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# Monitoring of oil lubrication limits, fuel consumption, and excess CO2 production on civilian vehicles in Mexico

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A B S T R A C T

The vehicle fleet in some regions of the world continues to age, so it is difficult to reduce the consumption of fuels, meet environmental objectives and mitigate the cost it represents. Studies exist regarding low mileage vehicles, yet it is important to know the effect generated by high mileage vehicles, which represents a higher percentage in the word. This work was based on the oil degradation. A maximum value of decrease in viscosity of 31% was found, from which the lubrication efficiency of the oil decreases. This also leads to a significant increase in gCO2/km and fuel consumption. In a deeper analysis of the Nissan Tsuru, we found an annual excess of 69.25 Lt of fuel consumption that produces 129.024 Kg additional of CO2 (12.18gCO2/km) with a cost of $1,414.08 Mexican pesos. Due to the average vehicle age in Mexico (15.3 years), these results can be taken as an average for the 45 million plus cars that are currently in circulation. Also, 5.806 million tons of CO2 are generated that represent 3.6% of all current emissions. This leads to a consumption of 3.11 billion liters of fuel at a cost of $63.63 billion Mexican pesos. This methodology can be generalized for different brands of cars and oils in countries with a vehicle fleet similar, in search of improving the monitoring and proper use of automotive oil. In addition, this provides information on the negative effects, so that the countries can establish procedures and strategies for compliance with low pollution policies.



## 1. Introduction

The development of new technologies worldwide has focused on providing the users with components or devices that facilitate and increase their quality of life, without neglecting the economic and environmental impact that this generates. The automotive area is one in which has evolved significantly in recent decades, by improving different aspects, such as new materials and coatings, electrical circuits with microsensors, structural components, surface treatments, use of alternative fuels, new additives for vegetable or synthetic oils, among others. These are all related to tribology and environment [1–5]. The degradation of motor oil can contribute to the generation of friction and wear if it is not changed on time, causing a negative economic and environment impact [6]. With respect to the use of oil and alternative fuels, a decrease in viscosity and an increase in acidity were reported, coupled with a slight increase in losses friction and wear, when approaching the oil change intervals [7]. In other research, a decrease of soot loading and an increase of fuel residue, corrosivity and oxidation of engine oil were also found [8–11]. It is also reported that the presence of soot in the engine oil is one of the most common reasons that leads to an increase in oil change intervals [12]. The use of different oils in the various engines is subject to extreme operating conditions. These oils are formulated to resist temperature variations, to maintain pumping capacity at low temperatures as well as to use sufficient film resistance at high temperatures [13]. The use of low viscosity of motor oils has been implemented for decades in light

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duty cars and now this has reached heavy-duty cars. Some results show a reduction in fuel consumption and a corresponding reduction in friction in the experimental measurement [8,14,15]. With regard to environmental pollution, oil wear causes an increase in energy consumption to overcome friction, which results in an increase in global greenhouse gas emissions [6].

In recent years some research has been carried out which provides more information to the end user, through the use of digital technology, sensors and the internet of things (IoT) in relationship to the degradation of oil and additives, based on their physicochemical, compositional and tribological properties [6]. Another alternative is to work in laboratories and use specialized equipment, however, this involves investing much more time and money [16]. The depth of wear due to friction on the main parts of the engine that present this phenomenon has also been explored theoretically and experimentally and a good correlation has been found [8,17,18]. Other research shows that more analysis is needed to optimize the models or methodologies [19]. Some automotive brands have implemented, in their premium models, oil pressure gauges, and an engine oil life system, which calculate the life of the oil based on the use of the vehicle. A number of authors have studied the accuracy of these systems based on the measurement of the most important physicochemical, composition and tribological properties, finding qualities in the oils that do not agree with the recommendations of the systems implemented by automotive companies [20,21]. Lei et al. [22] have proposed a theoretical-experimental model to predict oil wear in real time under urban and cruise traffic conditions, based on oil properties and operating parameters, obtaining a high degree of accuracy and precision. However, each car and type of oil has its own prediction model, so it is necessary to carry out more studies. In order to increment the amount of information, Lei et al. [23] expanded their study to other compact cars and with systematic road tests, in order to guarantee reliability of results. The results clearly show oil degradation based on mileage, time of use and more comprehensive parameters. An interesting result was found in the viscosity, where an initial stage of decrease was followed by a stage of stability to finally increase again.

Most of the studies have been carried out in developed countries, especially in recent vehicle models with an average age between 0 and 5 years and low mileage, which does not coincide with the characteristics of the vehicle fleet worldwide [20–23]. Ageing fleets is a phenomenon that occurs around the world. Considering countries throughout the world, we have found out the average age of the global vehicle fleet using the latest data spanning from 2015 to 2021, see Table 1 [24–26]. In each region, the countries in bold represent approximately 70% of the vehicle fleet, including passenger cars and commercial vehicles. Only 35% of the vehicle fleet has an average age of less than 10 years, in Asia. The other regions have a similar average age, so the problems of oil degradation, fuel consumption, generation of pollutants and economic impact will be similar. The way in which each of the countries implements efficient strategies to mitigate them depends to a great extent on their economic capacity and the purchasing power of their inhabitants.

Some of the reasons that can cause an increase in the average age of the vehicles fleet are described in the following list: a) many buyers especially those in developing or underdeveloped countries are seeking out used vehicles as new vehicle prices climb; b) cars are typically depreciating assets, and it more appealing for consumers to put money into the cars they already own; c) cars are getting faster, safer, more tech heavy, and the average age of a vehicle is rising. Therefore, drivers tend to hold on to their cars longer and cars spend more time in the used vehicle market before they head to the junkyard.

Various strategies have been implemented in the different regions to reduce the average age of the vehicle fleet; however, statistics indicate that it will take several years to reach this average age. In Africa, more than 60% of vehicles added to their fleet annually is through the import of used vehicles. At least 85% of the vehicle fleet are used vehicles, some of which are obsolete with outdated technologies. EU countries dominate the trade of used vehicles to African countries, followed by Japan and the US. More

**Table 1**
Average age and vehicle contribution by country.

| Region | Average car age by country in years | | | | Average car age in years | Vehicle contribution (%) | |
|---|---|---|---|---|---|---|---|
| | | | | | | Car | Trucks |
| Africa | **Morocco** | 6.2 | **Libya** | 16.1 | 14.75 | 3.25 | 4.16 |
| | **South Africa** | 9.9 | Guinea | 17.3 | | | |
| | **Egypt** | 11.2 | Gambia | 17.9 | | | |
| | Ethiopia | 12.3 | **Nigeria** | 18.3 | | | |
| | Ghana | 13.5 | Sierra Leone | 19.1 | | | |
| Asia | Saudi Arabia | 3.8 | Singapore | 5.5 | 6.8 | 36.37 | 27.40 |
| | **China** | 5.1 | **Japan** | 8.7 | | | |
| | United Arab Emirates | 5.2 | Finland | 12.5 | | | |
| Australia/Oceania | Australia | 9.9 | New Zealand | 14.5 | 12.2 | | |
| Europe | Austria | 8.3 | Netherlands | 11.0 | 11.20 | 35.22 | 16.10 |
| | Ireland | 8.4 | **Italy** | 11.4 | | | |
| | **United Kingdom** | 8.4 | Portugal | 12.8 | | | |
| | Switzerland | 8.6 | **Spain** | 13.1 | | | |
| | Denmark | 8.8 | Turkey | 13.4 | | | |
| | Belgium | 9.1 | **Russia** | 13.6 | | | |
| | **Germany** | 9.6 | **Poland** | 14.1 | | | |
| | Sweden | 10.0 | Czech Republic | 14.9 | | | |
| | **France** | 10.2 | Romania | 16.5 | | | |
| | Norway | 10.7 | | | | | |
| North America | Mexico | 15.3 | Canada | 10.1 | 12.43 | 18.09 | 31.93 |
| | **United States** | 11.9 | | | | | |
| Central America | Central America | 11.1 | | | 11.1 | 7.07 | 6.57 |
| South America | **Argentina** | 17.0 | Ecuador | 12.2 | 11.98 | | |
| | **Brasil** | 10.2 | Colombia | 10.5 | | | |
| | Chile | 10.0 | | | | | |

and more, African countries adopt policies for the import of used vehicles. Egypt and South Africa, for example, have banned the import of used vehicles. Morocco has an age restriction of five years for vehicles imported. Fifteen countries in West Africa agreed that as of 2021 all imported and newly registered vehicles would need to meet Euro 4/IV vehicles emission standards, and age limit [27,28].

In Asia, some countries have a high gross domestic product (GDP), which suggests it have higher incomes and therefore a high rate of automobile purchases, so it is not surprising that Saudi Arabia comes out on top. On the one hand, in 2010, China introduced a scheme that offered rebates to motorists who traded in old heavy polluting vehicles for low-emission vehicles. One solution for this is vehicle subscriptions, an idea that has been delved into a bit but not yet fully explored. The European Union has said it plans to start phasing out the sale of new internal combustion vehicles by 2035. New York and California have recently set similar targets. On the other hand, higher fuel prices or fees such as a gas guzzler tax on vehicles may turn consumers away from gas cars shortening their useable lives. In Latin American countries, there is no direct aid for the purchase of electric vehicles; however, a recent report by the United Nations Environment Program (*Programa de Naciones Unidas para el Medio Ambiente*, PNUMA for its acronym in Spanish) shows progress in tax incentives. Mexico, Costa Rica, Colombia, Ecuador and Paraguay have exempted these vehicles from paying the registration tax. These same above-mentioned countries and another five (Antigua and Barbuda, Argentina, Brazil, the Dominican Republic and Uruguay) have eliminated the import tariff. In 2018, Argentina established new vehicle categories plus a framework to promote more efficient and environmentally friendly vehicles. The aim is to reverse the emissions produced by larger, older, and heavier vehicles.

It is estimated that there are 1.2 billion light-duty passenger vehicles on the road globally. At the end of 2022, just over 2% of them will be electric. The next few years will bring remarkable progress regarding the adoption of electric vehicles (EV). Currently 20 million are in circulation globally. That is remarkable growth from only 1 million EVs on the road in 2016, yet it is worth keeping in mind what a huge task it is to convert the world's vehicle fleet. China accounts for 46% of the total sales to date, followed by Europe at 34%. North America is a distant third at 15% and all the remaining countries combined account for just 5% of the global EV fleet [29].

As can be seen, the strategies implemented so far have not significantly reduced the older vehicle fleet. In order to provide evidence of the negative effects of not renewing the vehicle fleet, there are studies that evaluate the impact of the vehicle fleet characteristics on pollutant emissions, under predictive scenarios of environmental policy [30,31]. To do this, the countries require information to feed these proposals, therefore, alternatives must be proposed and implemented to evidence the negative effects they generate. This study was carried out in Mexico, which has two clear characteristics: 1) Mexico has little renewal of the vehicle fleet and 2) Mexico is a country in full development. The analysis and information reviewed here could be taken up again in countries that meet one or two of these characteristics. According to the information collected here, this involves six of the seven regions of the world and about 70% of the automotive fleet (see Table 1). To visualize the current status of Mexico, an analysis of the vehicle fleet, the amount of motor oil it generates and its contribution to the generation of polluting gases is being carried out, as well as how the automotive oil change is monitored and carried out. All this, with the aim of proposing a methodology to analyze the degradation of the oil, the excess fuel consumption it generates and its effect on the environment.

In Mexico, vehicles and lubricating oil operate under different conditions, which depend on other factors of traffic, driving style, type of roads, environmental conditions, and quality of the fuel and oil used. There are regions in the north of the country where temperatures are extreme, between −10 and 50 °C and other regions to the south that are generally warm or hot, between 15 and 40 °C. It is also of value to point out that, as of 2018, foreign gas station companies, such as Chevron, ExxonMobil, Shell, and others, were opened to offer their products and fuel additives [32]. The Energy Regulatory Commission uses the norm NOM-016, which regulates the quality standards of the fuels used [33].

If burned oil is generated as a polluting waste, it is mandatory to register with the Ministry of the Environment, which is governed by the Official Mexican Norms, NOM-CRP-001-ECOL/1993 and NOM-CRP-003-ECOL/1993 [34]. According to preliminary data from the National Institute of Statistics and Geography [35], they indicate that in Mexico as of December 2020, 35,184,400 private vehicles, 637,582 passenger trucks and 10,753,513 cargo trucks were used and consumed an average of 3-6 Lt of oil in the engines. In 2000, the vehicle fleet in Mexico was 15.318 million, and that is, between 2000 and 2020, it increased by 204.60%, with an average annual growth rate of 5.485% (see Fig. 1). With these data, it is estimated that more than 350 million liters of used oil are generated annually, considering only these means of transportation.

Oil change also depends on: the region or country where the vehicle is located, the brand, and the improvements of the engine components and lubricating oil. In China, 56.1% of private vehicles carry out their oil change every 5,000 km according to the owner's manual [23]. In the United States, the maintenance program of the General Motors Corporation recommends that for private vehicles and light gasoline trucks used under normal conditions, the change should be made at 12,000 km or every 12 months [36]. In research carried out in regions of Europe, it is reported that oil changes are recommended between 10,000−30,000 km [37,38]. In Mexico, Mazda® maintenance programs recommend the change every 6 months or 10,000 km for private vehicles. Nissan® agencies advise changing the oil every 5,000 km or every three months [39].

The amount and type of pollutants that motor vehicles generate are due to many factors, and can be classified into two large groups: 1) the quality and improvement of the technology that is installed in the factory, such as emission control, the fuel injection system, the type of fuel and oil used, among others; and 2) those attributed to the end user, which consist of the driving style, the periodicity of maintenance and the activity for which the vehicle is intended. According to the National Institute of Ecology and Climate Change (INECC) and based on its studies and research between the years of 2013 and 2020 on climate change mitigation, Mexico emitted 471.17 million tons of carbon dioxide equivalent ($MtCO_2e$) in 2018, of which 34.3% were issued by the vehicle fleet [40]. Regarding the vehicle fleet in Mexico during the years of 2000 and 2018, the number of vehicles fleet increased by 55.63%, with an average annual growth rate of 2.42% (see Fig. 2). It is key to mention that the vehicle fleet in Mexico will continue to age by 2023, since by 2021 the sale of new cars will not reach one million units, which represents a decrease of 28% compared to 2019. In 2021, only 699 thousand cars will be less than five years old and by 2022, the number will only be 632 thousand. Hybrid and electric cars represent 0.3% of the vehicle fleet, and this represents approximately 84,500 of alternative cars which currently circulate with an average age of two years [41]. The use of new technology in Latin America depends on the global infrastructure of each country. For example, Brazil, with its 81% of renewable energy sources in its electricity mix, is ideal for the application of fuel cell hybrid electric vehicle and battery electric vehicle buses, even in the current scenario [5].

As can be seen, this information has greatly helped the

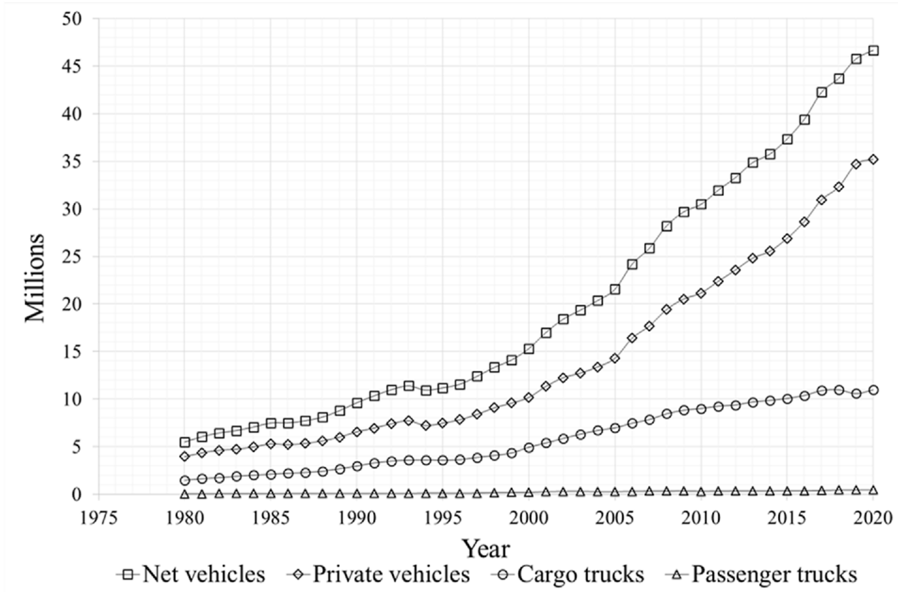


**Fig. 1.** Vehicle fleet in México for the years 1980–2020: private vehicles, cargo trucks and passenger trucks.

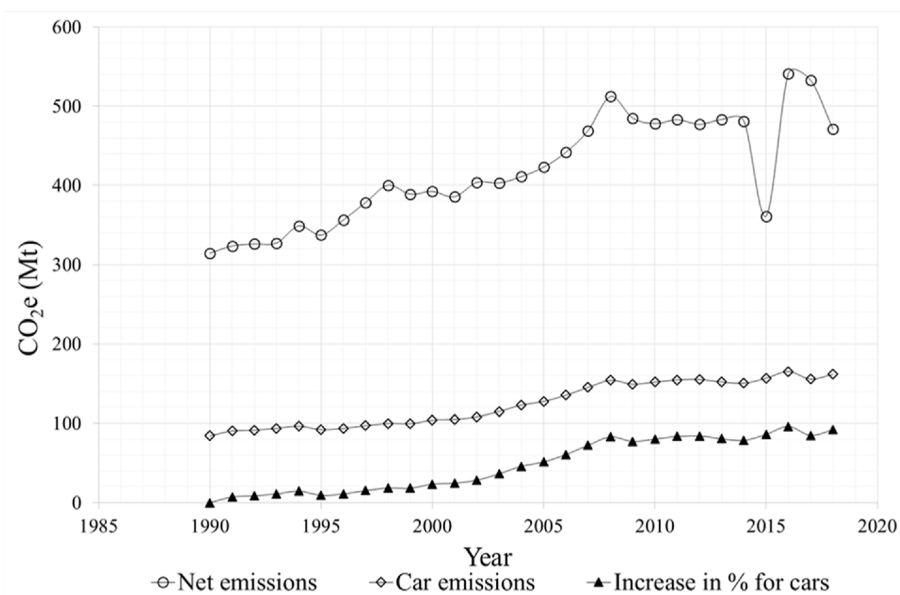


**Fig. 2.** $CO_2$ emissions in Mexico for the years 1980–2020: private vehicles, cargo trucks and passenger trucks.

operation of oil and therefore, increased the efficiency of the engine and reduced the negative effects on the environment. The automotive industry has implemented a motor oil life system in high-end cars, yet not everyone has access to this type of vehicle. In addition, some analyses of the oil properties indicate that the quality of the oils do not agree with the recommendations of these systems [20,21]. For this, Lei et al. [22,23] and others authors have made efforts to provide information for the end user regarding timely oil changes. The results are valuable and promising, however, the analyzes are performed observing changes of motor oils in the components of oxidation, nitration and sulfation, and physicochemical properties, such as total acid number (TAN) and oxidation onset temperature (OOT). These require the use of laboratories, large sample volumes, the constraint of fast turnaround times, and greater investment of capital. In addition, most of the studies were carried out on cars with an average age between 0 and 5 years, which represent a small part of the vehicle fleet in some countries. On the other hand, there are studies on fuel consumption and $CO_2$ emissions for lightduty passenger vehicles under different points of view, using driving conditions. For example, represents an area of opportunity if traffic sign management is analyzed or adjusted [42]; for develop a representative driving cycle with optimization-based methods to decrease deviations from the standard cycles [43]; also by simulation, when comparing mixed traffic flow with connected automated vehicles and human-driven vehicles on expressway [44] or for predicting real-world $CO_2$ emissions [45]. Other studies focus their research in the potential of eco-innovative technologies for the assessment of $CO_2$ [46] and energy efficiency technologies in reducing vehicle consumption [47].

Therefore, it is necessary to research this topic with more information in different regions of the world, because there is a wide range of car brands, oils, factors and operating parameters, which modify the properties of the oil throughout its useful life. It is value to mention that the vehicle fleet in Mexico and other countries will continue to age and that despite technological advances, the improvements in fuel performance and $CO_2$ generation in some of the most commercial models analyzed here have not been significant [40]. In search of complementing the information, with an environmental impact approach, from the point of view of the cost for the end user, and analysis alternatives using on road driving data and results assessed under standard conditions laboratory. In addition, visualizing the construction of devices that can be easy to implement in the body of the car with parameters obtained and analyzed in real time. The present study proposed a procedure to predict fuel economy, $CO_2$ emissions, and additional expense for the end user, in function of the oil degradation, which involves the following:

i) An analysis of the useful lifetime and the ideal oil change time, based on the maximum degradation that the oil can resist to provide good lubrication and protection, determined from a measurable property, such as viscosity and fluidity.
ii) A follow-up of the density and the added mass to identify the degree of wear of internal engine parts and its relevance in the degradation of lubricating oil.
iii) A proposal of a simple theoretical-experimental model to predict viscosity as a function of time and temperature. This can be a starting point for the development of an engine oil life system.
iv) The impact of degradation on exhaust gas generation, fuel consumption, and its economic impact to provide information on the behavior of these parameters. This in turn is to develop maintenance procedures based on experimental data for assisting countries to meeting with low pollution policies.

To achieve this, the present research seeks to show the influence of mileage and oil change intervals, taking into consideration the degradation of lubricating oil and its relationship with the behavior of exhaust gases, fuel consumption, and the economic impact for a Nissan® car. From these results, the feasibility of taking the above aspects as a reference point for the analysis of the influence of mileage and oil change intervals on the degradation of the lubricating oil of Volkswagen® and Mitsubishi® brand cars will be explored. This cars, belong to a group of two thirds of the vehicle fleet in Mexico with average age of 15.3 years and this is expected to increase in the future.

## 2. Methodology

This work is based on the considerations and characteristics for the quantification of parameters, and the physical and chemical properties reported by the authors in previous research [48].

### 2.1. Collection of samples and measurement of operating parameters

The brands studied were chosen according to a series of characteristics which make them popular or they represent a particular sector in Mexico. Regarding the age of the vehicle fleet, the consulting company Integrate Data Facts (IDF) reported that two thirds are made up of two blocks. The first one is with an age between 16 and 25 years and the second is between 6 and 15 years, both with a similar proportion. The average age of the vehicles in each of the countries that make up the Treaty of Mexico, the United States and Canada (T-MEC) at the end of 2019 was 15.3, 11.9 and 10.1 years, respectively [49].

Nissan® is one of the best-selling brands with four models, among which the Tsuru is analyzed here. Nissan® has maintained this status in the last five years, displacing General Motors of Mexico [50]. According to the Portal of Energy Efficiency and Vehicle Emissions Indicators [40], the Tsuru car has an average level in the generation and emission of greenhouse gases. On the list of the best-selling cars, the Volkswagen® brand also appears with three models, in addition to having one of the safest models in the Latin American market. On the other hand, Mitsubishi Motors Mexico is one of the brands that has had a difficult time positioning itself in the market. The Mitsubishi Mirage is analyzed here, with a city performance of 21.15km/Lt [40,51,52].

The oil change of a Nissan® brand vehicle, which uses SAE 20W-50 (API SN) synthetic oil and whose characteristics are presented in Table 2, was monitored. The owner and maintenance manuals of many new Nissan® cars recommend the change of oil every 5,000 km or every three months, through a service which includes oil filter replacement [39]. Samples of approximately 50 ml were collected at the end of the period for seven oil changes (tests 1–7), and the parameters of mileage, accumulated mileage and time of use are shown in Table 3. Each of these tests represent different driving styles, and some are more demanding than others, which will influence fuel consumption, gases generation, and lubricating oil degradation. Three of these tests were monitored through the weeks of use, in order to observe the behavior of the oil in more detail (see Table 4). For example, in test 1 a more demanding way of driving is observed compared to test 2, which refers to more kilometers traveled in less time. No new oil was fed to the engine during the experiments. In the case of Volkswagen® and Mitsubishi® brand cars, the collection of samples was carried out in the corresponding agencies, where the procedure was carried out

**Table 2**
Engine characteristics.

| Brand | Nissan® | Volkswagen® | Mitsubishi® |
|---|---|---|---|
| Model | Tsuru III 2007 | Jetta 2010 | Lancer 2013 |
| Fuel efficiency | 5.88 Lt/100 km | 6.80 Lt/100 km | 6.98 Lt/100 km |
| Total displacement | 1597 cc | 1984 cc | 1998 cc |
| Cylinders | 4 | 4 | 4 |
| Diameter x stroke [mm] | 76 × 88 | 82.5 × 92.8 | 86.0 × 86.0 |
| Compression ratio | 9.31: 1 | 10.0: 1 | 9.0: 1 |
| Maximum power | 105 HP @ 6000 rpm | 115 HP @ 5400 rpm | 152 HP @ 6000 rpm |
| Maximum torque | 138 Nm @ 4000 rpm | 165 Nm @ 2800 rpm | 198 Nm @ 4250 rpm |
| Idle speed | 625 ± 50 rpm | | |
| Combustible | Gasoline 87 octanes RON | Gasoline 87 octanes RON | Gasoline 87 octanes RON |
| Oil | 3.5 Lt; SAE 20W-50 | SAE 5W-30 | SAE 5W-30 |

**Table 3**
Operational parameters: Tests 1–7.

| Test | Accumulated mileage (km) | Mileage (km) |
|---|---|---|
| start | 137,500 | 0 |
| 1 | 144,070 | 6,570 |
| 2 | 149,805 | 5,735 |
| 3 | 155,815 | 6,010 |
| 4 | 161,193 | 5,378 |
| 5 | 166,615 | 5,422 |
| 6 | 170,992 | 4,377 |
| 7 | 173,701 | 2,709 |

under standardized norms. The engine characteristics for the models with the highest presence in the samples are presented in Table 2. These companies handle their own brand of synthetic oil SAE 5W-30. It is viable to mention that for Volkswagen® brand cars, customers focus heavily on oil change based on months of use (six months). On the other hand, for the Mitsubishi® brand cars, customers focus more on oil change based on kilometers traveled (10,000–15,000 km). The most relevant characteristics of the cars and the oil samples to carry out this study are presented in Tables 2 and 5.

### 2.2. Measurement of oil properties

For the characterization of the oil samples and their degradation analysis as a function of temperature, mileage, and time of use, the quantification of density, added mass, viscosity, fluidity, exhaust gases and content of suspended solids was used (see Fig. 3).

Density was measured using a portable density meter according to the ASTM D-1298 standard method. For the case of viscosity, measurements were carried out with a Brookfield LVDV-I viscometer and an ultra low adapter (UL) for the experiment. The UL adapter consists of a cylindrical shaft that rotates within a precision machined tube to accurately measure viscosity. It is water jacketed

**Table 4**
Operational parameters: Test 1, test 2 and test 5.

| Test 1 | | | Test 2 | | | Test 5 | | |
|---|---|---|---|---|---|---|---|---|
| Week | Accumulated mileage (km) | Mileage (km) | Week | Accumulated mileage (km) | Mileage (km) | Week | Accumulated mileage (km) | Mileage (km) |
| 0 | 137,500 | 0 | 0 | 144,070 | 0 | 0 | 161,193 | 0 |
| 2 | 139,785 | 2,285 | 1 | 144,397 | 327 | 1 | 161,936 | 743 |
| 3 | 140,407 | 2,907 | 3 | 145,977 | 1,907 | 2 | 162,550 | 1,357 |
| 5 | 141,931 | 4,431 | 4 | 146,759 | 2,689 | 3 | 163,711 | 2,518 |
| 6 | 142,266 | 4,766 | 5 | 147,081 | 3,011 | 4 | 164,433 | 3,240 |
| 7 | 142,643 | 5,143 | 6 | 147,675 | 3,605 | 5 | 165,087 | 3,894 |
| 8 | 143,224 | 5,724 | 7 | 147,970 | 3,900 | 6 | 165,629 | 4,436 |
| 9 | 144,070 | 6,570 | 9 | 149,041 | 4,971 | 7 | 166,615 | 5,422 |
| | | | 10 | 149,805 | 5,735 | | | |

**Table 5**
Operating parameters for the Volkswagen® and Mitsubishi® brands.

| Volkswagen | Year | Change time (months) | Accumulated mileage (km) | Mitsubishi | Year | Accumulated mileage (km) |
|---|---|---|---|---|---|---|
| Jetta | 2010 | 6 | 94,156 | Lancer | 2013 | 70,761 |
| Jetta | 2013 | 6 | 75,779 | Outlander | 2014 | 34,249 |
| Bora | 2014 | 6 | 75,580 | Lancer | 2015 | 38,000 |
| Bora | 2014 | 6 | 75,266 | Lancer | 2015 | 24,674 |
| Jetta | 2013 | 6 | 70,019 | Mirage | 2015 | 21,085 |
| Jetta | 2014 | 6 | 33,134 | Mirage | 2016 | 24,298 |
| Jetta | 2015 | 6 | 30,078 | Mirage | 2016 | 12,654 |
| | | | | Mirage | 2016 | 12,452 |

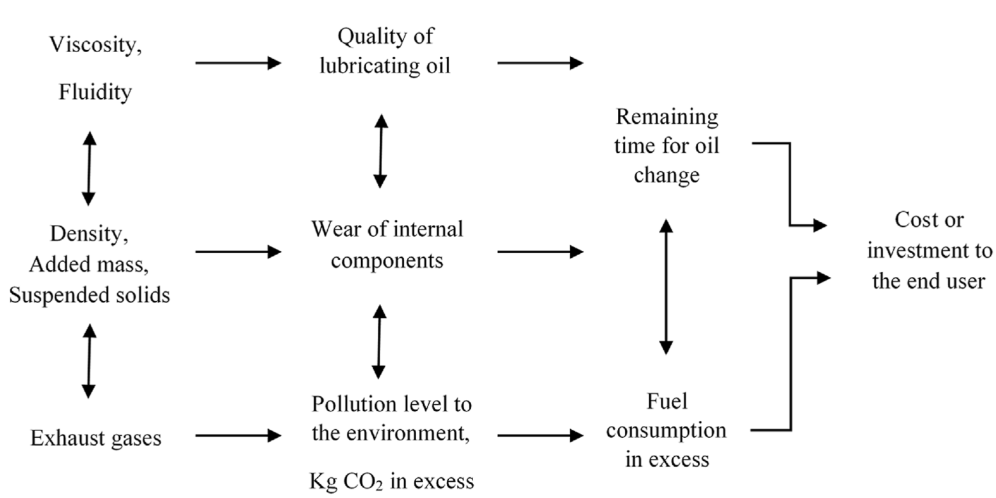


**Fig. 3.** Flow diagram of the tests and their interaction for the analysis, depending on the mileage, time of use and temperature.

to provide precise temperature control in accordance with the ASTM D-445 standard method. The speed of displacement or fluidity of the oil was quantified. The measurement was carried out on a flat surface and the quantification device was the researchers' own creation, through the use of sensors, resistors, integrated circuits, potentiometers, switches and programming of an Arduino Uno board. This board was programmed with the company's software. The IDE is open-source compatible with Mac OS X, Windows, and Linux. The main reason for creating a device and not using another, such as a manual capillary viscometer, for example, is to obtain data in a systematic, automated and accurate way, minimizing errors due to an appreciation reading. The device is operated in a laboratory with temperature control, to guarantee measurement conditions.

The quantification of the suspended solids was carried out by means of an X-ray fluorescence analysis (XRF), and the samples were sent to a specialized laboratory. XRF is an analytical technique for measuring particulate matter in various real-work applications, involving oil wear [53]. Finally, the VEA-501 gas analyzer was implemented to measure CO, HC, and $CO_2$ in emissions by the principle of infrared absorption without division. This process also measured $NO_x$ and $O_2$ by the electrochemical cell principle, calculating the excess air coefficient λ based on the composition of CO, $CO_2$, HC and $O_2$ measured. This instrument complies with the requirements of the International Measurement Rules [OIML R99/1998 (E)] elaborated by the Organization of International Measurement Laws (OIML) and the National Metrological Verification Regulations # JJG 688 for class 1 instruments. Table 6 lists the technical specifications of the gas analyzer.

**Table 6**
Technical specifications of the gas analyzer used in the present study.

| Measurement | Range | Resolution | Accuracy |
|---|---|---|---|
| $O_2$ | 0–25% | 0.01% | ±0.1% ± 5% |
| CO | 0–10% | 0.01% | ±0.06% ± 5% |
| $CO_2$ | 0–20% | 0.01% | ±0.5% ± 5% |
| $NO_x$ | 0–5000 ppm | 1 ppm | ±25 ppm ± 4% |
| HC | 0–10000 ppm | 1 ppm | < 2000 ppm; ±12 ppm ± 5%<br>> 2001 ppm; ±12 ppm ± 10% |

## 3. Results and discussion

### 3.1. Case 1: Nissan® vehicle

In this section, the characterization and analysis of the results of the collected samples for the used oil SAE 20W-50 (API SN) are presented. For a better analysis, it is divided into sets of properties, due to the relationship between them. Five readings were taken from each of the samples, for all the experimental parameters. The standard uncertainty for repeatability was obtained by calculating the experimental standard deviation of the mean. In the specific case of the viscometer, Brookfield viscometers are guaranteed to be accurate to within ±1% of the full-scale range of the spindle/speed combination in use. Repeatability is to within ±0.2% of the Full Scale Range. When viscosity measurements are carried out with coaxial cylinder geometries, an additional 1% is applied to the accuracy. Therefore, the combined accuracy for instrument and spindle geometry is ±2.0%. The maximum standard deviation for density and fluidity is 0.75% and 2.95%, respectively.

#### 3.1.1. Viscosity and fluidity

In recent years, the Society of Automotive Engineers (SAE) in cooperation with engine manufacturers, developed a classification system for motor oils, based in two separate viscosity measurements: one at cold temperatures and one at high temperatures [54]. With the introduction of viscosity measurement at cold temperatures, using a rotating viscometer, the centipoise (cP) or mPa·s are used to report the absolute viscosity at colder temperatures, reported as low as −30 °C. The number indicates the ease with which the oil can be moved. On the other hand, the centistoke (cSt) is used to report the kinematic viscosity at high temperatures, as high as 100 °C. In this case, this reflects the time required for a fixed amount of fluid to flow through a certain sized orifice on the testing device. The viscosity decreases in the first weeks of use, but in the last two weeks, it increases slightly which was also reported by Lei et al. [23] and Usman et al. [55]. This can be seen in Figs. 4–6. These results show the presence of a minimum, reaching a limit point of protection and lubrication. The greatest degradation occurs in the first three weeks, around 22%, increasing to 27–31%, at which time there is a minimum between 4,600 and 5,400 km (see Fig. 7). From

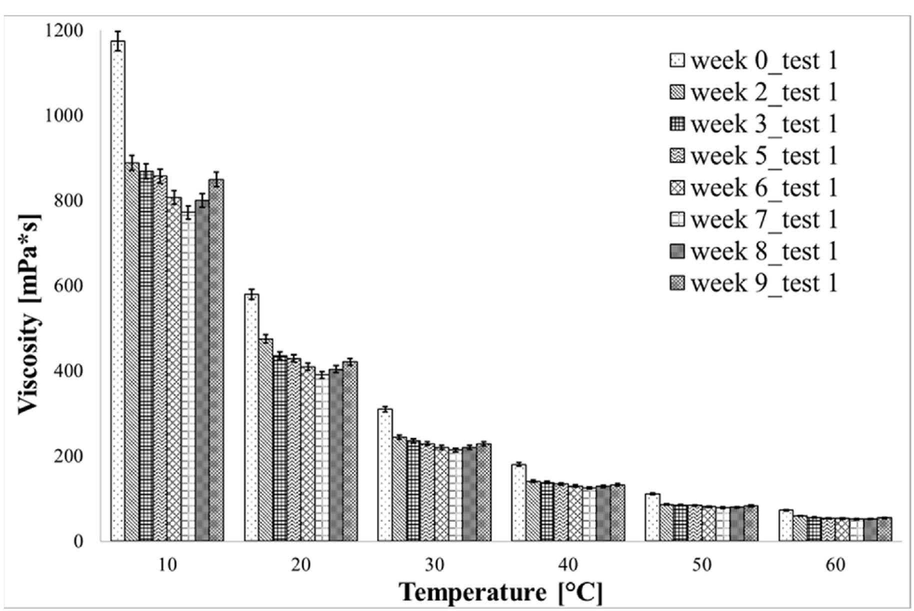


**Fig. 4.** Viscosity behavior with weeks of use and temperature: Test 1.

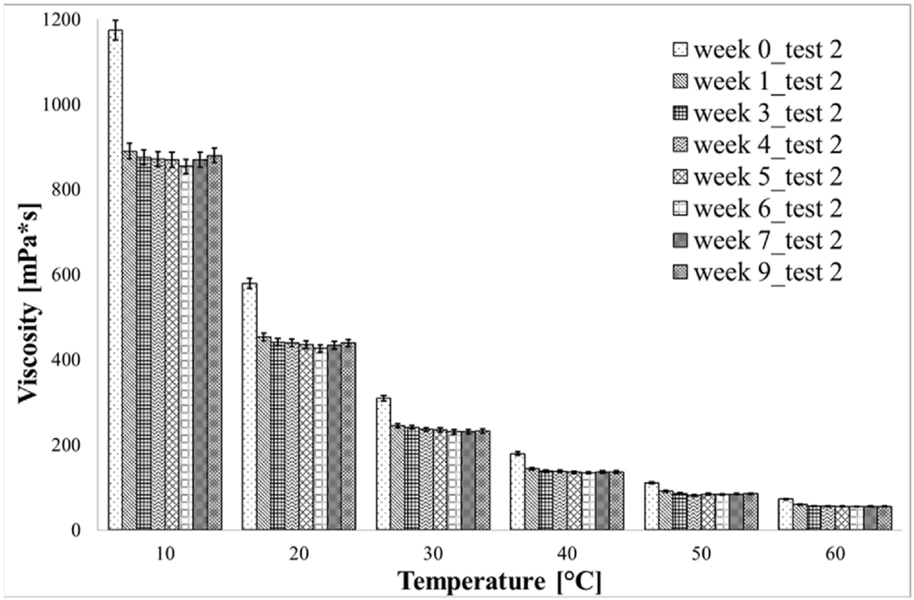


**Fig. 5.** Viscosity behavior with weeks of use and temperature: Test 2.

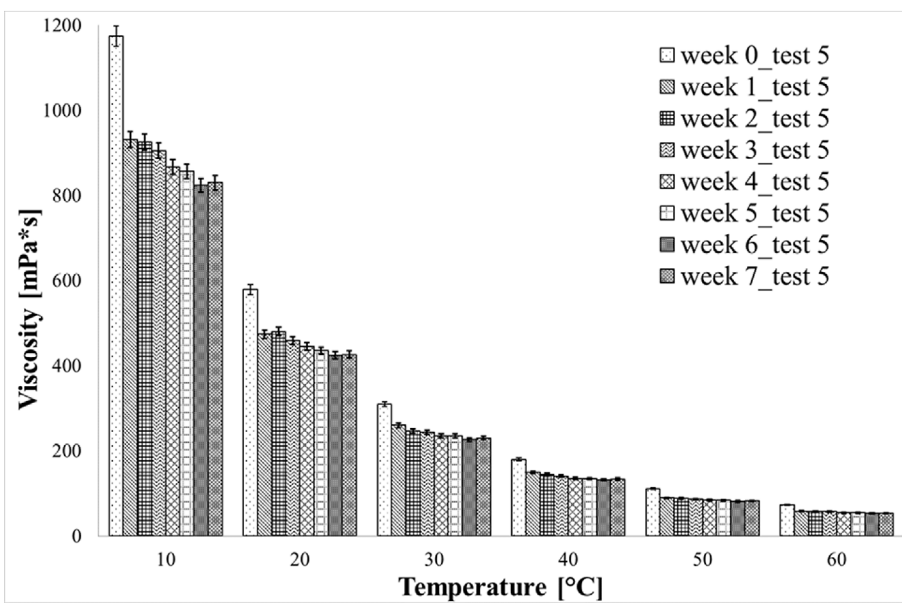


**Fig. 6.** Viscosity behavior with weeks of use and temperature: Test 5.

here, there is a slight increase between weeks seven and nine, which is an average of 6%, due to the addition of pollutants, which hinders its ability to flow. At the beginning, the fluidity is at its optimum point, which ensures adequate protection. As the oil degradation and the addition of dirt and solids advance (between weeks 6–7 or 4,500 km), a maximum is observed and a subsequent decrease, which coincide with a significant increase in density, suspended solids and viscosity (see Fig. 8). This decreases the lubrication capacity, increases energy consumption by the oil pump, and wears on parts.

To complement and verify the information provided in the weekly monitoring of viscosity and fluidity, Fig. 9 shows the viscosity graph of all the tests, for 10–100 °C. Although the temperature range is increased, the same trend in viscosity behavior is observed and verified. The minimum point of viscosity detected was added, taking it as a decrease of 31% with respect to the new oil. Tests 1–5 exceeded the minimum viscosity value, so an oil change was required. Test 6 with 4,377 km, was close to the minimum viscosity value, so it was at its limit point of use, and it was recommended to change it. On the other hand, test 7 with 2,709 km did not exceed the minimum value, and under these conditions the oil still had adequate properties lubrication and protection. As can be seen, the user's driving style varies, some more demanding than others, which influences the degradation of the lubricating oil and as a consequence, in the fuel consumption and gases generation, as also reported by Miotti et al. [56] and Agocs et al. [57].

### *3.1.2. Theoretical-experimental model to predict viscosity*

By analyzing the results for this car and oil model, it was possible to obtain a simple model of the viscosity as a function of

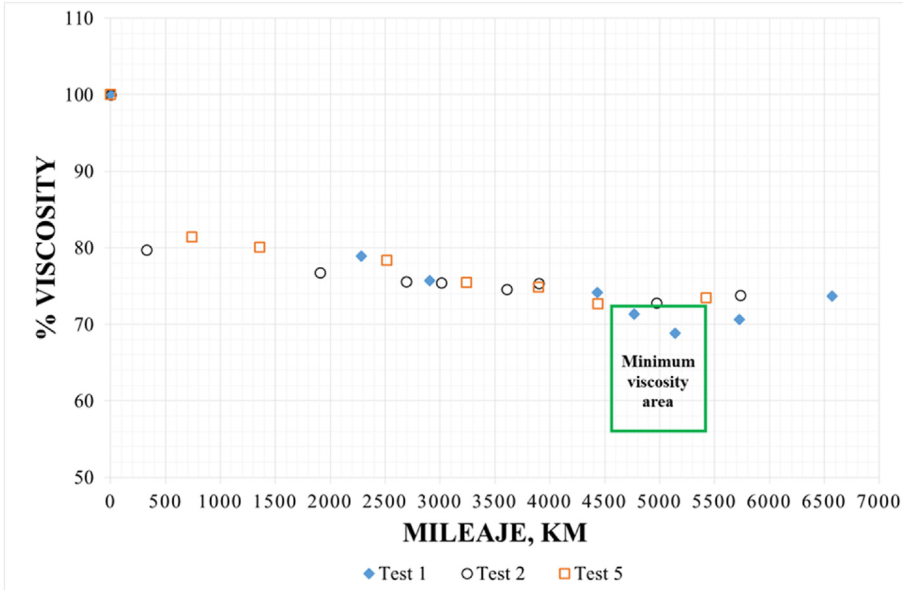


**Fig. 7.** Detection of a minimum of viscosity based on the kilometers traveled: Tests 1, 2 and 5.

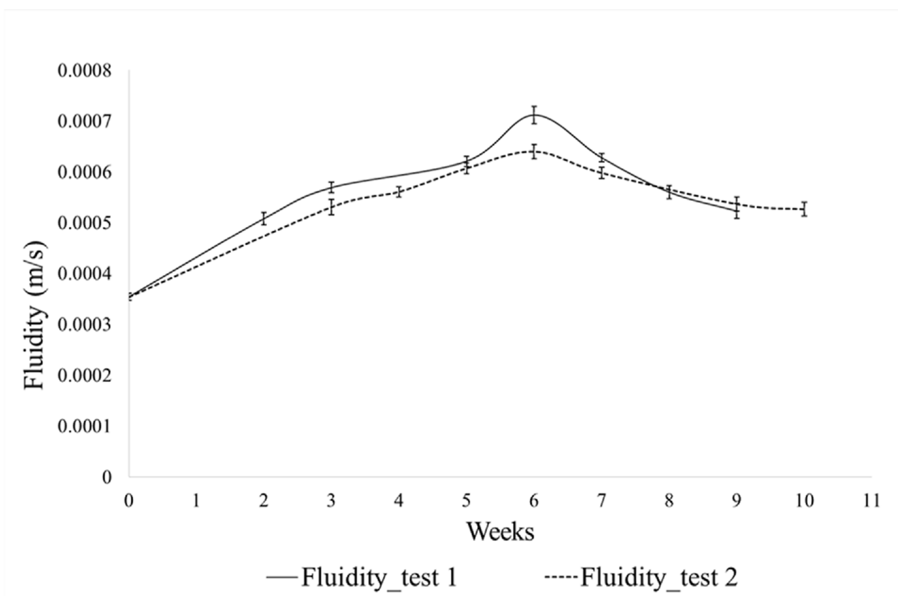


**Fig. 8.** Detection of a maximum of fluidity depending on the weeks of use: Tests 1 and 2.

temperature and time of use. This model could be improved and function as a predictive tool for the behavior of this type of car and oil. Applying a linear regression on the data, the following model, Eq. (1) and results were obtained.

$$\mu(T,t) = \mu(T) \cdot f_c(t) \cdot \left(\frac{T}{T+0.5}\right) \tag{1}$$

where $T$ is the temperature in °C, and $t$ is the time in week, $\mu(T)$ is the viscosity of the new oil as a function of temperature. $f_c(t)$ is a time correction factor and $\mu(T, t)$ is the viscosity as a function of temperature and time. The expressions and coefficients for these functions are presented in Table 7 and Eqs. (2) and (3).

$$\mu(T) = exp^{\left(a - bT + cT^2\right)} \tag{2}$$

$$f_c(t) = A - Bt - Ct^2 + Dt^3 - Et^4 + Ft^5 - Gt^6 \tag{3}$$

The proposed model seems to be built with a limited amount of data, however, it is important to remember that it is a weekly follow-up of approximately 18 months and for seven consecutive oil changes. Another imperative parameter to consider is the time correction factor, which adjusts the prediction regarding the time of oil use, taking into consideration that the user does not make all the oil changes in a certain number of weeks. The results of this approximation model are presented in Fig. 10, obtaining a global prediction error between the model and the experimental data of

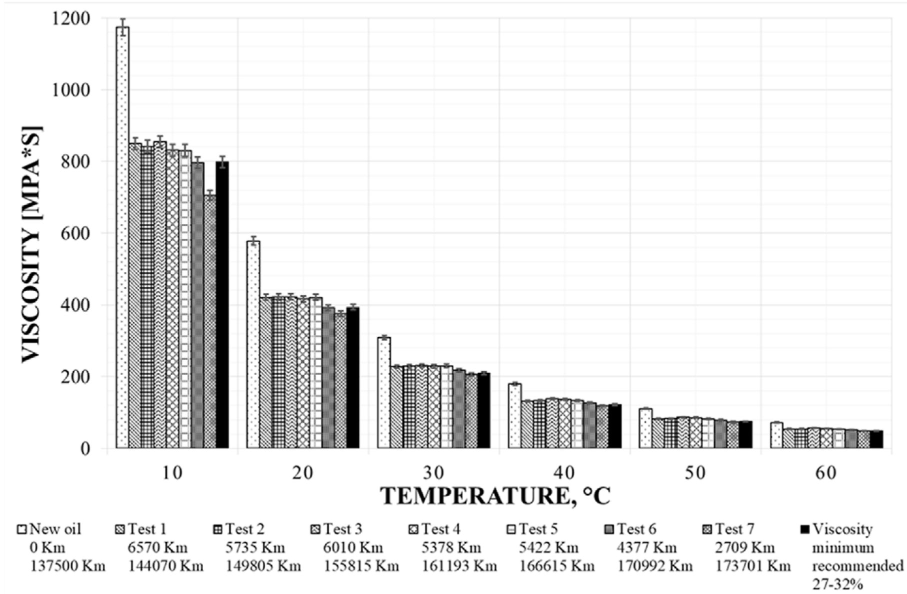


**Fig. 9.** Viscosity for each oil change: Tests 1–7, with respect to the minimum point.

**Table 7**
Factors: Eqs. (2) and (3).

| Equation 2 | | Equation 3 | |
|---|---|---|---|
| *a* | 7.85032 | *A* | 0.99999 |
| *b* | 0.08206 | *B* | 0.07370 |
| *c* | 0.00038 | *C* | 0.08010 |
| | | *D* | 0.05190 |
| | | *E* | 0.01172 |
| | | *F* | 0.00114 |
| | | *G* | 0.00004 |

less than 5%, for both tests. The most significant error percentages occurred at low temperatures, decreasing with increasing *T*. Therefore, it can be considered as a reliable prediction model and easily be extended to other types of cars and oils, which can be a starting point to improve oil change times.

### 3.1.3. Density and aggregate mass

The amount of mass added was calculated comparing the densities of the new oil and used oil, under standard ambient conditions and using 40 ml of sample, as shown in Figs. 11–12. The results show a significant increase (also reported by Sejkorová et al. [[58]), especially in test 1 with more kilometers traveled, 6,570 km in nine weeks: this is indicative of excessive wear on the parts since the manual recommends 5,000 km to the driver or three months of use [39]. Test 2 shows less significant wear, however, only 5,735 km were covered in 10 weeks. When analyzing Table 4, Figs. 4, 7 and 12,

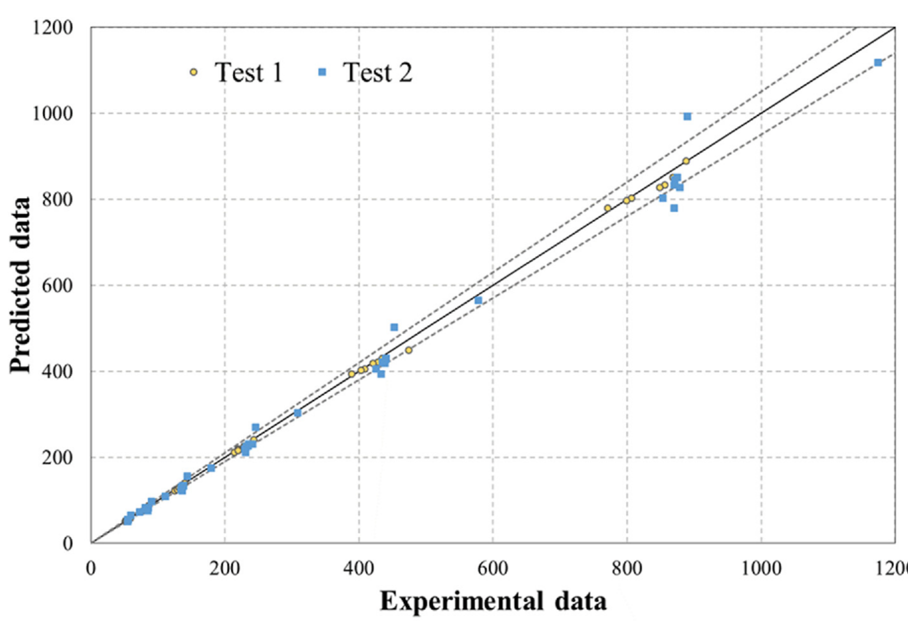


**Fig. 10.** Viscosity: experimental vs model: Test 1 and Test 2.

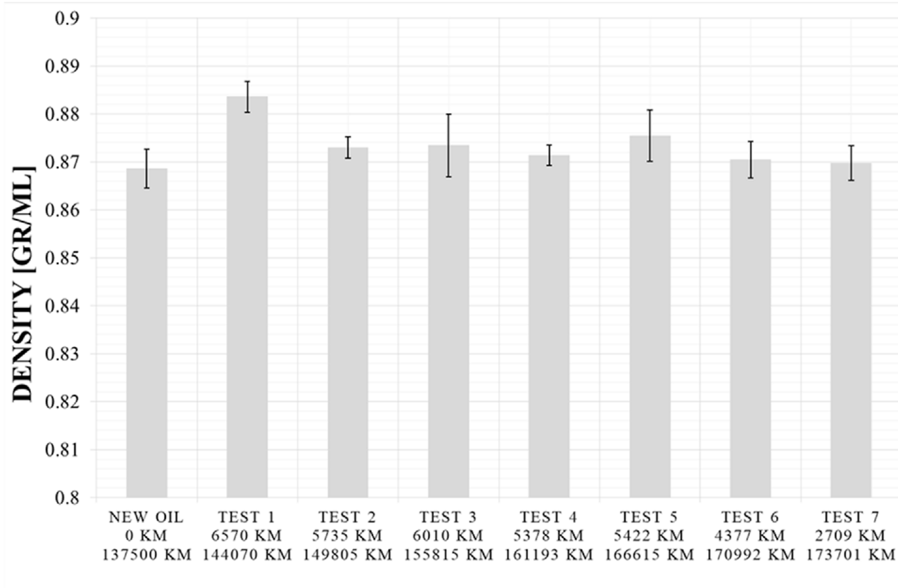


**Fig. 11.** Density for each oil change: Tests 1–7.

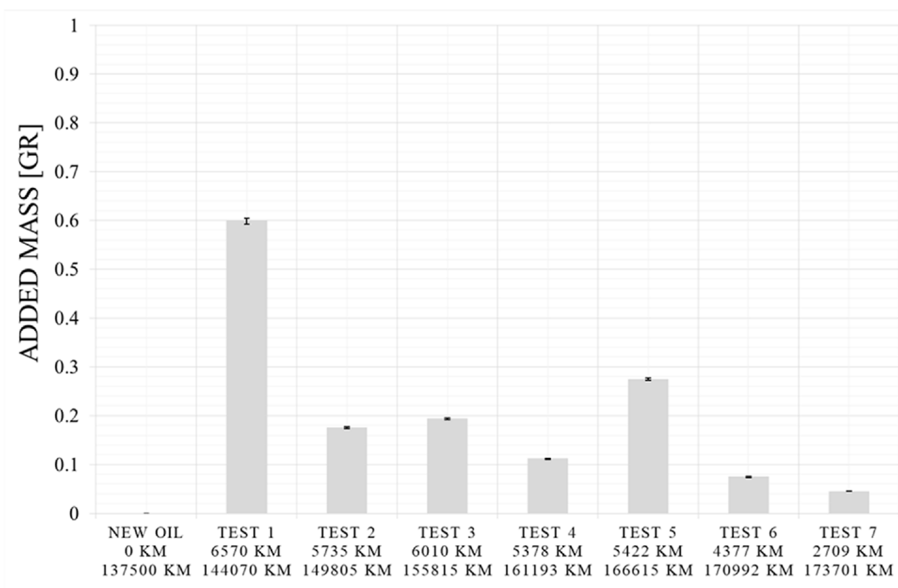


**Fig. 12.** Mass added for each oil change: Tests 1–7.

one can notice the effect caused by the added mass. Test 1 presents a minimum viscosity between 4,600 and 5,400 km, from here the increase in contaminants becomes considerable (about 0.60gr). A content of up to 0.10gr would be an acceptable limit to carry out the oil change, as presented in test 6, which is approximately reaches the recommended kilometers traveled.

*3.1.4. Impact of degradation on fuel consumption, exhaust gas generation and its economic impact*

Regarding the results in Figs. 13–15 of the quantification of the exhaust gases, an increase in concentration is observed when comparing tests 1 and 2. This increase becomes more significant as the oil change approaches. This behavior is reported in other publications, where the influence of driving cycles or driving style on energy demand, fuel consumption and $CO_2$ emissions is pointed out [42,59–61]. The level of oil degradation in both tests was significant (Figs. 9, 11 and 12), the higher emissions occur at the end of the weeks of use and could be explained by the increased demand for engine load to overcome resistance due to oil degradation and other phenomena present. In Figs. 14–15, greenhouse gases ($CO_2$ and $NO_x$) increased their concentration between the first and last week, on an average of 0.03 (vol. %) and 0.074 ppm respectively, contributing to this undesirable phenomenon. CO is produced by incomplete combustion and it increases on average approximately 0.935 (vol. %), which indicates that the proper operating conditions are not reached as the oil and the main parts of the engine show wear (see Fig. 13). This is related to the increase in HC concentration (on average of 0.0475 ppm) that is observed as the weeks progress, which also leads to excessive fuel consumption and, consequently, higher cost for the end user (see Fig. 15).

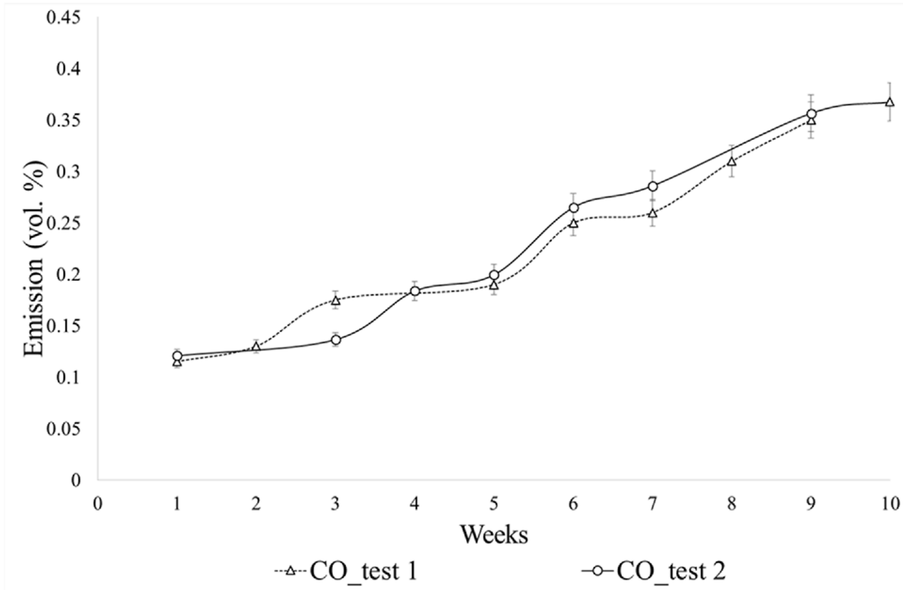


**Fig. 13.** Behavior of CO emissions as a function of weeks: Tests 1 and 2.

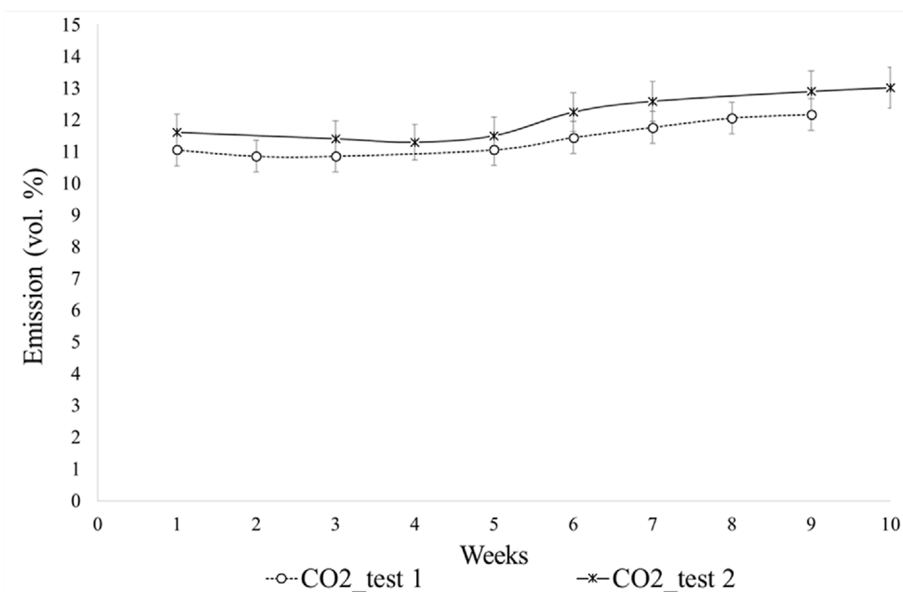


**Fig. 14.** Behavior of $CO_2$ emissions as a function of weeks: Tests 1 and 2.

The increase in $CO_2$ is due to the excessive consumption of fuel to overcome, among other aspects such as the friction and wear present in the operation of the engine, caused by the wear of parts and the degradation of the oil. There are methods to develop driving cycles in city under various driving conditions. Significant differences in cycle parameters have been observed in different driving conditions, and also deviations from the standard cycles from 22.8% to 29.4% for fuel consumption rate [43]. There are also studies focused on the impact of driving style changes. The simulated driving-style improvements provide an average fuel savings per trip of 6% [56]. Also by simulation, when comparing mixed traffic flow with connected automated vehicles and human-driven vehicles on expressway, the maximum reduction percentages of HC, $NO_X$, CO, and fuel consumption are 24.33%, 27.06%, 37.53%, and 40.58%, respectively [44]. Other studies indicate that there is a 30−40% difference between tests carried out in laboratories and those carried out in the real world or on the road, equivalent to an average production of 47.5g$CO_2$/km for 2015 average Europe fleet emissions [60]. Holmberg and Erdemir [6] indicate an approximate global average cost of 30.79 euros per ton of $CO_2$ generated. In the present research, taking into consideration the average stoichiometric ratio of air-fuel from the experiment (15.45: 1) and an average of the $CO_2$ concentration results for tests 1 and 2 (Fig. 14), in the first week approximately 1.863 Kg of $CO_2$ is formed per Lt of fuel (109.55g$CO_2$/km). For the last week of use 2.070 Kg of $CO_2$ per Lt of fuel are produced on average (121.73g$CO_2$/km) and this can be seen in Fig. 17. Which are values similar to those reported in other works, 130-140g$CO_2$/km, for vehicles with similar characteristics [45]. Taking the first week as a reference point, in the last week approximately 0.111 Lt of fuel is consumed to overcome friction and

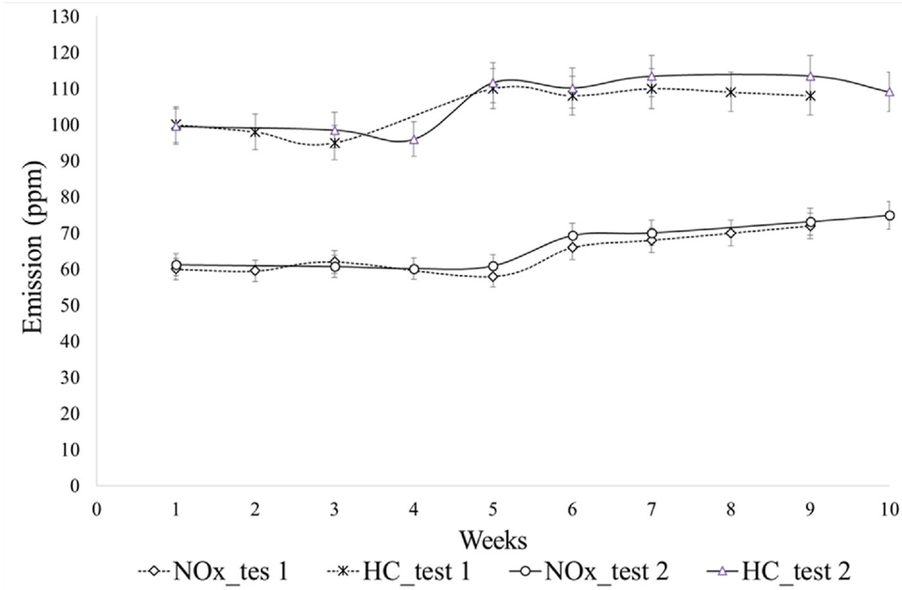


**Fig. 15.** Behavior of $NO_x$ and HC emissions as a function of weeks: Tests 1 and 2.

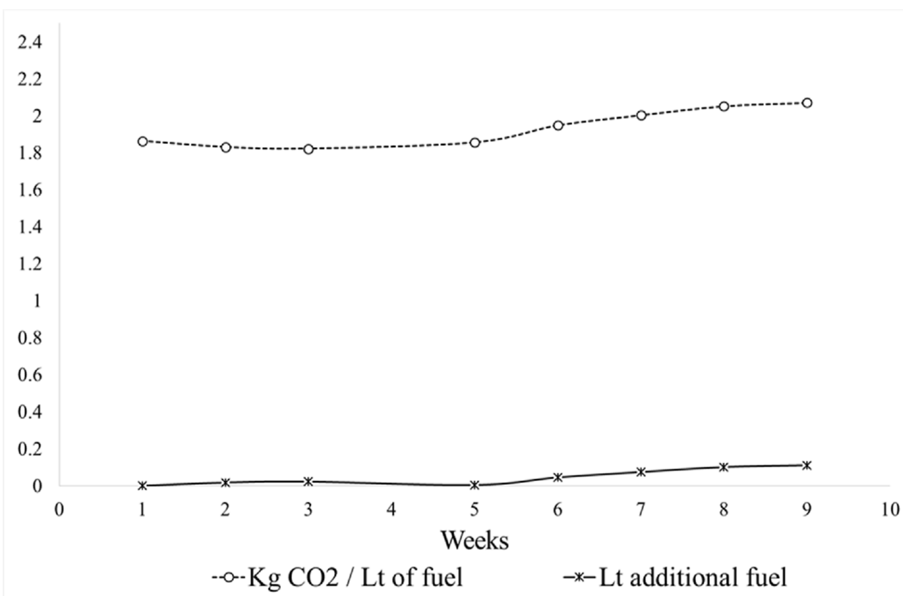


**Fig. 16.** Behavior of $CO_2$ emissions per Lt of fuel and additional consumption.

wear, which generates 0.207 Kg of additional $CO_2$ (12.18g$CO_2$/km), see Fig. 16. Which are values similar to those reported in other works, additional 29 and 25 g$CO_2$/km for vehicles emitting 100 and 119 g$CO_2$/km, respectively [62]. According to the owner's manual, the Nissan® car has a performance of 5.88 Lt/100 km. Assuming that these excesses occur after the first week of use and that annually the study car travels approximately 25,000 km and consumes 1,470 Lt, based on the data reported in Fig. 16, an average of 69.25 Lt or 4.71% of fuel is consumed and produce 129.024 Kg or 4.55% of $CO_2$ in excess. This translates into an additional expense of $1,414.08 Mexican pesos (56.92 euros), according to the average cost of fuel in México. Then, since $CO_2$ emissions are directly proportional to oil degradation (see Fig. 17), and higher $CO_2$ emissions indicates higher fuel consumption, the fuel economy and oil degradation will have a clear linear relationship, Fig. 18 [63]. This car is widely sold in México due to its cost and popularity, although its gases generation and emission levels are of a medium level [40,50].

### 3.2. Case 2: Volkswagen® and Mitsubishi® brand vehicles

In this section, other brands are analyzed to complement the study regarding oil degradation and find those weight factors or parameters that give a clear indication of the state of the oils, with respect to the change recommendations suggested by the assemblers, some agencies or automotive establishments. In the section 3.1, the results show that viscosity and fluidity can meet this goal.

#### 3.2.1. Viscosity

A maximum value of decrease in viscosity of 31% is

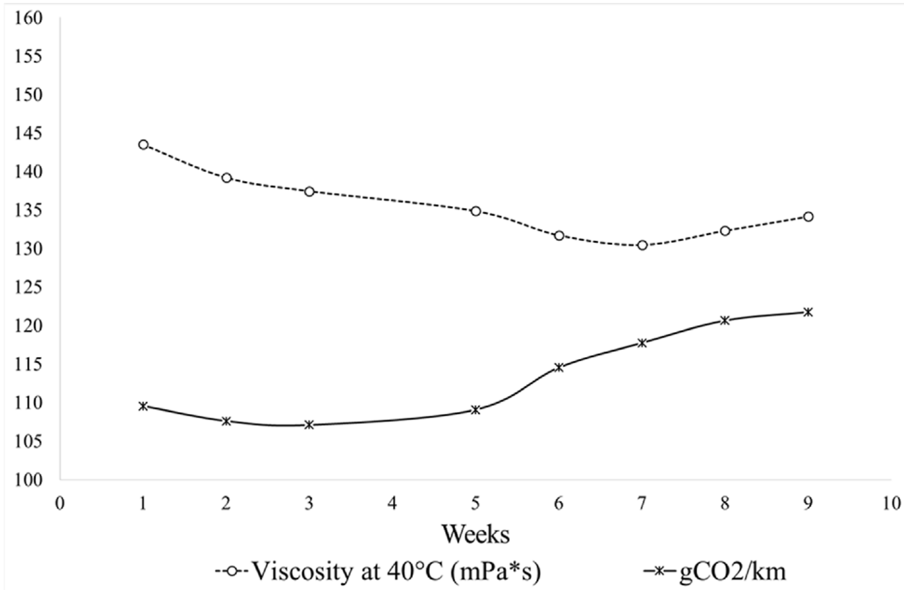


**Fig. 17.** Behavior of viscosity at 40 °C and $gCO_2$/km.

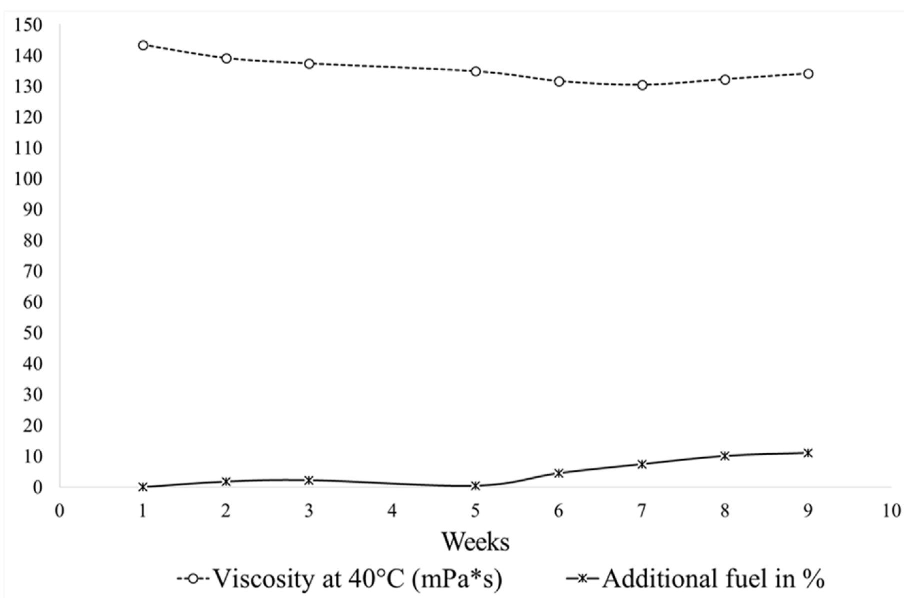


**Fig. 18.** Behavior of viscosity and additional consumption in %.

implemented, according to the results found for Nissan®. This represents an inflection point, from which the lubrication efficiency of the oil decreases, which leads to a more pronounced increase in $gCO_2$/km and additional fuel consumption, see Figs. 17–18. In Fig. 19 one can observe that for the Volkswagen® brand, 100% of the samples exceed this inflection point, which indicates that the ideal time for the oil change has been exceeded, contributing to the wear of the moving parts inside the engine. This suggests, as in other studies, that the lubricating oil exhibits premature degradation as a function of mileage and that the systems implemented by the manufacturers to measure the quality of the oil during operation do not always detect the degradation of the lubricating oil early enough [19,21]. According to INECC [40], these vehicles have a medium level of the generation and emission of greenhouse gases, so this quality and safety can be compromised due to the level of degradation found. For the Mitsubishi® brand, the results are more encouraging, since approximately 50% of the samples analyzed managed to remain at or below the inflection point. This suggests that the oil change was carried out more efficiently (see Fig. 20). In this case there is a trend depending on the accumulated mileage and the year of the car, which suggests that changing the oil based on the mileage and viscosity is a better indication for efficiency. At this point, 50% of cars that did not achieve a proper oil change can compromise their reported positive qualities, in terms of fuel save and low generation and emission of pollutants [40,52].

Finally, according to the results found, it was noticed that monitoring the oil change based on the mileage, viscosity, and fluidity can help to mitigate excessive oil degradation. It is of value

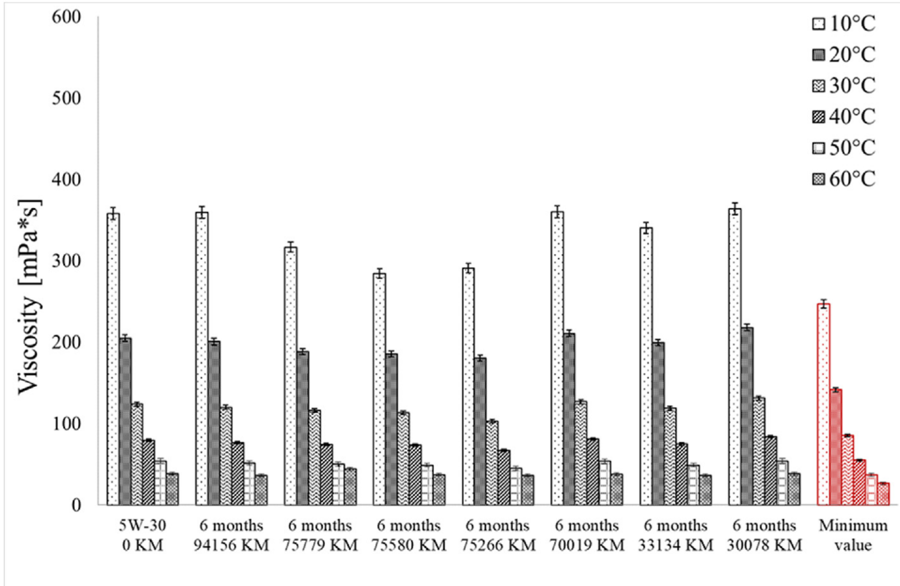


**Fig. 19.** Viscosity for Volkswagen® samples.

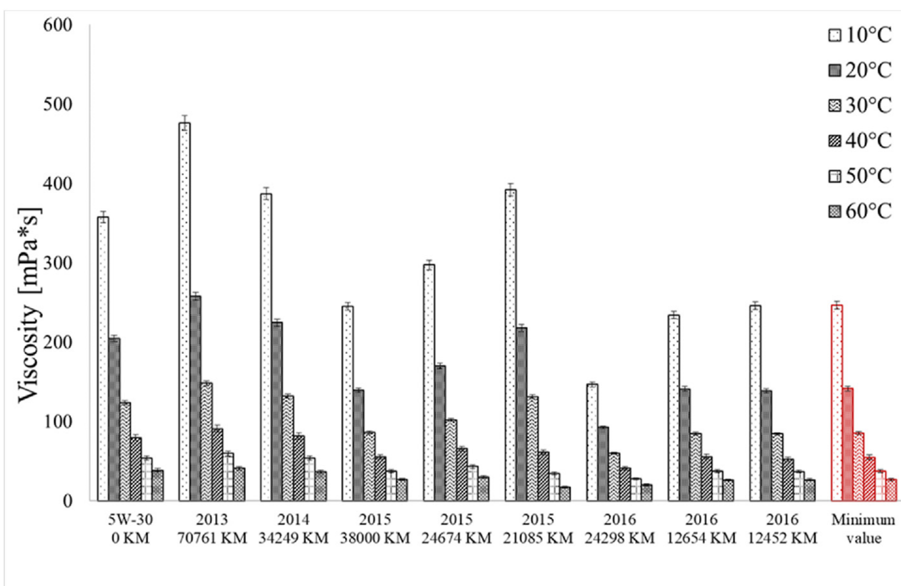


**Fig. 20.** Viscosity for Mitsubishi® samples.

to mention that despite technological advances, improvements in fuel performance and $CO_2$ generation in some of the most commercial models of these brands analyzed here, have not been significant, as can be seen in Figs. 21 and 22 [40]. These are carried out by combining city and highway performance, which represents an area of opportunity if traffic sign management is analyzed or adjusted [42,64]. Other works report fuel consumption reductions of 3.5% annually, when holding other vehicle characteristics constant and consider technological progress, which is an effective way to improve fuel economy in vehicles [65]. Some even explores examines the dynamic linkage among nuclear energy, the innovative technology and public service transportation, and results show that the positive and negative changes in nuclear energy reduce carbon emissions [66]. Then, methods to evaluate $CO_2$ savings from eco-innovations becomes more and more challenging because the electrification degree, and the interaction among technologies, increases [46]. Not neglecting that the vehicle fleet in Mexico and other countries will continue to age, even if $CO_2$ emissions are controlled, will hardly achieve the expected reductions to the real world, see Fig. 22. For example, the average age of the vehicles in each of the countries that make up the Treaty of Mexico, the United States and Canada, at the end of 2019 was 15.3, 11.9 and 10.1 years, respectively [49]. Therefore, the contribution and provision of information that seeks to mitigate these problems will always be valuable, especially for the end user. Taking these considerations and the results of Nissan® vehicle as an average value for the more than 45 million cars that are currently circulating. Around 5.806 million tons of $CO_2$ would be produced in excess, which represents approximately 3.6% of total emissions. This represents an additional consumption of 3,116.25 million liters of fuel that are equivalent to

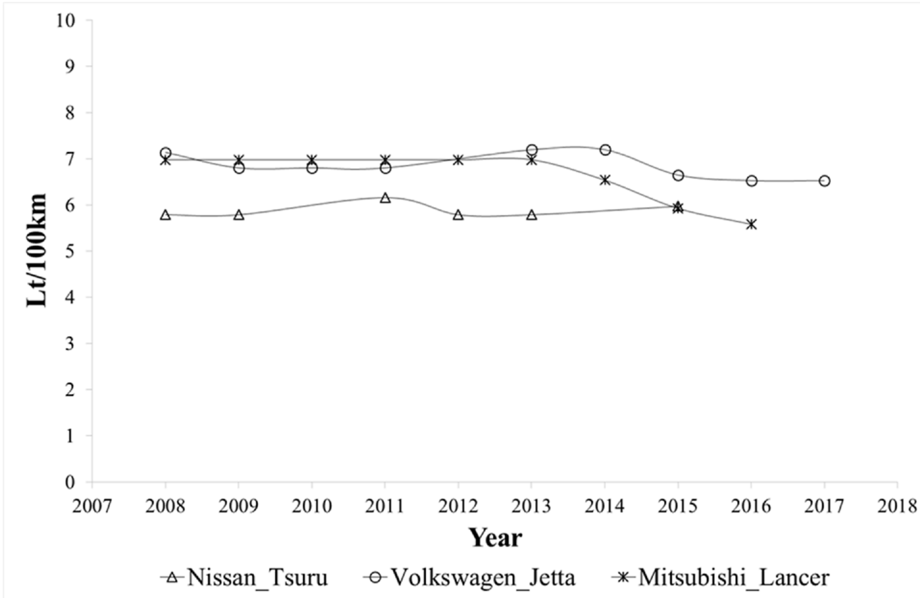


**Fig. 21.** Fuel performance of some of the most commercial models in México.

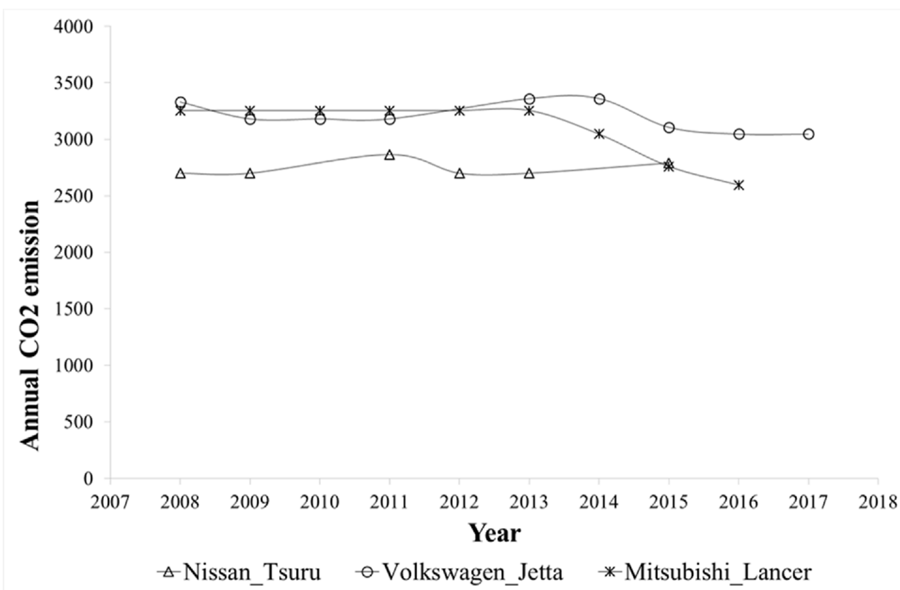


**Fig. 22.** Annual $CO_2$ emission of some of the most commercial models in México.

$63,633.6 million Mexican pesos. For comparison, if transition of the whole fleet to Hydrogen fuel cell buses is carried out in Argentina, $CO_2$ emissions could be reduced in 1.3 million tons [67].

## 4. Conclusions

According to the results, viscosity and fluidity are two useful and complementary parameters to predict oil degradation. The cars analyzed in this research belong to the group of two thirds of the vehicle fleet in Mexico with an average age of 15.3 years [49].

The most relevant results for the Tsuru Nissan® car are the following:

- With an age of 14 years, a minimum of viscosity was found, with a decrease of 27–31%, between 4,600 and 5,400 km. This indicates the most opportune moment for its change.
- A minimum of viscosity was also reported by Lei et al. [23], who suggest that each vehicle and oil demonstrate this behavior. This could be predicted and was observed in this research. This was carried out through a simple model as a function of viscosity, time, and temperature, with an average of less than 5% global errors, which can be a starting point to improve oil change times.
- By performing a simple analysis with the detected gases, an average consumption of excess of 69.25 Lt or 4.71% of fuel was

found and 129.024 Kg or 4.55% additional of $CO_2$ was produced. This is equivalent to 12.18g$CO_2$/km, which are values similar to those reported in other research [62]. This translates into an additional expense for the end user of $1,414.08 Mexican pesos (56.92 euros), according to the current average cost of fuel in Mexico.

- According to the average vehicle age in Mexico, these results can represent an average value for more than 45 million cars that are currently circulating. Approximately 5.806 million tons of $CO_2$ would be produced in excess, which represents around 3.6% of total emissions as well as an additional consumption of 3.11 billion liters of fuel. These are equivalent to $63.63 billion Mexican pesos.

The most relevant results for Volkswagen® and Mitsubishi® brand cars are the following:

- With a maximum value of decrease in viscosity of 31%, it was observed that 100% of the Volkswagen® vehicles exceeded this value at the end of the oil change. This suggests that their change was not conducted at the adequate moment.
- In contrast, only 50% of Mitsubishi® vehicles exceeded this value, and this implies that the users have better control of the oil change based on the kilometers traveled.
- As can be seen, more than 70% of the vehicles analyzed generate excess pollution, which means that policies should be developed to accelerate their removal from the fleet.

Most of the studies have been carried out in developed countries, especially in recent vehicle models with an average age between 0 and 5 years and low mileage, which does not coincide with the characteristics of the vehicle fleet worldwide. Aging fleets is a phenomenon that occurs around the world. Only 35% of the vehicle fleet has an average age of less than 10 years, focused on Asia. So, even if $CO_2$ emissions are controlled, it will be difficult to reach the expected reductions in the real world. This is due to the conventional powertrain technologies and lubrication oils fall short of expectations as well future $CO_2$ targets currently discussed in the order of 70g$CO_2$/km [47]. The way in which each of the countries implements efficient strategies to mitigate this problem depends largely on the country's economic capacity and the purchasing power of its inhabitants. Global standards, as well as their application and adaptation in emerging economies, do not always take into account the national contexts and often neglect specific economic and sectorial conditions [68].

This study was carried out in Mexico, which has little renewal of the automotive fleet and Mexico is in full development, as a country. The analysis and information reviewed in our study could be taken up again in countries that meet one or two of these characteristics. According to the information collected, this would involve six of the seven regions of the world and about 70% of the automotive fleet. Finally, according to the results presented and their comparison with the results reported in other studies, the parameters and analysis explored in this research have the potential to determine better operating conditions. An example is through the detection of a minimum value of viscosity based on the mileage traveled for different oils and automotive brands under different operating parameters. These results provide knowledge in the areas of oil degradation, costs, and environmental impact, which is useful to develop maintenance procedures based on experimental data and support compliance with low pollution policies.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgements

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