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Research Article

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Environmental Impact Assessment of Vehicle Fleet Dynamics in a Medium Sized Mexican City

Liliana Fausto-Castro[1*], José Enrique Botello-Álvarez[2], Arturo Mandujano-Nava[3], Aideé Hernández-López[4], José Ramón Castellanos-Castro[5], Roberto Carlos Salmorán-Salgado[5] and María Teresa Maldonado-Mancera[5]

[1]*Department of Industrial Engineering. Universidad del SABES, Constituyentes, 38163, campus Apaseo el Grande, Guanajuato, México*
[2]*Department of Biochemical Engineering, Tecnológico Nacional de México, Instituto Tecnológico de Celaya, Av. Tecnológico y A. García Cubas, 38010 Celaya, Guanajuato, México*
[3]*Department of Automotive Engineering, Polytechnic University of Guanajuato, Avenida Universidad Sur, 38496, Cortázar, Guanajuato, México*
[4]*Department of Industrial Engineering. Universidad del SABES campus Celaya, Av. Manuel Orozco y Berra, 38010, Celaya, Guanajuato, México*
[5]*Graduate Department, Doctorate in Engineering Sciences, Tecnológico Nacional de México, Instituto Tecnológico de Celaya, Av. Tecnológico y A. García Cubas, 38010 Celaya, Guanajuato, México*

[*]Corresponding author
Liliana Fausto Castro, Department of Industrial Engineering. Universidad del SABES , Constituyentes, 38163, campus Apaseo el Grande, Guanajuato, México.

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ABSTRACT
Urban expansion and accelerated industrialization have reinforced dependence on private automobiles, improving mobility but increasing air pollution and health risks, particularly due to the substantial proportion of obsolete vehicles still in circulation. This issue is especially relevant in medium sized cities undergoing rapid industrialization. A statistical assessment of the vehicle fleet of a medium sized Mexican city was conducted, analyzing CO_2 emissions by brand, vehicle type, and level of technological obsolescence using robust statistical methods and integrating technical specifications with local fuel consumption surveys to estimate annual emissions. Results indicate that 28% of vehicles are technologically obsolete; however, this segment generates nearly 55% of total CO_2 emissions. Significant differences were observed among brands: Brand 2 USA exhibited estimated emissions of 4.87 t CO_2/year, whereas the least polluting brand, Brand 1 ITA, emitted 2.37 t CO_2/year. Regarding vehicle type, sedans which account for 64% of the fleet produce 68% of total emissions, with an average of 5.04 t CO_2/year per vehicle. Hatchbacks demonstrated the best environmental performance, with 4.45 t CO_2/year. The disproportionate contribution of obsolete vehicles and high emitting brands high-lights the urgent need to implement targeted fleet modernization policies to reduce urban CO_2 emissions in medium sized cities.

Keywords: Fleet, Emissions, Fuel Economy, Obsolete Vehicles

Introduction

The mass production and global distribution of automobiles have been key drivers of economic development in many communities, as well as of lifestyles characterized by greater comfort and convenience [1]. It is estimated that 91% of the world's population lives in urban areas where air quality is inadequate, increasing the incidence of respiratory diseases and premature deaths. In urban zones, the transportation sector is identified as the main source of air pollution [2].

Across the world, large urban settlements affected by traffic related air pollution have enforced strict legislation on vehicle fleets and implemented effective measures to reduce overall traffic volume. These include speed and circulation restrictions on specific roads, economic penalties for highly polluting vehicles, and the creation of pedestrian zones with low exposure to air contaminants, among others [3]. At the same time, efforts are being directed toward a transition to sustainable urban mobility through vehicle electrification and light-weight design, along with regulations promoting the manufacture of low emission vehicles. Moreover, additional measures must be implemented to significantly reduce vehicle use [4].

Although the electrification of vehicle fleets is gaining increasing importance, internal combustion engine (ICE) vehicles will remain the dominant mode of mobility in the coming years [5].

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For this reason, automotive manufacturers continue to implement substantial modifications aimed at improving fuel efficiency and reducing emissions. Highlight the most significant advances in performance enhancement and emission control technologies, such as exhaust gas recirculation (EGR), fuel injection optimization, ignition retard, and intake system preheating. In parallel, describe recent innovations in engine design and combustion strategies, including variable compression ratio (VCR), variable valve actuation (VVA), and low temperature combustion modes such as HCCI (Homogeneous Charge Compression Ignition), PCCI (Premixed Charge Compression Ignition), and RCCI (Reactivity Controlled Compression Ignition), as well as the development of unconventional engines (e.g., free piston, lean burn, or multicycle designs) intended to maximize efficiency and extend the relevance of internal combustion engines during the transition toward electric mobility [6,7].

In Mexico, the number of motor vehicles increased from 15,611,916 in 2000 to 50,594,282 units in 2019. In Mexico City, which has a population of 20,116,842 inhabitants, approximately 16% of the national vehicle fleet circulates, with a density of 402 vehicles per 1,000 inhabitants [8]. In this metropolis, characterized by heavy traffic, a large number of industries, and geographical conditions that hinder air dispersion, high concentrations of air pollutants are recorded. Local authorities have implemented environmental contingency programs that restrict vehicle use, prohibit outdoor activities, and establish additional measures to prevent health risks to the population.

Other Mexican cities are also experiencing rapid urban and industrial growth, making it essential to develop and implement methodologies for estimating pollutant emissions, particularly those originating from vehicle fleets. The Intergovernmental Panel on Climate Change (IPCC) has proposed guidelines for estimating greenhouse gas emissions from internal combustion engine vehicles. These emissions are calculated as the product of the amount of fuel consumed and an emission factor. The emission factor represents the ratio between the quantity of gases emitted and the amount of fuel consumed, and it can be specific to the type of fuel, vehicle category, emission control technology, and operating conditions [9].

Several online platforms allow for the systematic estimation of greenhouse gas emissions, including New Version 2.98-IPCC Inventory Software GREET and MOBILE 6 [9-11]. The latter enables the estimation of various atmospheric pollutants such as hydrocarbons, carbon monoxide, nitrogen oxides, carbon dioxide, as well as particulate residues from tires and brakes. Emission factors in this model account for parameters such as ambient temperature, vehicle speed, mileage accumulation rates, and temporal ranges extending from 1952 to 2050. The MOBILE 6 model was later replaced by the more advanced MOVES, developed by the United States Environmental Protection Agency, which incorporates significant improvements in the accuracy of emission factors and in the representation of real-world driving conditions [11,12].

The transition toward sustainability requires analyzing how the composition of the local vehicle fleet influences energy consumption and CO_2 emissions, emphasizing that medium sized cities play a key role in promoting sustainable urban mobility. Notable among policy instruments are fleet renewal programs, which include scrappage schemes and incentives for technological substitution. In the United States, the Cash for Clunkers program encouraged the replacement of old vehicles with more efficient models, preceding the 2023 federal incentives that strengthened the transition toward electric vehicles [13,14]. In Germany, the Umwelt bonus program promotes the purchase of electric vehicles through federal subsidies supporting low emission mobility, while China fosters new energy vehicles (NEVs) through subsidies, tax exemptions, and vehicle replacement initiatives to accelerate the shift toward electric mobility [15,16]. These experiences confirm that fleet renewal policies oriented toward electrification represent an effective tool within sustainable mobility and greenhouse gas mitigation strategies [17] .

This study assessed the carbon dioxide (CO_2) emissions of the private vehicle fleet in a medium sized city in central Mexico undergoing rapid urban and industrial growth. The analysis was based on the emission factors reported in the technical data sheets of locally circulating vehicles. Fuel consumption was estimated through user interviews. A statistical analysis was conducted to determine whether vehicle brand and type exert a significant effect on CO_2 emissions. The specific contribution of obsolete vehicles to total CO_2 emissions was also quantified. The study provides a technical basis to support local sustainable mobility policies and to promote more informed vehicle purchasing decisions among users.

Materials and Methods

Vehicle Fleet

This analysis was conducted in the City of Celaya, located in central Mexico (Latitude: 20° 31′ 24″ N, Longitude: 101° 48′ 55″ W). The City has a population of 521,169 inhabitants, of which 72.00% is urban, and 92.00% is engaged in activities within the secondary and tertiary sectors.

Celaya's vehicle fleet comprises 228,162 units: 57.59% correspond to private use vehicles, mainly light duty units; 1.20% are urban passenger vehicles; 18.41% are freight vehicles; 21.49% are motorcycles; and 1.30% are trailers [18].

In this study, only light duty private vehicles were evaluated. A database containing 10,534 vehicles was obtained from the National Public Vehicle Registry (REPUVE), from which only 7,591 light duty vehicles were considered (Table 1). The vehicles were classified by brand and type: Hatchback, Sedan, Pickup, Minivan/Van, SUV, Coupé, and Crossover.

A survey was conducted in users' households, at gasoline service stations, and through social media platforms. The questionnaire requested information on the brand, model, type, and year of the vehicle. Participants were also asked to indicate the percentage of vehicle use in urban versus highway areas, the type of fuel used, and weekly fuel consumption.

The technical and performance information of the vehicles reported in the surveys was complemented using technical data sheets available from manufacturers' official websites, as well as public and private online platforms designed to guide buyers and users. These data sheets included the following variables: brand, model, type, year, start–stop system, model type and version, engine displacement, power, combustion system technology, and traction type. They also reported CO_2 emissions per kilometer traveled.

The online platforms consulted to obtain combined fuel economy (km/L) and specific emissions (g CO_2/km) were: EcoVehículos, Autodata, and Fuel Economy [19-21]. A final sample of 140 vehicles with complete data on technical characteristics, fuel consumption, and usage was consolidated.

Analysis of Variance: Brand Vehicle Type

A total of 140 vehicles were considered to evaluate the effect of brand and vehicle type on CO_2 emissions per kilometer traveled, without accounting for the year of manufacture. A one-way analysis of variance (ANOVA) was performed with a significance level (α) of 5% and a 95% confidence interval. When the ANOVA indicated significant differences among groups, a Tukey post hoc test was applied to identify which means differed from each other.

The assumptions of normality and homoscedasticity were verified prior to the analysis. In cases where the normality assumption was not met, the robustness of the ANOVA to moderate deviations was considered, given the balanced design of the study. All statistical analyses were performed using Minitab 21® software.

The representativeness of the sample (n = 140) was validated through a stratified design by vehicle brand and type. The coefficient of variation (CV) was calculated by brand, yielding a value of 16.06 [9]. According to the IPCC 2019 Refinement, datasets with CV below approximately 20–30% exhibit acceptable dispersion; therefore, the obtained CV confirms the representativeness and statistical robustness of the sample used in this study [9].

Emission Estimation

The equation proposed by IPCC (2019) [9] was replaced by a formulation that classifies vehicles according to their brand, i = 1…m (up to m), and, within each brand, by vehicle type, j = 1…n (up to n) (Equation 1). The annual distance traveled ($d_{i,j}$) is estimated as the product of annual fuel consumption and combined fuel economy (Equation 2).

Emission factors are expressed in kg CO_2 per kilometer traveled per year. The annual distances traveled ($d_{i,j}$) are used to derive the emission estimates, calculated as the product of annual fuel consumption and combined fuel economy (Equation 2).

$$\text{Emissions} = \sum\nolimits_{brand\ i=1}^{m} \sum\nolimits_{type\ j=1}^{n} (d_{i,j} \cdot EF_{ij}) \quad (1)$$

$$d_{i,j} = C_{i,j} \times r_{i,j} \quad (2)$$

In the analysis of variance, the response variable was the carbon dioxide (CO_2) emissions per kilometer traveled, as reported in the technical data sheets of the vehicles analyzed. The factors considered were brand and vehicle type. The analysis of variance showed that, at a 95% confidence level, both brand and vehicle type have a significant effect on carbon dioxide emissions.

The resulting information was consolidated in Table 1, corresponding to the Integrated Database of Vehicle Technology and Consumption (IDVTC), structured by brand and vehicle type (m, n). This database integrates four main variables: (i) combined fuel economy (km/L), $r_{(m,n)}$; (ii) the number of vehicles ($N_{(m,t)}$) obtained from the REPUVE [18] framework; (iii) the annual gasoline consumption (L/year), $C_{(m,n)}$, estimated from the hybrid surveys conducted; and (iv) the emission factors, expressed in kg CO_2 per kilometer traveled, $EF_{(m,n)}$.

This table also reports the number of (i,j) vehicles listed in the REPUVE registry [18] . The relationship between the units recorded in REPUVE and the total fleet size reported by the local authority results in a uniform expansion factor of 12.47, which was applied to estimate the number of (i,j) vehicles present in the municipal light duty fleet. The sample based parameters (fuel economy, annual gasoline consumption, and emission factors) were subsequently integrated with the expanded inventory to quantify total fuel consumption and CO_2 emissions by vehicle brand and type.

Table 1: Integrated Database on Municipal Vehicle Technology and Fuel Consumption

Brands	Vehicle type	Average combine fuel economy (sample) [=] km/L ($r_{m,n}$)	Annual gasoline consumption (L/year) ($C_{m,n}$)	Emission factors (kg CO_2/ km traveled) ($EF_{m,n}$)	Number of vehicles in REPUVE sample (Nm,t) N_s	Number of vehicles in the municipal vehicle fleet
Brand 1 DEU	Sedan	14.28	1,541.28	218.00	24	299
	SUV	14.82	3,302.52	210.00	11	137
Brand 1 USA	Hatchback	17.52	1,650.48	176.20	243	3032
	Pickup	11.75	1,265.68	267.00	379	4728
	Sedan	20.32	2,119.52	153.71	1124	14023
Brand 2 USA	Van	8.81	907.92	324.67	72	898
Brand 1 ITA	Hatchback	19.69	1,541.28	158.00	37	462

Brand 3 USA	Coupé	11.73	1,320.80	265.00	9	112
	Crossover	9.29	2,146.56	349.25	145	1809
	Hatchback	19.83	1,787.76	157.00	61	761
	Van	10.11	2,861.04	285.00	74	923
	Pickup	9.06	1,695.20	263.33	351	4379
	Sedan	16.63	1,696.24	180.38	363	4529
	SUV	9.43	1,907.36	189.00	129	1609
Brand 4 USA	Pickup	8.92	5,503.68	264.00	29	362
	SUV	9.28	1,100.84	335.00	13	162
Brand 1 JPN	Coupé	17.13	1,541.28	181.00	4	50
	Sedan	17.23	1,348.36	181.00	310	3868
	SUV	11.90	1,100.84	192.00	173	2158
	Van	13.12	770.64	237.00	90	1123
Brand 1 KOR	Sedan	19.26	935.48	143.00	90	1123
	SUV	10.67	2,090.40	291.00	37	462
Brand 5 USA	SUV	12.75	1,100.84	244.00	74	923
Brand 2 KOR	Hatchback	19.41	1,475.24	160.00	48	599
	Sedan	13.18	1,564.16	186.00	225	2807
	SUV	13.24	1,560.00	238.33	63	786
Brand 2 JPN	Hatchback	19.86	880.36	157.00	48	599
	Sedan	15.30	2,035.28	153.80	142	1772
Brand 3 JPN	Hatchback	20.07	2,025.40	137.00	20	250
	Pickup	8.07	2,772.64	385.00	29	362
	SUV	10.49	1,100.84	296.00	25	312
Brand 4 JPN	Sedan	14.95	1,559.48	193.58	1071	13362
Brand 1 FRA	Sedan	16.29	1,541.28	191.00	13	162
Brand 2 FRA	Crossover	17.00	1,541.28	183.00	57	711
	Van	12.20	1,320.80	255.00	5	62
Brand 1 ESP	Hatchback	18.81	1,649.96	165.00	79	986
Brand 5 JPN	Hatchback	19.7	495.56	158.50	65	811
Brand JPN	Hatchback	19.75	1,595.88	158.50	27	337
	Sedan	15.96	1,455.48	174.63	218	2720
Brand 2 DEU	Hatchback	11.47	1,705.60	206.00	146	1821
	Pickup	17.00	880.36	138.00	174	2171
	Sedan	13.11	1,743.04	213.39	1294	16144
Total				9014.27	7591	94706

Results

Characteristics of the Vehicle Fleet

According to the Public Vehicle Registry, REPUVE [18], the vehicle fleet in the city of Celaya consists of 228,162 units. The REPUVE sample of 7,591 vehicles was analyzed, and their distribution by year of manufacture is shown in Figure 1. Estimated that in Spain, the useful life of vehicles is 18.7 years or 187,000 km under normal use and with recommended maintenance [22]. Mention that, after 7 years, vehicles begin an annual decline in fuel efficiency of 0.19–0.80 km/ point out that in the United States, several factors affect vehicle performance; for example, it is estimated that a 100% increase in the cost of gasoline can increase fuel efficiency by 6–11% [23,24]. While stricter traffic and vehicle regulations could increase fuel efficiency by up to 3%, technological improvements in engines and lighter vehicle bodies have not shown such significant improvements. The combination of these factors could result in an overall vehicle efficiency improvement rate of 0.3% per year in the United States. Fuel efficiency has increased from 8 km/L to 11 km/L between 2007 and 2022.

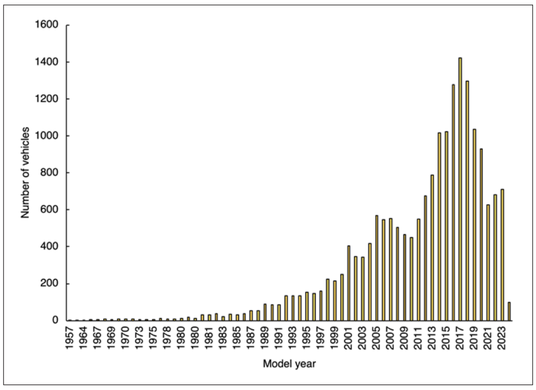

Figure 1: Manufacturing year of the Vehicle Fleet in the City of Celaya

Figure 2a shows that the brands with the largest number of vehicles correspond to manufacturers from the United States, Germany, and Japan, all of which have a long presence in the national market and a consolidated reputation. The region also hosts assembly plants from General Motors, Honda, Toyota, and Mazda. In recent years, an increasing number of Chinese brands has entered the local market.

Figure 2b presents the distribution of vehicles by type. Sedans clearly dominate user preference, while hatchbacks, pickup trucks, and SUVs each account for approximately 10% of the fleet. The number of hatchback (compact) vehicles has increased markedly in recent years. A user preference survey revealed that individuals aged 18–24 showed interest in acquiring the following vehicle types: 49.7% motorcycles, 24.6% compact cars, and 22.9% electric vehicles.

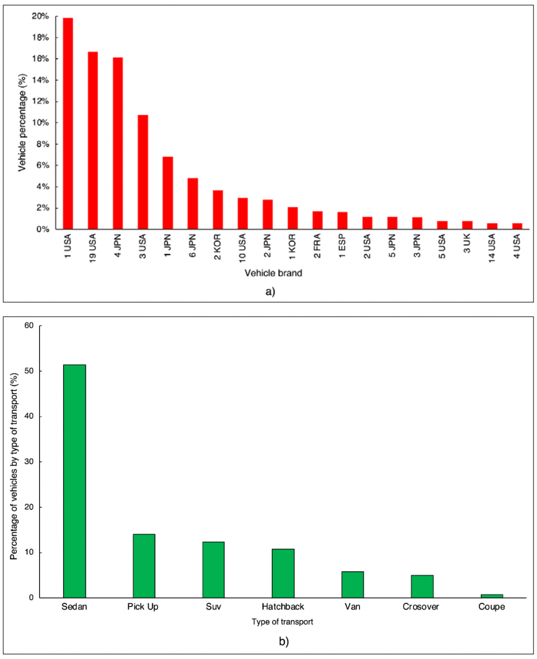

Figure 2: Distribution of the vehicle Fleet in the City of Celaya by Brand (a) and Vehicle type (b)

Effect of Brand and Vehicle Type on CO_2 Emissions

The analysis of variance showed that both vehicle type and brand significantly influence CO_2 emissions ($p < 0.05$). Figure 3 displays the means and 95% confidence intervals (CIs) of CO_2 emissions. Large confidence intervals were observed, indicating high dispersion within the categories. The Tukey test grouped vehicle types with similar mean values for high and low emissions. Crossover, Van, and Pickup vehicles exhibited the highest CO_2 emissions, whereas Hatchback and Sedan types stood out for their lower emissions.

As complementary validation, the Dunnett test was applied using Sedan and Hatchback as reference groups (Figures 4 and 5). The results show that the mean CO_2 emissions of Coupé, Pickup, SUV, Van, and Crossover vehicles are significantly higher than those of Sedan and Hatchback types ($p < 0.05$). In general, Sedan vehicles exhibit higher emissions than Hatchbacks; however, for certain specific brands, the differences were not statistically significant (the confidence interval crosses the zero line).

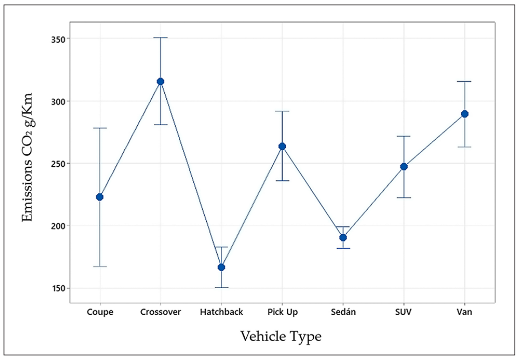

Figure 3: Mean CO_2 Emissions by Vehicle Type (95% CIs)

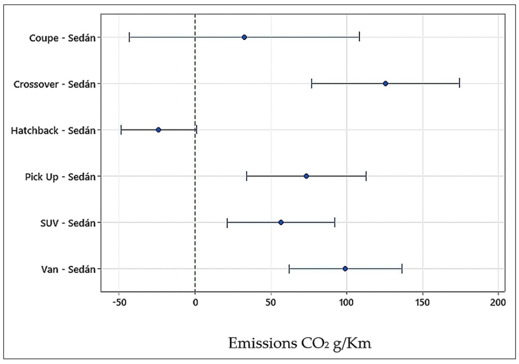

Figure 4: Dunnett Simultaneous 95% CIs for Mean CO_2 Emissions (g/km) Compared to Sedan (Control Group)

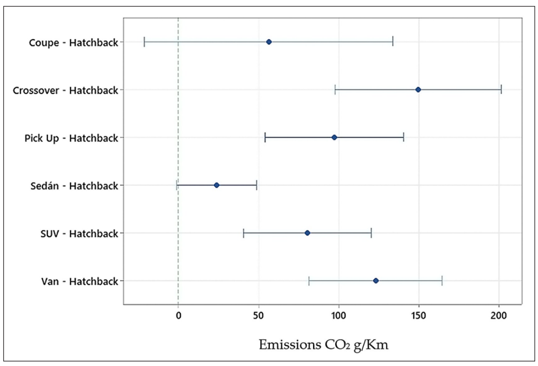

Figure 5: Dunnett Simultaneous 95% CIs for Mean CO_2 Emissions (g/km) Compared to Hatchback (Control Group)

Figure 6 shows the means and 95% confidence intervals (CIs) of CO_2 emissions by vehicle brand. Although the intervals overlap, the analysis of variance ($p < 0.05$) reveals a significant effect of brand on emissions. This effect is explained by the higher mean values of Brand 2 USA and Brand 4 USA, in contrast with the lower means of Brand 1 ITA, Brand 1 USA, Brand 2 JPN, and Brand 5 JPN.

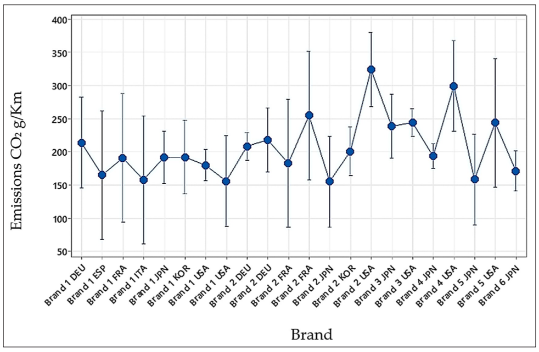

Figure 6: Mean CO_2 Emissions (g/km) across vehicle brands (95% CIs)

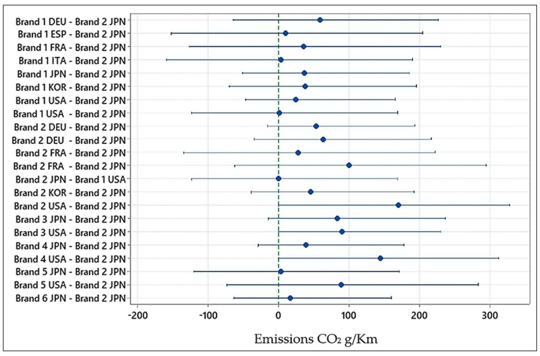

Figure 7: Comparative Analysis of CO_2 Emissions by Brand and Country of Manufacture

Figure 7 presents the multiple mean comparisons of CO_2 emissions among brands, along with their respective 95% CIs. Most intervals include the zero value, indicating no statistically significant differences among the majority of brands. However, some comparisons, such as those involving Brand 2 USA, show positive values without overlapping zero, indicating significantly higher CO_2 emissions compared with other brands.

In this study, most averages are close to 220 g CO_2/km. Published a Greenpeace report on the automotive industry's influence on climate issues, showing that the average emissions of the world's 12 largest car manufacturers amount to 195 g CO_2/km, with a range between 168.8 and 220 g CO_2/km [25].

Estimation of CO_2 Emissions from the Vehicle Fleet

In Mexico, gasoline prices are high, and fuel consumption can represent up to 13.70% of household expenditures for vehicle users [26]. For this reason, the population increasingly favors the use of motorcycles and compact cars with higher fuel efficiency; currently, 23.9% of the vehicle fleet consists of motorcycles, a sector not included in this study.

Table 2 presents the composition of the vehicle fleet by unit type, the emissions generated over the average vehicle lifetime, and their corresponding fuel efficiency. These average values are independent of vehicle brand. [27] estimated that a compact vehicle, over 150,000 km of driving, emits approximately 27.63 tons of CO_2.

Table 2: CO_2 Emissions by Vehicle type

Vehicle type	Percentage of vehicle fleet (%)	Emissions per unit (t CO_2 / 150,000 km)	Fuel efficiency (km/L)
Coupé	0.17	35861.11	13.40
Crossover	2.66	45351.56	11.47
Hatchback	10.20	25946.65	17.39
Pickup	12.67	36869.28	11.53
SUV	6.92	33000.70	11.42
Sedan	64.21	27702.60	16.02
Van	3.17	41744.99	10.89

Table 3 presents the contributions to total CO_2 emissions by vehicle type within the entire fleet. The data provided in this table depend not only on the technological characteristics of the vehicles and the properties of the fuel, but also on the frequency, conditions of use, and driving behavior of users. In this regard, a user owning multiple vehicles may choose a compact car for long distance travel and a larger vehicle for occasional trips.

Table 3: Emission Contributions by Vehicle type

Vehicle type	Emissions by type (t CO_2/year)	Percentage of emissions (%)	Emissions per vehicle (t CO_2/year)
Hatchback	43006.3	9.51	4.45
Sedan	306558.8	67.81	5.04
Pickup	48967.27	10.83	4.08
Van	12886.73	2.85	4.29
SUV	23955.27	5.3	3.66
Coupé	699.47	0.15	4.31
Crossover	16008.12	3.54	6.35

Table 4 presents the CO_2 emission contributions by vehicle brand within the municipal fleet. Emissions by brand reflect the actual distribution of each manufacturer in the fleet, their usage patterns, and the fuel economy (km/L) associated with their mechanical configurations. Since certain brands account for a larger number of circulating units, their relative contribution to annual emissions can be substantially higher, even when their per unit emission factors are similar.

To construct Table 4, the expanded vehicle fleet inventory was integrated with brand specific emission factors and fuel consumption values derived from the sample, using a standardized annual mileage of 15,000 km in accordance with the methodological recommendation of the IPCC 2019 Refinement [9].

Table 4: Emission Contributions by Brand

Brand	Total emissions (t CO_2/year)	Vehicles in fleet	Emissions per vehicle (t CO_2/year)	Percentage of emissions (%)
Brand 1 DEU	1409.28	436	3.23	0.50
Brand 1 USA	59281.35	21783	2.72	20.88
Brand 2 USA	4373.31	898	4.87	1.54
Brand 1 ITA	1094.94	462	2.37	0.39
Brand 3 USA	49772.54	14122	3.52	17.53
Brand 4 USA	2247.57	524	4.28	0.79
Brand 1 JPN	20844.68	7199	2.89	7.34
Brand 1 KOR	4425.47	1585	2.79	1.56
Brand 5 USA	3378.18	923	3.66	1.19
Brand 2 KOR	12079.04	4192	2.88	4.25
Brand 2 JPN	5498.65	2371	2.32	1.94
Brand 3 JPN	3989.58	924	4.32	1.41
Brand 4 JPN	38799.23	13362	2.90	13.66
Brand 1 FRA	464.13	162	2.87	0.16
Brand 2 FRA	2188.85	773	2.83	0.77
Brand 1 ESP	2440.35	986	2.48	0.86
Brand 5 JPN	1928.15	811	2.38	0.68
Brand JPN	7926.12	3057	2.59	2.79
Brand 2 DEU	61795.38	20136	3.07	21.76

The obsolescence and aging of the vehicle fleet negatively affect air quality by increasing pollutant emissions. The main objectives of the automotive industry are to manufacture lighter vehicles and to incorporate technologies that significantly improve fuel efficiency.

In the United States, the annual gasoline consumption per vehicle decreased from 729 to 621 gallons between 1999 and 2023. During the same period, fuel efficiency increased from 16.8 to 18.4 miles per gallon [28]. In controlled traffic tests conducted in Poland, it was determined that passenger trucks with mileage up to 86,000 km generate 182% fewer CO_2 emissions than trucks with 120,000 km of mileage [29].

Figure 8 shows the average gasoline efficiency estimated for local vehicles, as well as that reported by the Environmental Protection Agency in 2023 [12]. The general trend indicates an increase in fuel efficiency; local data show higher efficiency, mainly because the most commonly used vehicles in this locality are compact sedan and hatchback types, whereas in the United States, Van and Pickup vehicles are more prevalent.

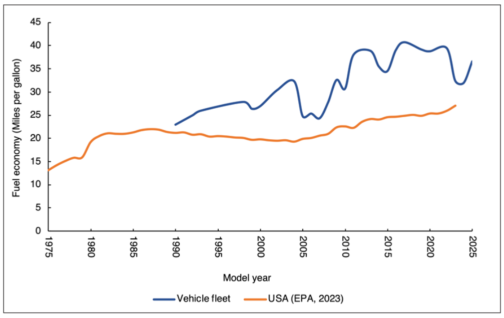

Figure 8: Comparison of Gasoline Mileage Reported by the EPA and the Estimate for Local Vehicles

Vehicles that are 17 years old or older (model year 2005 and earlier) are classified as obsolete. This threshold corresponds tothe period preceding the widespread adoption of the On Board Diagnostics system (OBDII) and three way catalytic converters in Mexico, both of which are essential for maintaining the air fuel mixture close to $\lambda \approx 1.00$ and for complying with the emission limits established in [30].

According to vehicles must maintain emissions within the permissible limits up to a durability standard of 80,000 to 100,000 km [31]. Therefore, those with higher mileage or lacking proper catalytic system maintenance are considered technologically degraded or out of specification.

Within this framework, vehicles manufactured before 2006 and with at least 80,000 km show greater mechanical deterioration, lower energy efficiency, and higher specific emission rates, justifying their classification as a significant obsolete source within the municipal inventory. Consequently, the categorization used is consistent with the concept of total and transitional obsolescence identified in the technical literature and in regu latory phases of vehicular emission control.

Figure 9 shows the percentage of CO_2 emissions associated with vehicle model years in the locality. The orange color represents the contribution of vehicles considered obsolete (≥17 years old). It can be concluded that 28% of the vehicle fleet, classified as obsolete, contributes 55% of total CO_2 emissions.

Based on these findings, a prioritized mitigation strategy is proposed, integrating the fleet composition by brand and vehicle type to optimize performance and reduce emissions: Progressive electrification of the sedan segment, given its high prevalence and substantial contribution to total fleet emissions.

Promotion of hatchbacks as transitional vehicles toward cleaner mobility technologies, due to their superior fuel economy and lower specific emissions.

Gradual reduction of Pickups, SUVs, Vans, and Crossovers, encouraging their replacement with lighter, hybrid, or electric models to decrease overall emissions and carbon footprint.

Preferential incorporation of brands with higher energy efficiency (km/L) and lower emission rates (g CO_2/km), prioritizing European and Asian technologies that demonstrate proven efficiency.

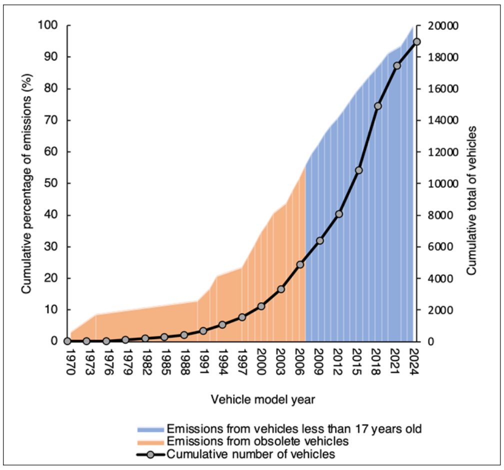

Figure 9: CO_2 Emission Contributions from Vehicles of Different Manufacturing Years Currently Operating Within the Vehicle Fleet

Comparative reviews of international vehicle renewal policies indicate that their effectiveness depends on the establishment of verifiable environmental targets and incentive mechanisms proportional to their climate impact. In Germany, green bonds issued by the public development bank Kreditanstalt für Wiederaufbau (KfW) since 2014, and expanded to federal issuances beginning in 2020, have strengthened the financing of sustainable mobility, allocating more than half of their resources to clean transport initiatives. This financing framework supports the purchase and leasing of hybrid and electric vehicles, as well as low emission electric motorcycles [32,34].

Although these incentives initially accelerated the growth of electric cars, sales declined in 2024, while the electric motorcycle segment expanded by 46.5%, reflecting a shift toward lighter and more energy efficient vehicle technologies [35,36].

Conclusions

The comparative analysis confirms that technological differences among manufacturers strongly influence the environmental performance of the vehicle fleet. The highest emitting brand, Brand 2 DEU, which accounts for 22% of the total inventory, generates 61,796 t CO_2/year. In contrast, the brand with the lowest impact reports 464 t CO_2/year, resulting in an emission gap of 61,332 t CO_2/year between the two.

Sedans, representing 64% of the fleet, account for 68% of total emissions, followed by utility vehicles (SUVs, vans, and crossovers), whose combined contribution exceeds 11%. Pickups exhibit the lowest fuel economy (11 km/L) and the highest emissions per vehicle, whereas hatchbacks show the best environmental performance, positioning themselves as a transitional segment toward mobility driven by cleaner technologies.

Vehicle obsolescence and aging substantially increase emissions. Units manufactured in 2005 or earlier, which constitute 28% of the local fleet, generate 55% of total CO_2. This finding provides strong evidence for local authorities to consider policies that discourage vehicle aging, as adopted in several countries through government inspection programs that determine mileage, model year, and manufacturer, and promote replacement with new vehicles under attractive financing schemes an approach similar to the MOVES model [12].

The nature and structure of this study should be replicated in most countries worldwide to establish clear indicators of how vehicle manufacturers are advancing toward cleaner technologies. There is, without question, a pressing need for more comprehensive datasets in countries such as Mexico to enable a complete and rigorous assessment of fleet performance and environmental impacts.

Looking ahead, it is essential to examine the effects of vehicle electrification and the growing prevalence of motorcycles on urban mobility and sustainability. Future research should therefore explore these segments in greater depth and incorporate direct measurements of fuel consumption and mileage to enhance the accuracy of emission estimates.

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