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AN INTEGRATED METHOD TO CALCULATE AN AUTOMOBILE'S EMISSIONS THROUGHOUT ITS LIFE CYCLE

Viñoles-Cebolla, Rosario[a]; Bastante-Ceca, María José[b]; Capuz-Rizo, Salvador F.[c]

(a) Universitat Politècnica de València. Camino de Vera, s/n. Departamento de Proyectos de Ingeniería. Edificio 5J. 46071 Valencia (Spain). rovice@dpi.upv.es
(b) Universitat Politècnica de València. Camino de Vera, s/n. Departamento de Proyectos de Ingeniería. Edificio 5J. 46071 Valencia (Spain). mabasce1@dpi.upv.es
(c) Universitat Politècnica de València. Camino de Vera, s/n. Departamento de Proyectos de Ingeniería. Edificio 5J. 46071 Valencia (Spain). scapuz@dpi.upv.es

Corresponding author: Rosario Viñoles-Cebolla. Telephone: +0034 963 879 860; Fax: +0034 963 879 869

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1. ABSTRACT

Although studies can be found in the literature that present emissions inventories associated with different types of automobiles, distinct technologies or various stages of their life cycles, they do not enable us to compare the environmental impact of the complete life cycle of two vehicles. This is because there is no valid emissions inventory for all types of automobiles that covers all the life cycle stages (the cradle to grave approach). This paper proposes a method to estimate the principal types of emissions throughout a vehicle's life cycle based on primary data (weight, year of manufacture, engine technology, fuel type used, etc.). The proposed method requires neither sophisticated life cycle assessment software nor knowledge of specific information on individual vehicles. The proposal has been validated by analyzing three different gasoline and diesel-fueled internal combustion engine vehicles and by considering a life span of 100,000 kilometers.

2. OBJECTIVE

This paper presents a method to estimate the emissions of an internal combustion engine vehicle throughout its life cycle. Although studies exist in the literature those present emissions inventories associated with different types of automobiles [1][2][3], distinct technologies and energies [4][5][6] or various stages of their life cycles [7][8][9], they cannot be used to compare the environmental impact of the complete life cycle of two vehicles. This is because there is no valid emissions inventory for all types of automobiles that covers all the stages of their life cycles, often referred to as the cradle to grave approach.

Although the use stage of a vehicle may represent between 46% and 76% of the total energy consumed during its life cycle, and in spite of the fact that between 67% and 74% of greenhouse gas emissions[1] are generated during its use, depending on engine type (varying from hydrogen-powered fuel cell vehicles to internal combustion fueled with gasoline) [7], the manufacturing and end-of-life stages cannot be left out of the analysis, and have to be taken into account in the life cycle assessment (LCA). Since a vehicle's fundamental impact can be expressed in terms of emissions and energy consumption, the term "emissions" has been chosen to address the matter.

When two gasoline and diesel-fueled vehicles were previously compared in their use stage, in relation to fuel consumption per kilometer, the latter has been traditionally associated with lower emissions of

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[1] For hydrogen-fueled engines, the greenhouse gas emissions generated during fuel production may represent up to 80% [7].

pollutant gases (including CO_2), together with higher emissions of particulate matter (PM). However, with the advance of engine technology and increasingly stringent regulations (Euro and EPA standards [10][11]), differences in PM emissions have been practically eliminated since the Euro 5 standard, which is currently in force, limits PM emissions to 5 mg/km, while the EPA standard limits PM emissions to 20 mg/mile for both vehicle types.

Apart from differences in the use stage, what other differences can be found between different types of vehicles in the other stages of their life cycles? Which vehicle performs better at the end-of-life stage from an environmental perspective? What influence does the choice of one material or another have on the vehicle's final impact?

When a vehicle is manufactured, the effect of changes on the materials used in its components (e.g. the recent trend of increased plastics and aluminum content, and less iron and steel) on its total environmental impact have to be taken into account since these changes affect not only emissions [12][13], but also the possible different end-of-life scenarios. It can, therefore, be stated that vehicle composition data are important since they will determine the vehicle's recyclability rate.

The emissions estimation method proposed herein allows the calculation of the emissions associated with a vehicle throughout its life cycle. It also enables a sensitivity analysis to estimate variations in emissions according to the mileage (in kilometers) covered, engine type, composition of vehicle components, and the end-of-life scenario.

The ultimate aim of this paper was to propose a method to estimate emissions from different types of internal combustion engine vehicles in order to determine which has the least environmental impact. To this end, it was necessary to find a way of complementing the existing data in the literature with additional data for the manufacturing and end-of-life stages in order to compare equivalent vehicles in both size and power terms.

Although for this paper only internal combustion engine technologies have been considered, it would be interesting to extend the method into the future to the rest of types of engines. The reason why this project considers initially the indicated technologies is due to the fact that nowadays internal combustion engines compose the greatest share of the market, and also because due to this it exists sufficient reference material available to define the proposed model.

3. ENVIRONMENTAL IMPACT OF AN AUTOMOBILE

Automobiles are involved in many different environmental problems, the best known of which is probably atmospheric pollution caused by engine emissions. Other existing problems are associated with the large amounts of materials and energy consumed in their manufacture and maintenance, the energy consumed and the emissions generated to extract and process fossil fuels, the liquids used as lubricants or coolants of engines, and those used to wash the vehicles, as well as the materials used to decontaminate them at the end of their life.

As various studies have pointed out [14][15][16][17], from a brief examination of an automobile's life cycle, it can be concluded that the use stage has a negative environmental impact, mainly due to the energy consumed in this stage, which is far greater than the amount consumed in other stages, even in the so-called low fuel-consumption vehicles [7].

However, when this impact is analyzed from the waste generation or global warming point of view, (greenhouse gas emissions, such as CO_2, CH_4, and so on), the raw materials extraction and processing stage is considered to be the most polluting one.

When analyzing the environmental impact due to particulate matters, and NO_x and CO_2 emissions, the raw materials extraction and processing stage is usually found to be the most polluting one. However, the largest amount of water is consumed in the manufacturing stage [16][18].

The concern voiced by the automobile industry for its environmental impact has increased in recent years due to more and more increasing pressure placed by public administrations, and given increasingly stricter European, Asian and US regulations. Car manufacturers are, thus, under growing pressure to improve their environmental performance, and, that they are doubtlessly responding to this challenge. Since 1990, the reuse and recycling rates of materials in production cycles and the industry's global productivity have substantially risen [19]. Since 1970, PM and toxic gas emissions in the vehicle usage stage have been considerably reduced and the trend still moves in this direction.

As regards the treatment of vehicles at the end of their life, and as different studies have pointed out [20][21][22][23][24], each country has introduced comprehensive regulations to control the end-of-life stage of discarded vehicles.

4. REVIEW OF THE STATE OF THE ART

There are different qualitative (MET Matrix, checklists, etc.) and quantitative techniques (ecoindicators, life cycle assessment, etc.) available to analyze a product's environmental profile; i.e. to obtain a general perspective of its most important environmental aspects throughout its life cycle, which, in some techniques, describe them as environmental impacts. All the techniques are based on an analysis which includes all the stages of the product's life cycle. Its complexity, cost, time required to carry it out and amount of information needed is what distinguish one method from another.

Life cycle assessment (LCA) is currently the most popular technique in the scientific community for analyzing a product's environmental load. According to the Society of Environmental Toxicology and Chemistry (SETAC), LCA can be defined as "an objective process for evaluating the environmental loads associated with a product, process or service" [25]. This involves identifying and quantifying the energy and materials used, as well as all the waste returned to the environment, with the objective of analyzing and assessing their environmental impact in order to adopt those measures that minimize negative effects and maximize positive ones.

From the literature review of methods or studies carried out to calculate the environmental impact of an automobile, surprisingly very few works include all the life cycle stages. Among them, these are noteworthy [2][7][8]. However, there are numerous studies that focus on only one stage, where the use stage predominates.

Regarding the studies that apply LCA to automobiles, the following are highlighted:

- Those that deal with LCA methods: authors like Lundqvist et al. [21], Hentges [26] and Saur et al. [27] consider specific aspects of LCA methods with a special emphasis placed on automobiles.
- LCA studies that focus on any vehicle component: Steele and Allen [28] made a simplified LCA of vehicle batteries. Other similar studies into batteries include [29][30][31]. It is also worth mentioning the work of Saur [32], who assessed five car fender designs. Keoleian et al. [33] and Joshi [34] made LCAs on alternative materials for fuel tanks.
- LCA studies that deal with materials: Gibson [35] compared components made of different materials to investigate the feasibility of using the lightest. Young and Vanderburg [36] analyzed an environment for applying LCA to materials in order to determine their extrinsic environmental properties. Other interesting studies have focused on one kind of raw material: e.g., diverse metals [12], magnesium [13][37], steel [38] and aluminum [39]. There are also studies that simultaneously compare different raw materials [3][40].

- LCA studies that focus on a specific life cycle stage: the most important ones are those that have analyzed the use stage because it is the most complex stage, there is considerable information available about it, and it accounts for most of the environmental impact throughout an automobile's life cycle [1][4][41][42][43][44][45][46]. Kirkpatrick et al. [47] analyzed the end-of-life stage and found only minor differences in the environmental impact when considering different end-of-life scenarios. Lave et al. [15] studied the manufacturing stage and Kaniut et al. [48] specified percentages of energy consumption and NO_x emissions for different automobile operating units in the manufacture stage.
- LCA studies that consider the complete life cycle: Sullivan and Hu [49] and Schweimer and Schuckert [50] were the first to publish LCA studies for conventional vehicles; MacLean and Lave [51] were the first to use the EIO-LCA Model (Economic Input-Output Life Cycle Assessment) and compared their findings with those obtained by Sullivan and Hu, and Schweimer and Schuckert. Later Sullivan and Cobas-Flores [52] analyzed and compared eight different published life cycle inventories. Among those on alternative fuel vehicles, the works by DeLucchi [53] and Wang [54] are highlighted, who proposed the models to be used as the basis for many other studies [30][55][56]. It is also worth mentioning the works of Mayyas [39], who performed a complete Life Cycle Assessment of a vehicle, and Wang et al. [57] who carried out several analysis for vehicles with different technologies, although only CO_2 emissions and energy consumptions were considered for these analyses.

Table 1 classifies some studies in this field according to engine technologies, energies, emissions and life cycle stages.

Reference	**Technologies**	**Energies**	**Emissions**	**Life cycle stages**
[1]	IC, E	G, M, GN, E	CO, NO_x, VOC, SO_x	U
[2]	IC, HE, E	G, D, BE, BD, NG, LPG, E	CO_2, CO, NO_x, SO_x, N_2O, VOC, CH_4, PM	RM, M, U
[3]	IC, E	G, E	CO_2, CO, NO_x, SO_x, VOC, CH_4, PM, Others	RM
[4]	IC, E, FC	G, D, NG, LPG, M, BE, BD, H, E	CO_2, CO, NO_x, N_2O, SO_x, VOC, CH_4, PM	U
[5]	IC, HE, E, FC	G, M, E	CO_2, CO, NOx, HC	U
[6]	IC, HE, E, FC	G, D, NG, LPG, BE, H, E	CO_2, CO, CH_4, NO_x, PM	U
[7]	IC, HE, FC	G, D, H, E	GHG	RM, M, D, U, EOL
[8]	IC, HE, FC	G, H	CO_2, CO, NO_x, SO_x, N_2O, VOC, CH_4, PM	RM, M, U, EOL
[9]	IC	G, D, NG, BE, BD	CO, NO_x, SO_x, VOC, PM	M, U, EOL
[40]	IC	G	CO_2	RM, M, U, EOL
[41]	IC	NG, LPG, BE, BD	CO, NO_x, VOC, CH_4, PM	U
[42]	IC, HE, E	G, D, BE, H, E	CO_2	U
[43]	IC, HE, E	G, D, NG, LPG, E	Ecoscore (CO_2, CO, NO_x, SO_x, N_2O, CH_4, PM)	U
[44]	IC, HE, FC	G, D, NG, LPG, BD, E, CC	CO_2, CO, NO_x, SO_x, VOC, CH_4, PM	U
[45]	IC, HE, E	G, D, NG, LPG, BE, BD, E	CO_2, CO, NO_x, VOC, CH_4, PM, Others	U
[58]	IC	G, D, NG, LPG, BE, BD	CO, NO_x, NO_2, VOC, PM, Others	U
[59]	IC, HE	G, E	CO_2, CO, NO_x, VOC	U
[60]	IC, HE	G, E	CO_2, CO, NO_x, VOC	U
[61]	IC, HE, E	G, E	CO_2	U
[62]	IC, HE,	G, D, NG, LPG	CO, NO_x, VOC, PM	U
[63]	IC, HE	G, D, BE, BD, GN, LPG	CO, VOC, NO_x, PM, GHG	M, U

Technologies: Internal combustion (IC); Hybrid-electric (HE); Battery electric (E); Fuel cell electric (FC).

Energies: Gasoline (G); Diesel (D); Natural gas (NG); Liquefied petroleum gas (LPG); Methanol (M); Ethanol (BE); Biodiesel (BD); Hydrogen (H); Electricity (E).

Emissions: Carbon dioxide (CO_2); Carbon monoxide (CO); Nitrogen oxide (NO_x); Sulfur oxide (SO_x); Nitrous oxide (N_2O); Nitrogen dioxide (NO_2); Volatile organic compounds (VOC); Methane (CH_4); Hydrocarbons (HC); Particulate matter (PM); Greenhouse gas (GHG).

Life cycle stages: Extraction and processing of raw materials (RM); Manufacturing (M); Distribution (D); Use (U); End of life (EOL).

Table 1. List of works published on vehicle emissions in one life cycle stage or more.

Nowadays, no single method is available to estimate the environmental impact of a vehicle throughout its life cycle from readily available primary data (such as weight, year of manufacture, engine technology, fuel type, etc.) and without having to use sophisticated LCA software or very specific information on individual vehicles.

5. METHOD

This section presents a method to calculate the emissions that a vehicle produces throughout its life cycle, which is based on published data taken from scientific journals, technical reports and studies; in other words, this proposal is based on bibliographical information. For this procedure, it is necessary to know the weight of the vehicle, its composition, its year of manufacture, the technology it incorporates, the fuel type it uses and consumption, and its annual mileage and life span.

Nowadays, different engine technologies linked to different fuel or energy types are being used. The method presented herein is applicable only to conventional technology; i.e., internal combustion engines, regardless of the fuel type used (gasoline, diesel fuel, natural gas, liquefied petroleum gas, ethanol, dimethylether and biodiesel).

5.1. INITIAL INPUT DATA

5.1.1. YEAR OF MANUFACTURE AND WEIGHT OF VEHICLE

Two key pieces of data to begin calculating a vehicles' life cycle emissions are year of manufacture and its weight. The year of manufacture is easily obtained from the vehicle's registration certificate, which specifies both the month and year in which it was manufactured. The vehicle number plate registration documents also provide the year in which the plates were issued, which is normally a few months after it has been manufactured, except when it has been imported by a private citizen. This information can also be obtained from the dealer or manufacturer. The weight of the vehicle is usually provided on its registration certificate, along with its engine capacity and engine power.

5.1.2. FUEL CONSUMPTION AND DRIVING

Fuel consumption data (in liters/km) can be obtained from the vehicle owner's manual or, if not available, from the manufacturer's web page or from research groups in the energy field. For example, in the US, information is available on www.fueleconomy.gov, which is managed by the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy, with figures provided by the U.S. Environmental Protection Agency (EPA). In the UK, this data can be obtained from the Vehicle Certification Agency (VCA) at www.dft.gov.uk/vca. In Australia, information is acquired from the Green Vehicle Guide of Department of Infrastructure and Regional Development at www.greenvehicleguide.gov.au, and in Spain, from the Institute for Energy Diversification and Saving (Instituto para la Diversificación y el Ahorro de la Energía, IDAE) at www.idae.es.

The proposed method allows, if information is available, to classify fuel consumption according to the type of journey as *city* or *non city* driving. Average consumption can also be indicated. If fuel consumption is specified according to the type of journey, it is also necessary to indicate the same type of use chosen for the vehicle (city or non city driving).

Some studies, which have mostly dealt with medium-sized vehicles, have considered different types of mileage, ranging from 25% to 80% in cities (see Table 2).

Reference	City Driving	Non City Driving
[43]	25%	75%
[61]	80%	20%
[64]	55%	45%

Table 2. Usage cycles applied in other studies.

Timmermans et al. [43] proposed a range of mixed driving modes for different vehicle types:

Vehicle Type	City Driving	Non City Driving
Light	25%	75%
Heavy	10%	90%
Two-Wheelers	40%	60%

Table 3. Mixed driving modes for different vehicle types [43].

5.1.3. ANNUAL MILEAGE AND LIFE SPAN

No general agreement has been reached on the consulted references for annual mileage. Table 4 shows the different total mileage and life span figures cited in different studies.

Reference	Life span in years	Km
[2]	15	225 000
[5]	7.8	n/a
[7]	15	300 000
[59]	14	250 000
[61]	10	100 000
[63]	15	300 000
[64]		200 000
[65]	15	300 000

Table 4. Vehicle's life span considered by different authors.

Another aspect that should be borne in mind is that annual mileage varies from year to year. Based on information from Germany, Denmark, France, The Netherlands, Italy and the United Kingdom, Hickman et al. [45] analyzed how annual mileage declines yearly.

5.2. ESTIMATING EMISSIONS OF EACH LIFE CYCLE STAGE

According to the literature review, it has been established that different studies divide the life cycle into a distinct number of stages: 4 [66], 5 [67], 6 [19], 8 [68]. For this work, the 4-stage life cycle proposed by Keoleian [66] was chosen, namely: (i) raw material extraction and processing; (ii) component manufacturing and vehicle assembly; (iii) use; (iv) end-of-life.

The main emissions included in leading studies have also been reviewed, considered to be the main references for the methodology proposal. These are: Carbon dioxide (CO_2); Carbon monoxide (CO); Nitrogen oxide (NO_x); Sulfur oxide (SO_x); Nitrous oxide (N_2O); Nitrogen dioxide (NO_2); Volatile Organic Compounds (VOC); Methane (CH_4); Non Methane Volatile Organic Compounds (NMVOC); Hydrocarbons (HC); Particulate Matter (PM); Greenhouse Gases (GHG); Lead (Pb); Chemical Oxygen Demand (COD); Biochemical Oxygen Demand (BOD_5). From the range of emissions, only the following have been calculated herein, CO; CO_2; CH_4; NMVOC; NO_x; PM and SO_x, since they had been included in most referenced studies and they are generally accepted as being representative of a vehicle's life cycle.

5.2.1. EMISSIONS IN THE RAW MATERIAL EXTRACTION AND PROCESSING STAGE

First of all, the composition of the vehicle (quantity and type of materials) has to be identified. If such information cannot be obtained from the manufacturer, the data from Table 5, obtained from different bibliographic references [3][24][69][70][71][72][73][74][75], can be used. To estimate the percentage rate for ferrous metals, between steel and iron, published data have also been used as a reference [24][75].

Secondly, from the year of manufacture and vehicle weight, the weight of each material can be calculated. Table 6 presents the composition of the vehicles analyzed in Section 6.

	1975-79	1980-84	1985-89	1990-94	1995-99	2000-05
Ferrous Metals	73.4	71.2	70.5	66.1	64.4	60.6
Non Ferrous Metals	5.4	6.0	6.7	7.6	8.7	10.2
Plastics	4.8	6.2	7.0	9.4	9.6	13.8
Rubber	4.0	4.2	4.3	4.9	5.5	4.7
Glass	2.4	2.6	2.7	3.0	3.0	2.2
Liquids/Fluids	5.4	5.6	5.5	2.5	1.8	2.1
Others	4.6	4.2	3.3	6.5	7.0	6.4

Table 5. Percentage share of materials in a vehicle according to its year of manufacture year, compiled from [3][24][69][70][71][72][73][74][75].

	VW Golf G	VW Golf D	MB Class B G
Ferrous Metals	645.28	719.62	746.44
Aluminum	116.49	129.91	134.75
Plastics	110.84	123.61	128.22
Rubber	45.89	51.18	53.08
Glass	28.24	31.49	32.67
Others	112.25	125.19	129.85
Total	1,059.00	1,181.00	1,225.00

Table 6. Estimation of weights (kg) according to the composition of the vehicles analyzed in Section 6.

After determining the quantity and type of materials used in the vehicle's composition, information on the different emissions involved in their manufacturing can be obtained from a number of studies. Those carried out by the Ecolane Transport Consultancy [2] (done in the U.K.), and by the Argonne National Laboratory, the National Renewable Energy Laboratory and the Pacific Northwest National Laboratory [3] (done in the U.S) present the emissions generated in the mining and processing of certain materials used to manufacture an automobile (see Tables 7 and 8).

$g_{emissions}/kg_{material}$	CO	CO_2	CH_4	HC	NO_x	SO_2	PM
Ferric	29.02	2,352	1.23	1.40	3.33	3.77	1.85
Composites	n/a	12,000	12.00	12.00	36.00	23.00	n/a[2]
Aluminum	1.65	6,049	n/a	15.45	12.00	33.15	8.25
Copper	n/a	20,000	1.40	1.40	10.00	658.00	n/a
Zinc	n/a	10,000	9.70	9.70	20.00	65.00	n/a
Lead	0.34	1,680	0.06	0.16	2.60	7.40	n/a
Magnesium	n/a	10,000	9.70	9.70	20.00	65.00	n/a
Nickel	n/a	20,000	1.40	1.40	10.00	658.00	n/a
Plastics	n/a	3,800	19.00	19.00	20.70	26.70	n/a
Rubber	n/a	1,700	5.00	5.00	10.00	15.00	n/a
Glass	n/a	760	0.79	0.79	2.30	2.30	n/a

Table 7. Emissions of the main materials used in automobile manufacturing according to Lane [2].

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[2] n/a: Data not available.

$g_{emissions}/kg_{material}$	CO	CO_2	CH_4	NMVOC	NO_x	SO_x	PM
Steel	86.00	3,000	0.320	0.130	0.18	6.40	0.37
Iron	0.30	4,200	0.016	0.052	10.00	18.00	1.70
Aluminum	0.83	3,700	0.083	0.130	8.30	32.00	0.29
Plastics	0.59	3,500	0.130	0.220	3.70	20.00	1.80
Rubber	1.70	900	0.320	5.700	10.00	36.00	4.60
Glass	0.22	950	0.020	0.180	5.00	6.40	1.10

Table 8. Emissions of the main materials used in automobile manufacturing according to Cuenca et al. [3].

In order to calculate the emissions produced during the extraction stage of raw materials, the emission values proposed by Lane [2] (Table 7) were used since they are fairly recent and generally accepted.

From the vehicle weight and composition data, and after combining them with the data in Table 7, the emissions produced in the raw materials extraction and processing stage can be calculated.

5.2.2. EMISSIONS IN THE MANUFACTURING STAGE

There is practically no published information available on the emissions produced in the vehicle manufacturing stage. It should be noted that more than 30 studies from scientific journals and research centers have been included in the literature review, and that only a small number of them offered no comprehensive data of this life cycle stage.

However, even when information on the emissions produced in the manufacturing stage or vehicle components is missing, extrapolation can be carried out based on the year of manufacture statistics provided by a car manufacturer. Table 9 provides an example of a Volkswagen vehicle. In this case, the emissions produced in the manufacturing stage can be estimated from all Volkswagen factories' emissions by dividing between the total units manufactured by the Volkswagen Group.

COMPANY: VOLKSWAGEN GROUP Annual production: 7,358,000 units	**Total**	**Per Manufactured Unit**
Energy Consumption (MWh)	18,830,000	2.55
Direct Emissions CO_2 (t)	1,290,000	175.31
Total Emissions CO_2 (t)	7,700,000	1.04
Emissions NO_x (t)	2,859	388.53E-06
Emissions SO_x (t)	371	50.42E-06
Emissions COV (t)	26,351	3.58E-03
DQO (t)	4,043	549.46E-06
Fresh Water (m^3)	36,850,000	5.01
Waste Water (m^3)	28,090,000	3.82
Non Dangerous Residue (t)	428,191	58.19E-03
Dangerous Residue (t)	188,621	25.63E-03
Waste Metal (t)	1,581,635	214.95E-03

Table 9. Example of estimating the environmental impact per manufactured unit from the data provided by a car producer [76].

Published information is also available from manufacturers [50][77], from which the data on the emissions deriving from the manufacturing of certain models can be extracted.

5.2.3. EMISSIONS IN THE USE STAGE

Two emission types are produced in the vehicle use stage: direct emissions from the vehicle when it is being driven; indirect emissions when manufacturing the fuel or energy it uses.

Nowadays, legislation to control direct emissions is currently in force. The evolution of emission limits for light vehicles is particularly significant; i.e.: Euro 1, Euro 2, Euro 3, Euro 4, Euro 5 and Euro 6 (the last one is due to come into force in 2014). These limits, included in [10], depend on fuel type and year of manufacture, and have been adopted as reference values to calculate emissions in the present proposal (see Table 10).

	CO		HC		NO_x		HC + NO_x		PM	
Fuel	**G**	**D**	**G**	**D**	**G**	**D**	**G**	**D**	**G**	**D**
Euro 1 (1993)	2.720	2.720		0.970			0.970	0.970		0.140
Euro 2 (1997)	2.200	1.000		0.700			0.500	0.700		0.080
Euro 3 (2000)	2.300	0.640	0.200	0.060	0.150	0.500		0.560		0.050
Euro 4 (2005)	1.000	0.500	0.100	0.050	0.080	0.250		0.300		0.025
Euro 5 (2009)	1.000	0.500	0.100	0.050	0.060	0.180		0.230	0.005	0.005

Table 10. Direct emissions (g/km) of gasoline and diesel vehicles based on Euro standards [10].

The above-mentioned standards do not include direct CO_2 and SO_2 emissions; however, given their importance, they have been estimated from these gas emission factors, together with fuel energy content and density, following the method proposed by some authors [42][43][76] (see Table 11).

	Energy Content (KJ/Kg)	Density (g/l)	CO_2 Emissions Factor (kg CO_2/l)	Sulfur Content (ppm)	SO_2 Emissions Factor (g SO_2/l)
Gasoline	42,715	755	2.212	50	7.55E-04
Diesel	43,274	850	2.697	50	8.50E-04

Table 11. Information for calculating direct CO_2 and SO_2 emissions. Compiled from [43][44][78].

Although EURO Standards values were considered the reference values for the proposal herein, Table 12 also shows the limit values established by the Environmental Protection Agency (EPA) in 2007 [11].

Bin	NMOG[3]	CO	NO_x	PM	HCHO[4]
8	0.125 (0.156)	4.2	0.20	0.02	0.018
7	0.090	4.2	0.15	0.02	0.018
6	0.090	4.2	0.10	0.01	0.018
5	0.090	4.2	0.07	0.01	0.018
4	0.070	2.1	0.04	0.01	0.011
3	0.055	2.1	0.03	0.01	0.011
2	0.010	2.1	0.02	0.01	0.004
1	0.000	0.0	0.00	0.00	0.000

Table 12. Direct emissions (g/mi) of gasoline and diesel vehicles based on EPA standards [11].

To calculate indirect emissions during fuel manufacturing, the reference data for different fuel types were extracted from several scientific papers [43][44][45][46][78] (see Table 13).

	CO	CO_2	CH_4	NMHC	NO_x	PM	SO_2
Gasoline	0.165	296.519	0.561	6.821	1.361	0.077	2.116
Diesel	0.170	250.328	0.577	3.223	1.324	0.037	1.780

Table 13. Indirect emissions (g/l) according to the fuel or energy used. Compiled from [43][44][45][46][78].

The total emissions produced in a vehicle use stage can be obtained from fuel consumption data and by adding direct and indirect emissions.

5.2.4. EMISSIONS IN THE END-OF-LIFE STAGE

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[3] For diesel fueled vehicle, NMOG (non-methane organic gases) means NMHC (non-methane hydrocarbons).

[4] HCHO: Formaldehyde.

After analyzing the information available in the bibliography, Sakai's criterion that 25% of a scrap vehicle becomes ASR was adopted [79]. Table 14 shows the emissions produced while incinerating this scrap to recover materials and energy [80].

CO	CO_2	NO_x	PM	SO_x
0.000098	1.54	0.00098	0.000049	0.000343

Table 14. Emissions ($kg_{emissions}/kg_{ASR\ incinerated}$) generated in the end-of-life stage [80].

The study by Lundqvist [21] presents four different scenarios of future recycling systems for end-of-life vehicles in Europe for the years 2015 and 2030. Most of the ELVs in 2015 will be the automobiles manufactured in 2000, and the ELVs in 2030 will be those designed today. The year 2030 also represents a year when more comprehensive changes in the recycling system have had time to occur. The four scenarios are:

- Scenario 1. Considers a moderate technical development of recycling processes for the vehicles withdrawn before 2015.
- Scenario 2. It is considered that several components will be dismantled for recycling before shredding for the vehicles withdrawn between 2015 and 2030.
- Scenario 3. Considers a significant technical development of recycling processes; i.e. shredder processes and processes for the pre-treatment of shredder residues for those vehicles withdrawn between 2015 and 2030.
- Scenario 4. It is considered that a larger share of energy recovery is accepted if compared to the present ELV directive for the vehicles withdrawn between 2015 and 2030.

Materials	**Dismantling and/or recycling**				**Energy recovery**[5]				**Landfill**		**Reuse as filling material**	
	1	2	3	4	1	2	3	4	1	2	3	4
Ferrous Metals	99.6%	99.9%	99.9%	99.9%	0.0%	0.0%	0.0%	0.0%	0.4%	0.1%	0.1%	0.1%
Non Ferrous Metals	91.4%	96.6%	96.6%	96.6%	0.0%	0.0%	0.0%	0.0%	8.6%	3.4%	3.4%	3.4%
Rubber	87.5%	87.5%	87.5%	0.0%	5.0%	10.0%	12.5%	100.0%	7.5%	2.5%	0.0%	0.0%
Plastic	22.2%	88.9%	77.8%	0.0%	60.0%	6.7%	22.2%	100.0%	17.8%	4.4%	0.0%	0.0%
Glass	41.2%	47.1%	52.9%	0.0%	0.0%	0.0%	0.0%	0.0%	58.2%	52.9%	47.1%	100.0%
Composites	0.0%	0.0%	0.0%	0.0%	91.9%	96.8%	100.0%	100.0%	8.1%	3.2%	0.0%	0.0%

Table 15. Scenarios of future recycling systems for end-of-life vehicles [21].

Currently, for the present study, Europe is in a situation corresponding to scenario 1. In the future, according to the development of technologies forecasted by Lundqvist [21] the method can be parameterized for other scenarios.

Total end-of-life emissions can be obtained from vehicle weight combined with the data provided in Tables 14 and 15.

5.2.5. TOTAL EMISSIONS THAT A VEHICLE PRODUCES THROUGHOUT ITS LIFE CYCLE

Basically, Figure 1 illustrates the proposed method to calculate the emissions that a vehicle produces throughout its life cycle based on the data obtained in the literature

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[5] Recovery is defined as the incineration process to generate energy

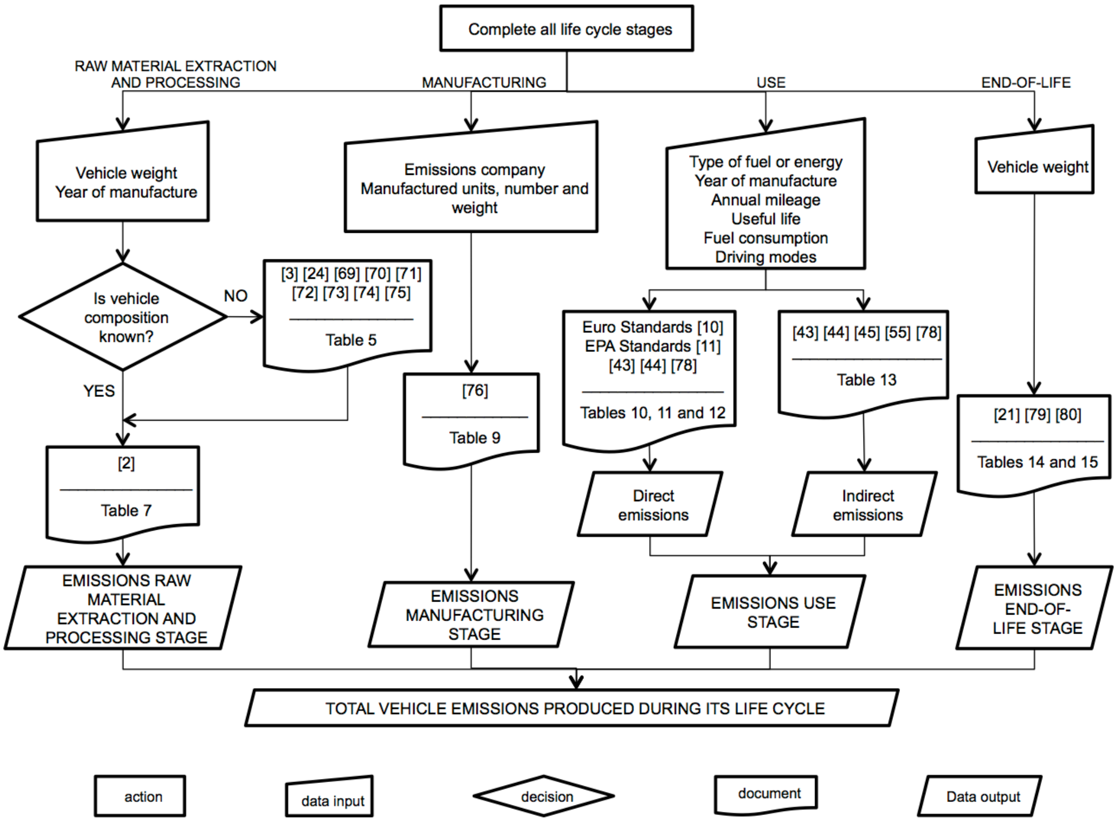

Figure 1. Proposal to calculate the emissions that an automobile produces throughout its life cycle, based on the data compiled from the bibliography.

6. CASE STUDIES AND INTERPRETATION OF THE RESULTS

The inputted data specified in Section 5 were implemented on a spreadsheet to enable the analysis of three internal combustion vehicles fueled by either gasoline or diesel, whose mileage was 100,000 kilometers during their life span. Table 16 shows the characteristics of the analyzed vehicles. In all cases, environmental information was made publicly available by the manufacturers [77][81].

Model	Volkswagen Golf A4	Volkswagen Golf A4	Mercedes Benz Class B
Acronym	VW Golf G	VW Golf D	MB Class B G
Year of Manufacture	1999	1999	2008
Weight (kg)	1,059	1,181	1,225
Cubic Capacity (cm^3)	1,400	1,900	1,498
Horsepower (kW)	55	66	70
Consumption (l/100 km)	6.6	5.0	6.6
Fuel tTpe	Gasoline	Diesel	Gasoline

Table 16. Basic data of the analyzed vehicles.

The results obtained for the different emission types and life cycle stages after applying the proposed method to the three vehicle models are shown below, together with a comparison made between the results obtained from the method (named “M”) and the data published by the manufacturing companies (named “C”) (Figures 2 to 9). It should be noted that although the method proposed herein considers CH_4 and NMVOC emissions separately, Figure 6 shows the aggregated data for both emission types since this is the way in which the manufacturer sometimes publishes these data.

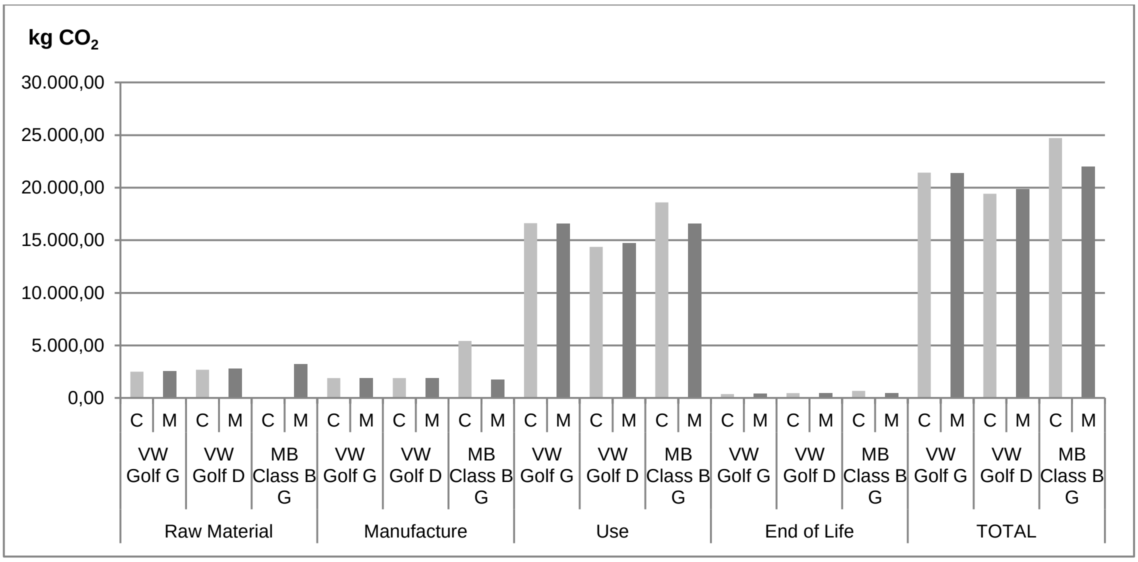

Figure 2. Comparison of CO_2 emissions.

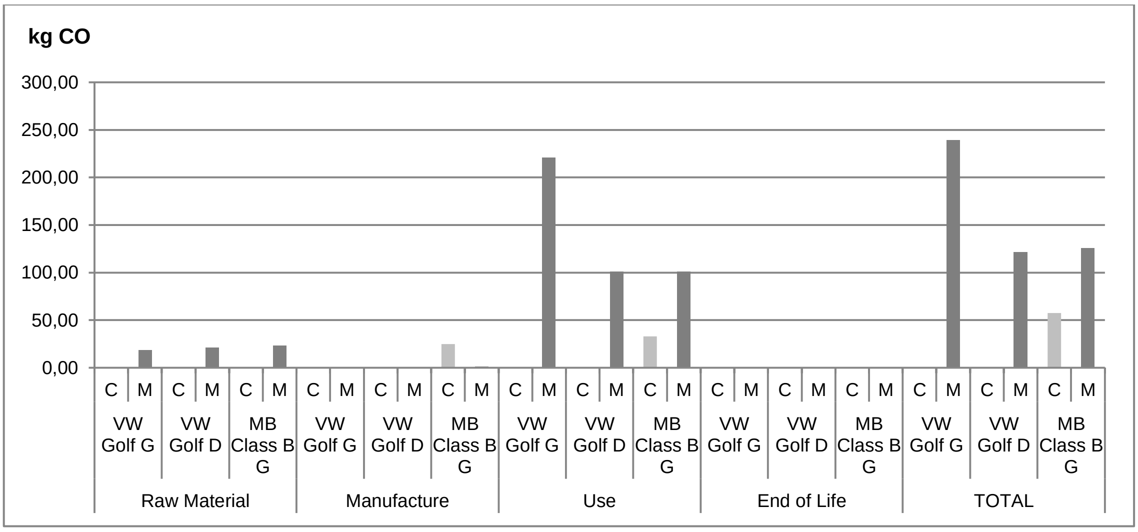

Figure 3. Comparison of CO emissions.

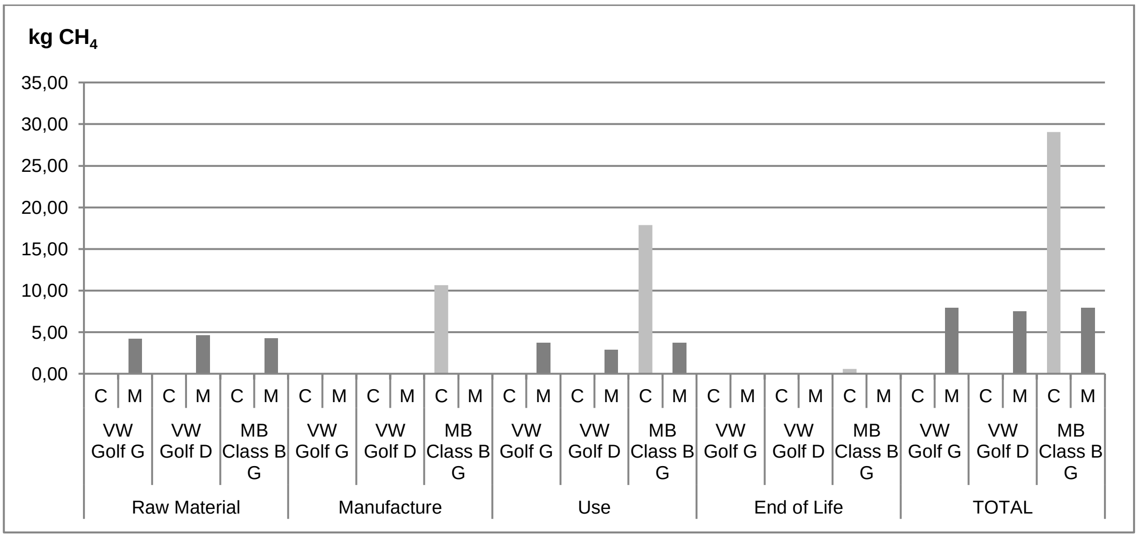

Figure 4. Comparison of CH_4 emissions.

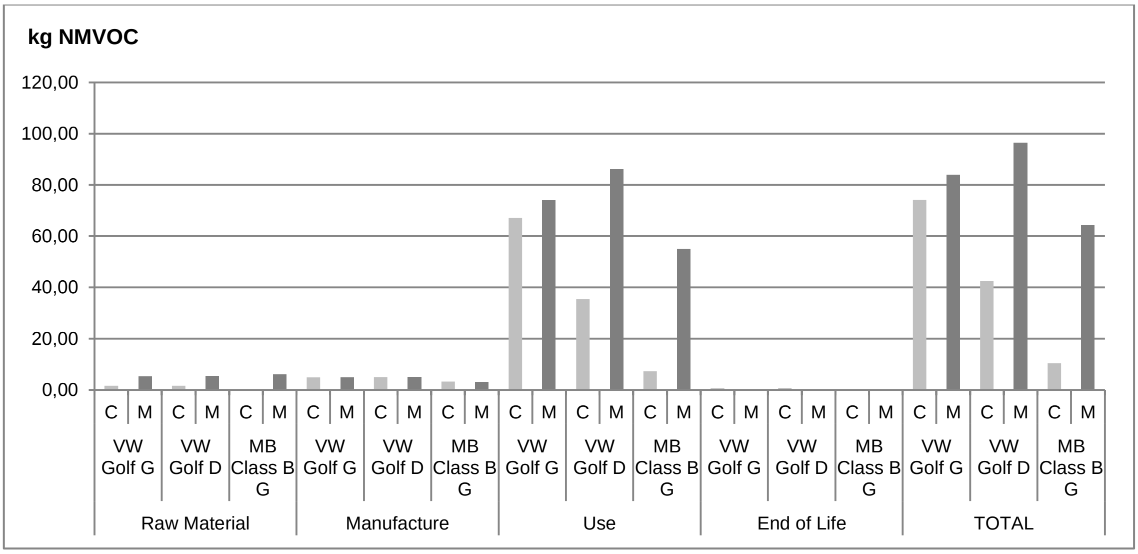

Figure 5. Comparison of NMVOC emissions.

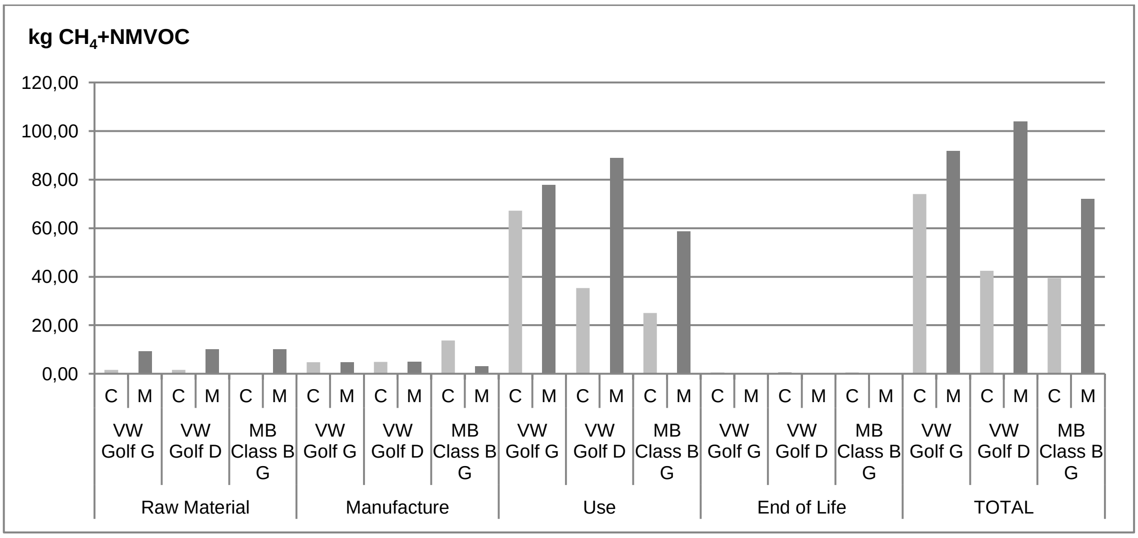

Figure 6. Comparison of CH_4+NMVOC emissions.

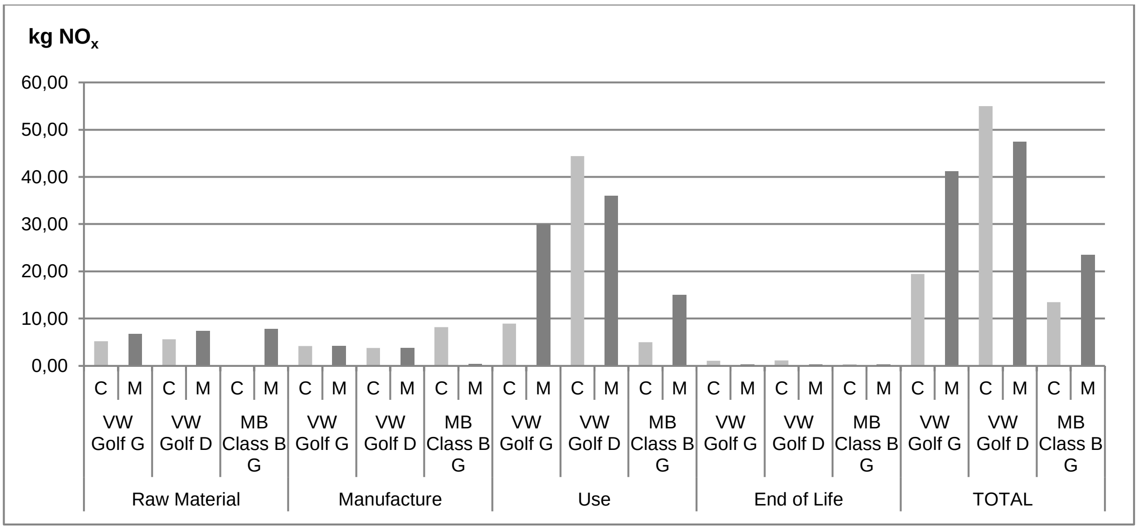

Figure 7. Comparison of NO_x emissions.

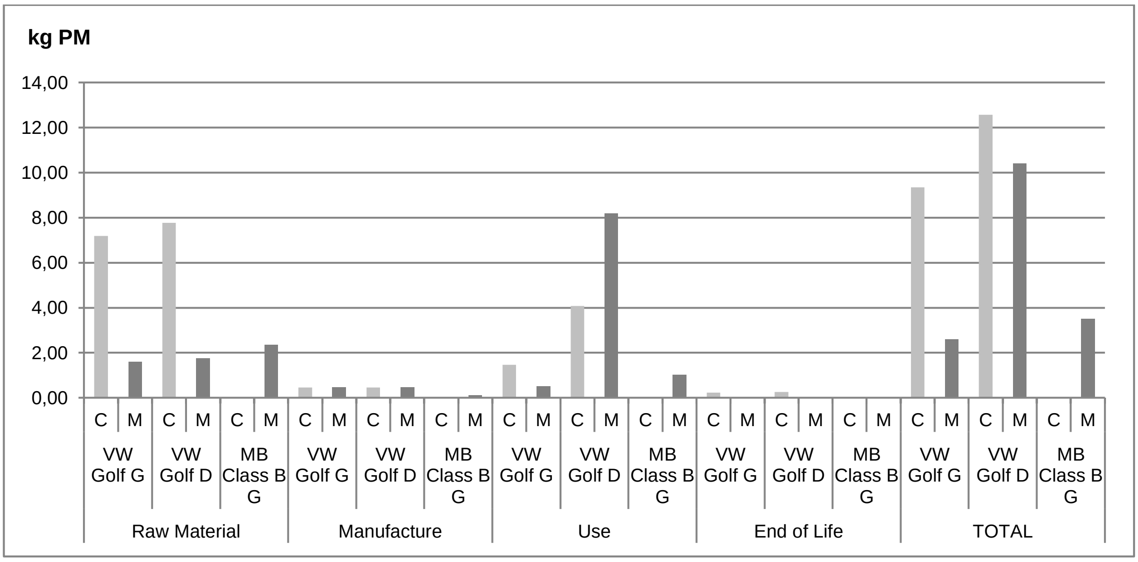

Figure 8. Comparison of PM emissions.

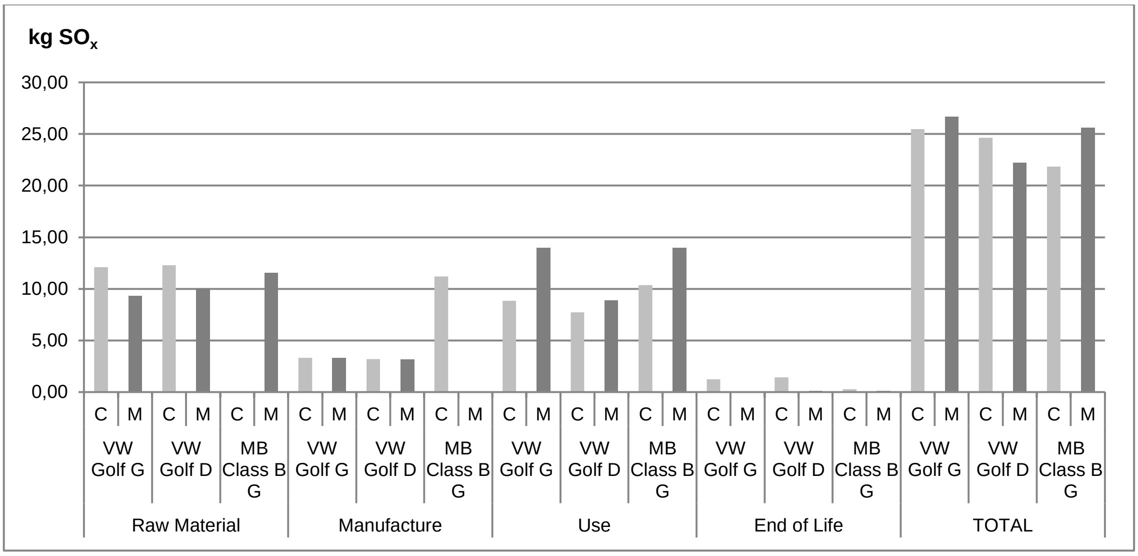

Figure 9. Comparison of SO_x emissions.

The analysis of the results shows that the most important stage for most emissions is the use stage, while the raw materials extraction and processing stage is also important for some emissions.

Differences in use stage emissions can be attributed to differences as regards year of manufacture (Euro 2 Standard applies to calculate the direct emissions of the two Volkswagen models, and Euro 4 Standard applies to calculate those of the Mercedes Benz). Differences were also due to their fuel consumption (lower in the diesel-fueled vehicle) and to the fuel type used. The emissions produced in the raw materials extraction and processing stage depend on both vehicle composition and vehicle weight.

- CO_2 emissions in the use stage are due mainly to direct emissions, which, as mentioned in Section 5.2.3, are not regulated. These have been estimated by applying factors that depend on consumption and mileage (see Table 11), which were the same for the VW Golf G and MB Class B G. Indirect emissions were lower in diesel-fueled vehicles because their consumption is lower or the emissions per liter were lower than in gasoline-fueled vehicles (see Table 13).

- As the CO emissions in the use stage were affected by a less strict standard (Euro 2 in the case of the VW Golf G, if compared to Euro 4 for the MB Class B G), direct emissions were higher for the VW Golg G. Regarding fuel type, indirect emissions in diesel-fueled vehicles were higher, as in the VW Golf D, but direct emissions were considerably lower than gasoline-fueled cars which, in this case, was not relevant if they were affected by the same Euro regulations (as in the VW Golf G), or they were affected by stricter Euro regulations (MB Class BG).

- The CH_4 emissions in the use stage, when comparing two similar vehicles (e.g., the two Volkswagens) were lower in diesel-fueled vehicles. This is because the direct emissions were not regulated, and only the indirect emissions could be quantified. Despite the fact that emissions per liter were higher in diesel-fueled vehicles, the average consumption in the VW Golf D was lower. In the raw materials extraction and processing stage, CH_4 emissions were mainly due to the use of plastics, which represents between 12.8% and 15.8% of the weight of all three vehicles. For the VW Golf D, CH_4 emissions were slightly higher than for the VW Golf G since they contained almost the same percentage of plastics (15.4% and 15.8%, respectively), but the VW Golf D was heavier. Although the MB Class B G contained a lower percentage of plastics (12.8%), it weighed more than the VW Golf D, and for this reason, the CH_4 emissions were similar for both vehicles.

- The direct NMVOC emissions in the use stage in diesel-fueled vehicles were higher because they had to comply to a less strict Euro standard, while the indirect emissions were higher in gasoline-fueled vehicles. Indirect emissions were, thus, more significant in the latter, while direct emissions were more relevant in the former.

- It should be noted that the total hydrocarbon emissions (CH_4 + NMVOC) were higher in diesel-fueled vehicles. The differences between gasoline-fueled vehicles were due to the different Euro standards governing each vehicle type (the stricter the standard, the lower the emissions).

- The NO_x emissions in the use stage were due mainly to direct emissions, especially in those vehicles subject to EURO 3 or previous standards. For the vehicles subject to Euros 4 and 5, which is the case of MB Class B G, the direct emissions were lower and were even less than the direct emissions. The NO_x emissions in the raw materials extraction and processing stage were attributed mainly to the use of plastics and non ferrous metals, which represents around 20% of the weight of all three vehicles.

- The PM emissions in the use stage in the analyzed cases were higher for the VW Golf D. This was because it was manufactured in 1999, when the Euro standard for this aspect was not as stricit as Euro 5, which is presently in force. The PM emissions in the raw materials extraction and processing stage were due to ferric metals and aluminum since the bibliographic reference employed to make a comparison [2] did not consider emissions from other materials.

- The SO_x emissions in the use stage were mainly due to indirect fuel emissions. Like CO_2, direct SO_x emissions were not regulated and their value was estimated, although it was not relevant in the comparison made with the indirect emissions. It is worth noting that the SO_x emissions due to casting materials, such as copper and nickel, were also important in the raw materials extraction and processing stage.

After comparing the results from the methodological proposal with those published by the manufacturers, it should first be pointed out that Volkswagen did not include CO and CH_4 emissions, and the PM emissions were not included by Mercedes Benz. Secondly, it should be noted that in the data published by Mercedes Benz for the MB Class B G, the emissions produced in the raw materials extraction and processing stage were aggregated with the emissions produced in the manufacturing stage. Thirdly, it is important to note that the differences in the emissions in the use stage were probably due to the fact that manufacturers measured their direct emissions, while in the proposed method, these emissions were calculated on the basis of the limits fixed by Euro standards. We should bear in mind that not all emission types are controlled by these standards.

7. DISCUSSION AND CONCLUSIONS

The journey towards a sustainable society requires, apart from social and economical considerations, reliable environmental information of different systems (cities, companies, products, services and so on). When a stakeholder has to make a decision about those systems, it is not generally easy to know the right data and information about their environmental impacts throughout their life span.

In order to perform an LCA of a system, it is essential to know the inventory data. When this system is an automobile, the inventory data are not always available, at least not all the necessary data. Therefore, making an automobile environmental impact estimation method available can be useful for many environmental analysis and its different scenarios.

It has to be considered that for most of the vehicles currently on the market there is no LCA study that indicates the emissions generated throughout their life cycle. What does exist, at least since the implementation of different policies by public administrations, is the obligation to publish vehicle emissions (in grams per mile average CO_2-equivalent) in the use stage, specifically g/km. This means that this environmental variable is the only one used in most cases to make a comparison between different vehicles; i.e., comparisons are limited to the use stage and only to one emission type. Yet in the few cases in which an LCA analysis for vehicles already on the market is available, as mentioned above, there is no uniformity in either the number of stages life cycle or the emission type considered.

A method to estimate the main emission types of an automobile that considers all its life cycle stages is presented herein. This method uses primary automobile data (such as weight, year of manufacture, engine technology, fuel type, and so on), and sophisticated LCA software or knowledge of very specific information about the vehicle is not necessary.

It should be noted that in order to estimate a vehicle’s environmental impact throughout its lifecycle without detailed data provided by the manufacturer, making simplifications and estimations from indirect sources is required, which may influence the final result. In the proposed method, assumptions and simplifications were made in some life cycle stages, particularly in the first two (extraction of raw materials and processing and manufacturing). Note, however, that the impact or deviation on the final result was not significant given the relevance of the emissions in these stages if compared to the entire life cycle. This method also requires constant data updating since an automobile is a product that can undergo many variations, such as changes in its design (materials, technology, fuel type), and also in administrative policies (EURO Standards, En-of-life Vehicles Directive, and so on).

By also taking the analyzed case studies and a sensitivity analysis as a starting point, the proposed method can be used as the basis for the decision making about the most appropiate time for replacing a vehicle in accordance with reduced emissions thanks to new technologies. Nowadays, studies that focus on domestic products, such as domestic washing machines, have been carried out [82]. For the case of the automobile, it is necessary to compare several scenarios of use (mileage and life span of automobiles), and to see both the economic and environmental impact that maintaining a vehicle on the market for many years would have, or to proceed to its replacement with vehicles equipped with new technologies. Mijailovic, at [83], analyzes the optimization of the life span of vehicles but just considering the minimization of CO_2 emissions. In order to carry out an eco-efficiency analysis (measurement of the economic and environmental impact), estimating a vehicle’s life cycle costs may be easy, and the proposed method would help estimate life cycle environmental impacts.

It is important to highlight the usefulness of this method. On the one hand, public authorities can use it as a basis for many initiatives, such as tax policies (i.e. with higher taxation on vehicles with higher emissions as it happen in some european countries, or tax exemption for certain fuels [84]) or even subventions (i.e.

the incentives to discard the old and more contaminants vehicles when a new vehicle is bought) [85]. For instance, the method can be used to calculate environmental fees, to compare the results with the data provided by manufacturers, to establish a fee to enter cities depending on the level of emissions, and so on. On the other hand, economic instruments are approaches characterized by the use of market forces, which employ economic incentives or disincentives to achieve a political objective. There are two types of economic instruments: a) instruments of prices, which immediately affect the prices of goods; b) instruments of quantity, which restrict the amount of good used as a generator of pollution. Taxes and fees: they are used to reduce transport demand, and to also discourage the use of some forms of transport and technologies. Payments are usually linked directly with the public supply of services since the decisions made by individuals are based on the costs that they may incur in different scenarios (charges for using streets, parking rates), which may be required by local authorities in each city. Taxes do not have this direct link to any particular service and can be seen as sources of income.

In cities, especially in developed countries, transportation policies based on this type of incentives are being implemented to counteract environmental and congestion problems in urban areas. European cities, such as London in United Kingdom, are implementing road pricing policies. This means that users must pay to enter the city center and the payment fee depends on vehicle type and time of entry.

Note that, as discussed above, one of the issues identified while compiling information to design the method was to find the information published in scientific journals on the environmental impact measured in emissions, and by the new technologies and materials currently being implemented in the automobile industry. One way of improving the results would be to use the databases incorporated into LCA softwares. So one proposal for future works is to conduct research in this field to answer the question of what to do when data are not available.

Finally, in order to fulfill the objective proposed at the beginning of this paper, the method here presented allows the estimation of the estimation of the emissions of an internal combustion automobile engine throughout its life cycle using primary data and the use of complex software for LCA is not necessary. The results have been validated by comparing them with the data published by manufacturers. The proposed method is also structured in such a way that it can be applied to other vehicle types, as long as new information is published, and the environmental impact data are expressed as emissions and are life cycle allstage-disaggregated.

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