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Measurement of Road Transport Emissions. Case Study: Centinela-La Rumorosa Road, Baja California, México

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Abstract: Air pollution is a global issue, and the transportation sector is recognized as the third-largest contributor to anthropogenic greenhouse gas emissions. Vehicles emit a range of chemical compounds as a direct result of the combustion process. The nature and quantity of these emissions depend on the vehicle's characteristics, road, and local weather conditions. As a result, these emissions require special attention due to the adverse effects contributing to global warming and significantly impacting human health. In this regard, diagnosing and monitoring air quality is crucial for understanding the nature and quantity of emissions generated by various sources. However, in developing countries, the necessary inputs, and data for conducting such analyses are not always available. Therefore, the purpose of this study is to estimate emissions specifically generated from road operations. To achieve this, HDM-4 calculation tool is utilized to quantitatively estimate these emissions. This tool was applied in Baja California, Mexico, on the Centinela-La Rumorosa highway. The results obtained show that annually, 372.5 tons of pollutant emissions are generated, composed of HC, CO, CO_2, NO_x, Par, SO_2, and PB, covering a mere 128 kilometers of length within a state road network spanning 11,429 kilometers. This highlights the necessity of implementing strategies to reduce emissions or the environmental impact generated by vehicular operations on roads in developing countries.

Keywords: pollutant emissions; highways; CO_2; developing countries

1. Introduction

Since the late 1970s, air pollution has been one of the main topics on global political agendas. Before this period, it was believed that anthropogenic activities were largely responsible for negative environmental changes. However, it was not until then that scientific evidence emerged to support this assertion and the impact it had on a global scale. Nowadays, there is a generally accepted urgency to reduce environmental emissions due to the considerable harm caused by the resulting pollution [1]. This is why environmental pollution, global warming, and loss of biodiversity are concerns worldwide across different countries. Human activities exacerbate these issues. On the other hand, without raising awareness and taking preventive or mitigating measures, the causes of these problems could lead to irreparable consequences that would affect both our survival and the planet's [2]. As a result of 20th-century environmental concerns, various efforts have been made in favor of sustainability since the 21st century. For instance, the Johannesburg Summit on Sustainable Development in 2002 defined a broad and long-term vision for the future of environmental conservation on the planet. However, it is also recognized that long-term goals should not equate to postponing actions now. Therefore, environmental policies need to be implemented with a perspective that extends beyond the planned date for the next review of international agreements

and each country's borders [1]. On the other hand, the European Environment Agency (EEA) produced the State and Outlook of the European Environment report in 2005, concluding that significant progress had been made in the field. In this report, the intuitive understanding among the European population that environmental protection and economic growth are not mutually exclusive was highlighted. This understanding is confirmed by sampling studies, with over 70% of Europeans expressing the desire for decision-makers to give equal value to environmental, social, and economic policies [3]. Lastly, the International Energy Agency (IEA) stated in 2023 that over the past 5 years, the transportation sector has been the third-largest contributor to CO2 emissions, ranking only below the energy sector in first place and the industrial sector in second place.

Mexico is among the list of countries that contribute the most to climate change, a list led by the United States and China [4,5]. In 2002, Mexico contributed 643.183 million tons of CO2, of which 18% were generated by the transportation sector. Within this sector, vehicular operation accounted for 16.2%, with the remaining emissions attributed to other modes like aviation, rail, and maritime transport [6]. This highlights that within the transportation sector, vehicular operation is responsible for 90% of the emissions. On another note, the IEA states that by 2021, Mexico will contribute just over 400 million tons of CO2. This suggests that efforts made by various agencies and entities have helped decrease CO2 emissions. However, Mexico, like many other countries globally, has faced severe issues of pollution, environmental impact, and loss of natural resources. These issues mainly stem from three factors: rapid population growth, lack of planning strategies, and a lack of understanding of ecological value. Similarly, in Mexico, around 9,300 deaths occur annually due to causes associated with air pollution [7]. The World Health Organization (2004) states that these pollutant emissions primarily come from the transportation sector, whose inefficient fleet has significantly expanded in recent years. There are currently over 21 million cars circulating in the country, of which approximately 46% are more than 18 years old. This indicates that a significant portion of the cars are inefficient and consume large amounts of fuel. Combustion caused by these vehicles not only emits greenhouse gases but also releases suspended particles that contribute to poor air quality and public health impacts [8].

In this regard, the transportation sector is recognized as one of the major contributors to anthropogenic greenhouse gas emissions, particularly carbon dioxide (CO2) [9]. On the other hand, figures from the Organization for Economic Cooperation and Development (OECD) indicate that this sector accounts for approximately 27% of emissions in countries. Within this number, 55 to 99% of emissions are attributed to the road transport subsector, with two-thirds of these assigned to automobiles. This is why the issue of pollution caused by vehicle emissions has been of great global importance in recent decades, as it brings forth factors that affect both humans and the environment. Emissions from motor vehicles comprise a wide range of pollutants stemming from various processes, with exhaust emissions resulting from fuel combustion being among the most frequently considered. Key pollutants of concern in these emissions include carbon dioxide (CO2), total organic gases (TOG), carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM) [10]. It is important to note that the health effects of atmospheric particulate matter depend on particle size and chemical composition [11,12].

On the other hand, in 2009, the Ministry of Infrastructure, Communications, and Transport (SICT) published a methodological proposal for calculating emissions generated by the consumption of fossil fuels in urban transportation. In this proposal, atmospheric pollution in the Mexican Republic primarily originated from vehicles was recognized. Gathering the necessary information, such as fuel type, use of air conditioning, fuel consumption price, accumulated mileage, among other aspects. The results of this study indicate that CO represents an average of 84% of the total emissions generated. These emissions predominantly come from gasoline-fueled vehicles, as well as particulate matter. Meanwhile, heavy vehicles and diesel buses, constituting only 3% of the vehicle fleet, are the category that generates the highest emissions of nitrogen oxides, contributing 79%, and 74% of PM10 [13].

In the year 2011, the Emissions and Vehicle Activity Study was conducted in Baja California, in which the Government of California, the Sustainable Transport Center of Mexico, and the National Institute of Ecology and Climate Change (INECC) collaborated [14]. This study identified different

types of pollutant gas emissions from the vehicle fleet traveling in the main areas of Baja California, such as carbon monoxide (CO), carbon dioxide (CO2), total hydrocarbons (HC), and nitrogen oxide (NO). The results were compared with other cities in the northern and central regions of Mexico [14]. Regarding CO emissions, the border cities in northern Mexico are the ones producing the highest amounts, with vehicles alone responsible for over 90% of the total emissions [15].

Emission analyses provide a useful tool for air quality management. The results describe the extent of the pollutant burden and characteristics of the pollutant source, allowing for the development and updating of action plans with more effective strategies for air quality improvement [2]. Therefore, for the diagnosis and monitoring of air quality, it is essential to understand the nature and quantity of emissions generated by different sources of such pollutants. While there are various tools and methods available to reliably quantify emissions from any given source, the complexity, implementation costs, and data input requirements contribute to its restricted use in Mexico [1].

According to the literature, various methodological approaches exist for the identification and quantification of pollutant emissions. However, these approaches often involve a model with various input variables, and in developing countries, the application of such tools is challenging due to the lack of inputs and data required for their proper implementation. Therefore, the objective of this study is to adapt a methodology by incorporating calculation tools using available or easily obtainable information to quantitatively estimate pollutant emissions produced by vehicular transportation on roads. It is worth mentioning that emissions on roads are important to analyze because even though there might not typically be immediate populations near road sections, the emissions disperse into the atmosphere, negatively impacting the environment.

To validate the results, the Centinela—La Rumorosa highway (Figure 1) is used as a case study, located in the northwest of Mexico, specifically in the state of Baja California between the municipalities of Mexicali and Tecate. This road section is significant for the country, as it serves as the only land communication route connecting the states of Baja California and Baja California Sur with the rest of the country. The traffic on this highway averages around 7,000 vehicles daily, with a vehicle composition of 70% cars and 30% freight trucks. The highway consists of separated carriageways with varying alignments and different topographic conditions throughout its stretch. Both uphill and downhill sections span 64 kilometers in total length, comprising 40 kilometers on level terrain and 20 kilometers through mountainous terrain. It is important to highlight that this highway experiences an average of 200 accidents annually due to its complex system of curves and slopes, as well as the environmental conditions of the area. These conditions include minimum temperatures dropping below -7 degrees Celsius and maximum temperatures exceeding 54.3 degrees Celsius, coupled with strong winds, rain, and snow. Additionally, the highway is located in a seismic zone [16].
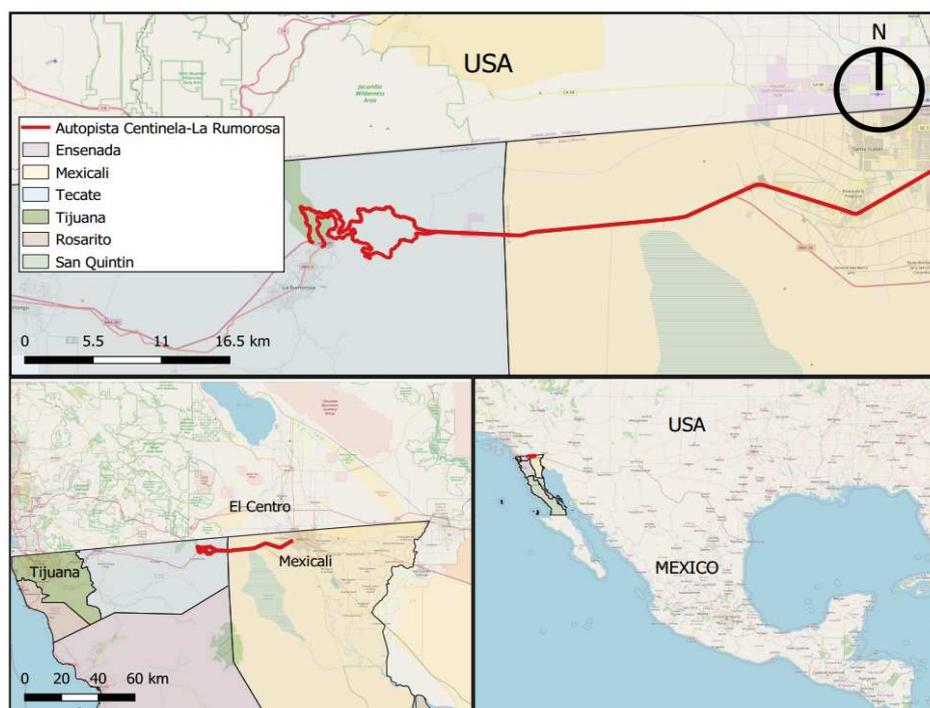
Figure 1. Case Study: Centinela—La Rumorosa Highway, Baja California, Mexico.

2. Literature Review

Road transport constitutes one of the essential elements of macroeconomic policies aimed at contributing efficiently and effectively to economic and social development, territorial integration, and spatial cohesion [17]. Roads not only yield economic benefits; at a fundamental level, roads provide access, although not all the benefits of providing access translate easily into economic outcomes [18]. In other words, roads are significant national assets providing an essential foundation for the functioning of all national economies and generate a wide range of economic and social benefits. Globally, roads are the primary transportation asset, spanning millions of kilometers. In terms of the value added by transportation services, road transport typically accounts for a percentage ranging from 3 to 5% of a country's GDP [18]. This underscores the evident contributions it brings to the economy become evident. However, despite all the benefits road transport provides, it also brings costs derived from accidents, problems caused in terms of pollution, land use, and infrastructure congestion [17]. For this research, special attention will be paid to the issue of pollution generated by road transport.

2.1. Generation of polluting emissions

In the first instance, it's important to mention that greenhouse gases are those that trap heat in the atmosphere. However, since the Industrial Revolution, human activities have significantly increased the amount of greenhouse gases present in the atmosphere, which has intensified the natural greenhouse effect. This, by raising the average planetary temperature, has serious effects on the climate. Some of the naturally generated gases are emitted into the atmosphere through both natural and anthropogenic processes. The main greenhouse gases emitted by human activities, particularly through the burning of fossil fuels, are carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O). On the other hand, anthropogenically generated gases include chlorofluorocarbons (CFCs), produced exclusively by industrial activities [19].

In the second instance, it is important to mention that certain pollutants have experienced significant growth since the end of the last century. For example, in the case of carbon dioxide, these progressive increases in Greenhouse Gas emissions mostly originate from road transportation [17], and in turn, one of the pollutant categories that greatly affect the environment is vehicular emissions

[4,6]. These environmental impacts are because vehicles are powered by internal combustion engines that run on gasoline, diesel, liquefied petroleum gas, natural gas, etc. An internal combustion engine operates based on the combustion of a compressed mixture of air and fuel inside a closed chamber or cylinder, to increase the pressure and generate sufficient power to propel the vehicle at the desired speed and with the required cargo. Through the combustion process, the chemical energy contained in the fuel is first transformed into thermal energy, part of which is converted into kinetic energy (movement), which in turn becomes useful work applied to the driving wheels. The other part is dissipated in the cooling system, exhaust gas system, accessory drives, and friction losses [20]. Furthermore, the quantity of emissions depends on the age, technology, usage, and maintenance of the engines [15]. In this regard, the motor vehicle is one of the main sources of atmospheric pollutant emissions, including CO [21].

According to the above, here is a brief description of the types of emissions generated by road transport:

- Carbon monoxide (CO) is generated from the incomplete combustion of organic matter, with one of the significant emission sources being transportation and the combustion of related fossil hydrocarbons. Even in small concentrations, it is toxic to humans. It serves as a precursor to carbon dioxide and ozone [22]. The effects of breathing in CO have been extensively studied in recent decades, particularly in Latin American countries where air quality and pollution are focal points that impact human health [21,23,24]. In some cases, cardiovascular and neuropsychological problems associated with low levels of this gas have been reported [23,24]. The emission of CO, which occurs between the earth's surface and the stratosphere, results from the incomplete combustion of carbon, usually caused by vehicular transportation or mobile sources [25,26], and it is both colorless and odorless [23,27]. When this pollutant gas combines with the hemoglobin in the blood, it reduces the flow of necessary oxygen to the human body [28].
- Carbon dioxide (CO_2) is a gas formed from the oxidation of carbon atoms during the combustion of all fuels. Emissions from anthropogenic sources are primarily attributed to energy production, vehicles, waste treatment plants, etc. [29]. When studying several types of gases, it is noteworthy that carbon dioxide is the primary one emitted into the atmosphere [17].
- Sulfur oxides (SO_x) are colorless gases that originate from the combustion of any substance containing sulfur. We encounter them artificially through the combustion of fossil fuels [32]. On the other hand, SO_2 is produced when burning coal and petroleum-derived fuels, which is why we find them in vehicles and automobiles. It is also a cause of acid rain.
- The primary anthropogenic source of nitrogen dioxide (NO_2) is from the use of fossil fuels [30]. This is one of the main contributors to smog, and when it converts to nitric acid, it can also lead to acid rain [29]. On the other hand, the most common natural sources are wildfires, grassland fires, and volcanic activity.
- Particulate matter (PM), also known as suspended particles, consists of solid fragments or droplets with various chemical compositions. PM10 refers to particles with a diameter smaller than 10 micrometers, and PM2.5 represents particles with a diameter smaller than 2.5 micrometers [29]. Among them, particles are generated from tire wear due to pavement friction, as well as dust particles.

According to the above, the operation of road transport generates significant negative effects on the environment. Directly, emissions generated by vehicle operations that contribute to atmospheric pollution in terms of air quality and global climate change were identified. Other aspects identified as environmental impacts of vehicle operation include traffic accidents, hazardous waste spills, and the generation of waste such as solid waste. [6].

2.2. Impact of emissions on the environment

The atmosphere is a common good essential for life, and everyone should conserve it. Due to its status as a non-renewable resource and the potential damages that pollution can cause to human health and the environment, air quality and atmospheric protection have been a priority in environmental policy for decades [31]. Air pollution is defined as the presence of substances or forms

of energy in the air that pose a risk, harm, or serious inconvenience to people and any type of property [32]. These emissions impact the environment both locally and in terms of human health, affecting natural resources and material goods in the area, as well as globally through the greenhouse effect. Air pollution is induced by the presence of toxic substances in the atmosphere, primarily produced by human activity. These gases and chemicals lead to a range of phenomena and consequences for ecosystems and living beings [33]. Pollutant substances, which can be emitted from various sources, become diluted in the atmosphere and undergo a variety of physical and chemical processes. For instance, they may react with other substances in the air or be broken down by sunlight. These substances can also be transported to areas different from where they were emitted, and eventually, can return to the Earth through rainfall or dry deposition. In these processes, these elements come into contact with receptors, which can be people, animals, plants, aquifers, soil, etc. Ultimately, these receptors are the ones that feel the effects of the air quality they come into contact with [34].

The accumulation of gases in the atmosphere creates environmental problems with well-known consequences: acid rain, depletion of the ozone layer, global warming, greenhouse effect, and more. The concentration of these gases in the atmosphere, primarily carbon dioxide, increases on average by 1% per year. This phenomenon is due to the properties of certain gases like carbon dioxide, methane, nitrous oxide, ozone, and chlorofluorocarbons to trap solar heat in the atmosphere, preventing it from escaping back into space after being reflected by the Earth. The effects of atmospheric warming include desert expansion, polar ice melting, rising sea levels, climatic catastrophes, biological stress, and potentially other unknown effects with corresponding impacts on human well-being and the global economy [2,35].

Nitrogen oxides, when exposed to sunlight, combine with unburned hydrocarbons, forming the visible pollutant known as photochemical smog. Likewise, acid rain is caused by the presence of nitrogen oxides and sulfur oxides derived from the combustion of fossil fuels mixing with moisture in the atmosphere [34]. This rain affects the levels of chemicals in soils and freshwater, disrupting food chains. Finally, it is important to mention that air pollution has a significant impact on the plant evolution process by hindering photosynthesis in many cases; with severe consequences for the purification of the air we breathe [33].

2.3. The importance of environmental monitoring on roads

As mentioned earlier, environmental pollution impacts the overall quality of our surrounding environment and can jeopardize our health and well-being. Therefore, environmental pollution control is necessary in nearly all communities and countries to safeguard the population's health [30].

Inventories represent one of the general methodologies applicable for quantifying emissions. The usage of these methodologies varies depending on the characteristics of each organization, activity, or product, as well as the objectives and strategies for mitigating greenhouse gas effects. Emission inventories serve as useful tools for environmental and public health policies, impacting on economic, industrial, energy, and transportation activities within a country. Likewise, inventories encompass reliable emission estimates and data that can be employed in managing and monitoring air quality, as this information can be traced over time and updated [6]. Emission data included in inventories constitute a compilation of both reported and estimated data (when measurements/reporting are not available and based on the accessible data) These estimations are founded on activity data and emission factors (quantity of emission per unit of activity), specific to each type of source. For instance, constructing the emissions inventory for a given year required the utilization of multiple sources and diverse databases [36]. Thus, environmental assessment serves to proactively identify actions that might potentially yield significant effects on natural resources, the quality of the local, regional, or national environment, and human health and safety. In this context, environmental assessment emerges as an important preventive measure that mitigates potential risks to the well-being of the natural environment.

Air pollution is a complex mixture of gases and particles whose sources and composition vary spatially and temporally. On the other hand, literature reviews conducted by the U.S. Environmental Protection Agency, the WHO, and others have demonstrated that prolonged exposure to

environmental air pollution increases mortality and morbidity from cardiovascular and respiratory diseases and lung cancer and shortens life expectancy [38].

In the United States, emission inventories are used for a wide variety of purposes, but the most common is for regulatory purposes. Emission inventory information is employed to assess the state of existing air quality in relation to air quality standards, and air pollution issues, evaluate the effectiveness of air pollution policy, and make necessary adjustments to regulatory frameworks. On the other hand, in Mexico, the Ministry of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales, SEMARNAT) uses emission inventories as strategic instruments for environmental management and administration, specifically for air quality. These inventories provide information about the type and quantity of pollutants emitted by each source, aiding in understanding the source's contribution to air quality [6].

In the case of transportation, from a sectoral perspective, inventories can consider measuring solely the fuel associated with vehicle usage, in such a way that only the greenhouse gas emissions when the vehicle is in operation are taken into account, quantifying direct emissions [39]. Environmental monitoring on roads is a system through which the environmental impact is assessed, using periodic measurements and the utilization of environmental indicators. It is commonly employed for monitoring and controlling environmental impacts during transportation infrastructure operations [40]. Emission models predict vehicle exhaust emissions based on road characteristics, traffic, and the vehicle. The main characteristics used for vehicular emission modeling are traffic volume and composition, type and geometry of the road section, vehicle operating speed, fuel type, and vehicle lifespan [41]. Exhaust emissions are one of the significant outputs of vehicle performance models, useful for evaluating the feasibility of investment options and the activities of environmental impact assessment [42].

The maximum emission limits are governed in different countries by European Union policies or those defined by the World Health Organization (WHO). Mexico has allowed emission limits for various types of motor vehicles that must be adhered to during vehicle operation. Several countries possess databases resulting from emission monitoring, aiding decision-making in the field. These decisions range from legal regulatory actions to vehicular enhancement measures targeting emission reduction. Current road operation demands sustainability; therefore, relevant authorities in different countries have taken on the responsibility of establishing environmental monitoring programs along the main roadways. These programs aim to address various environmental components, striving to set appropriate limits for the protection of human health and biodiversity. They also implement necessary mitigation measures to control environmental impacts [40].

3. Materials and Methods

The methodology for conducting this research is focused on obtaining pollutant emissions produced by the vehicular operation of a roadway. In this regard, Figure 2 outlines the methodological approach for quantifying emissions from road operations.
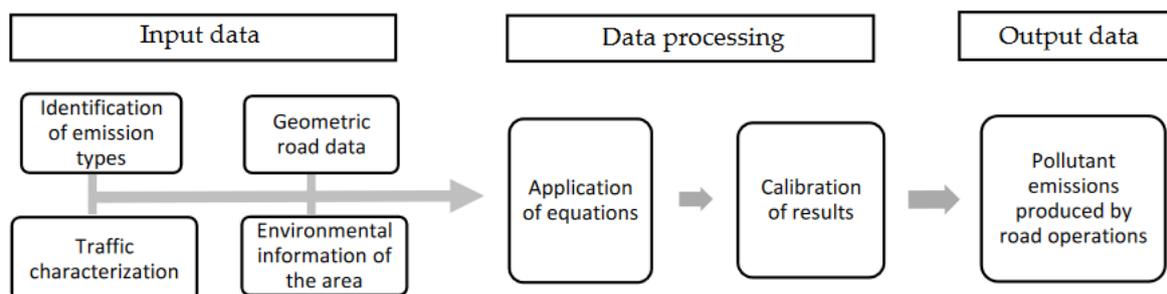

Figure 2. Methodological approach for quantifying pollutant emissions from road operations.

Through a review of the literature, it was possible to identify the types of pollutant emissions generated by vehicles in road operations. It is important to note that the case study is located in Mexico, a developing country. Consequently, there are challenges in obtaining data for the necessary variables to create a traditional inventory. In this context, to conduct this research, aside from exploring various databases, fieldwork was essential to gather and verify statistical data about vehicles using the road and existing geometric data. The consulted databases included traffic data from the Ministry of Infrastructure, Communications, and Transportation (Secretaria de Infraestructura, Comunicaciones y Transportes, SICT) [43] and data from the Public Trust for Road Funds and Investment Administration of the Centinela-Rumorosa Highway Section (Fideicomiso Público de Administración de Fondos e Inversión del Tramo Carretero Cen-tinela-Rumorosa, FI-ARUM) [44], as well as environmental information data from the Ministry of Environment and Natural Resources (SEMARNAT) [45].

Traffic composition is defined as the proportions of different types of vehicles using the road [46]. To obtain the annual average daily traffic and vehicle characterization, the configuration scheme of the main vehicles circulating on the national network published in the Mexican official standard by the Ministry of Infrastructure, Communications, and Transportation (SICT) was used [47] (Table 1).

Table 1. Vehicle Configuration Scheme.

	A2	Light Vehicles
	A'2	Pick Ups
	B2	2-Axle Buses
	B3	3-Axle Buses
	C2	2-Axle Cargo Trucks
	C3	3-Axle Cargo Trucks
	T3-S2	
	T3-S3	Articulated Truck
	T3-S2-R4	

Based on the above, the minimum input variables necessary to be introduced into the calculation tool are as follows:

- Traffic volume on the road section, refers to the annual traffic volume in each flow period, i.e., vehicles per year.
- Characteristics of the road section, such as section length, slopes, and road surface.
- Vehicle speeds, operational speed of vehicles when traveling on the road.
- Fuel consumption, pertaining to the instantaneous fuel consumption of each vehicle type, in each traffic intensity period.
- Vehicle lifespan and model parameters.
- Maximum and minimum temperatures of the study area.

Subsequently, once the input data is obtained, the model proposed by [48] is applied. This model predicts vehicle exhaust emissions based on fuel consumption and speed. Similarly, fuel

consumption is influenced by vehicle speed, which in turn depends on road characteristics and the vehicle itself. This approach allows for the analysis of changes in emission levels as a result of implementing various road maintenance and improvement strategies or when significant changes occur in the vehicle fleet on the road network. On the other hand, the coefficients and constants mentioned in the formulas are derived from various studies under controlled conditions, which have enabled the creation of tables with recommended values for use in the model [1].

Next, the equations applied for calculating the various emissions produced by road operations are presented.

Hydrocarbons (HC)

$$EHC = \frac{(3.6)(kehc0)(a0 + a1 * kehc1 * IFC)(1 + 0.5 * a2 * LIFE)(10^3)}{SPEED} \tag{1}$$

where:

EHC: Hydrocarbon Emissions (g/veh-km)
IFC: Instantaneous Fuel Consumption (ml/s)
LIFE: Vehicle Lifetime (years)
SPEED: Vehicle Speed (km/h)
A0 a A2: Model Parameters
Kehc0: Calibration Factor (predefined = 1.0)
Kehc1: Calibration Factor (predefined = 1.0)

Carbon Monoxide (CO)

$$ECO = \frac{(3.6)(kec0)(a0 + a1 * kec1 * IFC)(1 + 0.5 * a2 * LIFE)(10^3)}{SPEED} \tag{2}$$

where:

ECO: Carbon Monoxide Emissions (g/veh-km)
A0 a A2: Model Parameters
Kec0: Calibration Factor (predefined = 1.0)
Kec1: Calibration Factor (predefined = 1.0)

Nitrogen Oxide (NOx)

$$ENOX = \frac{(3.6)(kenox0)(a0 + a1 * kenox1 * IFC)(1 + 0.5 * a2 * LIFE)(10^3)}{SPEED} \tag{3}$$

where:

ENOX: Nitrogen Oxide Emissions (g/veh-km)
A0 a A2: Model Parameters
Kenox0: Calibration Factor (predefined = 1.0)
Kenox1: Calibration Factor (predefined = 1.0)

Sulfur Dioxide

$$ESO2 = \frac{(3.6)(Keso0)(a0)(a1)(IFC)(10^3)}{SPEED} \tag{4}$$

where:

ESO2: Sulfur Dioxide Emissions (g/veh-km)
A0, A1: Model Parameters
Keso0: Calibration Factor (predefined = 1.0)

Carbon Dioxide (CO2)

$$ECO2 = \frac{(3.6)(Keco0)(a0)(IFC)(10^3)}{SPEED} \tag{5}$$

where:

ECO2: carbon dioxide emissions (g/veh-km)
A0: model parameters
Keco0: Calibration Factor (predefined = 1.0)

Particulate Matter (PM)

$$EPAR = \frac{(3.6)(Kepar0)(a0 + a1 * kepar1 * IFC)(10^3)}{SPEED}$$ (6)

where:

EPAR: Particulate Matter Emissions (g/veh-km)
A0, A1: Model Parameters
Kepar0: Calibration Factor (predefined = 1.0)
Kepar1: Calibration Factor (predefined = 1.0)

Lead (PB)

$$EPB = \frac{(3.6)(Kepb0)(a0)(a1)(IFC)(10^3)}{SPEED}$$ (7)

where:

EPB: lead emissions (g/veh-km)
A0, A1: model parameters
Kepb0: Calibration Factor (predefined = 1.0)

Currently, there are different software programs that apply these models to calculate vehicle emissions, among them are the following:

- HDM-4 is a model developed for road management that allows calculating the amount of pollutant emissions in the form of chemical substances [49].
- COPERT 3 is a software used to calculate road transport emissions. This program classifies vehicles into categories and subcategories, according to the type of fuel, vehicle weight, size, engine technology, etc. [50].
- MOBILE 6.0 calculates emission factors for specific vehicle types; the estimation of emission factors depends on conditions such as ambient temperature, travel speed, operating modes, fuel volatility, and the proportion of distances traveled by each vehicle type [51].
- CALINE 4 It is a dispersion model for measuring air quality [52].

It is worth noting that for the purposes of this research, the HDM-4 software has been chosen as the calculation tool, as its application has been successful in over 100 countries, both developed and developing, and provides results for each generated chemical substance. On the other hand, to obtain the results, it is necessary to apply the basic equation used to estimate emissions from motor vehicles, which involves vehicle activity data and an emission factor where the factor is provided by the aforementioned models [10].

$$Ep = KRV \times FEp$$ (8)

where:

Ep = Total emissions of pollutant p
KRV = Kilometers traveled by the vehicle
FEp = Emission factor of pollutant p

The data used, as well as the data obtained from the calculation tool, are applied to the basic equation. However, due to the fact that the software provides results per thousand vehicles, the emission generated by each vehicle is calculated using the following equation:

$$EV \text{ (Emissions per vehicle)} = \frac{\text{Software results}}{1000}$$ (9)

Finally, with the results obtained from the calculation tool, it is necessary to make adjustments for the case study. To do this, the average annual daily traffic is obtained, along with its classification, and the total distance of the road section under analysis. Thus, the following equation is derived:

$$TEOC= (TDPA \times CLV) (EV) (D) \qquad (10)$$

where:

TEOC = Total emissions from road operation

TDPA = Average annual daily traffic

CLV = Vehicle classification

EV = Emissions per vehicle

D = Distance in kilometers

3. Results

The first input data pertains to traffic and vehicle composition. This information was taken from the year 2018 as a complete count was available for this period and to avoid biased data due to the reduction in traffic in subsequent years caused by the COVID-19 pandemic. Additionally, it is important to mention that these data correspond to the typical highway traffic. On the other hand, it should be noted that the case study has specific characteristics along its route. Therefore, the segment was divided into three subsections. The first segment, from kilometers 0 to 18, it is located in an urban area. The second subsection is situated around the Laguna Salada, spanning from kilometers 18 to 42, characterized by a non-urban environment with a completely flat and straight terrain. The third subsection covers the range from kilometer 42 to 64, as it traverses a mountainous area with a series of curves and significant slopes. Furthermore, the entire route has two separate lanes of traffic. In this context, Table 2 presents the average annual daily traffic for both lanes, categorized within the three aforementioned subsections.

Table 2. Annual average daily traffic (AADT)).

Section	Km from 0–18	Km from 18–42	Km from 42–64
Uphill	6,307	5,513	4,185
Downhill	6,358	5,622	3,775

In addition to the above, Table 3 shows the vehicular classification of the road section; it is noteworthy that the highest traffic is recorded in the urban area. Vehicles type A2 (light vehicles) account for 75% on uphill and 73% on downhill.

Table 3. Vehicle Classification for Section 0+000 al 18+000.

Uphill			Downhill		
Vehicle Type	Quantity	Vehicle Percentage	Vehicle Type	Quantity	Vehicle Percentage
A2	4,730	75	A2	4,641	73
A´2	25	0.4	A´2	64	1
B2	63	1	B2	64	1
B3	139	2.2	B3	134	2.1
C2	675	10.7	C2	648	10.2
C3	151	2.4	C3	203	3.2
T3-S2	372	5.9	T3-S2	439	6.9
T3-S3	76	1.2	T3-S3	76	1.2
T3-S2-R4	76	1.2	T3-S2-R4	89	1.4
Total	6,307	100	Total	6,358	100

In the same way, Table 4 displays the vehicle classification for the section located at Laguna Salada from kilometer 18 to 42. It is worth noting that this is no longer an urban area, but it does have recreational areas. The most prevalent vehicle with the highest traffic is the A2 light vehicle, accounting for 72% on the uphill and 70% on the downhill.

Table 4. Vehicle Classification for Section 18+000 al 42+000.

Uphill			Downhill		
Vehicle Type	Quantity	Vehicle Percentage	Vehicle Type	Quantity	Vehicle Percentage
A2	3,969	72	A2	3,935	70
A´2	6	0.1	A´2	34	0.6
B2	55	1	B2	56	1
B3	127	2.3	B3	135	2.4
C2	474	8.6	C2	522	9.3
C3	72	1.3	C3	79	1.4
T3-S2	529	9.6	T3-S2	557	9.9
T3-S3	154	2.8	T3-S3	163	2.9
T3-S2-R4	127	2.3	T3-S2-R4	141	2.5
Total	5,513	100	Total	5,622	100

Table 5 presents the vehicle classification for the section located in the mountainous area from kilometers 42 to 64. This section represents lower traffic. Nevertheless, it accounts for a daily circulation of four thousand vehicles, with 65% being light vehicles on the uphill and 68% on the downhill.

Table 5. Vehicle Classification for Section 42+000 al 64+000.

Uphill			Downhill		
Vehicle Type	Quantity	Vehicle Percentage	Vehicle Type	Quantity	Vehicle Percentage
A2	2,720	65	A2	2,567	68
A´2	17	0.4	A´2	8	0.2
B2	80	1.9	B2	72	1.9
B3	126	3	B3	113	3
C2	397	9.5	C2	339	9
C3	42	1	C3	34	0.9
T3-S2	556	13.3	T3-S2	457	12.1
T3-S3	80	1.9	T3-S3	23	0.6
T3-S2-R4	167	4	T3-S2-R4	162	4.3
Total	4,185	100	Total	3,775	100

Subsequently, in the HDM-4 software, in addition to traffic and its characterization, vehicle information is input, including operating speeds, types of fuel used, and specific vehicle characteristics. Furthermore, it includes road geometric features such as distances, widths, and slopes, as well as climatic conditions of the area.

Finally, by applying the equations of the calculation tool and calibrating the results using equations 8, 9, and 10, the pollutant emissions generated by the operation of the Centinela—La Rumorosa road, spanning 64 kilometers, are obtained. Table 6 illustrates that 372.5 tons of pollutant emissions are produced annually. Among these, 82.3% is carbon dioxide (CO_2), and 2.7% is carbon monoxide (CO), together accounting for a total of 85% of the overall emissions. The second most prominent pollutant in terms of emissions is lead, constituting 13.36%. Subsequently, nitrates contribute 1.2%, hydrocarbons 0.4%, PM particles 0.03%, and sulfur dioxide 0.01%.

Table 6. Vehicle Classification for Section 42+000 al 64+000.

Kilometers/Compound	Urban Area km 0 al 18	Laguna Salada km 18 al 42	Mountainous Area km 42 al 64	Totals (gr)	Totals (Ton)
Hydrocarbons (HC)	535,569.18	620,600.50	315,859.84	1´472,029.52	1.47
Carbon Monoxide (CO)	3´901,463.07	4´336,926.05	1´965,043.53	10´203,432.64	10.20
Nitrate (NOx)	1´392,773.90	1´855,356.39	1´243,735.03	4´491,865.32	4.49
Particulate (Par)	27,720.09	35,998.32	32,220.99	95,939.40	0.10

Carbon Dioxide (CO2)	95´241,818.04	124´295,181.33	86´868,295.74	306´405,295.11	306.41
Sulfur Dioxide (SO2)	14,018.98	19,191.13	14,578.02	47,788.12	0.05
Lead (PB)	18´765,391.86	20´958,666.62	10´052,981.52	49´777,040.00	49.78

4. Discussion

This research presents an estimation of the quantity of pollutant emissions generated by vehicles circulating on roads. Consequently, an analysis was conducted on carbon dioxide (CO2), carbon monoxide (CO), hydrocarbons (HC), nitrates (NOx), particulates (Par), sulfur dioxide (SO2), and lead (Pb) emitted through vehicle combustion in the case study. The findings reveal that the highest amount of generated pollutant emissions is CO2, with 306.4 annual tons, making it the most prominent, which aligns with the literature review conducted. Furthermore, the results also correspond to the understanding that the emission factor for suspended particulates from heavy vehicles is greater than the emission factor for light vehicles [53]. In this context, the section with fewer heavy vehicles generates a smaller quantity of particulates (Par).

It is possible that the concentrations of polluting emissions emitted into the atmosphere reach urban areas and when these have pollution levels that exceed air quality standards, they are a danger to human health. Fine particles can penetrate the deeper regions of the lungs such as bronchi and alveoli, causing cardiopulmonary diseases and lung cancer [54]. Likewise, SO2 causes clouding of the cornea (keratitis), difficulty breathing, inflammation of the respiratory tract, eye irritation due to the formation of sulfurous acid on moist mucous membranes, mental disorders, pulmonary edema, cardiac arrest, and circulatory collapse [55]. In general, the road transport emissions mainly affect respiratory and cardiovascular diseases, bronchial asthma, lung cancer, acute respiratory infections, eye irritation and headache [56,57]. In addition, CO2 emissions cause sea level rise, freshwater depletion, erosion, flooding and heat waves [58].

The importance of good air quality lies in providing a healthy environment that en-hances the quality of life. However, achieving this requires the commitment and participation of everyone involved. Firstly, as users, we must be aware of the environmental re-percussions of unsustainable mobility. Additionally, the entities responsible for road ad-ministration hold the responsibility to implement necessary measures to ensure compliance with significant environmental management tools, such as ambient quality stand-ards, maximum permissible limits, and action plans. Therefore, it is deemed essential that in the future, regular environmental assessments and mitigation proposals should be established for the pollutant emissions generated by transportation.

The case study has the particularity of encompassing three distinct characteristics: urban area (18 km), flat terrain area (24 km), and mountainous terrain area (22 km). As a result, traffic and its classification align with these characteristics. In this regard, Tables 3–5 reveal that the urban area exhibits the highest traffic (39.88%) with a greater percentage of light vehicles. Subsequently, within the flat terrain area, the highest percentage of light vehicles prevails, albeit with a lower traffic percentage than in the urban area (35.06%). Lastly, in the mountainous area, both traffic (25.06%) and the quantity of light vehicles decrease, while the number of heavy vehicles increases. Despite the aforementioned, the number of emissions generated per section does not correspond solely to the traffic volume or the length of the sections. For instance, the flat terrain section, while having the most kilometers, does not possess the highest traffic volume but generates 40.84% of emissions. This is followed by the urban segment, contributing 32.18% of emissions, even though it has the highest traffic but the lowest length. Lastly, the mountainous section, with the lowest vehicle count but a longer length than the urban segment, generates 26.98% of emissions.

On the other hand, a limitation of this study is that it analyzes vehicle emissions entirely during their operation, that is, while being in constant circulation. However, there are other circumstances that can cause congestion on a road, such as toll booths, vehicle inspections, accidents, or road maintenance work, which are not considered in this analysis. These aspects are proposed as future work, promoting comprehensive emissions models.

In a general sense, this research provides an initial approach for quantifying pollu-tant emissions specifically along road sections in Baja California. However, this initial endeavor should be complemented by solutions or mitigation plans aimed at reducing the amount of emissions produced on roads.

5. Concluding Remarks

The transportation sector is one of the main sources of pollutant emissions. In this regard, it is important to generate research that contributes to this topic. Hence, this work presents a quantitative analysis of emissions generated by the operation of a road section, specifically with a case study in a developing country. However, this road has an approximate daily average of five thousand vehicles and is the only land communication route between the states of Baja California and Baja California Sur with the rest of the country, reflecting a high vehicular flow. Nevertheless, there are no studies or analyses of the pollutant emissions generated by the operation of this road.

While there are various methodologies to calculate pollutant emissions, most of them focus on urban areas due to the proximity of people to these emissions. However, on roads, pollutant emissions are generated in the same way that are not in close proximity to people. Nevertheless, these emissions accumulate in the atmosphere, contributing to various environmental issues such as the greenhouse effect and global warming, affecting the biodiversity in the vicinity of the case study.

On the other hand, it is established that the calculation tool used allows for obtaining results with the available information in a developing country, such as Mexico. Currently, the SICT is responsible for collecting traffic data from all the roads in the country. Therefore, it is possible to replicate this methodology with any road.

In this regard, the results provide valuable insights for environmental researchers and could serve as a basis for new considerations in environmental analysis on highways. This research demonstrates that it is possible to quantify emissions even in developing countries with limited databases available for such applications.

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