projections.
- Optimise the logistics of material transport and prioritise on-site recycling at the end-of-life stage to reduce emissions associated with machinery and transport.
- The adoption of more efficient or energy-efficient machinery.

4.4 Contrast with other studies

The results are consistent with recent reviews that point out that many LCAs applied to pavements do not consider or only address the use and end-of-life stages to a limited extent, which may not fully reflect the total effect of greenhouse gases. For example, of 67 studies analysed, the use phase and end-of-life phases were considered in fewer studies, where they accounted for around 41% and 24% of cases [19]. This is because the use phase is the most challenging and uncertain of all life cycle stages, as there may often be a lack of data or difficulties in accurately estimating the factors that may affect impacts at this stage [20].

Other studies have shown that reusing asphalt and using new technologies such as warm mix asphalt can reduce GHG emissions by between 12% and 19%. This is because the temperature of the mix is lower and energy consumption is reduced, while in scenarios with a high content of recovered asphalt, a reduction of up to 60% can be achieved [21], [22]. At the end-of-life stage, various studies indicate that the management of recovered pavement material, the use of recycled mixtures and on-site recycling can reduce emissions by up to 65%, depending on the proportion of recycled material [23], [24].

5. CONCLUSIONS

This study provides a broader view of how to assess the environmental impact of asphalt pavements. This is achieved by specifically including the use and end-of-life stages in the life cycle assessment. This approach responds to the limited attention these stages have received in national research and is in line with international trends in sustainable road infrastructure management. This allows for the detection of impacts that have been commonly overlooked but constitute a significant part of the total emissions generated throughout their life cycle.

The results obtained show that including these stages in the LCA of asphalt pavement is essential for obtaining a more accurate estimate of the environmental impact generated by the different activities that constitute each stage. It also highlights the importance of implementing mitigation measures both in the daily operation of the road and at the end of its useful life, for example:

- During the use phase: To optimise traffic flow, promote sustainable transport or use pavements with lower rolling resistance.
- At the end of life: To reuse materials, implement on-site recycling techniques or reduce emissions in demolition and transport processes.

In addition, the tool developed in this study offers a practical and adaptable solution for future LCAs in road projects by public and private organisations. Its design allows it to be

applied in different regional or technological contexts, facilitating a clear and consistent assessment of the damage that activities can cause to the environment. Its adoption could improve decision-making to promote more sustainable road infrastructure.

Finally, the research recommends expanding the analysis to incorporate other greenhouse gases and evaluate different pavement management scenarios in various climatic and traffic conditions. This will strengthen the technical basis for the design of low-carbon infrastructure policies and the adoption of more responsible construction practices. Therefore, systematically incorporating the use and end-of-life stages into LCA studies is not an option, but an essential requirement for moving towards sustainable roads that are capable of adapting to future challenges.

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