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Safety Engineering for Transport, Logistics, and Production

Comparison of Emissive Behavior of Conventional and Alternative Powertrain Systems for Vehicles Circulating in Urban Areas

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ABSTRACT

Urban pollution may come from natural sources, but the most detrimental are those emissions related to human activities. The anthropogenic sources of pollution, such as factories, industries, transportation, and so on, are typically exacerbated in cities due to the local concentration of humans and human activities. For instance, pollution in cities is affected by global environmental threads, such as global warming, and by locally originated environmental challenges, such as waste management, recycling, and light and noise generation. Population in urban areas has been gradually increasing since years, due to this rapid increase of population the usage of vehicles and all will also be increased automatically, where the usage of vehicles is more pollution will be more. As we can see these population, vehicle usage and pollution are directly proportional.

The emission of gases into the atmosphere will be calculated and their behavior for vehicle fleet in urban areas according to the coming years of 2030. So that we can know what are the emissions which are been into the atmosphere released by the vehicles and we can find a solution to reduce them and can concentrate on the sustainability in the coming years.

This master Thesis is inserted in such context, as the comparison of emissive behavior of conventional and alternative power train systems for vehicles circulating in urban areas is presented and discussed. The model aims to represent a useful tool to evaluate the emission released by vehicles travelling in urban environments. Conventional and alternative vehicles are considered, with propulsion systems based on internal combustion engines, electric motors and battery packs, hybrid units and fuel cell systems.

As closing remark, PROGRESS allows to estimate the improvement of emission factors due to the renewal of vehicular fleet and most importantly, it validates the potentialities of hybrid and electric vehicles, fuel cell vehicles which are the key to reduce the global pollution in road mobility, allowing the passenger car fleet now we are at 95% g/km more than 50% reduction to comply with the future limit of 42 g/km, came into force in European Union in 2030.

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NOMENCLATURE

Emission factors		**Units**
CH_4	Methane	[g/km] or [g/kWh]
CO	Carbon monoxide	[g/km] or [g/kWh]
CO_2	Carbon dioxide	[g/km] or [g/kWh]
HC	Unburnt hydrocarbons	[g/km] or [g/kWh]
NO	Nitrogen monoxide	[g/km] or [g/kWh]
NO_2	Nitrogen dioxide	[g/km] or [g/kWh]
N_2O	Nitrous oxide	[g/km] or [g/kWh]
NO_x	Nitrogen oxides	[g/km] or [g/kWh]
NMVOC	Non-methane volatile organic compounds	[g/km] or [g/kWh]
PM	Particulate matter	[g/km] or [g/kWh]
$PM_{2.5}$	Particulate matter with diameter under 2.5 μm	[g/km] or [g/kWh]
PM_{10}	Particulate matter with diameter under 10 μm	[g/km] or [g/kWh]
SO_x	Sulphur oxides	[g/km] or [g/kWh]

Abbreviations

2ST	Two-strokes engine
4ST	Four-strokes engine
CI	Compression ignition
ICE	Internal combustion engine
EM	Electric motor
SI	Spark ignition

Subscripts

el	Electrical energy
p	Primary energy

Hybrid-electric engine types

CV	Conventional vehicle
μHV	Micro hybrid vehicle
MHV	Mild hybrid vehicle
FHV	Full hybrid vehicle
PHEV	Plugin hybrid vehicle
EV	Electric vehicle
EREV	Extended range electric vehicle

Vehicle categories

SI PC	Spark ignition passenger cars
CI PC	Compression ignition passenger cars
SI LDV	Spark ignition light duty vehicles
CI LDV	Compression ignition light duty vehicles
HDV	Heavy duty vehicles
BS	Buses
MC	Motorcycles
MP	Mopeds

CHAPTER 1: INTRODUCTION

One of the important sources of atmospheric pollution is vehicular emission. The combustion of fuels (gasoline, diesel oil, etc) within automobile engines releases a lot of harmful substances and gases into the atmosphere. Rapid urbanization together with industrialization and exponential growth in vehicular fleet are important factors for air pollution.

In recent years, the number of vehicles have increased enormously resulting in corresponding increment in air pollution. Air quality depends on the emissions from anthropogenic activities, topography and atmospheric circulation patterns. Traffic is a major source of air pollution, mainly in urban regions.

This increase in global pollutant emissions of the transport sector has encouraged in last years the research and the development of alternative ways to power the engines. Engines hybridization and electrification, and also alternative fuels (such as LPG, methane or biofuels) were studied in order to reduce consumption, emissions and fuel cost.

1.1. Aim of the study

The present study focusing on the pollution in urban areas, which is a very serious problem, whose two main direct consequences are human health issues and traffic blocks. Here, the comparison of emissive behavior of conventional and alternative power train systems for vehicles circulating in urban areas is evaluated. The study is done through the PROGRESS software

(PROGramme for Road vehicles EmiSSions evaluation) developed jointly in the first years of 2000, by the Internal Combustion Engines Group (ICEG) operating at the Department of Thermal Machines, Energy Systems and Transportation (DIMSET) of the University of Genova (Italy), the Environmental Department of the Genova Provincial Administration and Genova Municipality. This model was initially actualized to the year 2019 to evaluate actual urban pollution due to road mobility in present years, then is used to study a 2030 future scenario, comparing the normalized emission factors for different vehicle classes, to know the better solution depending on the type of vehicle.

1.2. Legislations for road mobility sector

Internal combustion engines are interested by a wide range of regulations, usually depending on the geographical area, the vehicle type and the final application. The legislative scenario is very wide and complex, as every nation allows different maximum levels of emissions.

There are three main legislations types, the European (*Euro*-, currently Euro 6 is used), the American (*EPA Phase*-, currently EPA Phase 3A) and the Japanese ones (based on American legislation, but with some modifications); while the other countries don't have their own standards but uses the previous ones, usually with delayed introduction dates respect the original ones.

Vehicle types are classified in various categories, which refer to passenger cars, light duty vehicles, heavy duty vehicles and buses together, motorcycles and finally mopeds. Each category has different emission limits and testing procedures. In the end, there are also some differences regarding the final application, which refers to the destination of the engine, specifying if it will be applied in road, marine or power generation applications.

1.2.1. European current legislation on emissions

Usually, these limits refer to the emission of thermal and chemical pollutants, whose main elements are CO_2, CO, HC, NO_x and PM. Current legislation in Europe is Euro 6 for passenger cars, light and heavy duty vehicles, while Euro 4 is used for motorcycles and mopeds. Otherwise, CO_2 emissions are regulated with EU Regulation 443/2009 and successive amendments.

1.2.1.1. CO, HC, NO_X and PM emissions

The following tables shows the current Euro 6 legislation, which fixes the limit values of pollutant emissions (European Parliament, 2007) (European Parliament, 2009). The maximum values of these substances must not be exceeded, otherwise the vehicles which doesn't comply these rules cannot be sold in the market.

Table 1-1: Euro 6 regulations for passenger cars and light duty vehicles

	Fuel	CO [g/km]	HC [g/km]	HC + NO_x [g/km]	NO_x [g/km]	PM [g/km]
Passenger cars	Gasoline	1.0	0.1	-	0.06	0.005
	Diesel	0.5	-	0.17	0.08	0.005
Light duty vehicles < 1250 kg	Gasoline	1.0	0.1	-	0.06	0.005
	Diesel	0.5	-	0.17	0.105	0.005
Light duty vehicles > 1250 and < 1700 kg	Gasoline	1.81	0.13	-	0.075	0.005
	Diesel	0.63	-	0.195	0.125	0.005
Light duty vehicles > 1700 kg	Gasoline	2.27	0.16	-	0.082	0.005
	Diesel	0.74	-	0.215	0.125	0.005

Table 1-2: Euro 6 regulations for heavy duty vehicles and buses

	Fuel	Test procedure	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PM [g/kWh]
Heavy duty vehicles	Diesel	WHSC	1.5	0.13	0.4	0.01
		WHTC	4.0	0.16	0.4	0.01

The main difference from heavy duty to other vehicle categories is the different measurement units, being g/km in the first table and g/kWh in the second. This is because the test for lighter categories is performed running the whole vehicle on a chassis dynamometer; while for the heavy-duty ones, the measurements are done connecting only the engine to the dynamometer test bench, for obvious space reasons. Another difference is related to the testing procedures, which are different from the two categories, the light vehicles are tested with the NEDC (New European Driving Cycle) and the WLTC (World Harmonized Light-duty Vehicle Test Cycle) cycles, while heavy duty vehicles use both WHSC and WHTC (respectively, Worldwide Harmonized Stationary Cycle and Worldwide Harmonized Transient Cycle).

Respect to the motorcycles and mopeds, the current Euro 4 limits are the following (European Parliament, 2013):

Table 1-3: Euro 4 regulations for motorcycles and mopeds

	Engine type	Maximum speed	CO [g/km]	HC [g/km]	NOx [g/km]	Test procedure
Motorcycles	2 and 4 strokes	< 130 km/h	1.14	0.38	0.07	WMTC stage 2
		> 130 km/h	1.14	0.17	0.09	
Mopeds	2 and 4 strokes	-	1.0	0.63	0.17	ECE R47

The above limits are also valid for three- and four-wheel motorcycles. It has to be taken in account that motorcycles and mopeds use different test cycles for the current legislation, while with the upcoming Euro 5 regulation, WMTC (Worldwide harmonized Motorcycle Testing Cycle) will be used for both the categories.

1.2.1.2. CO_2 emissions

Carbon dioxide emissions are controlled through another legislation, different from Euro-ones, which fixes maximum values for the whole fleet of new vehicles per each car producer.

Manufacturers can sell their cars even if this limit value is exceeded, by paying a fee with values proportional to each CO_2 gram over the maximum.

The current limit, which entered into force in 2012, imposes a specific emission of 130 g/km by the whole fleet. The limit is said specific because it is referred to a reference vehicle weight, as the actual limit changes accordingly to the mass with this law:

$$specific\ CO_2\ emissions\ [\frac{g}{km}] = 130 + 0.0457 * (M - M_0) \qquad (1.1)$$

Where 0.0457 is a corrective factor, measured in g/(km·kg), M is the vehicle mass, M_0 is the reference vehicle weight and its value was equal to 1372.0 kg from 2012, then from 2016 it was increased to 1392.4 kg (European Parliament, 2014) and finally from 2019 it will be reduced to 1379.88 kg (European Parliament, 2018). If car manufacturers cannot comply with this limit, there are variable penalties in function of each CO_2 gram released over the limit: currently, the first gram fee is paid 5€ for each vehicle, the second 15€, the third 25€ and from the fourth and the successive ones, each one of them is paid 95€ (European Parliament, 2009).

Starting from 2021, these limits will be exacerbated, dropping to a maximum specific emission value of 95 g/km, with fees of 95€ per every gram, even for the first one. The corrective law in function of the vehicle weight will be the following:

$$specific\ CO_2\ emissions\ [\frac{g}{km}] = 95 + 0.0333 * (M - M_0) \qquad (1.2)$$

Again, 0.0333 is a corrective factor measured in g/(km·kg), M is the vehicle mass, while M_0 has not been defined yet in the current amendment and will be defined soon; in fact, M_0 is a value which undergoes to continues changes and corrections, according to the global vehicle fleet in the market, as seen before.

It is important to state that there is an immediate correspondence between grams of CO_2 and fuel consumption, being the conversion factor equal to:

$$\frac{gram\ of\ CO_2}{km} = 0.0431\ \frac{litres\ of\ gasoline\ 1}{100\ km} \tag{1.3}$$

$$\frac{gram\ of\ CO_2}{km} = 0.0377\ \frac{litres\ of\ diesel\ 1}{100\ km} \tag{1.4}$$

Consequently, limits on CO_2 emissions are also limits on fuel consumption: the actual value of 130 g/km corresponds to 5.6 litres of gasoline and 4.8 litres of diesel per 100 kilometres (or 18.0 and 20.6 km/l), while 95 g/km are equal to 4.1 and 3.5 l/100km of gasoline and diesel respectively (or 24.6 and 28.3 km/l). Therefore, to comply with CO_2 standards, a great increase in fuel economy (and so in the engine efficiency) must be reached.

Similar regulations are currently in force for light duty vehicles, allowing emissions of 175 g/km since 2014, with a successive reduction to 147 g/km from 2021. (European Parliament, 2011)

1.3. Conventional Vehicles emissions control: characteristics and issues

To comply with current legislations, all the vehicles must employ advanced combustion strategies and post-treatment devices to limit emissions and to increase fuel economy. The simultaneous reductions in pollutants such as CO_2, CO, HC, NO_x and PM are very severe and difficult to achieve, especially for diesel engines.

The well-known "Diesel gate" scandal is an example of how the fulfilment of these legislation is difficult: some Volkswagen-group vehicles were equipped with a customized control unit which was able to recognise NEDC testing conditions, changing the engine working point and so reducing its performances, in order to comply with pollutant regulations (especially regarding NO_x) during the tests, returning then back to the usual performances in real driving, overcoming the limits in emissions when not tested. In fact, it is not a case that some car manufacturers will progressively stop the production of diesel-fuelled passenger vehicles (i.e. FCA Group, Volvo, Toyota and Nissan will stop the research and/or the production of diesel powertrains within 2022), because NO_x and PM control in compression ignition engines is very difficult, requiring complex after-treatment systems and nonoptimal engine working points. Otherwise, gasoline engines have much easier emission control, usually requiring just a simple three-way catalytic converter in order to comply with regulations (this is true for manifold injection gasoline engines, while direct injection ones are nearer to diesel emissions characteristics, requiring however a simpler control than this last kind of engines).

As a matter of fact, pollution control techniques can be divided in two main categories: internal and external. The difference is represented on where the pollutants are controlled and reduced in number: if internally, the engine working point is changed in order to produce a smaller quantity of pollutants, but it usually has an impact on fuel consumption (i.e. techniques like “after” injection for the particulate control increase the fuel consumption; or the techniques which lowers combustion temperatures, obtained delaying the ignition of the fuel, reducing NO_x but also the efficiency of the engine). On the other hand, external pollution control techniques employ post-treatment devices, which allow the engine to work in the optimal working point with maximum efficiency, then abating the pollutants at the exhaust. However, this implies an increase in costs, space requirements and complexity and furthermore, also an increase in fuel consumption for many types of post-treatment devices (e.g. regenerations needed by particulate filters and NO_x adsorber catalysts increase the global fuel consumption).

Now, the main characteristics of gasoline and diesel engines are shown, in order to have a better understanding on how and why emissions control is an issue in modern vehicles.

1.3.1. Main features of gasoline engines

Petrol engine or gasoline engine is an internal combustion engine with spark-ignition, designed to run on gasoline and similar volatile fuels. In most of gasoline engines, the fuel and air are usually pre-mixed before compression (although some modern gasoline engines now use cylinder-direct gasoline injection).

The pre-mixing was formerly done in a carburettor, but now it is done by electronically controlled fuel injection, except in small engines where the cost of electronics does not justify the added engine efficiency. The process differs from a diesel engine in the method of mixing the fuel and air, and in using spark plugs to initiate the combustion process.

Gasoline engines run at higher rotation speeds than diesels, partially due to their lighter pistons, connecting rods and crankshaft and due to gasoline burning more quickly than diesel. Because pistons in gasoline engines tend to have much shorter strokes than pistons in diesel engines, typically it takes less time for a piston in a gasoline engine to complete its stroke than a piston in a diesel engine.

However, the lower compression ratios of gasoline engines give gasoline engines lower efficiency than diesel engines. Typically, most of the gasoline engines have approximately 20% (avg.) thermal efficiency, which is nearly half of diesel engines. However, some newer engines are reported to be much more efficient (thermal efficiency up to 38%) than previous spark-ignition engines.

Direct injection allows to reach various advantages respect to port fuel injection, the most important are reduction in fuel consumption, charge cooling, a better cylinder volumetric efficiency and adoption of multiple and different injections strategies. Stoichiometric mixtures allow to achieve a better fuel efficiency with respect to manifold injection and emissions control is achieved with the same kind of three- way catalytic converters.

On the other hand, lean mixtures are able to achieve even greater fuel economy, requiring however a more complex after-treatment system, because they release a great quantity of NO_x and a significant amount of PM in a lean mixture, with a profile similar to diesel engines. As it will be explained in the next paragraphs, the abatement of these two compounds is difficult in these conditions.

1.3.2. Main features of diesel engines

Diesel The diesel engine, named after Rudolf Diesel, is an internal combustion engine in which ignition of the fuel is caused by the elevated temperature of the air in the cylinder due to the mechanical compression; thus, the diesel engine is a so-called compression-ignition engine (CI engine). This contrasts with engines using spark plug-ignition of the air-fuel mixture, such as a petrol engine (gasoline engine) or a gas engine (using a gaseous fuel like natural gas or liquefied petroleum gas).

Diesel engines work by compressing only the air. This increases the air temperature inside the cylinder to such a high degree that atomised diesel fuel injected into the combustion chamber ignites spontaneously. With the fuel being injected into the air just before combustion, the dispersion of the fuel is uneven; this is called a heterogeneous air-fuel mixture. The torque a diesel engine produces is controlled by manipulating the air-fuel ratio (λ); instead of throttling the intake air, the diesel engine relies on altering the amount of fuel that is injected, and the air-fuel ratio is usually high.

The diesel engine has the highest thermal efficiency (engine efficiency) of any practical internal or external combustion engine due to its very high expansion ratio and inherent lean burn which enables heat dissipation by the excess air. A small efficiency loss is also avoided compared with non-direct-injection gasoline engines since unburned fuel is not present during valve overlap and therefore no fuel goes directly from the intake/injection to the exhaust. Low-speed diesel engines (as used in ships and other applications where overall engine weight is relatively unimportant) can reach effective efficiencies of up to 55%.

Due to its high compression ratio, the diesel engine has a high efficiency, and the lack of a throttle valve means that the charge-exchange losses are fairly low, resulting in a low specific fuel consumption, especially in medium and low load situations. This makes the diesel engine very economical. Even though diesel engines have a theoretical efficiency of 75%, in practice it is much lower.

In his 1893 essay Theory and Construction of a Rational Heat Motor, Rudolf Diesel describes that the effective efficiency of the diesel engine would be in between 43.2% and 50.4%, or maybe even greater. Modern passenger car diesel engines may have an effective efficiency of up to 43%, whilst engines in large diesel trucks, and buses can achieve peak efficiencies around 45%. However, average efficiency over a driving cycle is lower than peak efficiency. For example, it might be 37% for an engine with a peak efficiency of 44%. The highest diesel engine efficiency of up to 55% is achieved by large two-stroke watercraft diesel engines.

Diesel engines rely on the air/fuel mixing being done in the cylinder, which means they need a fuel injection system. The fuel is injected directly into the combustion chamber, which can be either a segmented combustion chamber, known as indirect injection (IDI), or an unsegmented combustion chamber, known as direct injection (DI). The definition of the diesel engine is specific in requiring that the fuel be introduced directly into the combustion, or pre-combustion chamber, rather than initially into an external manifold. For creating the fuel pressure, diesel engines usually have an injection pump.

As diesel engines burn a mixture of fuel and air, the exhaust therefore contains substances that consist of the same chemical elements, as fuel and air. The main elements of air are nitrogen (N_2) and oxygen (O_2), fuel consists of hydrogen (H_2) and carbon (C). Burning the fuel will result in the final stage of oxidation. An ideal diesel engine, (a hypothetical model that we use as an example), running on an ideal air-fuel mixture, produces an exhaust that consists of carbon dioxide (CO2), water (H2O), nitrogen (N2), and the remaining oxygen (O2). The combustion process in a real engine differs from an ideal engine's combustion process, and due to incomplete combustion, the exhaust contains additional substances, most notably, carbon monoxide (CO), diesel particulate matter (PM), and nitrogen oxides (NOx).

Table 1-4: Diesel Engine Exhaust Composition

Species	Mass [%]	Volume [%]
N2	75.2%	72.1%
O2	15%	0.7%
CO2	7.1%	12.3%
H2O	2.6%	13.8%
CO	0.043%	0.09%
NOX	0.034%	0.13%
HC	0.005%	0.09%
PM	0.008%	0.0008%

1.3.3. CO and HC emissions control

Carbon monoxide (CO) is also called carbonous oxide, is a colourless, odourless and tasteless gas, which creates very difficult for humans to perceive. CO has been called “the unnoticed poison of the 21st century” and “the silent killer”, because it gives no clear warning to its victims that they were at risk. The small amount of CO poisoning causes hypoxic injury and neurological damage of humans. Due to CO exposure the plant respiration and nitrogen fixation are failures. The presence of CO on earth’s atmosphere effects the atmospheric chemistry as well as the environment.

When CO enter into the ground level ozone, it can creates serious respiratory problems and also increases the global warming level. Therefore, CO levels in the atmosphere play a significant role in influential the air quality of region. Carbon monoxide is produced into the environment by partial oxidation of carbon-containing compounds and also produced by the catalytic cycle of heme degradation and approved by the enzyme heme oxygenase (HO-1) within the human body.

In the assessment of diesel engine, the petrol engine emitted more CO into the atmosphere. The CO emission from CNG vehicles is two times less than the gasoline engine vehicles. The vehicle emissions are also depending upon the vehicle design, maintenance, operation conditions and fuel composition, etc.

The CO emissions are also contributed to environmental from the incineration of solid wastes in urban and other incinerators. Carbon monoxide is also encountered in mining operations in which explosives are used in confined spaces. The exposure of CO in warehouses propane-powered floor polishers are operated. The major hazardous levels of CO contamination generally take place in air of buildings or enclosed spaces.

The increasing of number of automobile vehicles on roads, the CO concentrations have reached an alarming level in metropolitan areas. To regulatory actions have been adopted to restrain the danger of automobile pollution. There had been a much perceptible concern in the early 1980s on the adverse environmental impact of increased automobile traffic in developing countries like India. India has started adopting European emission norms and fuel regulations for four-wheeled light-duty and heavy-duty vehicles.

All vehicles produced after the exploit of norms have to be compliant with the regulations. At present, Bharat Stage IV (BS IV) parallel to Euro IV regulations since April 1st, 2010 is applicable for various types of vehicles; this is given in Table 5 for CO emissions. The automobile emissions are affected by driving pattern; overcrowding, temperature, traffic speed, vehicle's engine conditions and emissions control equipment and its maintenance.

A catalytic converter is an automobile emissions control device that converts more contaminated pollutants present in the exhaust gasses to the lower poisonous pollutants by a catalyzing redox reaction. The basic reactions of HC and CO in the exhaust are oxidation with the certain products being CO_2 and H_2O, while the NOx reaction is a reduction with preferred products of N_2. The major three pollutants (CO, HC and NOx) are concurrently impassive from the exhaust by a sole converter. These converters often function at 90% efficiency, almost removing the diesel odor and decreases the particulates (soot).

1.3.4. PM and NO_x emissions control

The diesel engine is being widely used in day to day life in both mobile and stationary applications. The main drawback is the release of harmful gasses like NOx and particulate matter into the atmosphere. This affects both human beings and environment to a great extent and should be controlled effectively.

1.3.4.1. Particulate matter

Particulate matter, or PM, is formed mainly of carbonaceous solid particles of very small diameter (usually in the range of 2.5 μm and 10 μm, called $PM_{2.5}$ and PM_{10}) dispersed in the flue gases. They are originated in rich zones of the fuel jets, where pyrolysis reactions are promoted by high temperatures and by the presence of very low oxygen fraction in these zones. However, particulate emissions are due to low temperatures, because at high temperatures take place both pyrolysis and particulate oxidation, so the simultaneous generation and destruction of PM. The low temperatures reached in the exhaust phase stops the PM oxidation and so they cause the actual emission of particulate in atmosphere.

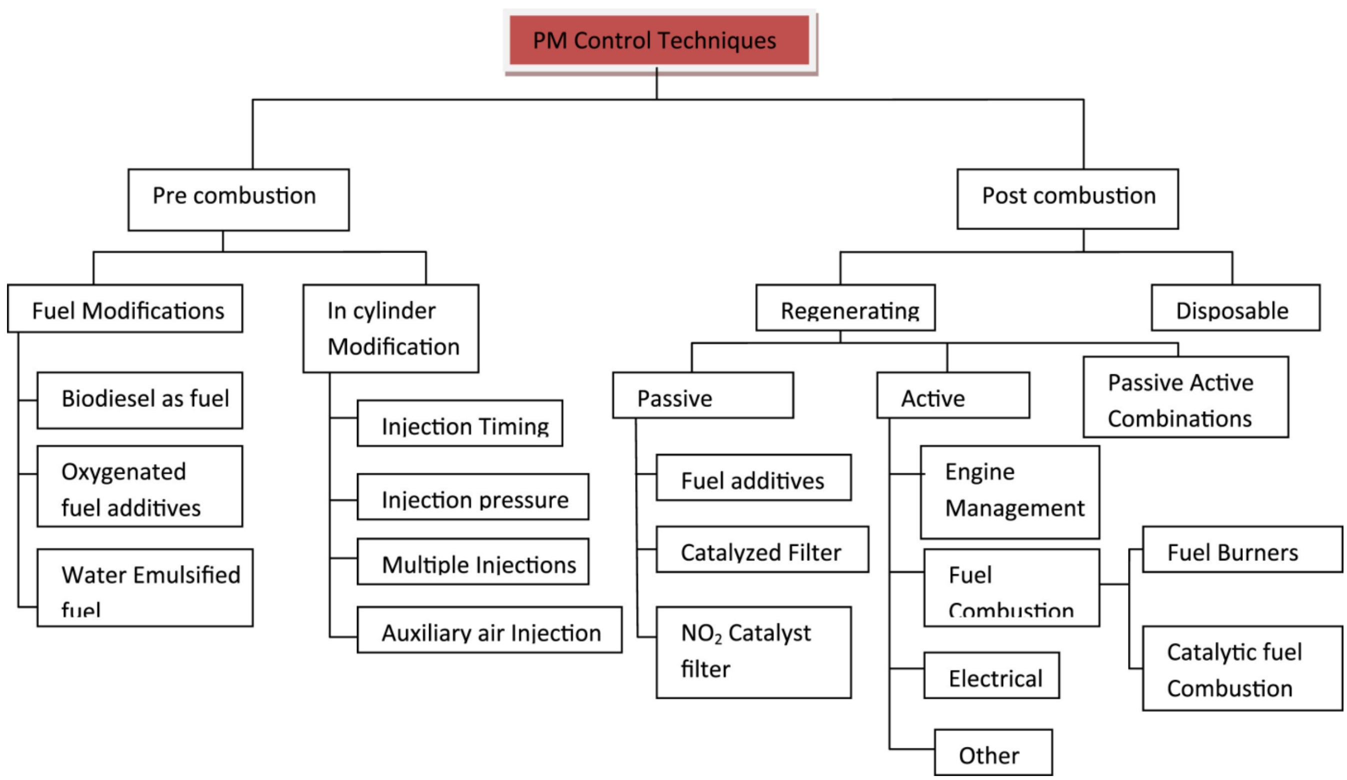


Figure 1-1: Particulate matter emission control techniques

1.3.4.2. Nitrogen oxides

In atmospheric chemistry, NOx is a generic term for the nitrogen oxides that are most relevant for air pollution, namely nitric oxide (NO) and nitrogen dioxide (NO2). These gases contribute to the formation of smog and acid rain, as well as affecting tropospheric ozone. NOx gases are usually produced from the reaction among nitrogen and oxygen during combustion of fuels, such as hydrocarbons, in air; especially at high temperatures, such as in car engines. In areas of high motor vehicle traffic, such as in large cities, the nitrogen oxides emitted can be a significant source of air pollution. NOx gases are also produced naturally by lightning. The term NOx is chemistry shorthand for molecules containing one nitrogen and one or more oxygen atom. It is generally meant to include nitrous oxide (N2O), although nitrous oxide is a fairly inert oxide of nitrogen that has many uses as an oxidizer for rockets and car engines, an anesthetic, and a propellant for aerosol sprays and whipped cream. Nitrous oxide plays hardly any role in air pollution, although it may have a significant impact on the ozone layer, and is a significant greenhouse gas. NOy is defined as the sum of NOx plus the NOz compounds produced from the oxidation of NOx which include nitric acid, nitrous acid (HONO), dinitrogen pentoxide (N_2O_5), peroxyacetyl nitrate (PAN), alkyl nitrates ($RONO_2$), peroxyalkyl nitrates ($ROONO_2$), the nitrate radical (NO_3), and peroxynitric acid (HNO_4).

Because of energy limitations, oxygen and nitrogen do not react at ambient temperatures. But at high temperatures, they undergo an endothermic reaction producing various oxides of nitrogen. Such temperatures arise inside an internal combustion engine or a power station boiler, during the combustion of a mixture of air and fuel, and naturally in a lightning flash.

In atmospheric chemistry, the term NOx denotes the total concentration of NO and NO_2 since the conversion between these two species is rapid in the stratosphere and troposphere. During daylight hours, these concentrations together with that of ozone are in steady state, also known as photostationary state(PSS); the ratio of NO to NO_2 is determined by the intensity of sunshine (which converts NO_2 to NO) and the concentration of ozone (which reacts with NO to again form NO_2). It is estimated that transportation fuels cause 54% of the anthropogenic (i.e. human-caused) NOx. The major source of NOx production from nitrogen-bearing fuels such as certain coals and oil, is the conversion of fuel bound nitrogen to NOx during combustion. During combustion, the nitrogen bound in the fuel is released as a free radical and ultimately forms free N_2, or NO. Fuel NOx can contribute as much as 50% of total emissions through the combusting oil and as much as 80% through the combusting of coal.

Although the complete mechanism is not fully understood, there are two primary pathways of formation. The first involves the oxidation of volatile nitrogen species during the initial stages of combustion. During the release and before the oxidation of the volatiles, nitrogen reacts to form several intermediaries which are then oxidized into NO. If the volatiles evolve into a reducing atmosphere, the nitrogen evolved can readily be made to form nitrogen gas, rather than NOx. The second pathway involves the combustion of nitrogen contained in the char matrix during the combustion of the char portion of the fuels. This reaction occurs much more slowly than the volatile phase. Only around 20% of the char nitrogen is ultimately emitted as NOx, since much of the NOx that forms during this process is reduced to nitrogen by the char, which is nearly pure carbon.

Selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) reduce post combustion NOx by reacting the exhaust with urea or ammonia to produce nitrogen and water. SCR is now being used in ships, diesel trucks and in some diesel cars. The use of exhaust gas recirculation and catalytic converters in motor vehicle engines have significantly reduced vehicular emissions. NOx was the main focus of the Volkswagen emissions violations.

Other technologies such as flameless oxidation (FLOX) and staged combustion significantly reduce thermal NOx in industrial processes. Bowin low NOx technology is a hybrid of staged-premixed-radiant combustion technology with a major surface combustion preceded by a minor radiant combustion. In the Bowin burner, air and fuel gas are premixed at a ratio greater than or equal to the stoichiometric combustion requirement. Water Injection technology, whereby water is introduced into the combustion chamber, is also becoming an important means of NOx reduction through increased efficiency in the overall combustion process. Alternatively, the water (e.g. 10 to 50%) is emulsified into the fuel oil before the injection and combustion. This emulsification can either be made in-line (unstabilized) just before the injection or as a drop-in fuel with chemical additives for long term emulsion stability (stabilized).

1.3.4.3. PM-NOx trade-off

The term trade-off refers to a particular behaviour of diesel engines, where usually modifications and strategies which aims to decrease NOx often increase PM emissions and vice versa. For example, lowering the flame temperature during the combustion reduces NOx, but doesn't allow a complete particulate oxidation, increasing in this way PM emissions.

A physical explanation of this phenomena can be given remembering that nitrogen oxides are formed with lean mixtures at high temperatures, while particulate matter is released in rich conditions at low temperatures. Therefore, it is clear to see the opposite conditions where the two pollutants are originated, giving the trade-off behaviour.

However, simultaneous reduction of these two pollutants is partially possible, but the measures that allow this condition are constrained by costs and by technological limits. One of the main solutions which allows to reduce simultaneously NOx and PM emissions is to reduce the compression ratio, increasing the preliminary mixing before the combustion. In this way lower temperatures and pressures after the compression are achieved, increasing the delay time of the autoignition and so increasing the effect of premixing. This allows to achieve a better distribution of fuel inside the chamber, reducing the inhomogeneities in the mixture, limiting rich and lean zones, and so also their influence on the generation of NO_x and PM. On the other hand, this reduction in compression rate reduces the cycle efficiency, increasing fuel consumption.

Then, to comply with Euro 6 standards, a combination of internal solutions and external post-treatment devices is mandatory, with the aforementioned effects on costs, complications and fuel economy. This is the reason why diesel emissions problem has become such a concern in the last years, especially with Euro 5 and Euro 6 legislations, forcing some manufacturers to plan a complete stop in production and sales for diesel passenger cars.

1.3.5. CO_2 emissions control

Compression Ignition engines (CI Engines) are used in mainly transportation and power generation sectors due to their higher thermal efficiency and torque as compared to spark ignition engines. However, these engines emit harmful emissions such as NOx, smoke/PM and GHG emissions (CO2, CH4 and N2O). As GHG emissions contribute to global warming and climate change, these emissions need to be reduced in internal combustion engines at source level.

As biodiesel has desirable fuel quality including higher cetane number, less sulphur and absence of aromatic substance, a biodiesel fueled compression ignition engine could operate with reduced emissions (CO, HC, Smoke/Particulate matter) along with performance improvement. Senthil et al. Biodiesel fueled diesel engines produce less greenhouse gas emissions as compared to diesel fuel. Many studies on effects of biodiesel-diesel blends on performance and emissions characteristics of compression ignition engines are available in literature. Biodiesel fueled engine can work well with the blends from 10% to 20%. However, modification of engines are needed to use higher biodiesel-diesel blends. Few studies are only available on 100% biodiesel (B100) use in compression ignition engines and the available information indicates engine's hardware needs to be modified to use B100 for better performance and emissions reduction. In addition, studies on the main GHG emissions including CO2, N2O and CH4 from biodiesel fueled engines are not available in literature. However, the effect of individual GHG emissions such as CO2, N2O and CH4 is not reported in literature. Most of the studies reported in literature indicate the bio fueled engine could decrease degree of carbon neutral or carbon foot print or carbon dioxide emission. This problem on the fulfilment on CO_2 emissions is deeply analysed by a study carried out by “PA Consulting” (PA Consulting, 2018); where the projections confirm the problems of emissions control, as 7 out of 11 manufacturers are expected to have problems on meeting their CO_2 target (see the following Figure 1-3).

		Actual data ($g\ CO_2/km$)**				PA forecast (g CO2/km)***		($g\ CO_2/km$)	
Rank*	Carmaker	2011	2013	2015	2016	2018	2021	2021 Target	Deviation
1	Volvo	154.0	130.8	121.9	119.2	110.0	83.1	103.5	-20.4
2	Toyota	126.4	116.8	108.3	105.5	91.7	83.5	94.3	-10.8
3	Renault-Nissan	129.0	119.2	112.1	109.7	106.5	91.4	92.1	-0.7
4	Hyundai-Kia	134.0	129.8	127.3	124.4	115.3	94.9	91.7	3.2
5	PSA (Peugeot Citroen) + Opel	128.5	115.7	104.6	110.3	104.4	95.6	92.6	3.0
6	Ford	132.7	121.8	118.0	120.0	110.8	96.1	93.0	3.1
7	Volkswagen	135.4	128.9	121.5	120.0	115.7	100.3	96.3	4.0
8	FCA (Fiat Chrysler)	118.3	123.8	122.2	120.0	116.6	101.2	91.1	10.1
9	Daimler	153.0	136.6	124.7	124.7	117.2	102.1	100.7	1.4
10	BMW	145.0	134.4	126.4	121.4	119.3	104.7	100.3	4.4
11	JLR (Jaguar Land Rover)	206.0	182.0	165.0	150.0	142.3	130.9	132.0	-1.1

*rank on 2021 forecast **data from ICCT 2016 ***based on actual data until 2016 (ICCT) and PA forecast estimation < 0 0-2 > 2

Figure 1-2: 2021 CO2 forecasted and target emissions of the main car manufacturers in Europe (PA Consulting, 2018)

A re-elaboration of PA Consulting's projections was made by "Automotive News Europe" (Sigal, 2017), estimating CO_2 excess fees amount for the seven producers which will not reach their target in the projections. The following results are obtained, having considered the planned fees of 95€ per car and per gram of exceeding CO_2:

Table 1-5: Predicted CO_2 excess fees in 2021 (Sigal, 2017)

Volkswagen	1360 million €	**Ford**	307 million €
FCA	950 million €	**Hyundai-Kia**	283 million €
PSA + Opel	787 million €	**Daimler**	126 million €
BMW	430 million €		

Even if this is only a preliminary estimation, it is easy to see how the amount of fees can have an enormous impact on the economy of car manufacturers, forcing them to make other investments on research and development, employing increasingly complex and expensive powertrains and post-treatment devices, until the technological limits of internal combustion engines are reached or until their production will be no longer cost effective (in this case, the diesel market example is very exemplifying).

A different solution of this problem is represented by a technologic change, that is the electrification of the powertrains. As it will be explained in the next paragraph, this solution allows to obtain huge environmental advantages referring to the conventional powertrains based on internal combustion engines.

1.4. Hybrid, electric and fuel vehicles: characteristics and issues

A hybrid vehicle is one that uses two or more distinct types of power, such as submarines that use diesel when surfaced and batteries when submerged. Other means to store energy include pressurized fluid in hydraulic hybrids.

The basic principle with hybrid vehicles is that the different motors work better at different speeds; the electric motor is more efficient at producing torque, or turning power, and the combustion engine is better for maintaining high speed (better than a typical electric motor). Switching from one to the other at the proper time while speeding up yields a win-win in terms of energy efficiency, as such that translates into greater fuel efficiency, for example.

In a parallel hybrid vehicle, an electric motor and an internal combustion engine are coupled such that they can power the vehicle either individually or together. Most commonly the internal combustion engine, the electric motor and gearbox are coupled by automatically controlled clutches. For electric driving, the clutch between the internal combustion engine is open while the clutch to the gearbox is engaged. While in combustion mode the engine and motor run at the same speed.

A series- or serial-hybrid vehicle is driven by an electric motor, functioning as an electric vehicle while the battery pack energy supply is sufficient, with an engine tuned for running as a generator when the battery pack is insufficient. There is typically no mechanical connection between the engine and the wheels, and the primary purpose of the range extender is to charge the battery. Series-hybrids have also been referred to as extended range electric vehicle, range-extended electric vehicle, or electric vehicle-extended range (EREV/REEV/EVER).

Another subtype of hybrid vehicles is the plug-in hybrid electric vehicle. The plug-in hybrid is usually a general fuel-electric (parallel or serial) hybrid with increased energy storage capacity, usually through a lithium-ion battery, which allows the vehicle to drive on all-electric mode a distance that depends on the battery size and its mechanical layout(series or parallel). It may be connected to mains electricity supply at the end of the journey to avoid charging using the on-board internal combustion engine.

This concept is attractive to those seeking to minimize on-road emissions by avoiding – or at least minimizing – the use of ICE during daily driving. As with pure electric vehicles, the total emissions saving, for example in CO_2 terms, is dependent upon the energy source of the electricity generating company.

For some users, this type of vehicle may also be financially attractive so long as the electrical energy being used is cheaper than the petrol/diesel that they would have otherwise used. Current tax systems in many European countries use mineral oil taxation as a major income source. This is generally not the case for electricity, which is taxed uniformly for the domestic customer, however that person uses it. Some electricity suppliers also offer price benefits for off-peak night users, which may further increase the attractiveness of the plug-in option for commuters and urban motorists.

The hybrid vehicle typically achieves greater fuel economy and lower emissions than conventional internal combustion engine vehicles (ICEVs), resulting in fewer emissions being generated. These savings are primarily achieved by three elements of a typical hybrid design: Relying on both the engine and the electric motors for peak power needs, resulting in a smaller engine size more for average usage rather than peak power usage. A smaller engine can have fewer internal losses and lower weight. Having significant battery storage capacity to store and reuse recaptured energy, especially in stop-and-go traffic typical of the city driving cycle.

Recapturing significant amounts of energy during braking that are normally wasted as heat.

This regenerative braking reduces vehicle speed by converting some of its kinetic energy into electricity, depending upon the power rating of the motor/generator; Other techniques that are not necessarily 'hybrid' features, but that are frequently found on hybrid vehicles include: Using Atkinson cycle engines instead of Otto cycle engines for improved fuel economy. Shutting down the engine during traffic stops or while coasting or during other idle periods.

Improving aerodynamics; (part of the reason that SUVs get such bad fuel economy is the drag on the car. A box-shaped car or truck has to exert more force to move through the air causing more stress on the engine making it work harder). Improving the shape and aerodynamics of a car is a good way to help better the fuel economy and also improve vehicle handling at the same time.

Using low rolling resistance tires (tires were often made to give a quiet, smooth ride, high grip, etc., but efficiency was a lower priority). Tires cause mechanical drag, once again making the engine work harder, consuming more fuel. Hybrid cars may use special tires that are more inflated than regular tires and stiffer or by choice of carcass structure and rubber compound have lower rolling resistance while retaining acceptable grip, and so improving fuel economy whatever the power source.

Powering the a/c, power steering, and other auxiliary pumps electrically as and when needed; this reduces mechanical losses when compared with driving them continuously with traditional engine belts. These features make a hybrid vehicle particularly efficient for city traffic where there are frequent stops, coasting, and idling periods. In addition noise emissions are reduced, particularly at idling and low operating speeds, in comparison to conventional engine vehicles. For continuous high-speed highway use, these features are much less useful in reducing emissions.

An electric vehicle (EV) is a vehicle that uses one or more electric motors or traction motors for propulsion. An electric vehicle may be powered through a collector system by electricity from off-vehicle sources, or may be self-contained with a battery, solar panels, fuel cells or an electric generator to convert fuel to electricity. EVs include, but are not limited to, road and rail vehicles, surface and underwater vessels, electric aircraft and electric spacecraft.

A hybrid electric vehicle combines a conventional powertrain (usually an internal combustion engine) with an electric engine. As of April 2016, over 11 million hybrid electric vehicles have been sold worldwide since their inception in 1997. Japan is the market leader with more than 5 million hybrids sold, followed by the United States with cumulative sales of over 4 million units since 1999, and Europe with about 1.5 million hybrids delivered since 2000. Japan has the world's highest hybrid market penetration. By 2013 the hybrid market share accounted for more than 30% of new standard passenger car sold, and about 20% new passenger vehicle sales including kei cars. Norway ranks second with a hybrid market share of 6.9% of new car sales in 2014, followed by the Netherlands with 3.7%. The electrification of powertrains is performed at different levels, with increasing relevance, power, size and available driving mileage of the electric motor. Currently, in the market are present both partially electrified vehicles (or hybrid vehicles) and totally electrified vehicles. Hybrid vehicles are moved by a conventional internal combustion engine paired with one or more electric motors, which helps in start/stop cycles of the engine and/or in torque generation. These twin sources help to reduce the fuel consumption, lowering also environmental pollution. Usually, the ICE used in hybrids is a spark ignition engine, fortwo reasons: the first is the overall cost of the powertrain (which is already increased by the adoption of batteries and one or more electric motors) so, the cost is kept as low as possible adopting cheaper and simpler gasoline engines. The second reason is environmental, as compression ignition engines are affected by NO_x and PM control issues, and for this reason, large cities are progressively restricting the use of diesel engines, so CI engines also suffer the risk of being banned from circulation. For these two reasons, HV adopt almost always gasoline engines. As said, hybrid solutions use both electric and internal combustion engine, allowing to reduce fuel consumption and pollutant emissions of internal combustion engines; while full electric vehicles are equipped with batteries and electric motors, with the only exception of extended range electric vehicles, which equips also a small combustion engine used to power a generator in order to recharge the batteries.

More specifically, the main differences between full and plugin hybrids are power and driving range of electric motors and also the source of battery charge. Full hybrids can work in pure electric mode just for few kilometres, usually not more than 5 km. On the other hand, plugin hybrids have much higher driving ranges in electric mode: usually from 30 to 50 km. The small range of FHV could be useful in example for the cities which have instituted limited traffic areas (LTA, or ZTL in Italian) or low emission zones (LEZ) which limit the circulation of pollutant vehicles (for example, the cities of Milan and Rome will implement in the next years these special environmental measures). On the contrary, PHEV allows a greater electric drivability, with the possibility to conduct daily urban travels uniquely in electric mode. The dimension and power of EM is also different between the two hybrid categories, being a simple support to the ICE the first, while representing a primary driving source for the second. Finally, FHV can recharge their battery through regenerative braking only, instead PHEV are charged plugging them directly to wall sockets, like electric vehicles, together with regenerative braking, which is still present.

Among different hybrid configurations, there are three main engine integration schemes:

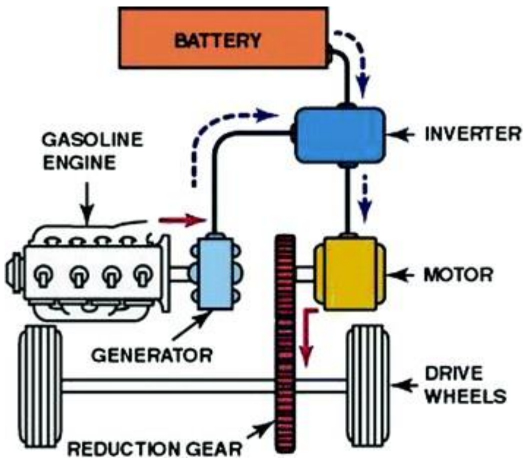


Figure 1-3: Hybrid series scheme

In hybrid series scheme the ICE is not directly connected to driven wheels. All the power is given by the EM and the ICE is only used to power the inverter, charging the battery.

Of course, the ICE is not essential, and is switched on only when the batteries are depleting.

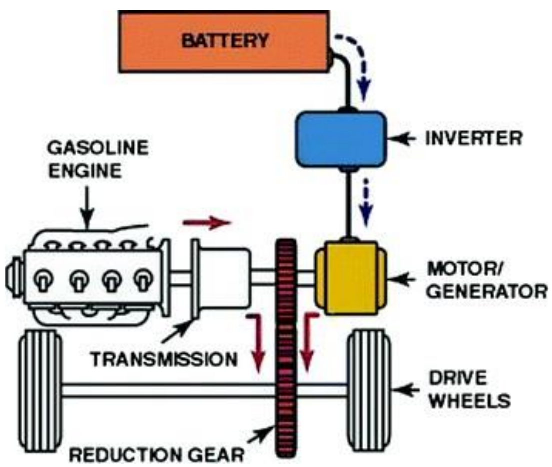


Figure 1-4: Hybrid parallel scheme

In hybrid parallel scheme both ICE and EM are connected to driven wheels. The overall torque and power are summed between the two engines.

If necessary, one of the engines can be shut off and just the other is used for the propulsion.

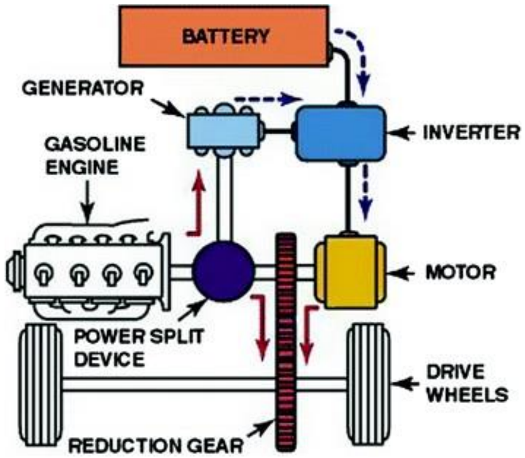


Figure 1-5: Hybrid power split scheme

In hybrid power split scheme both ICE and EM are connected to driven wheels, but they are also mutually connected. This solution is flexible but also complicated, as it allows to combine the advantages of both series and parallel solutions.

The vehicle control unit is responsible to combine the two engines in order to achieve the highest efficiency and fuel savings.

Usually, all modern advanced hybrid cars (both FHV and PHEV) use power split configuration, managing the engine repartition according to different control parameters, such as battery state of charge, driving conditions, hybrid strategies implemented by vehicle control unit and hybrid mode chosen by the user.

On the other hand, smaller hybrids (usually MHV) adopt parallel scheme, being simpler and cheaper. Finally, series scheme is adopted only for electric vehicles with gasoline or diesel generator for increase the range of the electric motor (EREV).

A plug-in electric vehicle (PEV) is any motor vehicle that can be recharged from any external source of electricity, such as wall sockets, and the electricity stored in the Rechargeable battery packs drives or contributes to drive the wheels. PEV is a subcategory of electric vehicles that includes battery electric vehicles (BEVs), plug-in hybrid vehicles, (PHEVs), and electric vehicle conversions of hybrid electric vehicles and conventional internal combustion engine vehicles.

A range-extended electric vehicle (REV) is a vehicle powered by an electric motor and a plug-in battery. An auxiliary combustion engine is used only to supplement battery charging and not as the primary source of power.

A fuel cell vehicle (FCV) or fuel cell electric vehicle (FCEV) is an electric vehicle that uses a fuel cell, sometimes in combination with a small battery or supercapacitor, to power its onboard electric motor. Fuel cells in vehicles generate electricity generally using oxygen from the air and compressed hydrogen. Most fuel cell vehicles are classified as zero-emissions vehicles that emit only water and heat. As compared with internal combustion vehicles, hydrogen vehicles centralize pollutants at the site of the hydrogen production, where hydrogen is typically derived from reformed natural gas. Transporting and storing hydrogen may also create pollutants.

The environmental impact of fuel cell vehicles depends on the primary energy with which the hydrogen was produced. Fuel cell vehicles are only environmentally benign when the hydrogen was produced with renewable energy. If this is the case fuel cell cars are cleaner and more efficient than fossil fuel cars.

However, they are not as efficient as battery electric vehicles which consume much less energy. Usually a fuel cell car consumes 2.4 times more energy than a battery electric car, because electrolysis and storage of hydrogen is much less efficient than using electricity to directly load a battery.

As of 2009, motor vehicles used most of the petroleum consumed in the U.S. and produced over 60% of the carbon monoxide emissions and about 20% of greenhouse gas emissions in the United States, however production of hydrogen for hydro cracking used in gasoline production chief amongst its industrial uses was responsible for approximately 10% of fleet wide greenhouse gas emissions.

In contrast, a vehicle fueled with pure hydrogen emits few pollutants, producing mainly water and heat, although the production of the hydrogen would create pollutants unless the hydrogen used in the fuel cell were produced using only renewable energy.

CHAPTER 2: PROGRESS MODEL

2.1. Model Description

The amount of pollutants released in atmosphere by private and public vehicles fleet is evaluated through PROGRESS software (PROGramme for Road vehicles EmiSSions evaluation, realized in Office Excel), developed in the first years of 2000. It was realized jointly by the Internal Combustion Engines Group (ICEG) operating at the Department of Thermal Machines, Energy Systems and Transportation (DIMSET) of the University of Genova (Italy), the Environmental Department of the Genova Provincial Administration and Genova Municipality.

The first version of this model evaluated 2001 fleet in Genova Municipality, obtaining interesting results about the emissions of CO, HC, NO_x and PM and their distribution between the different vehicle classes (Capobianco, et al., 2003). The second version is more recent and studied the urban pollution of eight different years, from 1992 to 2010, evaluating CO, HC, NO_x, NO_2 and PM. This study compared also road vehicles emissions with air quality data from the monitoring network of the Genova Municipality, allowing to establish a link between vehicular mobility and global air quality (Zamboni, et al., 2009).

The model used in this thesis is based on previous versions of PROGRESS, being actualized in order to account for new vehicle legislative classes, hybrid and electric cars, and of course new circulating fleets mileage and distribution percentages. Some interesting features were added to the previous version, for example the evaluation of CO_2, of fuel consumption and, for electric cars, also of battery usage and indirect emissions due to the generation of energy used for vehicle recharge.

2.1.1. Vehicle categories and classes

PROGRESS model allows to predict emissions (CO, CO_2, HC, NO_x, NO_2, PM) for each vehicle category and class of the circulating fleet. The inputs needed from the model are fleet composition and mileage, as well as typical driving conditions.

The circulating fleet is divided in nine categories, distinguishing the vehicle type, size, fuel and powertrain technology. The vehicle categories are:

1. Passenger cars with spark ignition engine (SI PC);
2. Passenger cars with compression ignition engine (CI PC);
3. Passenger cars with hybrid or electric engine (H/E PC);
4. Light duty vehicles with spark ignition engine (SI LDV);
5. Light duty vehicles with compression ignition engine (CI LDV);
6. Heavy duty vehicles (HDV);
7. Buses (BS);
8. Motorcycles (MC);
9. Mopeds (MP).

Each category is sorted in classes, according to the European legislation which it belongs or according to its powertrain technology for hybrid and electric vehicles.

- Category 3 has four classes: Full Hybrid, Plugin Hybrid ,Full Electric and fuel cell all of them follow Euro 6 legislation;
- Categories from 1 to 7, except from the 3rd, have seven legislative classes: from Euro 0 to Euro 7;
- Category 7 and 8 has respectively eight and ten legislative categories: from Euro 0 to Euro 5, considering also the subdivision between 2- and 4-strokes classes.

Considering all the subdivisions, the model works with 82 vehicle classes:

Passenger cars with spark ignition engine (SI PC)			
EURO 0	EURO 1	EURO 2	EURO 3
EURO 4	EURO 5	EURO 6	EURO 7

Passenger cars with compression ignition engine (CI PC)			
EURO 0	EURO 1	EURO 2	EURO 3
EURO 4	EURO 5	EURO 6	EURO 7

Passenger cars with hybrid or electric engine (H/E PC)			
FULL HYBRID	PLUGIN HYBRID	FULL ELECTRIC	FUEL CELL

Light duty vehicles with spark ignition engine (SI LDV)			
EURO 0	EURO 1	EURO 2	EURO 3
EURO 4	EURO 5	EURO 6	EURO 7
ELECTRIC			

Light duty vehicles with compression ignition engine (CI LDV)			
EURO 0	EURO 1	EURO 2	EURO 3
EURO 4	EURO 5	EURO 6	EURO 7

Heavy duty vehicles (HDV)			
EURO 0	EURO 1	EURO 2	EURO 3
EURO 4	EURO 5	EURO 6	EURO 7
LNG	ELECTRIC	FUEL CELL	

Buses (BS)			
EURO 0	EURO 1	EURO 2	EURO 3
EURO 4	EURO 5	EURO 6	EURO 7
HYBRID	ELECTRIC	FUEL CELL	

Motorcycles (MC)			
EURO 0 - 2 strokes	EURO 0 - 4 strokes	EURO 1 - 2 strokes	EURO 1 - 4 strokes
EURO 2 - 4 strokes	EURO 3 - 4 strokes	EURO 4 - 4 strokes	EURO 5 - 4 strokes
EURO 6 - 4 strokes	ELECTRIC	FUEL CELL	

Mopeds (MP)			
EURO 0 - 2 strokes	EURO 0 - 4 strokes	EURO 1 - 2 strokes	EURO 1 - 4 strokes
EURO 2 - 2 strokes	EURO 2 - 4 strokes	EURO 3 - 2 strokes	EURO 3 - 4 strokes
EURO 4 - 4 strokes	EURO 5 - 4 strokes	EURO 6 - 4 strokes	ELECTRIC

Figure 2-1: Categories and legislative classes subdivision in PROGRESS model

In PROGRESS, each class needs two inputs, the number of vehicles and the average yearly driving mileage. The other inputs that this model needs are traffic and environmental characteristics of the municipality analysed: the urban speed distribution of the vehicles, the average length of road trips and the monthly ambient temperature.

2.1.2. Definition of vehicles number and mileage

ACI data splits the fleet on the basis of vehicle category, of fuel and of legislative class. The data regarding the Municipality of Genova is therefore extracted and is organized in the classes seen before, in Figure 2-1. Some changes on the original ACI data were done moving these numbers in PROGRESS, for this reason, some clarifications must be done.

Just to start, heavy duty vehicles and buses in the model are considered to have only diesel motorization. The actual circulating fleet is slightly different, as there are some gasoline vehicles in these categories, but they have such a low share (less than 1%) that this fraction is not considered, in order to simplify the model, neglecting gasoline categories of heavy duty vehicles and buses.

For passenger cars and light duty vehicles, ACI data also makes the distinction between common gasoline and diesel engines, gasoline-methane, gasoline-LPG and hybrid-electric. However, also in this case, the share of these alternative categories is very low: both for passenger cars and light duty vehicles, the diffusion of common gasoline and diesel engines is between 96 and 97%. More precisely, gasoline-methane reaches around 2.5-3.0% share, gasoline-LPG around 1% and hybrid-electric less than 0.5%. Thanks to this prevalent share, only conventional gasoline and diesel engines are considered, as the other classes represent globally a low number of vehicles respect to total, and because the emissions of methane and LPG are comparable to conventional gasoline engines. For these reasons, only conventional engine types will be accounted, without losing too much accuracy. Regarding hybrid-electric, neither this category will be considered, because ACI data does not specify in which category they belong to (μHV, MHV, FHV, PHEV, EV, EREV). Even so, the final results are not compromised, as this category reaches an irrelevant share in 2019 fleet (which is less than 0.5%). Also, these classes will be the main focus of the third simulation, as it will be explained later.

Finally, mopeds data is not shown in ACI data, due to Italian legislation, as mopeds are not directly registered in the Italian public vehicle registry. For this reason, data from ANCMA (ANCMA, 2018) was used, in order to extrapolate the number of circulating vehicles starting from historical datasets and annual new registrations. In this version of PROGESS three simulations will be performed, the first regards 2019 fleet, while the second and the third will consider 2030 fleet, obtained by projections based on past years statistics. Historical dataset from ACI was used, based on 2010, 2013, 2016 and 2019 vehicle numbers, in addition to future market forecasts.

The second simulation is based on these projections, without modifications. Instead, the third supposes a sudden increase of hybrid and electric technologies, accounting for a widespread adoption of this kind of vehicles. This is done to allow qualitative and quantitative estimation of environmental pollution variations linked to the fleet renewal occurred from 2019 to 2030.

The third simulation is performed assuming the partial replacement of older passenger cars with newer cars. More precisely, the classes affected are Euro 0, 1, 2, 3 and 4 for gasoline passenger cars and Euro 0, 1, 2 ,3, 4 and 5 for diesel ones, this substitution is performed assuming that one third of these classes is dismissed, replaced with full hybrids, plugin hybrids, electric and fuel cell vehicles.

The numbers of each vehicle category and class for each of the three simulations is shown in Appendix A, at page 91. It is remarkable to note that in the second simulation, conventional gasoline and diesel passenger cars are composed respectively by a total of 279188 and 28628 vehicles, being reduced in the third simulation to 52945 and 28628 units, as these vehicles are converted in 107735 electric cars, 107735 plugin hybrids, 7695 full hybrids and 3078 fuel cell meaning a substitution of 226243 vehicles, representing the 81.1% of total passenger cars. Mileages are obtained by ISPRA historical series about national mileage data and are re-elaborated thanks to regional and municipal data. However, the data of this section will not be analysed in detail, because these are the results of another thesis developed inside the same Department of the University of Genova. For this reason, the determination of mileage results does not concern directly this thesis, and this data is simply listed in Appendix B at page 94.

2.1.3. Direct (exhaust) emissions Hot + Cold

Hot emission factors are related to the reference emissions due to vehicle circulation. These coefficients are measured in grams of pollutant per kilometre and depends obviously by type and category of the vehicle. The total hot emissions for a year are calculated as follows:

$$E_{hot}\left[\frac{g}{year}\right] = EF_{hot}\left[\frac{g}{km}\right] * M\left[\frac{km}{year}\right] \tag{2.1}$$

Where E_{hot} are the total yearly hot emissions of a specific pollutant, EF_{hot} are the hot emissions factors for the same pollutant and M is the average yearly mileage of the selected vehicle categories.

Hot emission factors are mainly based on ARTEMIS European project results, for passenger cars and light duty vehicles (Joumard, et al., 2007), for heavy duty vehicles (Rexeis, et al., 2005) and also for mopeds and motorcycles (Elst, et al., 2006).

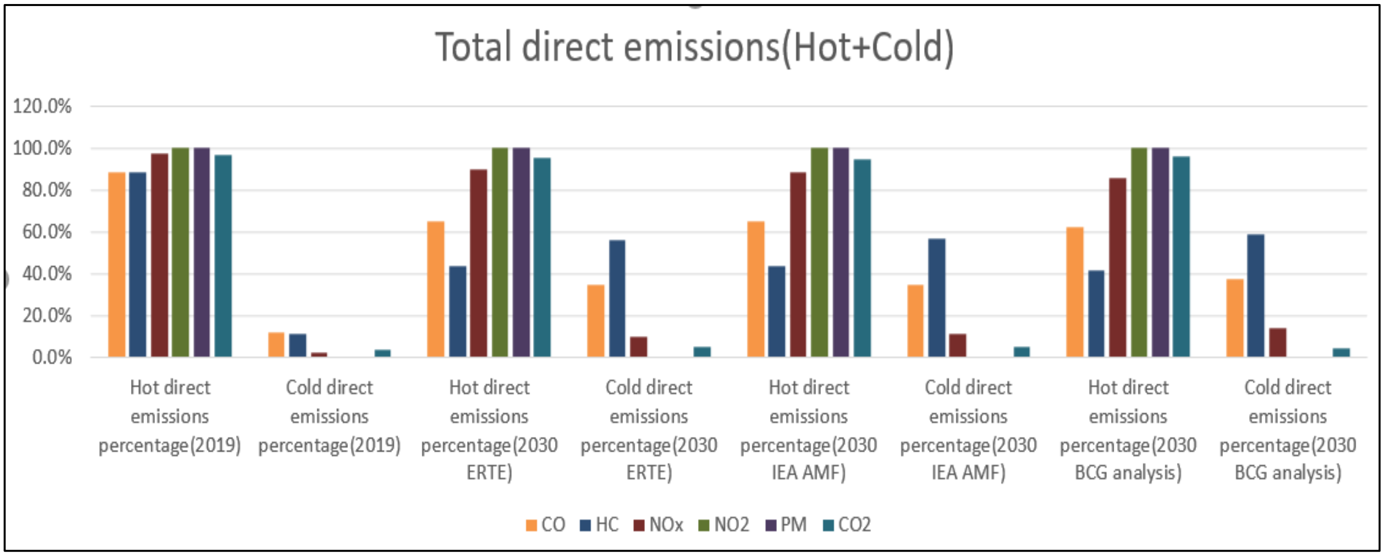
The exceptions regard partially and fully electrified vehicles, whose data were obtained by EMEP/EEA emissions inventory guidebook (Kouridis, et al., 2016) for hybrid passenger cars. The characterization of the emission factors of full electric and plugin hybrid vehicles is more complicated and is also a key passage of this thesis, for this reason this subject will be explained separately in the next paragraphs.

Hot emission factors are strongly influenced by vehicle speed and, for this reason, in PROGRESS there are three subdivisions depending on average velocity: less than 10 km/h, from 10 to 40 km/h and more than 40 km/h, each of them having its average emission factor.

Total Direct Emissions	CO	HC	NOx	NO2	PM	CO2
Hot direct emissions percentage(2019)	88.2%	88.8%	97.8%	100.0%	100.0%	96.5%
Cold direct emissions percentage(2019)	11.8%	11.2%	2.2%	0.0%	0.0%	3.5%
Hot direct emissions percentage(2030 ERTE)	65.1%	43.8%	89.8%	100.0%	100.0%	95.1%
Cold direct emissions percentage(2030 ERTE)	34.9%	56.2%	10.2%	0.0%	0.0%	4.9%
Hot direct emissions percentage(2030 IEA AMF)	64.9%	43.5%	88.8%	100.0%	100.0%	95.0%
Cold direct emissions percentage(2030 IEA AMF)	35.1%	56.5%	11.2%	0.0%	0.0%	5.0%
Hot direct emissions percentage(2030 BCG analysis)	62.6%	41.3%	86.0%	100.0%	100.0%	95.7%
Cold direct emissions percentage(2030 BCG analysis)	37.4%	58.7%	14.0%	0.0%	0.0%	4.3%

Figure 2-2: Total Direct Emissions of vehicles

Figure 2-3: Total Direct Emissions(hot+cold) of vehicles



So, for each category and class of vehicles, there will be 6 pollutants (CO, HC, NO_x, NO_2, PM and CO_2), each one with 3 subdivisions of average velocity, resulting in 18 hot emission factors per vehicle. There will be also 3 additional factors related to the fuel consumption of the vehicle, obtained by the previous 18 thanks to the following formulas, obtained applying a carbon balance to exhaust gases composition (Joumard, et al., 2007):

$$FC_{gasoline} = \left[\left(\frac{CO_2}{44.011}\right) + \left(\frac{CO}{28.011}\right) + \left(\frac{HC}{13.825}\right)\right] + \frac{PM}{12.011} * (12.011 + 1.008 * 1.8) \quad (2.2)$$

$$FC_{diesel} = \left[\left(\frac{CO_2}{44.011}\right) + \left(\frac{CO}{28.011}\right) + \left(\frac{HC}{14.027}\right)\right] + \frac{PM}{12.011} * (12.011 + 1.008 * 2) \quad (2.3)$$

The two formulations are very similar and express the results in grams of fuel per each km. The only difference is the H/C ratio (hydrogen to carbon ratio, that is how many H atoms are present for each atom of C), which is equal to 1.8 for gasoline and 2 for diesel. These formulas sum all the carbonaceous products of the combustion (each one divided by its molecular mass), to estimate how many atoms of carbon were involved in the combustion and then this number is multiplied for the molecular weight of each carbon molecule contained in the elemental hydrocarbon ($C_{MW} + H_{MW} * H/C\ ratio$), giving the global mass of fuel consumed in the combustion. Instead, if the calculation in litres of fuel is preferred, the two formulas must be divided by 740 g/l and 830 g/l, representing the fuel density at ambient temperature respectively for gasoline and diesel, obtaining fuel consumption in l/km.

Cold emission factors are related to startup of the vehicle, a transient condition in which the heating up of the engine, of the post treatment devices, of the oil and of the coolant liquid lead to some additional emissions until this startup cycle is ended. Usually, the temperatures are normalized after a certain distance, after that the transitory is considered to be finished, and the vehicle behaviour is then ideally modelled only with the hot emission factors. Like hot emissions, also cold emission factors are mainly based on ARTEMIS European project results, for passenger cars and light duty vehicles the data comes from a work in which the cold emission factors are expressed directly in g/km and they are dependent by average speed and temperature (André, et al., 2005).

Cold emission factors for the two-wheelers have different calculation procedures, for both motorcycles (Zamboni, et al., 2007) and mopeds (Zamboni, et al., 2011) the over emissions are expressed in grams per each startup cycle of the engine. Then the evaluation of yearly emitted grams is obtained multiplying those coefficients with the number of average yearly startup.

Heavy duty vehicles and buses are not considered in cold emissions calculation, because in the scientific literature there are no sufficient data to accurately characterize their over emissions due to startup of the engine. However, both the classes regard vehicles which cover usually long distances for each trip, implying a lower number of startup cycles respect to other vehicles. So, cold emissions are expected to have a lower incidence respect to the total and they can be neglected without losing too much accuracy.

Finally, cold emissions of NO2 and PM are not accounted in any of vehicular classes, because the data about these two pollutants is lacking. This is due to the difficulties in the estimation about cold start behaviour, which implies over emissions which are added to hot emissions, so the separation and the distinction between them is a difficult and uncertain process. This fact results in an uncertainty on results and in a lack of studies about this subject, leading to uncomplete cold emission factors. However, these coefficients represent only a fraction respect to the total emissions, so this fact is not compromising the global results of this study.

2.1.4. Indirect emissions

The indirect emissions of the vehicles are calculated using the electricity mix during the time of charging events and vehicles' electricity consumption during the associated trips. Additionally, by computing the indirect emissions, we also consider energy loses during the charging process. The stationary combustion plants for energy production have no transient, as those systems are usually big generation systems kept always active, so even the indirect cold emissions can be considered equal to zero with a good accuracy. indirect emission factors for electric vehicles on the bases of the location are shown in the following Table 2-1:

	CO	HC	NO_x	PM	CO_2
Italy	0.0150 g/km	0.0053 g/km	0.0227 g/km	0.0006 g/km	58.17 g/km

Table 2-1: Indirect emission factors for EV

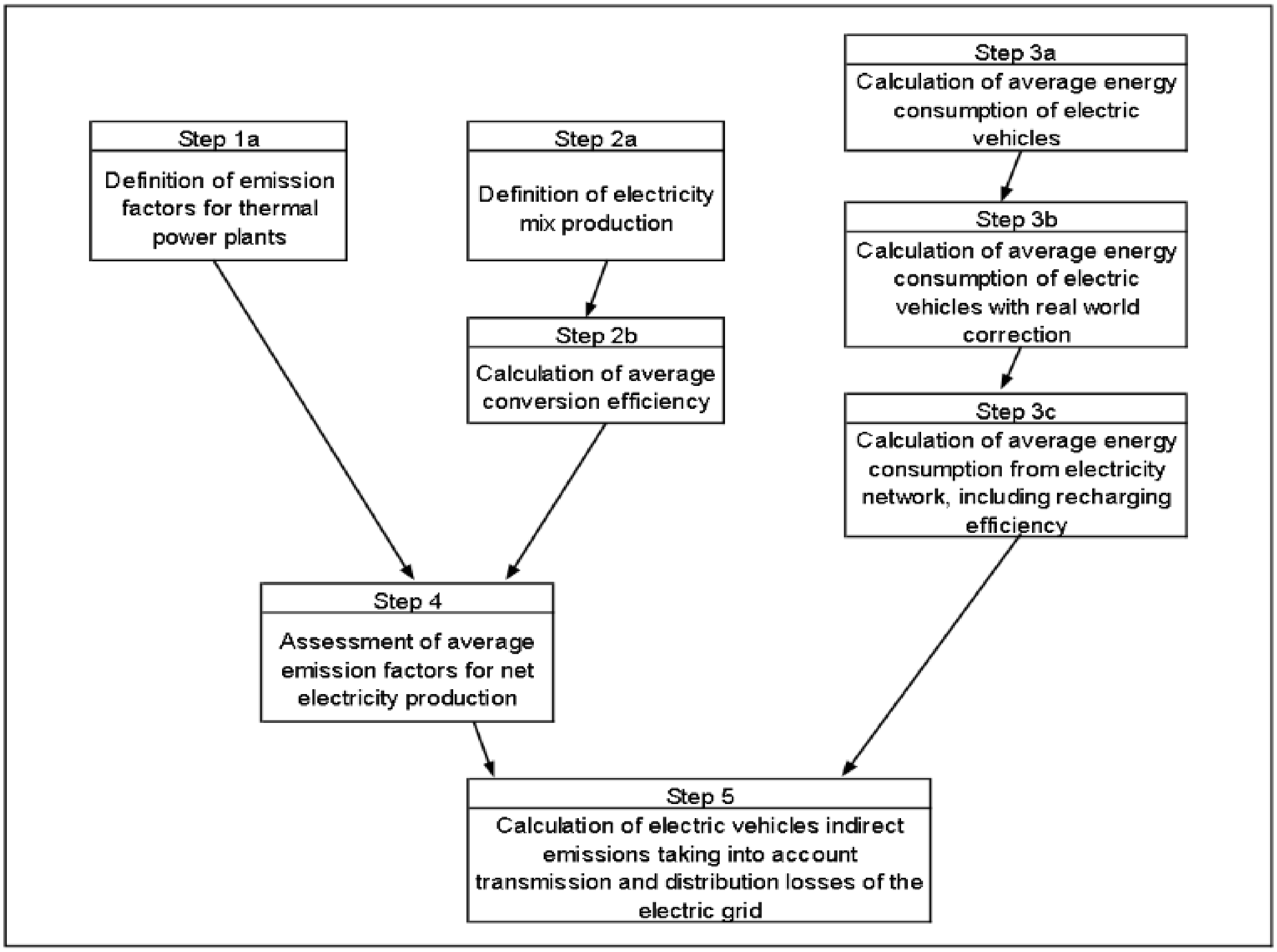
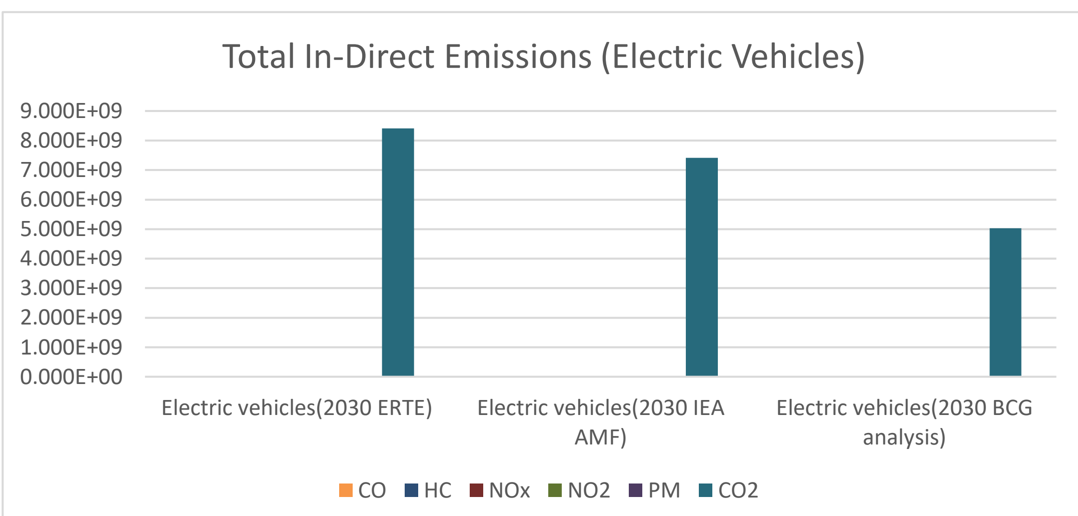


Figure 2-4: Procedure for evaluating the Indirect emission factors for EV

Figure 2-5: Indirect emission factors for EV



Total indirect emissions [g]	CO	HC	NOx	NO2	PM	CO2
Electric vehicles(2030 ERTE)	2.628E+06	8.889E+05	3.073E+06	3.073E+05	6.746E+04	8.417E+09
Electric vehicles(2030 IEA AMF)	2.315E+06	7.827E+05	2.706E+06	2.706E+05	5.950E+04	7.412E+09
Electric vehicles(2030 BCG analysis)	1.570E+06	5.310E+05	1.836E+06	1.836E+05	4.036E+04	5.028E+09

Table 2-2: Total indirect emissions of vehicles

2.2. Update of the Model

In the update of the model the emission factors of NO_2 for the electricity production have been defined and we have assumed that the NO_2 emission factors correspond to 10% of NO_X emission factors in the progress model. NO_X is produced (during high-temperature combustion processes) when fossil fuels (coal, natural gas and so on) are burned. When a pollutant is released directly into the atmosphere it is known as an emission.The concentration of NO_2 is measured in micrograms in each cubic meter of air (µg m^{-3}). A microgram (µg) is one millionth of a gram. A concentration of 1 µg m^{-3} means that one cubic meter of air contains one microgram of pollutant.

Nitrogen Dioxide and Nitrous Oxide:

Small amounts of nitrogen dioxide (NO_2) and nitrous oxide (N_2O) are formed during coal combustion, but they comprise less than 5 percent of the total NO_X production. The oxygen levels are too low and the residence times are too short in high-temperature coal flames for much of the NO to be oxidized to NO_2. Nitrous oxide, however, can be formed in the early part of fuel-lean flames by gas phase reaction by the reactions.

$$O \bullet + N_2 \leftrightarrow N_2O$$

$$NH \bullet + NO \leftrightarrow N_2O + H\bullet$$

$$NCO \bullet + NO \leftrightarrow N_2O + \mathrm{CO}$$

***No_2* Emission Factors For Electricity Production**

NOx refers to both nitric oxide (NO) and nitrogen dioxide (NO_2). The environmental effects of releasing too much NOx into the atmosphere are listed below.

- NOx is a main constituent in the formation of ground-level ozone which causes severe respiratory problems.
- Respiratory problems may result from exposure to NO_2 by itself, but also of concern is NOx reacting to form airborne nitrate particles or acid aerosols which have similar effects.
- Along with sulfur oxides (SOx), NOx contributes to the formation of acid rain and causes a wide range of environmental concerns.
- NOx can deteriorate water quality by overloading the water with nutrients causing an overabundance of algae.
- Atmospheric nitrogen-containing particles decrease visibility.
- NOx can react to form nitrous oxide (N_2O), which is a greenhouse gas, and contribute to global warming.

Coal usually contains between 0.5 and 3 percent nitrogen on a dry weight basis. The nitrogen found in coal typically takes the form of aromatic structures such as pyridines and pyrroles. The feedstock flexibility of gasification allows for a wide variation in the nitrogen content of coal.

During gasification, most of the nitrogen in the coal is converted into harmless nitrogen gas (N_2)

which makes up a large portion of the atmosphere. Small levels of ammonia (NH_3) and hydrogen cyanide (HCN) are produced, however, and must be removed during the syngas cooling process. Since both NH_3 and HCN are water soluble, this is a straightforward process.

In coal gasification-based processes, NOx can be formed downstream by the combustion of syngas with air in electricity-producing gas turbines. However, known methods for controlling NOx formation keep these levels to a minimum and result in NOx emissions substantially below those associated with other coal-fired electrical production technologies.

	Total (direct+indirect) NO2 emissions	
	Number of vehicles	Mileage
Gasoline vehicles	26.48%	2.567E+06
Diesel vehicles	63.97%	3.046E+07
LNG vehicles	3.72%	5.797E+05
Hybrid vehicles	3.49%	5.667E+05
Electric vehicles	1.97%	3.073E+05
Fuel cell vehicles	0.37%	5.759E+04
Total	100.00%	3.453E+07

Table 2-3: Total direct + Indirect emissions of NO_2

A fuel cell vehicle (FCV) or fuel cell electric vehicle (FCEV) is an electric vehicle that uses a fuel cell, sometimes in combination with a small battery or supercapacitor, to power its onboard electric motor. Fuel cells in vehicles generate electricity generally using oxygen from the air and compressed hydrogen. Most fuel cell vehicles are classified as zero-emissions vehicles that emit only water and heat. As compared with internal combustion vehicles, hydrogen vehicles centralize pollutants at the site of the hydrogen production, where hydrogen is typically derived from reformed natural gas. Transporting and storing hydrogen may also create pollutants.

All fuel cells are made up of three parts: an electrolyte, an anode and a cathode. In principle, a hydrogen fuel cell functions like a battery, producing electricity, which can run an electric motor. Instead of requiring recharging, however, the fuel cell can be refilled with hydrogen. Different types of fuel cells include polymer electrolyte membrane (PEM) Fuel Cells, direct methanol fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, solid oxide fuel cells, reformed methanol fuel cell and Regenerative Fuel Cells.

Different types of fuel cell vehicles:

1)cars

2)buses

3)forklifts

4)material handling vehicles.

5) Motorcycles and bicycles

6)Trucks

Fuel cell vehicles use hydrogen gas to power an electric motor. Unlike conventional vehicles which run on gasoline or diesel, fuel cell cars and trucks combine hydrogen and oxygen to produce electricity, which runs a motor. Since they're powered entirely by electricity, fuel cell vehicles are considered electric vehicles ("EVs")—but unlike other EVs, their range and refueling processes are comparable to conventional cars and trucks.

Converting hydrogen gas into electricity produces only water and heat as a byproduct, meaning fuel cell vehicles don't create tailpipe pollution when they're driven. Producing the hydrogen itself can lead to pollution, including greenhouse gas emissions, but even when the fuel comes from one of the dirtiest sources of hydrogen, natural gas, today's early fuel cell cars and trucks can cut emissions by over 30 percent when compared with their gasoline-powered counterparts. Fuel consumption:

Explanation and specification of the issue in legislation the fuel consumption of Passenger Cars, Light Duty Vehicles and Motorcycles is tested on a roller test bench; for Heavy Duty Vehicles are tested on an engine test bench, following test cycle or steady state test. National/regional prescriptions provide specifications for test procedures and driving profile both for regulation and for standard. Determination of fuel consumption is a fundamental issue for all vehicle categories, since it constitutes: - an element required for certification/homologation - a parameter for possible definition of taxation - a common basis for comparing energy performance of different vehicles and different power train solutions - a basis to determine the "Well To Wheel" energy effectiveness of the various solutions with respect to the primary energy source.

Measurement of H_2-Fuel Consumption:

H_2-Fuel consumption is defined as the mass amount of fuel used by a vehicle in a prescribed test cycle, expressed in g/km. In principle, three methods exist for experimentally determining gaseous H_2 consumption in FC or ICE-vehicles:

(i) determination of fuel mass change in the container before and after test,

(ii) determination of H_2 flow rate and

(iii) measuring the concentration of relevant species in the exhaust with subsequent back-calculation to fuel consumption.

(i) and (ii) require a test vehicle to be supplied with hydrogen from an external, rather than the onboard tank. This requires dedicated live hydrogen feeds during testing and adjustment of various components in the test vehicle (with associated safety implications). These methods are also not suitable for vehicles with liquid hydrogen storage.

Determination of mass change

Mass change is measured statically before and after the test, either by weighing the fuel tank with its H_2 contents, or by determining the equilibrium temperature and pressure before and after testing in a storage tank of known volume (PVT). The former method suffers from the disadvantage that the weight of H_2 is very small compared to that of the tank, resulting in low measurement accuracy. PVT measurement needs also less instrumentation and test personnel, and hence potentially offers higher repeatability and lab-to-lab reproducibility. It requires use of a standardised equation for hydrogen density as a function of temperature and pressure.

Flow rate measurement

This type of measurement allows determining the instantaneous flow rate of hydrogen. Different measurement principles exist: mechanical, optical, thermal, ultrasonic, Coriolis, etc. They all require an intervention to the fuel supply line which can introduce inaccuracies. Also dedicated signal treatment and analysis equipment is needed for all but the simplest flow meters. Measurement of fuel consumption

Vehicle certification requires measurement of fuel consumption during a test cycle. For H_2-powered vehicles a number of methods have been identified and are under investigation. Each of these methods has disadvantages. The need for harmonisation of fuel consumption measurement procedures in the context of regulations is addressed in one of the previous chapters of this technical report. The present chapter therefore focuses on the potential role that reference gases could play in this respect. In the context of regulations, the use of a single universally accepted method definitely provides added value. Moreover, for reasons of economy, efficiency and comparability with certification of non-H_2 powered vehicles, the use of an "elemental balance" method as for conventional ICE vehicles (carbon-balance) that does not require vehicle modifications, presents huge advantages. This is achieved by using the so-called Hydrogen-Balance method which measures the hydrogen-containing compounds H_2O (non-dispersive infra-red analyser) and unburned H_2 (sector field mass spectroscopy) from the FC or ICE exhaust. The method requires some modifications to the testing procedures and system that are used for conventional ICE vehicles. Because they are based on the same measurement principle, fuel consumption and emission monitoring have similar requirements for equipment calibration.. Extra requirements originate from the use of additional H_2O and H_2 analysers. Because the expected concentration of H_2 in the exhaust is very low, the H_2 sensor can be calibrated using a readily available appropriate reference gas. However 19 calibration of the H_2O NDIR analyser calibration requires a dedicated humidification system. For FC vehicles an Oxygen-Balance method based on measurement of the oxygen concentration in the exhaust has also been proposed. The method is not directly based on mass conservation, but on the measurement of a relatively small decrease in oxygen concentration between the inlet and outlet of the fuel cell stack, which requires a high accuracy of the oxygen analyser. For FC vehicles, measurement of electrical current generated by the FC can also be translated into H_2 consumption. However internal losses from hydrogen leaks and crossover, while definitely contributing to consumption, are not captured by such a measurement.

2.3. Definition of 2030 simulation scenarios

There are three scenarios in this updated version of 2030. ERTE scenario 2030 is one of the scenario starts from the projections of passenger cars circulating fleet in 2030 for EU28. IEA AMF scenario is derived from the expected share of electric cars in Germany in 2030. Therefore, distributions for all the other vehicle categories are referred to the situation of the cars.

BCG analysis is the scenario where the distributions of worldwide sale in different years were expected. There was a study which was released in January 2020, this is a pre-covid investigation. After that a study performed after the covid pandemic start , there were some changes not a drastic variations.

In this case, the problem is related that market distribution does not correspond to the circulating fleet, which is influenced by the lifetime of the different vehicles, substitution rate. Therefore, we applied the distribution of sales expected for 2025 to circulating fleet of 2030, assuming that the replacement of older vehicles may require around five years, which is probably rather optimistic. In the scenarios of ERTE, IEA AMF, BCG analysis, we assumed 1% of fuel cell vehicles, which means a very reduced share, but to be considered.

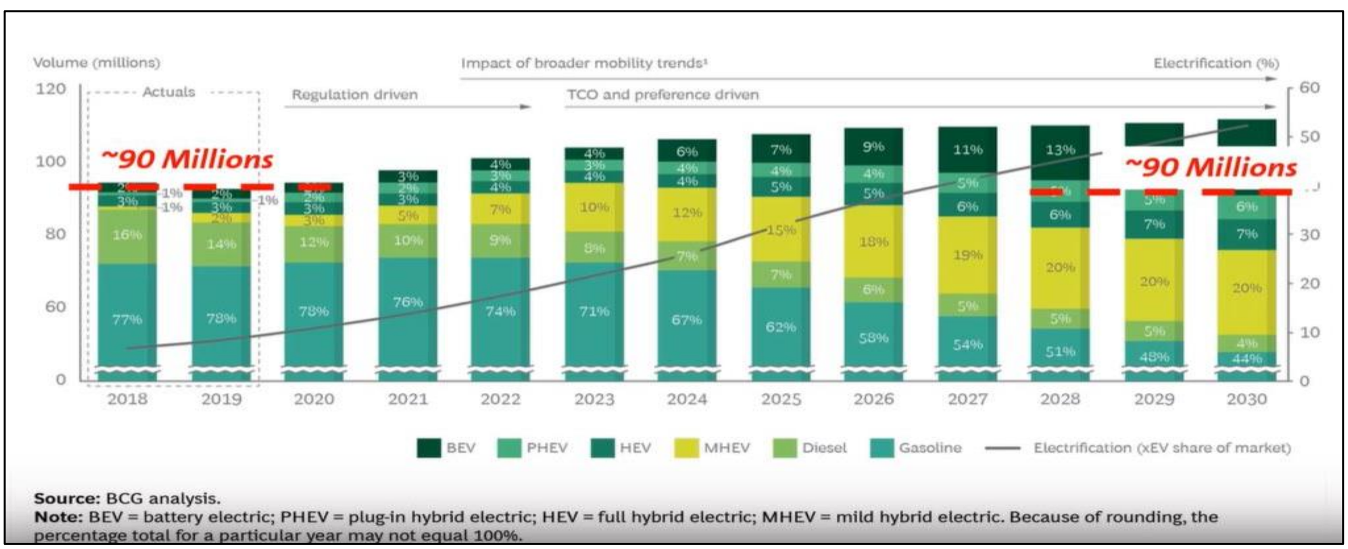


Figure 2-5: Global vehicle production by propulsion system (Pre Covid-19 crisis Jan 2020)

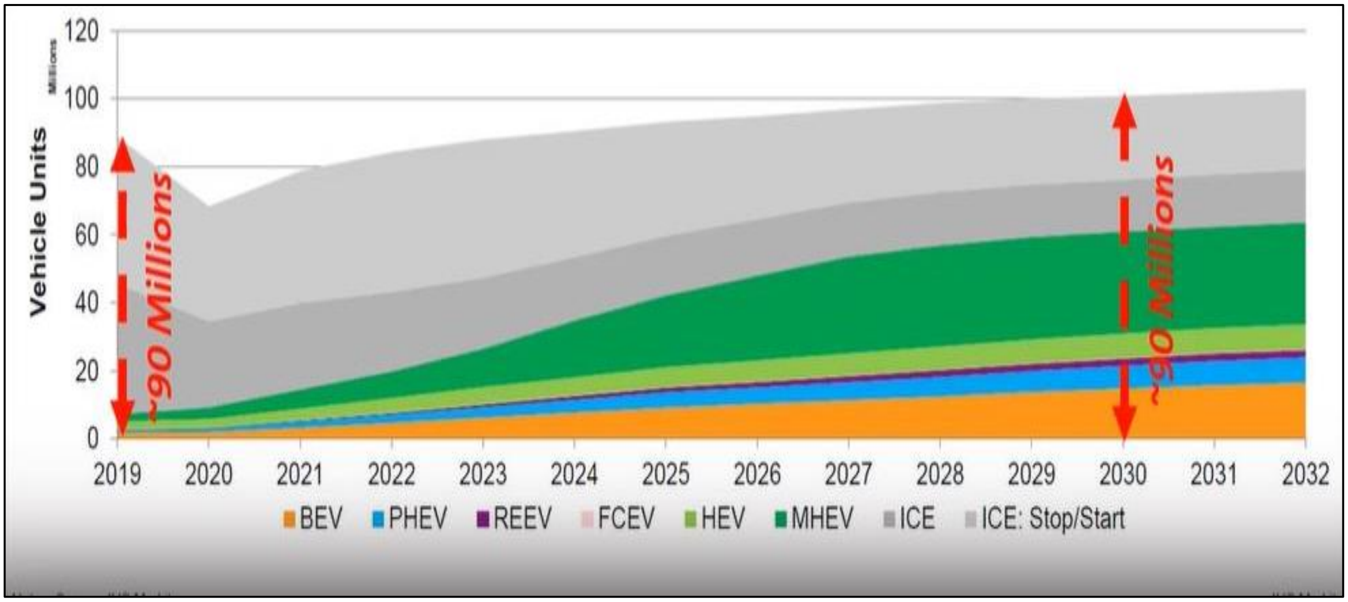


Figure 2-6: Global vehicle production by propulsion system (Post Covid-19 crisis Jan 2020)

The total direct emissions contributing hot and cold emission results are shown in the figure below. They are described in the percentages for the vehicle types and the gases or emissions which are CO, HC, NO_X, NO_2, PM, CO_2, Fuel. Where the emissions of hydro carbons in the hot direct emissions category is less comparing to that of other emissions which is of 43.8%. when it comes to cold emissions percentage hydrocarbons casts the highest percentage of about 56.2%.

As you can see in the graph the emissions of motor cycles of HC has the highest percentage of about 80% and the same emissions record for the carbon monoxides in the category of motor cycles. These are represented in the below figures

ERTE Scenario 2030: The overall number of vehicles for each category is increased between 3 up to 8.5% referring to the situation 2020. For passenger cars, the increase is evaluated according to this scenario and have been reported results are given below. For all the other vehicle categories also the same process is applicable and the lowest being applied to the mopeds, because there is a decreasing popularity for these vehicle category in Italy.

Simulation three is associated with the scenario of ERTE 2030, in this simulation, the results obtained according to the vehicle fleet, mileage and the emissions are described below.

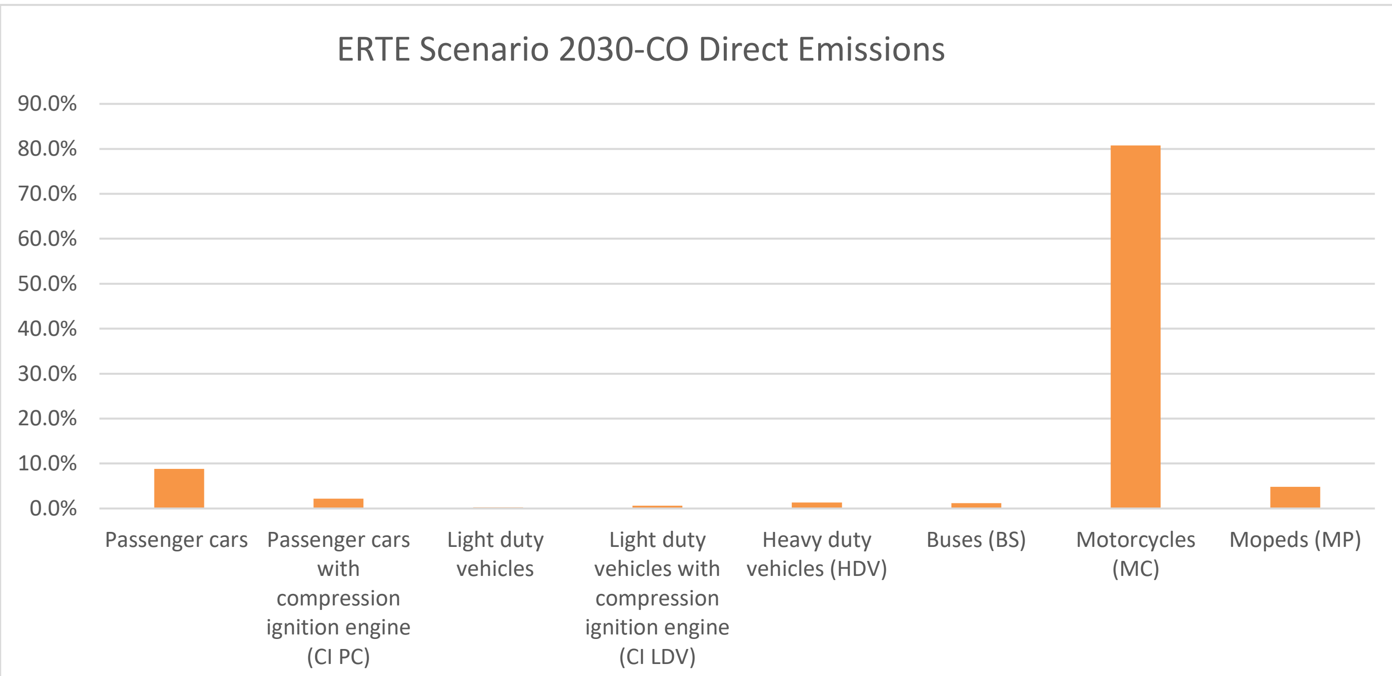


Figure 2-7: ERTE 2030 Direct emissions for CO

The above figure represents the CO emissions percentages for different vehicle categories. As you can see the graph the CO emissions are more in the vehicle category of motorcycles and less in the LDV where the percentage of CO emissions regarding motorcycles are 80.7% and the less percentage of LDV is 0.7%.

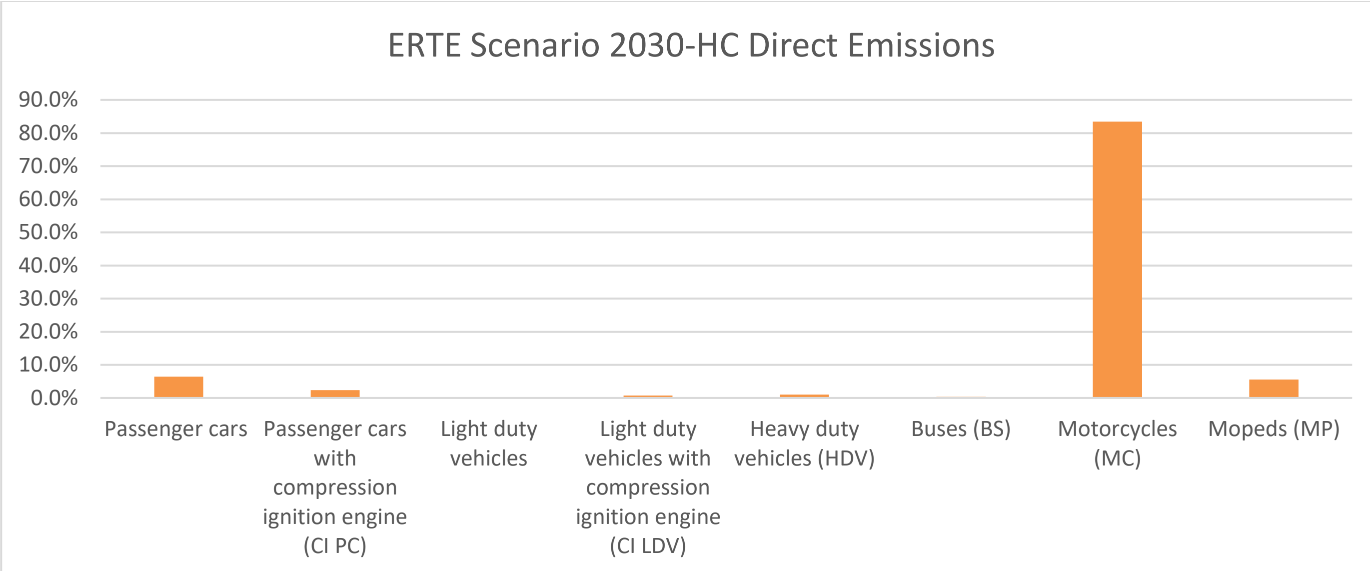


Figure 2-8: ERTE 2030 Direct emissions for HC

The above figure represents the HC emissions percentages for different vehicle categories. As you can see the graph the HC emissions are more in the vehicle category of motorcycles and less in the LDV where the percentage of HC emissions regarding motorcycles are 83.5% and the less percentage of LDV is 0.2%.

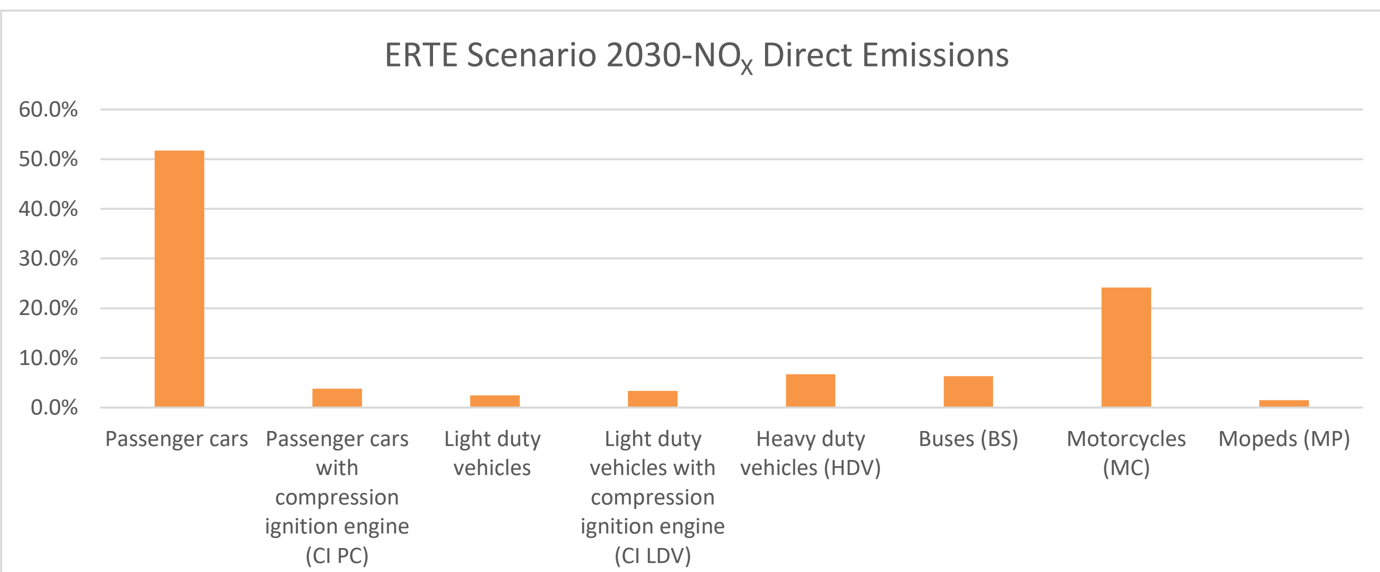


Figure 2-9: ERTE 2030 Direct emissions for NO_X

The above figure represents the NO_X emissions percentages for different vehicle categories. As you can see the graph the NO_X emissions are more in the vehicle category of CI PC and less in the LDV where the percentage of NO_X emissions regarding CI PC are 25.3% and the less percentage of LDV is 0.2%.

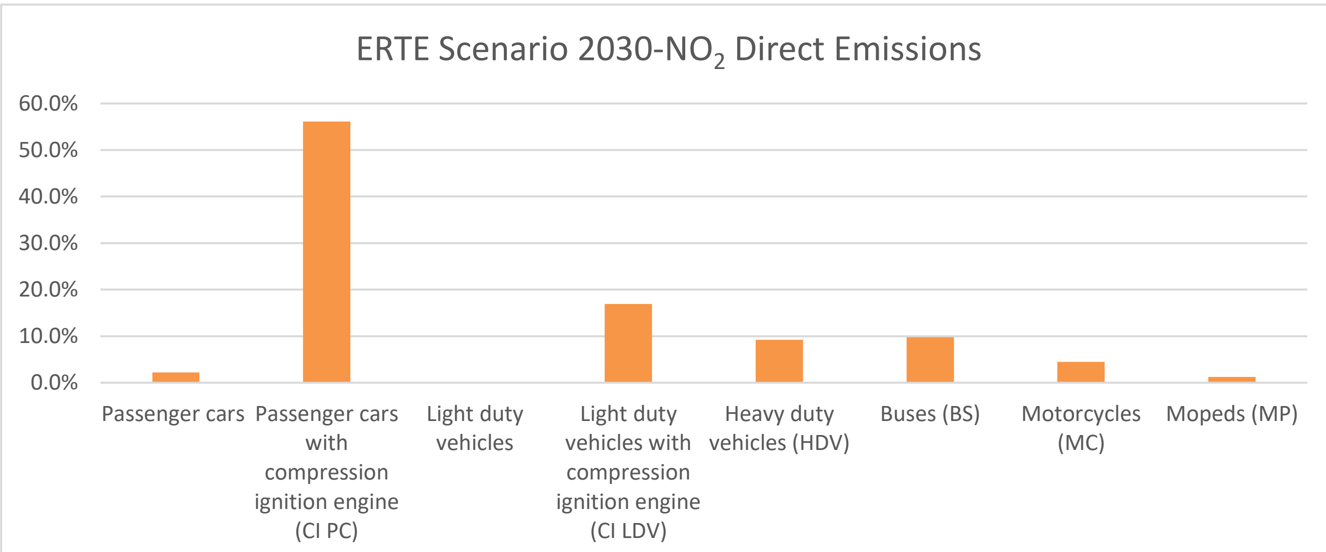


Figure 2-10: ERTE 2030 Direct emissions for NO_2

The above figure represents the NO_2 emissions percentages for different vehicle categories. As you can see the graph the NO_2 emissions are more in the vehicle category of CI PC and less in the LDV where the percentage of NO_2 emissions regarding CI PC are 56.1% and the less percentage of LDV is 0.1%.

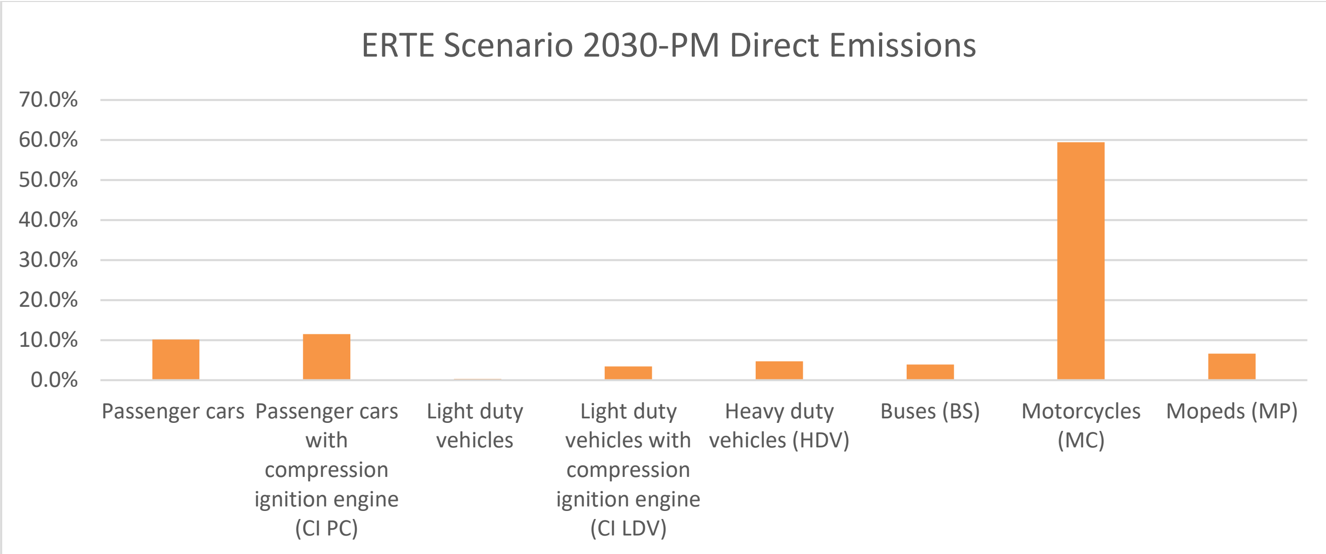


Figure 2-11: ERTE 2030 Direct emissions for PM

The above figure represents the PM direct emissions percentages for different vehicle categories. As you can see the graph the PM emissions are more in the vehicle category of motorcycles and less in the LDV where the percentage of PM emissions regarding motorcycles are 59.4% and the less percentage of LDV is 0.3%.

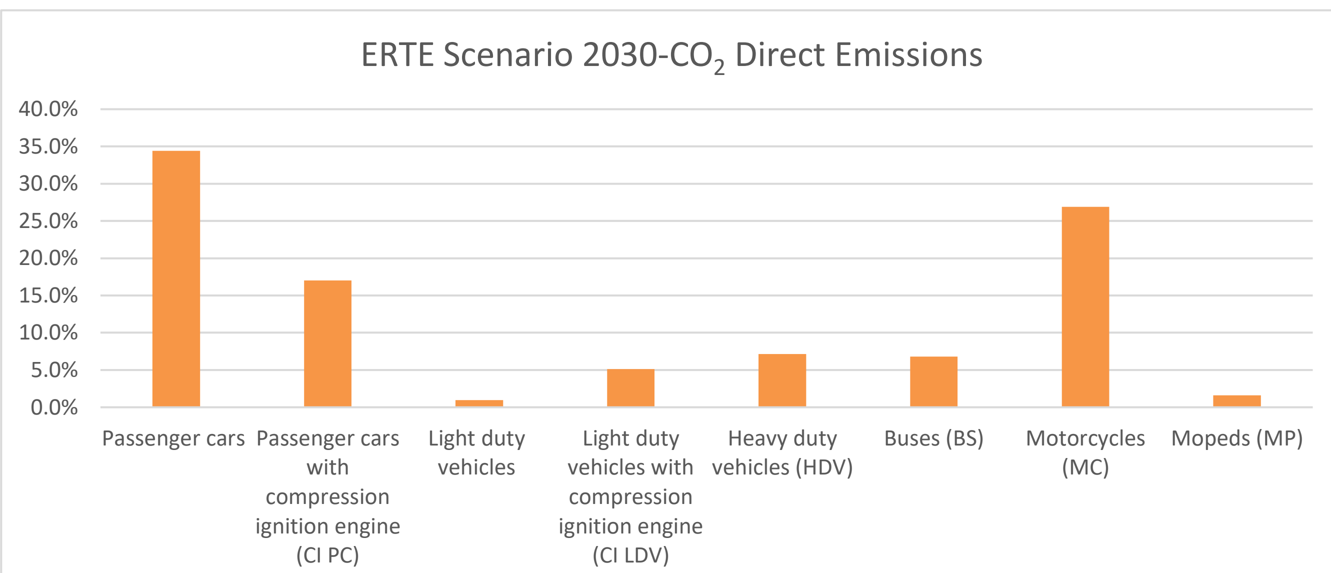


Figure 2-12: ERTE 2030 Direct emissions for CO_2

The above figure represents the CO_2 emissions percentages for different vehicle categories. As you can see the graph the CO_2 emissions are more in the vehicle category of PC and less in the LDV where the percentage of CO_2 emissions regarding CI PC are 37.4% and the less percentage of LDV is 1.0%.

The below figure represents 2030 IEA AMF total direct emissions for the vehicle categories of passenger cars, Passenger cars with compression ignition engine (CI PC), Light duty vehicles, Light duty vehicles with compression ignition engine (CI LDV), Heavy duty vehicles, Buses, Motor cycles, Mopeds.

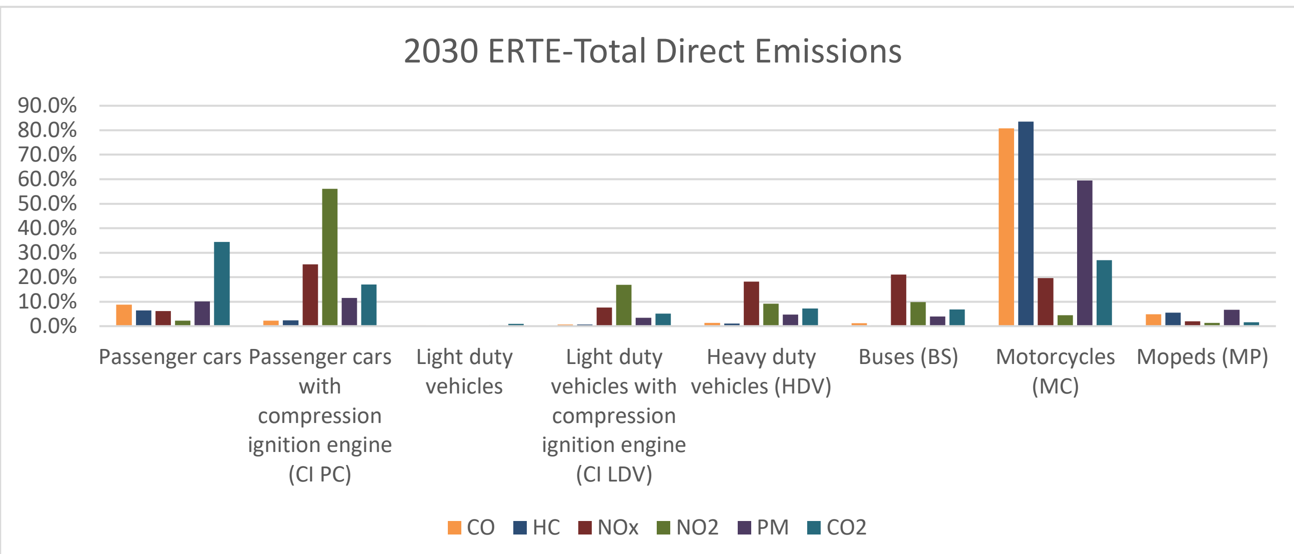


Figure 2-13: Fleet distribution with the direct emissions percentages-2030 ERTE

The below table represents 2030 ERTE total direct emissions for the vehicle categories of passenger cars, Passenger cars with compression ignition engine (CI PC), Light duty vehicles, Light duty vehicles with compression ignition engine (CI LDV), Heavy duty vehicles, Buses, Motor cycles, Mopeds.

2030 ERTE						
	CO	**HC**	**NOx**	**NO2**	**PM**	**CO2**
Total direct emissions [g]	1.751E+09	2.285E+08	1.503E+08	3.399E+07	3.568E+06	2.860E+11
	CO	**HC**	**NOx**	**NO2**	**PM**	**CO2**
Passenger cars	8.8%	6.4%	6.1%	2.2%	10.1%	34.4%
Passenger cars with compression ignition engine (CI PC)	2.2%	2.4%	25.3%	56.1%	11.5%	17.0%
Light duty vehicles	0.3%	0.2%	0.2%	0.1%	0.3%	1.0%
Light duty vehicles with compression ignition engine (CI LDV)	0.7%	0.7%	7.6%	16.9%	3.5%	5.1%
Heavy duty vehicles (HDV)	1.3%	1.0%	18.2%	9.2%	4.7%	7.2%
Buses (BS)	1.2%	0.3%	21.0%	9.8%	3.9%	6.8%
Motorcycles (MC)	80.7%	83.5%	19.6%	4.5%	59.4%	26.9%
Mopeds (MP)	4.9%	5.5%	2.0%	1.3%	6.6%	1.6%

Table 2-3: Total direct emissions-2030 ERTE

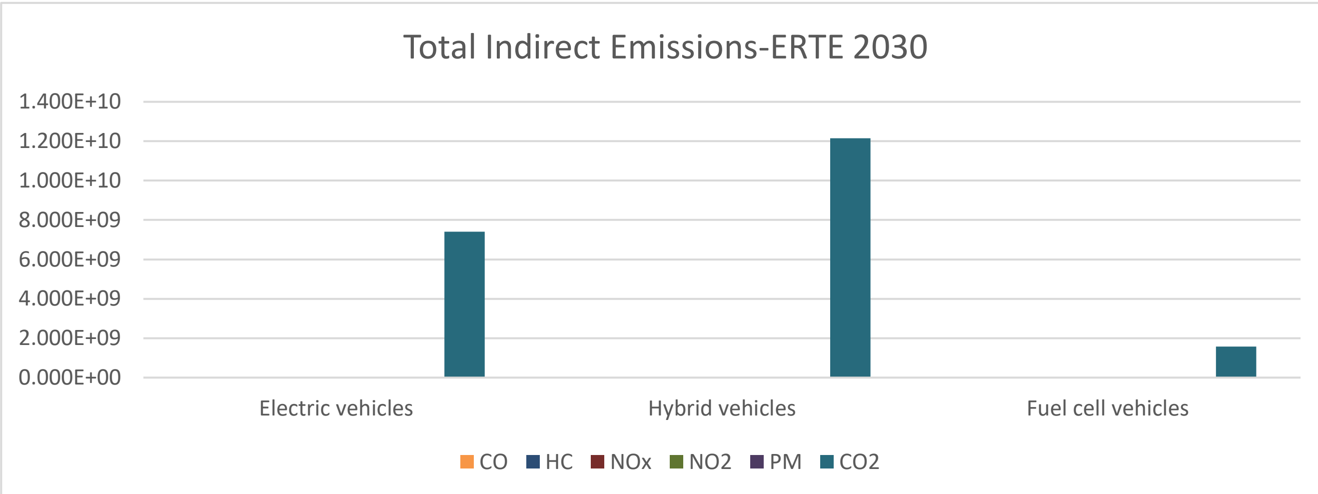


Figure 2-14: Total indirect emissions-ERTE 2030

	2030 ERTE					
	CO	HC	NOx	NO2	PM	CO2
Total indirect emissions [g]	4.639E+06	1.569E+06	5.423E+06	5.423E+05	1.189E+05	1.485E+10
Electric vehicles	2.628E+06	8.889E+05	3.073E+06	3.073E+05	6.746E+04	8.417E+09
Hybrid vehicles	1.517E+06	5.135E+05	1.774E+06	1.774E+05	3.873E+04	4.859E+09
Fuel cell vehicles	4.928E+05	1.665E+05	5.759E+05	5.759E+04	1.267E+04	1.577E+09

Table2-4 : Total in-direct emissions-ERTE 2030

Total indirect emissions are calculated and the total emissions which are of direct and indirect emissions and they are compared to the reference year 2019 with the simulation number 1 are described below with the results obtained. These total indirect emissions are calculated for the distribution of alternative propulsion systems which consists of different vehicle types of electric vehicles, hybrid vehicles and fuel cell vehicles. For the distributions of different alternative propulsion systems in the category of electric vehicles the emissions for all the emissions are around the same difference.

Distributions of indirect emissions between different alternative propulsion systems							
	CO	HC	NOx	NO2	PM	CO2
Electric vehicles	56.66%	56.66%	56.66%	56.66%	56.76%	56.66%
Hybrid vehicles	32.71%	32.73%	32.72%	32.72%	32.58%	32.72%
Fuel cell vehicles	10.62%	10.61%	10.62%	10.62%	10.66%	10.62%

Table 2-5 : Total indirect emissions and the distributions between different alternative propulsion systems

IEA AMF Scenario 2030: This scenario of IEA AMF is derived from the expected share of electric cars in Germany in 2030. Therefore, distributions for all the other vehicle categories are assumed referring to the situation for the cars. The fuel cell vehicles are assumed to be about 1% , which means a very reduced shares. This scenario of IEA AMF 2030 is associated with the simulation four.

Simulation four is associated with the scenario of IEA AMF 2030, in this simulation, the results obtained according to the vehicle fleet, mileage and the emissions are described below.

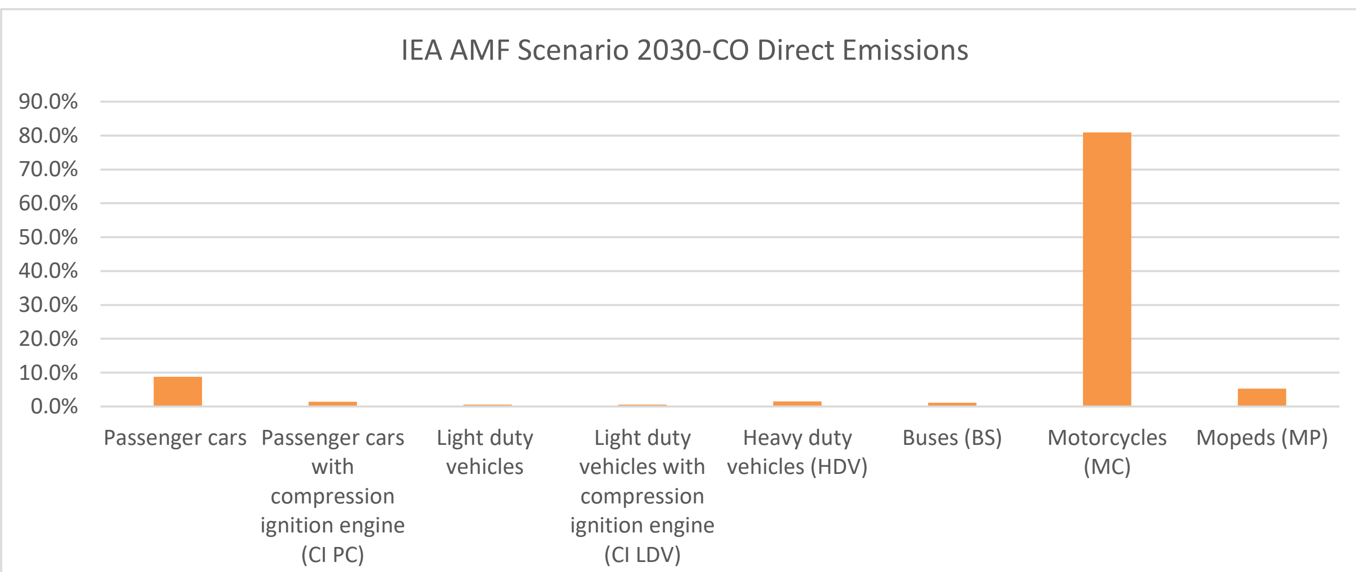


Figure 2-15: IEA AMF 2030 Direct emissions for CO

The above figure represents the CO emissions percentages for different vehicle categories. As you can see the graph the CO emissions are more in the vehicle category of motorcycles and less in the LDV and CI LDV where the percentage of CO emissions regarding motorcycles are 80.9% and the less percentage of LDV and CI LDV is 0.5%.

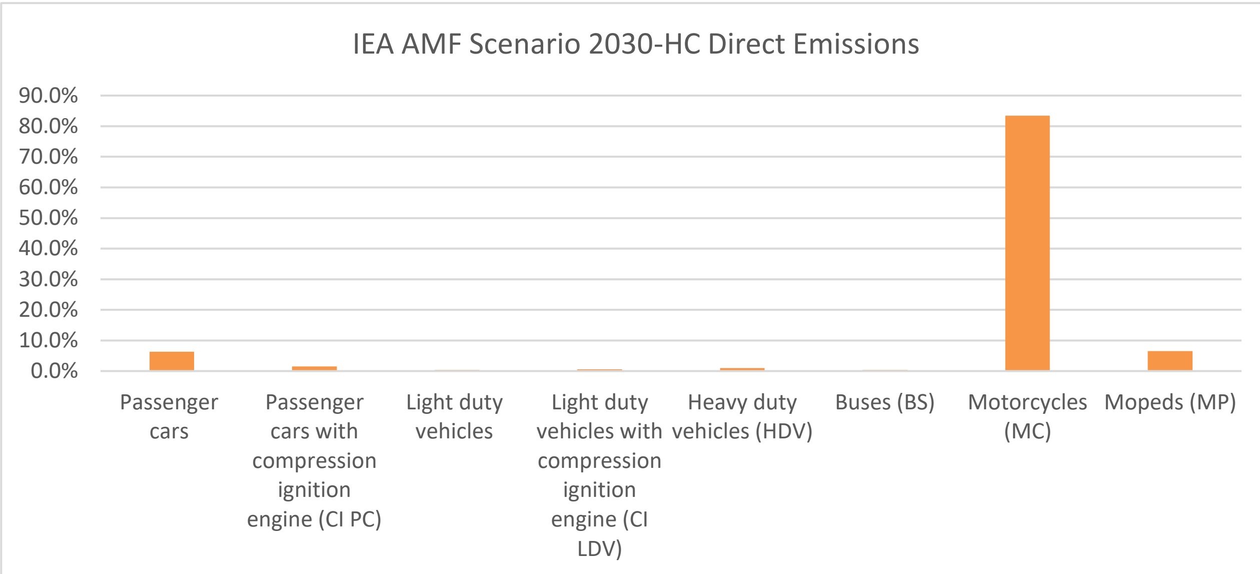


Figure 2-16: IEA AMF 2030 Direct emissions for HC

The above figure represents the HC emissions percentages for different vehicle categories. As you can see the graph the HC emissions are more in the vehicle category of motorcycles and less in the LDV where the percentage of HC emissions regarding motorcycles are 83.4% and the less percentage of LDV is 0.4%.

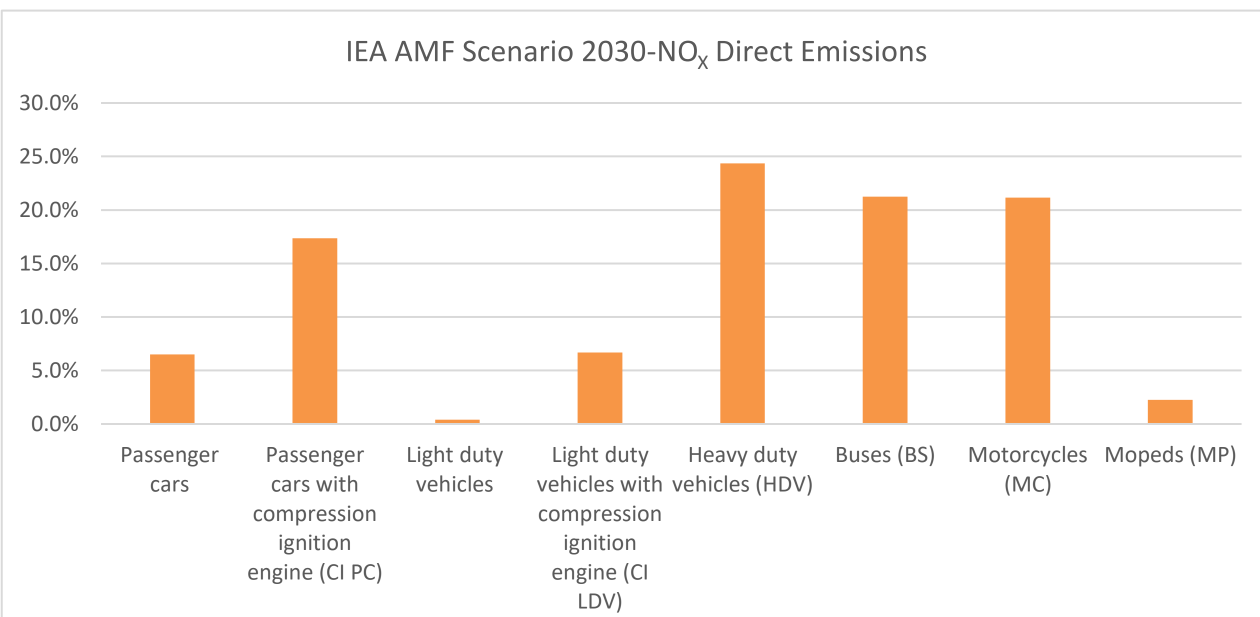


Figure 2-17: IEA AMF 2030 Direct emissions for NO_X

The above figure represents the NO_X emissions percentages for different vehicle categories. As you can see the graph the NO_X emissions are more in the vehicle category of HDV and less in the LDV where the percentage of NO_X emissions regarding HDV are 24.4% and the less percentage of LDV is 0.4%.

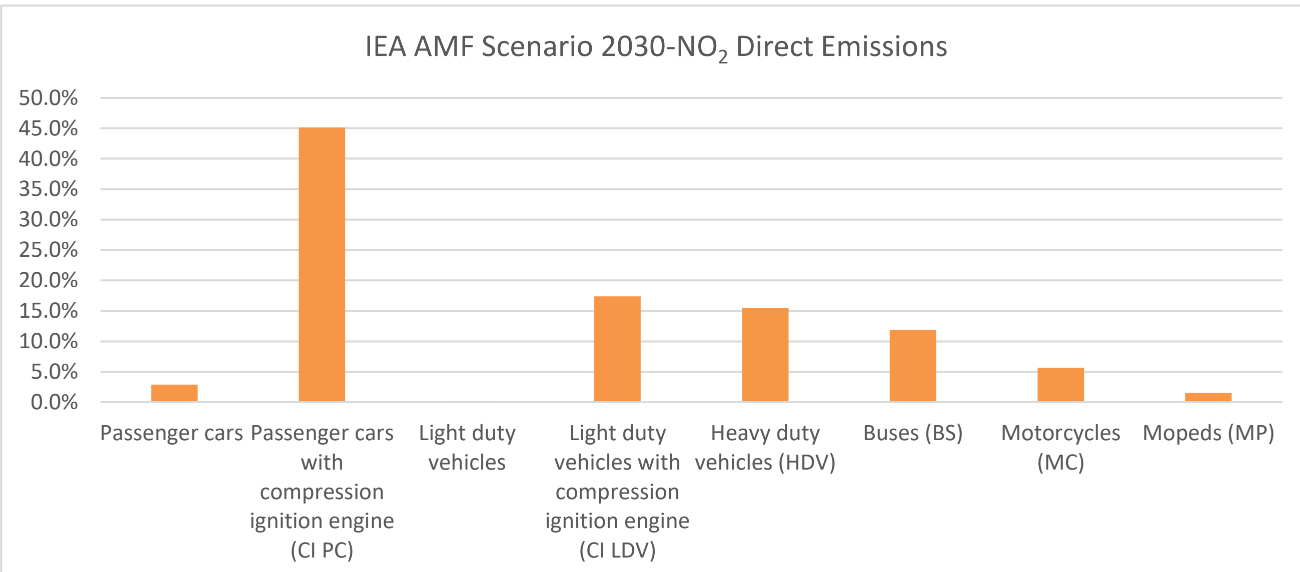


Figure 2-18: IEA AMF 2030 Direct emissions for NO_2

The above figure represents the NO_2 emissions percentages for different vehicle categories. As you can see the graph the NO_2 emissions are more in the vehicle category of CI PC and less in the LDV where the percentage of NO_2 emissions regarding CI PC are 45.1% and the less percentage of LDV is 0.1%.

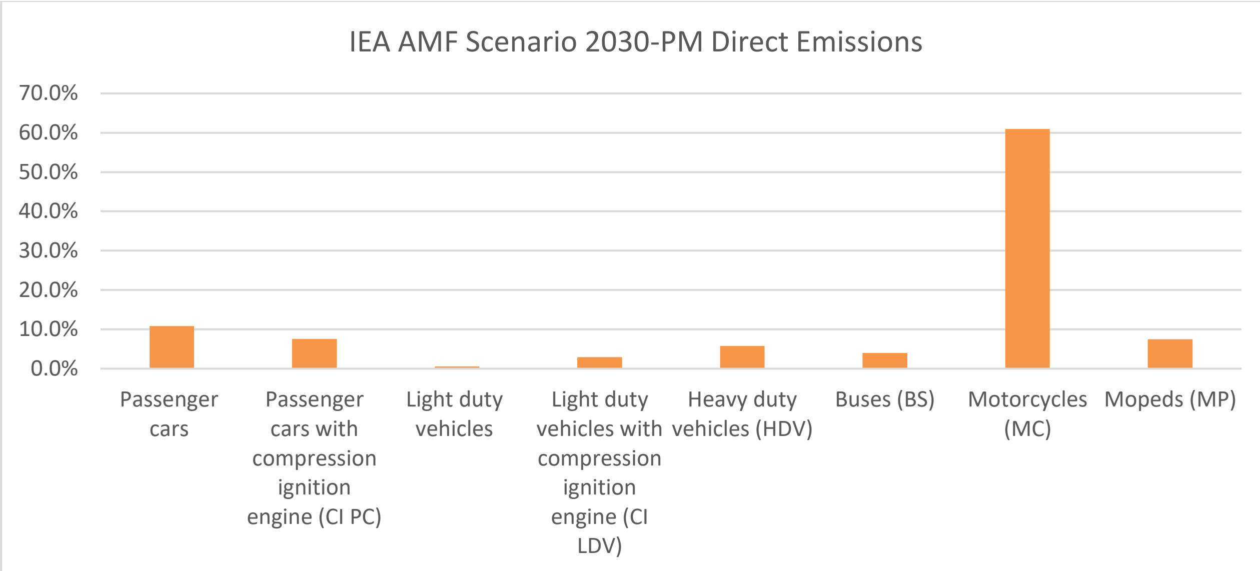


Figure 2-19: IEA AMF 2030 Direct emissions for PM

The above figure represents the PM direct emissions percentages for different vehicle categories. As you can see the graph the PM emissions are more in the vehicle category of motorcycles and less in the LDV where the percentage of PM emissions regarding motorcycles are 61.0% and the less percentage of LDV is 0.6%.

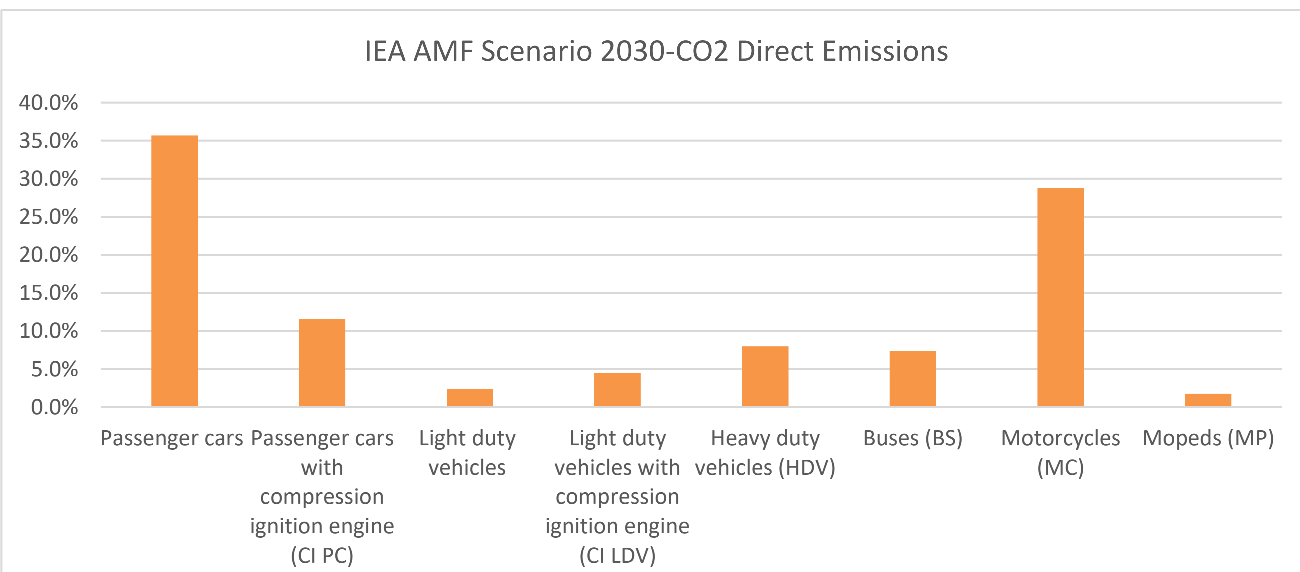


Figure 2-20: IEA AMF 2030 Direct emissions for CO_2

The above figure represents the CO_2 emissions percentages for different vehicle categories. As you can see the graph the CO_2 emissions are more in the vehicle category of PC and less in the Mopeds where the percentage of CO_2 emissions regarding PC are 35.7% and the less percentage of Mopeds is 1.8%.

The below figure represents 2030 IEA AMF total direct emissions for the vehicle categories of passenger cars, Passenger cars with compression ignition engine (CI PC), Light duty vehicles, Light duty vehicles with compression ignition engine (CI LDV), Heavy duty vehicles, Buses, Motor cycles, Mopeds.

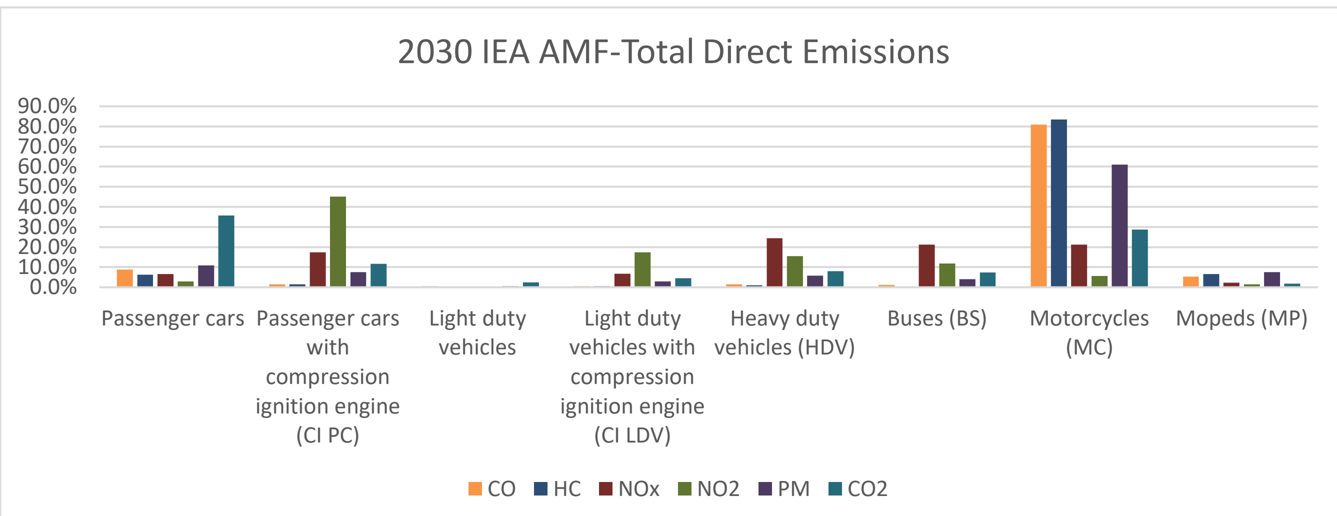


Figure2-21: Fleet distribution with the direct emissions percentages- IEA AMF 2030

The below table represents 2030 IEA AMF total direct emissions for the vehicle categories of passenger cars, Passenger cars with compression ignition engine (CI PC), Light duty vehicles, Light duty vehicles with compression ignition engine (CI LDV), Heavy duty vehicles, Buses, Motor cycles, Mopeds.

2030 IEA AMF						
	CO	**HC**	**NOx**	**NO2**	**PM**	**CO2**
Total direct emissions [g]	1.713E+09	2.244E+08	1.366E+08	2.641E+07	3.405E+06	2.619E+11
	CO	HC	NOx	NO2	PM	CO2
Passenger cars	8.7%	6.3%	6.5%	2.9%	10.8%	35.7%
Passenger cars with compression ignition engine (CI PC)	1.4%	1.5%	17.4%	45.1%	7.5%	11.6%
Light duty vehicles	0.5%	0.4%	0.4%	0.1%	0.6%	2.4%
Light duty vehicles with compression ignition engine (CI LDV)	0.5%	0.6%	6.7%	17.4%	2.9%	4.5%
Heavy duty vehicles (HDV)	1.5%	0.9%	24.4%	15.5%	5.8%	8.0%
Buses (BS)	1.1%	0.3%	21.3%	11.9%	4.0%	7.4%
Motorcycles (MC)	**80.9%**	**83.4%**	**21.1%**	**5.7%**	**61.0%**	**28.7%**
Mopeds (MP)	**5.3%**	**6.5%**	**2.3%**	**1.5%**	**7.5%**	**1.8%**

Table 2-6: Total direct emissions- IEA AMF 2030

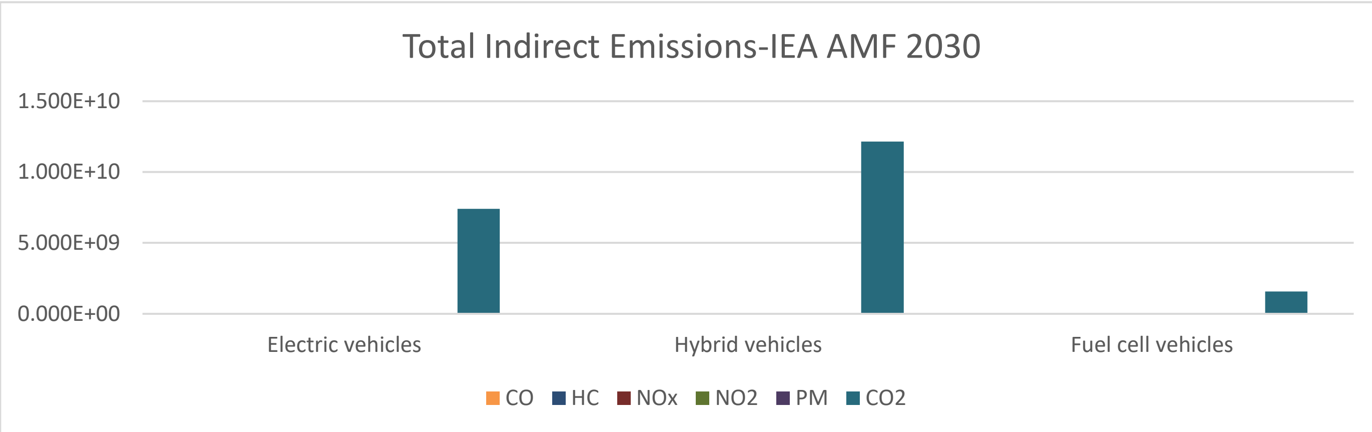


Figure 2-22: Total indirect emissions- IEA AMF 2030

	2030 IEA AMF					
	CO	HC	NOx	NO2	PM	CO2
Total indirect emissions [g]	6.600E+06	2.233E+06	7.717E+06	7.717E+05	1.690E+05	2.114E+10
Electric vehicles	2.315E+06	7.827E+05	2.706E+06	2.706E+05	5.950E+04	7.412E+09
Hybrid vehicles	3.794E+06	1.284E+06	4.436E+06	4.436E+05	9.682E+04	1.215E+10
Fuel cell vehicles	4.920E+05	1.662E+05	5.751E+05	5.751E+04	1.265E+04	1.575E+09

Table2-7: Total in-direct emissions- IEA AMF 2030

Total indirect emissions are calculated and the total emissions which are of direct and indirect emissions and they are compared to the reference year 2019 with the simulation number 1 are described below with the results obtained. These total indirect emissions are calculated for the distribution of alternative propulsion systems which consists of different vehicle types of electric vehicles, hybrid vehicles and fuel cell vehicles. For the distributions of different alternative propulsion systems in the category of electric vehicles the emissions for all the emissions are around the same difference.

Distributions of indirect emissions between different alternative propulsion systems						
	CO	HC	NOx	NO2	PM	CO2
Electric vehicles	35.07%	35.06%	35.07%	35.07%	35.22%	35.07%
Hybrid vehicles	57.48%	57.50%	57.48%	57.48%	57.30%	57.48%
Fuel cell vehicles	7.45%	7.45%	7.45%	7.45%	7.49%	7.45%

Table2-8: Total indirect emissions and the distributions between different alternative propulsion systems

BCG Analysis 2030: This scenario three is based on an analysis by BCG, expected distributions worldwide sale in different years. As this study was released in January 2020, which means that, it is a pre-covid investigation. Where a study was performed after the covid pandemic start shows some changes, but there were not that drastic changes in the investigations. We have applied the distribution of sales in 2025, to the circulating fleet of 2030.

Simulation five is associated with the scenario of BCG Analysis 2030, in this simulation, the results obtained according to the vehicle fleet, mileage and the emissions are described below.

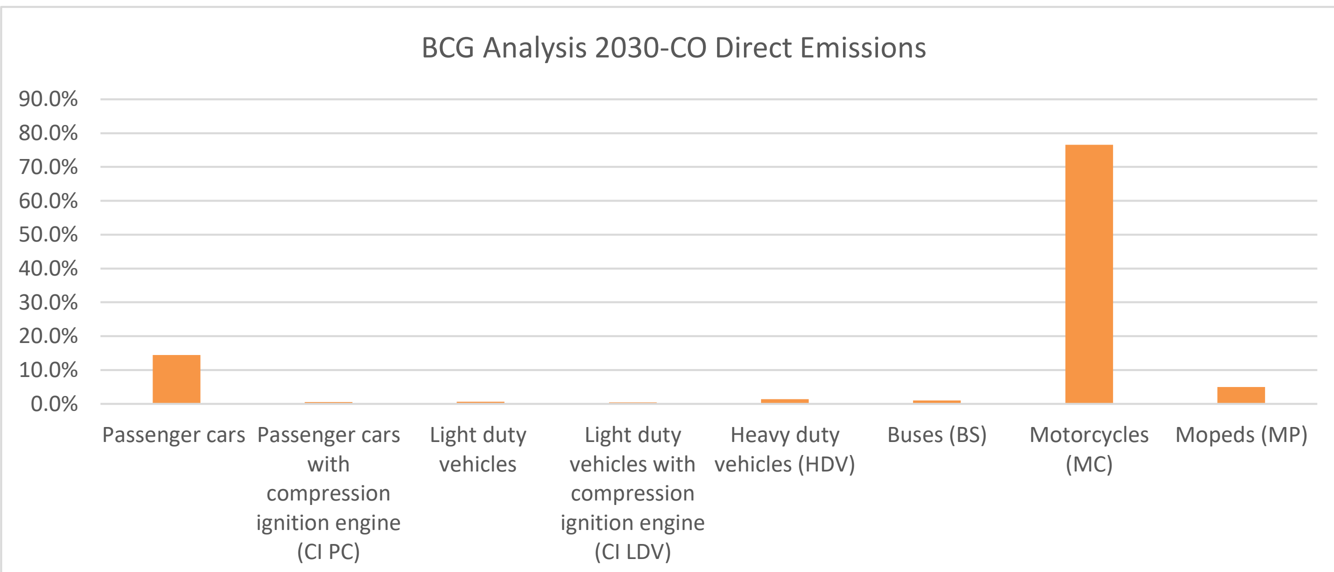


Figure 2-23: BCG Analysis 2030 Direct emissions for CO

The above figure represents the CO emissions percentages for different vehicle categories. As you can see the graph the CO emissions are more in the vehicle category of motorcycles and less in the CI PC where the percentage of CO emissions regarding motorcycles are 76.6% and the less percentage of CI PC is 0.5%.

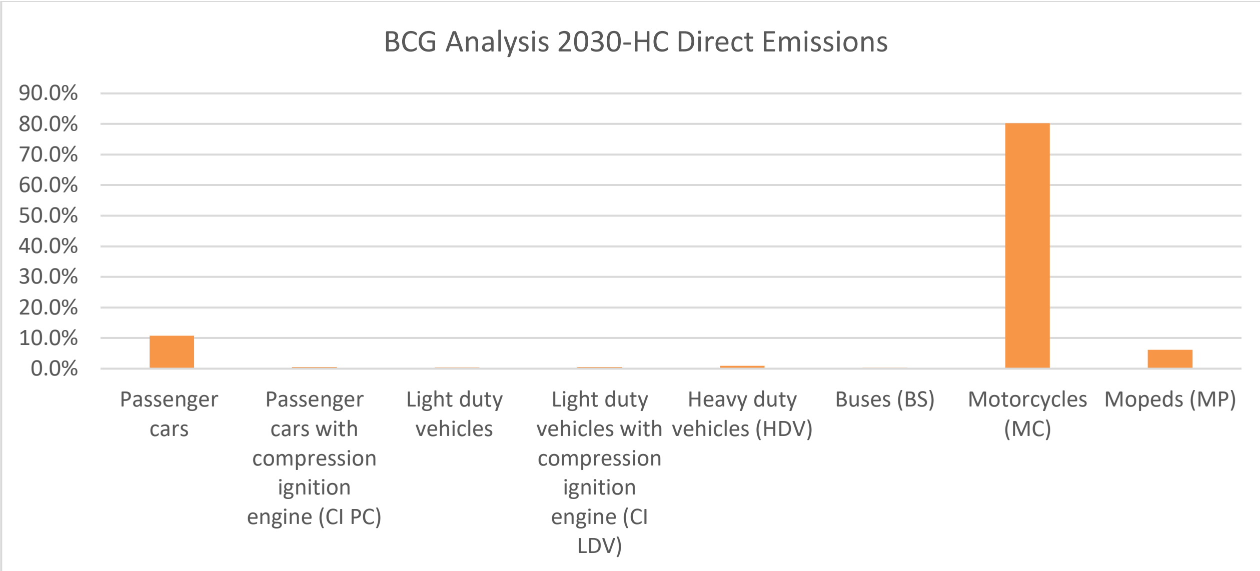


Figure 2-24: BCG Analysis Direct emissions for HC

The above figure represents the HC emissions percentages for different vehicle categories. As you can see the graph the HC emissions are more in the vehicle category of motorcycles and less in the Buses where the percentage of HC emissions regarding motorcycles are 80.2% and the less percentage of Buses is 0.3%.

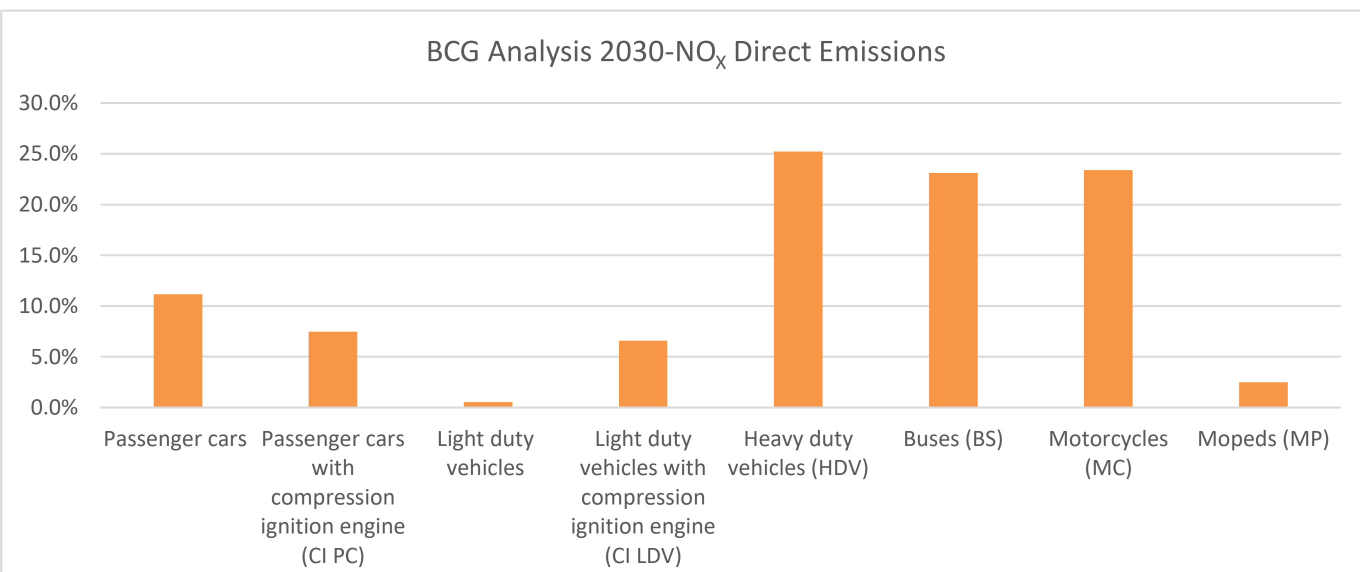


Figure 2-25: BCG Analysis Direct emissions for NO_X

The above figure represents the NO_X emissions percentages for different vehicle categories. As you can see the graph the NO_X emissions are more in the vehicle category of HDV and less in the LDV where the percentage of NO_X emissions regarding HDV are 25.2% and the less percentage of LDV is 0.6%.

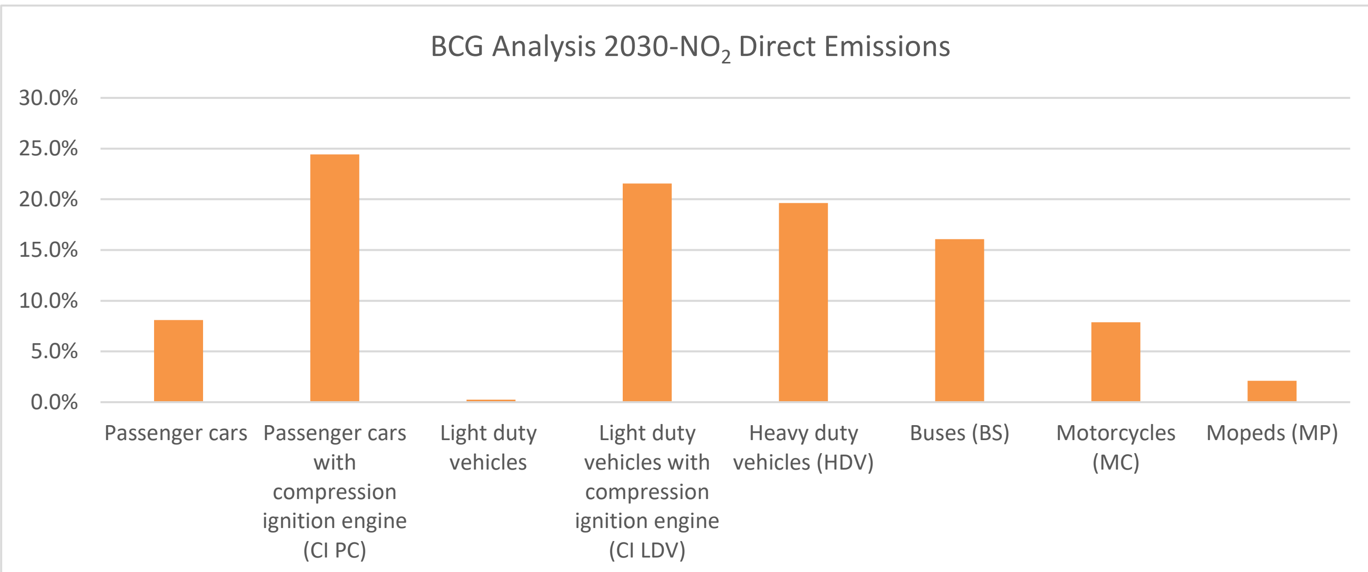


Figure 2-26: BCG Analysis 2030 Direct emissions for NO_2

The above figure represents the NO_2 emissions percentages for different vehicle categories. As you can see the graph the NO_2 emissions are more in the vehicle category of CI PC and less in the LDV where the percentage of NO_2 emissions regarding CI PC are 24.4% and the less percentage of LDV is 0.2%.

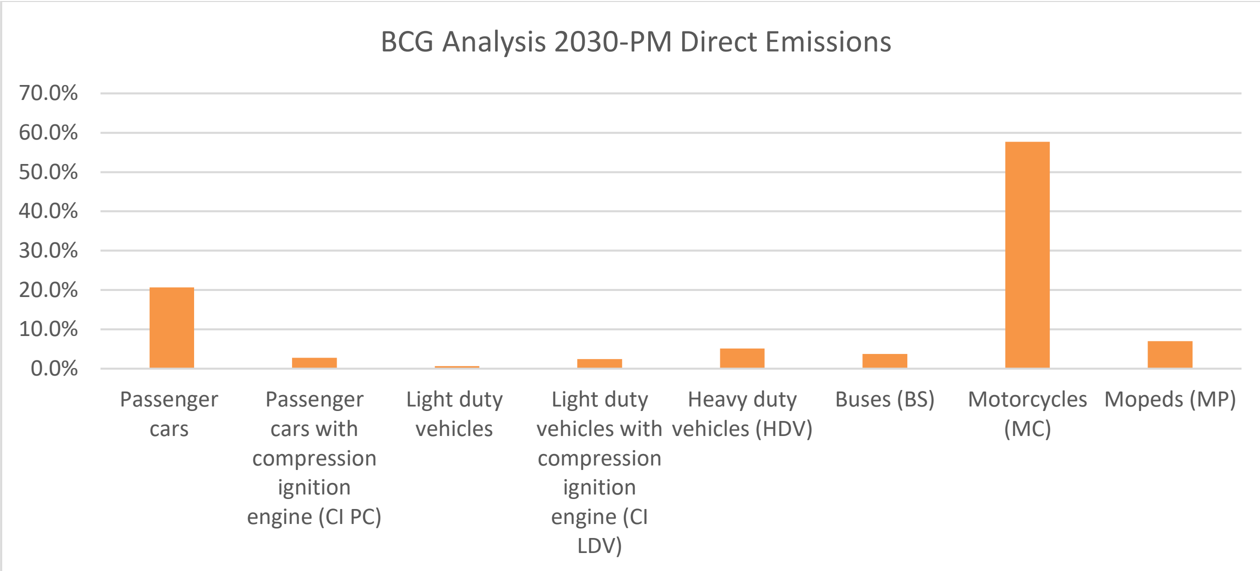


Figure 2-27: BCG Analysis 2030 Direct emissions for PM

The above figure represents the PM direct emissions percentages for different vehicle categories. As you can see the graph the PM emissions are more in the vehicle category of motorcycles and less in the LDV where the percentage of PM emissions regarding motorcycles are 57.7% and the less percentage of LDV is 0.6%.

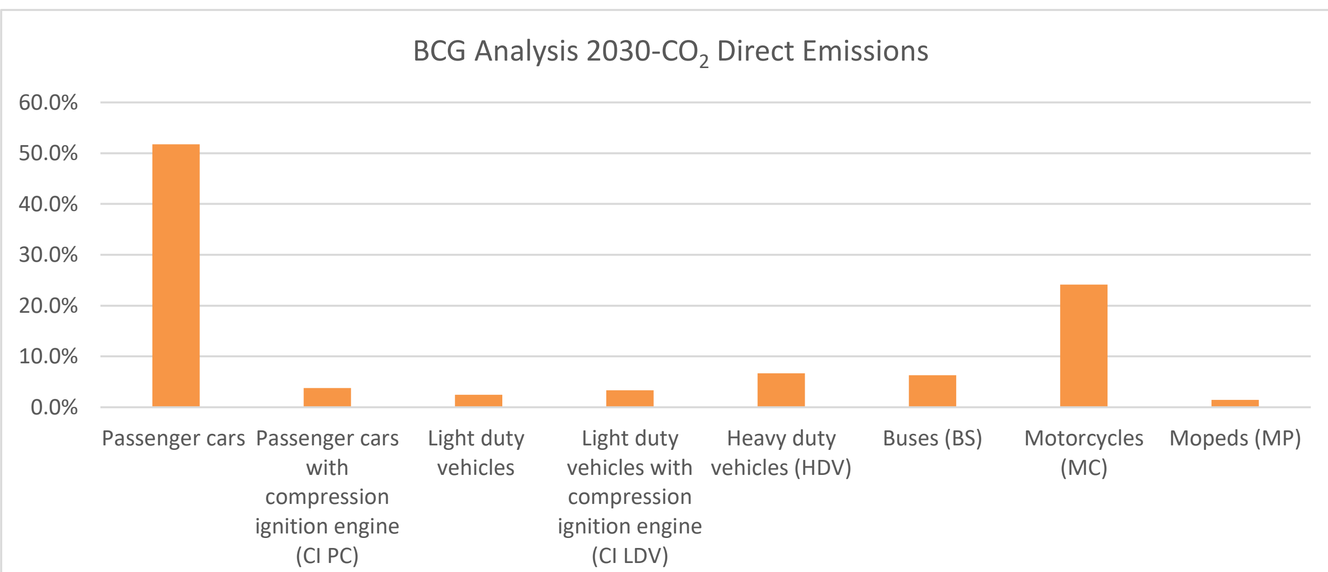


Figure 2-28: BCG Analysis 2030 Direct emissions for CO_2

The above figure represents the CO_2 emissions percentages for different vehicle categories. As you can see the graph the CO_2 emissions are more in the vehicle category of PC and less in the Mopeds where the percentage of CO_2 emissions regarding PC are 51.7% and the less percentage of Mopeds is 1.5%.

The below figure represents 2030 IEA AMF total direct emissions for the vehicle categories of passenger cars, Passenger cars with compression ignition engine (CI PC), Light duty vehicles, Light duty vehicles with compression ignition engine (CI LDV), Heavy duty vehicles, Buses, Motor cycles, Mopeds.

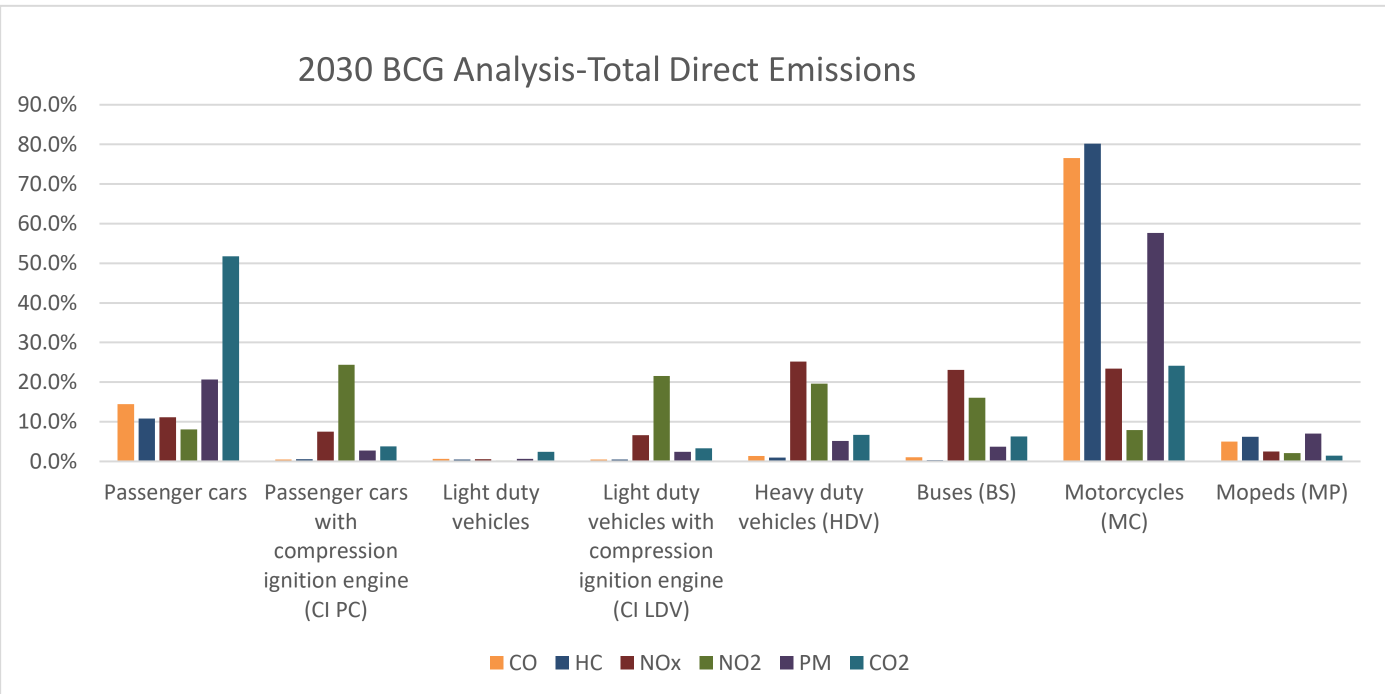


Figure2-29: Fleet distribution with the direct emissions percentages-2030 BCG Analysis

The below table represents 2030 BCG Analysis total direct emissions for the vehicle categories of passenger cars, Passenger cars with compression ignition engine (CI PC), Light duty vehicles, Light duty vehicles with compression ignition engine (CI LDV), Heavy duty vehicles, Buses, Motor cycles, Mopeds.

2030 BCG analysis						
	CO	**HC**	**NOx**	**NO2**	**PM**	**CO2**
Total direct emissions [g]	1.864E+09	2.401E+08	1.270E+08	1.952E+07	3.715E+06	3.217E+11
	CO	HC	NOx	NO2	PM	CO2
Passenger cars	14.5%	10.8%	11.2%	8.1%	20.6%	51.7%
Passenger cars with compression ignition engine (CI PC)	0.5%	0.6%	7.5%	24.4%	2.8%	3.8%
Light duty vehicles	0.6%	0.5%	0.6%	0.2%	0.6%	2.5%
Light duty vehicles with compression ignition engine (CI LDV)	0.5%	0.5%	6.6%	21.6%	2.4%	3.3%
Heavy duty vehicles (HDV)	1.4%	1.0%	25.2%	19.6%	5.1%	6.7%
Buses (BS)	1.0%	0.3%	23.1%	16.1%	3.7%	6.3%
Motorcycles (MC)	76.6%	80.2%	23.4%	7.9%	57.7%	24.2%
Mopeds (MP)	5.0%	6.2%	2.5%	2.1%	7.0%	1.5%

Table 2-9: Total direct emissions-2030 BCG Analysis

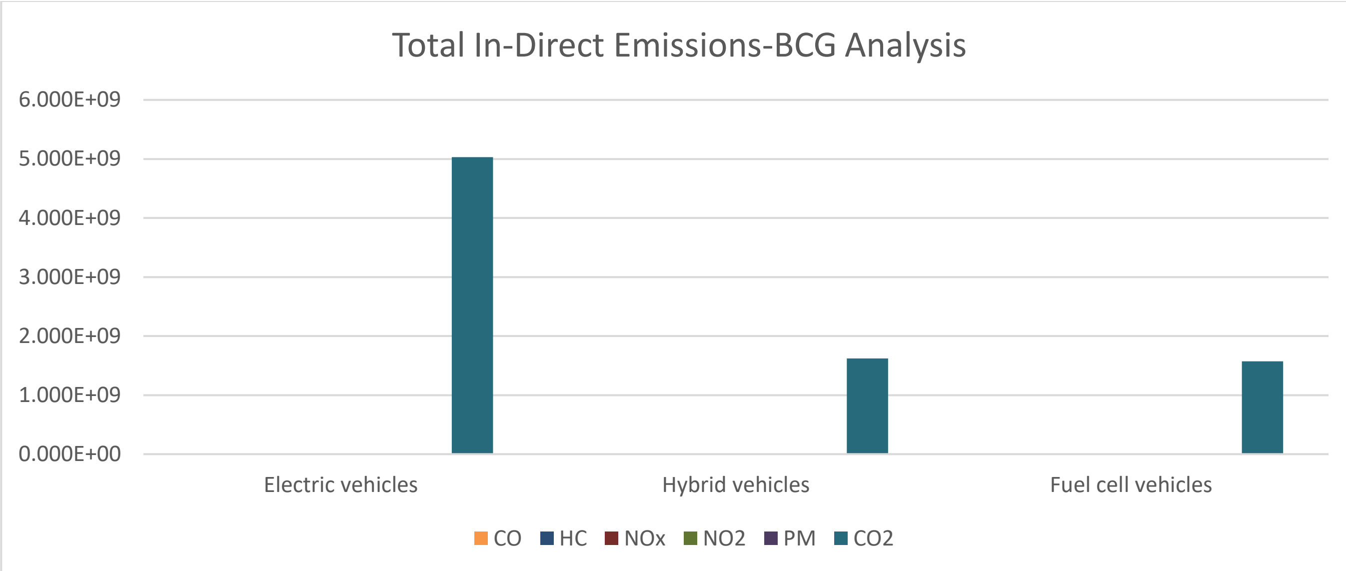


Figure 2-30: Total indirect emissions- BCG Analysis

	2030 BCG analysis					
	CO	HC	NOx	NO2	PM	CO2
Total indirect emissions [g]	2.568E+06	8.684E+05	3.002E+06	3.002E+05	6.592E+04	8.223E+09
Electric vehicles	1.570E+06	5.310E+05	1.836E+06	1.836E+05	4.036E+04	5.028E+09
Hybrid vehicles	5.058E+05	1.712E+05	5.914E+05	5.914E+04	1.291E+04	1.620E+09
Fuel cell vehicles	4.920E+05	1.662E+05	5.751E+05	5.751E+04	1.265E+04	1.575E+09

Table2-10: Total in-direct emissions- BCG Analysis

Total indirect emissions are calculated and the total emissions which are of direct and indirect emissions and they are compared to the reference year 2019 with the simulation number 1 are described below with the results obtained. These total indirect emissions are calculated for the distribution of alternative propulsion systems which consists of different vehicle types of electric vehicles, hybrid vehicles and fuel cell vehicles. For the distributions of different alternative propulsion systems in the category of electric vehicles the emissions for all the emissions are around the same difference.

Distributions of indirect emissions between different alternative propulsion systems						
	CO	HC	NOx	NO2	PM	CO2
Electric vehicles	61.14%	61.15%	61.15%	61.15%	61.23%	61.15%
Hybrid vehicles	19.70%	19.71%	19.70%	19.70%	19.58%	19.70%
Fuel cell vehicles	19.16%	19.14%	19.15%	19.15%	19.19%	19.15%

Table2-11: Total indirect emissions and the distributions between different alternative propulsion systems

2.4. Changes in travelled mileage

Travelled mileage in the urban region and we are here considering the travelled mileages for the scenarios of 2019, 2030 ERTE, 2030 IEA AMF and 2030 BCG analysis. In the 2019 scenario the urban mileage which means the travelled mileage in the 2019 is 1.699E+09, units are of 'Km'. The travelled mileage for the scenario 2030 ERTE is 2.180E+09. The travelled mileage for the scenario 2030 IEA AMF is 2.198E+09 and the travelled mileage for scenario 2030 BCG Analysis is 2.197E+09. The Total urban mileage travelled and the changes in the mileage are shown in the table below.

	2019	2030 ERTE	2030 IEA AMF	2030 BCG Analysis
Total Urban Mileage(Km)	1.699E+09	2.180E+09	2.198E+09	2.197E+09
Change in the Mileage		1.284	1.294	1.293

Table2-12: Total urban mileage travelled and the changes in the mileage

CHAPTER 3: SIMULATION RESULTS

In this chapter, the final data of the various simulations will be shown. A complete estimation on the results of reference simulations of 2019, 2030 ERTE Old will be performed and then, an estimation of 2030 ERTE, 2030 IEA AMF, 2030 BCG Analysis scenario's with hybrid, electric and fuel cell vehicles are carried out. Finally, distributions of indirect emissions between different alternative propulsion systems has to be carried out for the 2030 ERTE, 2030 IEA AMF and 2030 BCG Analysis scenarios.

3.1. Reference Scenario 2019

On the basis of ACI data, in the 2019 there were 499415 vehicles circulating, with the following subdivision:

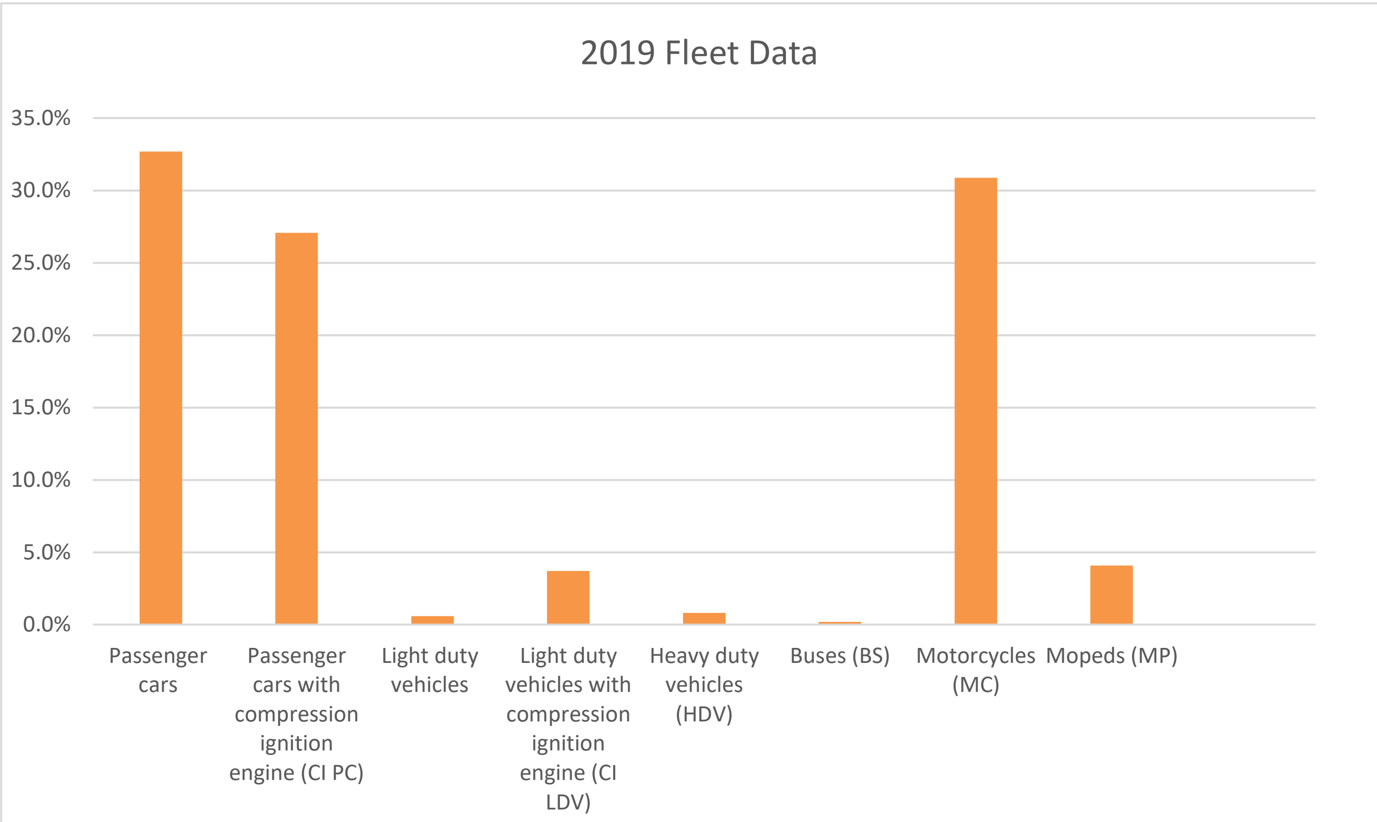


Figure 3-1: 2019 fleet distribution

As it is clearly visible in Figure 3-1, the majority of vehicles is represented by passenger cars, with a share of 32.7% of the total vehicular fleet. PC are globally subdivided on the basis of a ratio 59/41% between gasoline and diesel engines, respectively. Another important contribution to total vehicles number is represented by two-wheelers, very widespread being the 30% of the total. About driving mileage, the results are shown in Figure 3-2:

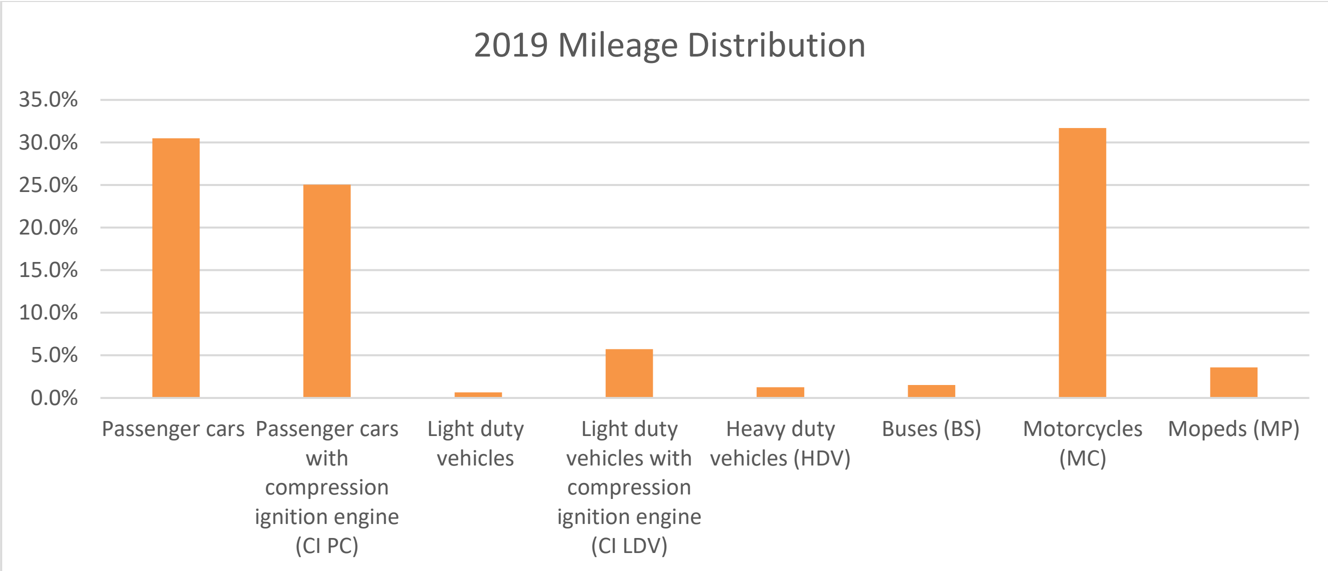


Figure 3-2: 2019 mileage distribution

The total mileage distribution reflects quite accurately the fleet subdivision, even if slight changes are reported for BS, CI LDV and HDV. These categories have a yearly driving mileage quite higher respect than the one of other vehicles (for reference see Appendix B), and this increases of course their share in mileage distribution.

Now, the distributions of total emitted pollutants will be analysed for CO, HC, NO_x, NO_2, PM and CO_2. Of course, only direct emissions are considered in this paragraph, as 2019 fleet distribution does not consider any hybrid or electric vehicle. For this reason, the emissions considered here are only direct, as in this simulation they come uniquely from the tailpipe of vehicles. Moreover, in Chapter 3 only total emissions are considered, as the repartition of hot and cold emissions between the different vehicle classes are very similar, and so it is not necessary to consider them separately, allowing to consider them summed inside a unique value. It has also to be considered that cold emission factors were not available for heavy duty vehicles and buses. As a consequence, the analysis of this aspect requires further development of the model.

Starting with carbon monoxide, the results are the following:

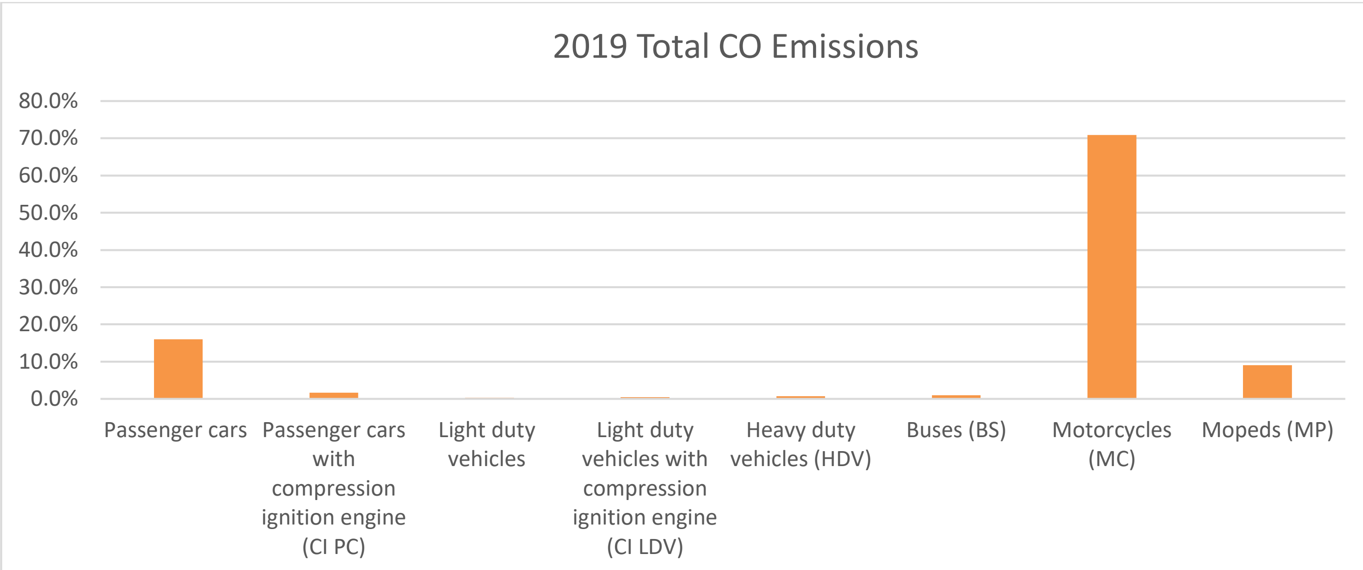


Figure 3-3: 2019 total CO emissions

As it is clearly visible, CO emissions are predominant in two-wheelers, due to higher emission factors caused by the adoption of two-strokes engines in older classes, which are used only on mopeds and motorcycles. In fact, this typology of engines is more pollutant than four strokes, especially considering the products of incomplete combustion, namely CO and HC.

For this reason, also HC distribution has a similar graph (see Figure 3-4), as unburnt hydrocarbons have a prevalent share for two-wheelers. Here, mopeds have an increased contribution respect than the one they had for CO, while passenger cars see their relevance in this pollutant being reduced.

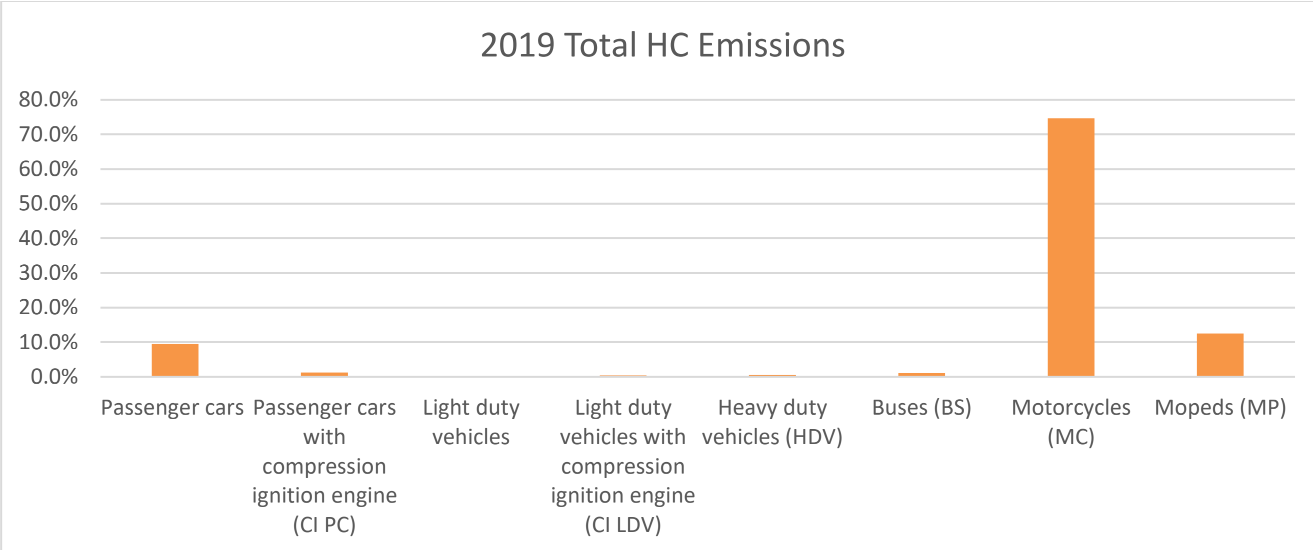


Figure 3-4: 2019 total HC emissions

The distribution changes drastically when considering nitrogen oxides, as compression ignition engines release the highest part of these emissions (Figure 3-5):

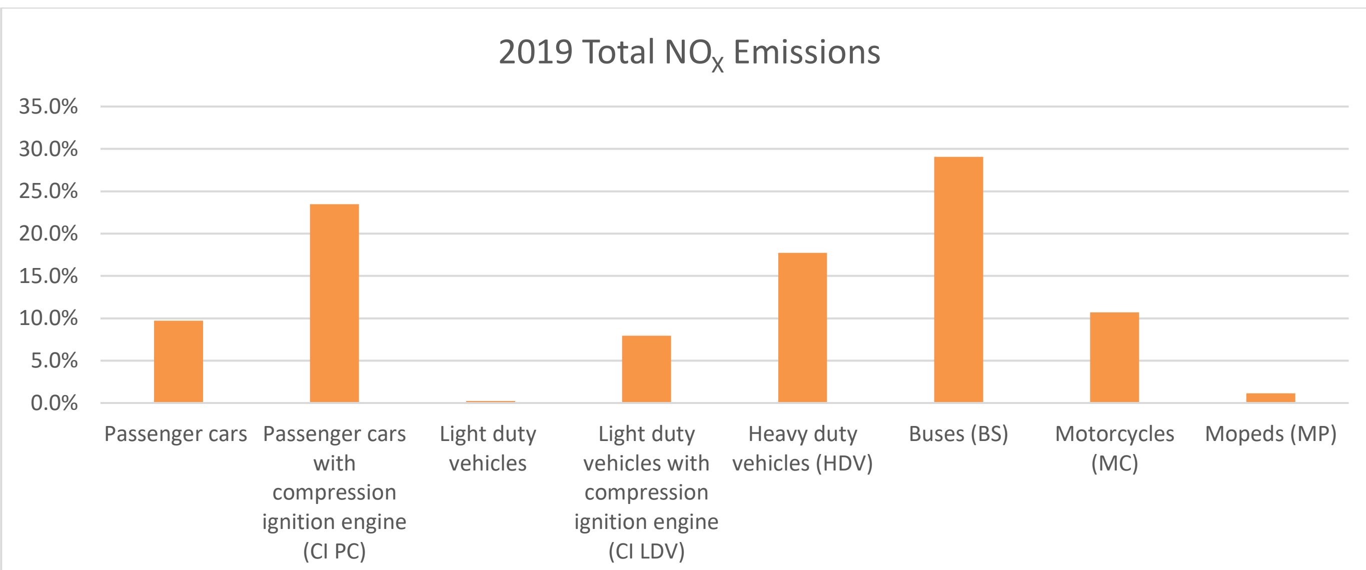


Figure 3-5: 2019 total NO_x emissions

This distribution is not unexpected, as is known that NO_x is a primary issue for diesel engines, while their gasoline counterparts are not affected too much by this problem. For example, SI PC covers just the 9.8% of NO_x total emissions, even if they represent the 23.5% of total vehicles. Also, the emissions of NO_2 behaves in the same way, being a trait of diesel engines:

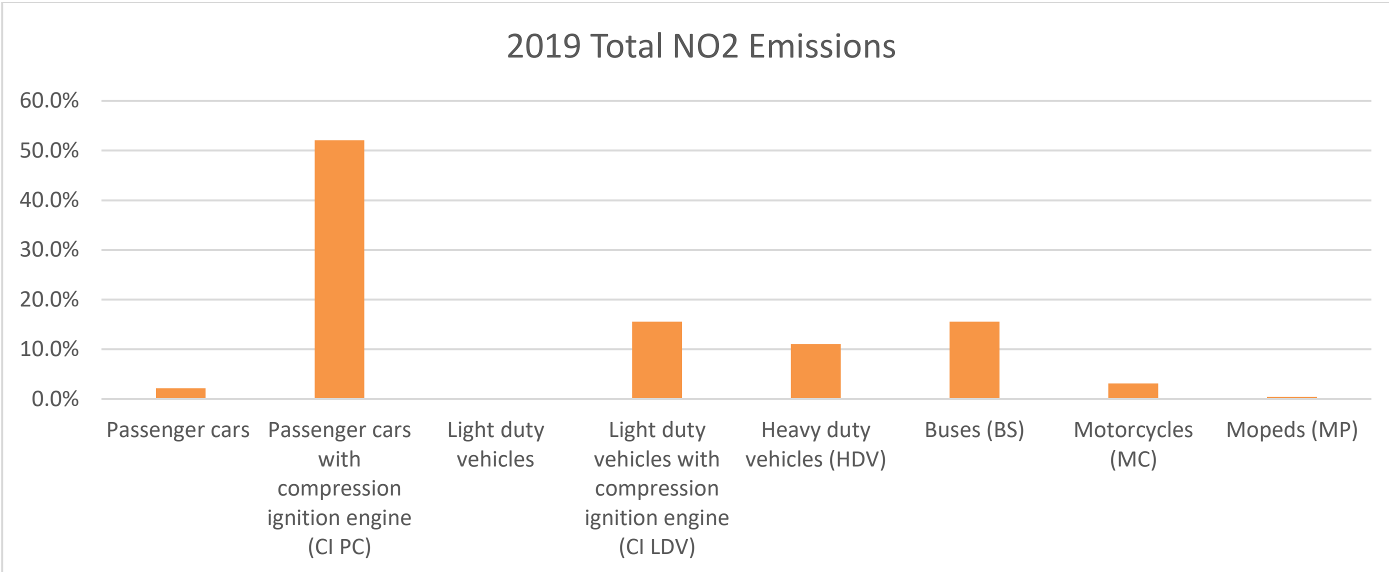


Figure 3-6: 2019 total NO_2 emissions

For what concerns NO_2, CI PC and LDV are more relevant respect HDV and BS, due to higher emissions factors of passenger cars for this pollutant. As expected, the relevance of gasoline engines on this pollutant is not high, as nitrogen oxides are a typical problem for diesel engines. In fact, gasoline engines release in atmosphere only the 21.5% of total NO_x, even though this type of motor is fitted on the 72% of total vehicles. The share of NO_2 coming from gasoline engines is even lower, as these vehicles release only the 5.2% of total nitrogen dioxide emissions.

In Figure 3-7, a similar distribution can be observed for PM, where compression ignition engines maintain their prevailing share, even if an unexpected contribution appears for two-wheelers:

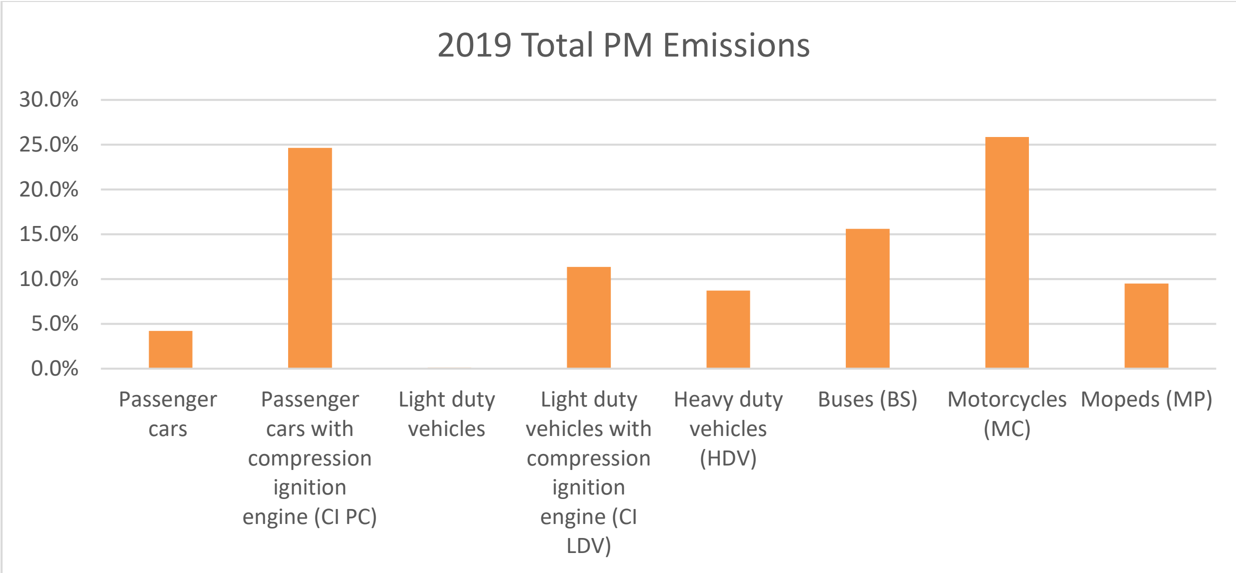


Figure 3-7: 2019 total PM emissions

However, it must be considered the contribution of two-strokes engines, which have very high PM emission factors. In fact, comparing 2 and 4 ST in the same category, these emissions factors are more than ten times higher for the first typology of engine. To confirm this statement, the very high diffusion of two strokes in mopeds (73.4% of MP is 2 ST) is the reason why a category representing just the 4.1% share of the total fleet, can have an incidence of 19.1% on total particulate emissions.

However, the highest part of PM emission comes from compression ignition engines, as it was expected. Other high contributions are coming from buses and heavy-duty vehicles, which represent respectively just the 0.2% and 0.8% of vehicular fleet, but nevertheless they release respectively the 14.7% and the 8.2% of total particulate matter due to their very high emission factors, related to the size and to the weight of those vehicles.

Finally, the total CO_2 share is shown in Figure 3-8:

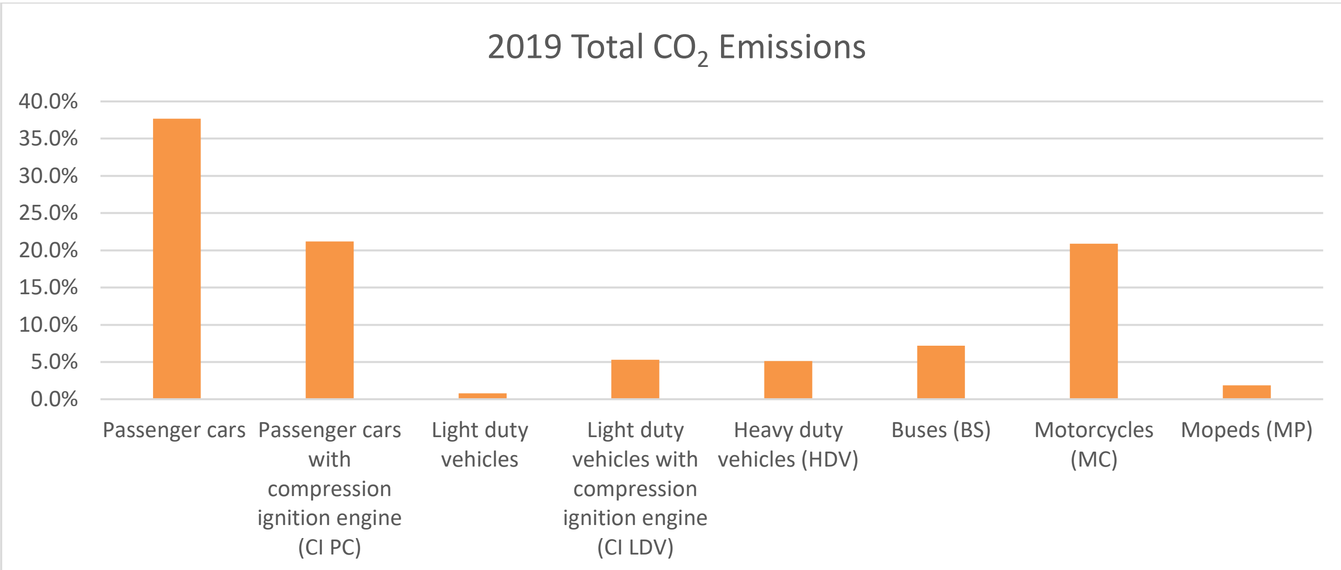


Figure 3-8: 2019 total CO_2 emissions

The Figure 3-8 can somewhat resemble Figure 3-1 and Figure 3-2, as this graph shows a quite similar repartition. However, there are some differences, especially for BS and HDV, which give a relatively high contribution to CO_2, in spite of their very low diffusion (summing both categories, they represent just the 1% of total vehicles). This is due to the higher emission factors, as their fuel consumption (and so the CO_2) is increased because of the higher overall vehicle size and mass. Another interesting fact is represented by the contribution of passenger cars: as it is known, SI PC have a higher fuel consumption than CI PC and, in fact, the first category has a CO_2 contribution slightly higher than its diffusion (37.5% of CO_2, while representing a 36.5% of total vehicles), while CI PC has the opposite behaviour, seeing a reduced contribution compared to its share (21.1% of CO_2, while representing a 26.2% of total vehicles).

In conclusion, the overall data and percentages of 2019 fleet can be summarized in Table 3-1 and Table 3-2:

Table 3-1: 2019 fleet total direct emissions[1]

	CO	HC	NO_x	NO_2	PM	CO_2
Total 2019 emissions	5.232E+09 g	1.058E+09 g	6.177E+08 g	1.361E+08 g	2.270E+07 g	3.259E+11 g
Hot emissions share	88.2%	88.8%	97.8%	100.0%	100.0%	96.5%
Cold emissions share	11.8%	11.2%	2.2%	0.0%	0.0%	3.5%

Table 3-2: 2019 fleet global distributions

	Share	Mileage	CO	HC	NO_x	NO_2	PM	CO_2
SI PC	32.7%	30.5%	16.0%	9.5%	9.7%	2.2%	4.2%	37.7%
CI PS	27.1%	25%	1.6%	1.3%	23.5%	52.1%	24.6%	21.2%
SI LDV	0.6%	0.6%	0.3%	0.2%	0.3%	0.1%	0.1%	0.8%
CI LDV	3.7%	5.7%	0.5%	0.4%	8.0%	15.6%	11.4%	5.3%
HDV	0.8%	1.3%	0.7%	0.5%	17.7%	11.1%	8.7%	5.1%
BS	0.2%	1.5%	1.0%	1.0%	29.0%	15.5%	15.6%	7.2%
MC	30.9%	31.7%	70.9%	74.7%	10.7%	3.1%	25.9%	20.9%
MP	4.1%	3.7%	9.0%	12.5%	1.2%	0.4%	9.5%	1.9%

From the Table 3-1, it is possible to see the relationship between hot and cold emissions. This comparison is very interesting, because it allows to observe the relevance of cold start transient, as the low temperature reached in this condition promotes incomplete combustion phenomena, with an increase on the correlated pollutants, namely carbon monoxide and unburnt hydrocarbons. Instead, carbon dioxide (or in other words, fuel consumption) and nitrogen oxides are not too much affected by cold start.

3.2. Simulated Scenarios

2030 ERTE, IEA AMF, BCG Analysis Simulated Scenario:

The forecasted 2030 fleet is divided into three scenarios ERTE, IEA AMF and BCG Analysis as follows:

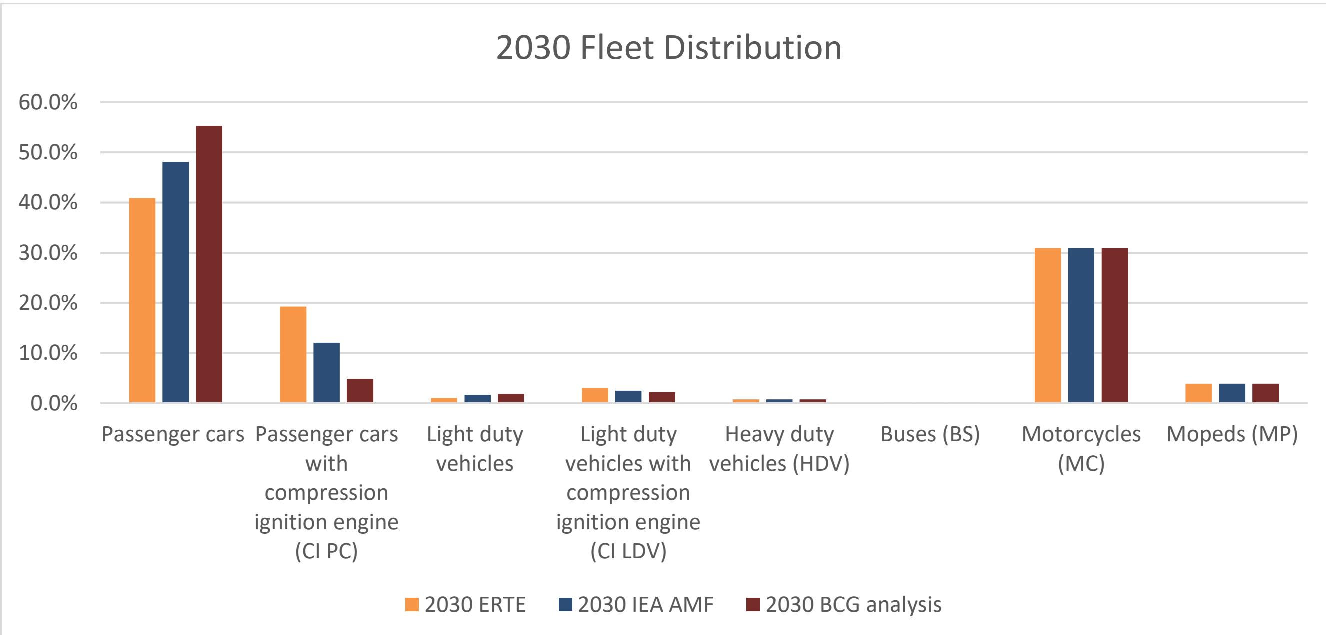


Figure 3-9: 2030 fleet distribution

The distribution between the different vehicle categories is similar to the one of 2019, however some slight differences are present: for passenger cars, CI PC have decreased their share, while SI PC had the opposite trend, mopeds reduced their quota, while motorcycles increased it and the other categories maintained a constant share.

These vehicles, even if reduced in number, reported an increased collective driving mileage, passing from $1.59 \cdot 10^9$ km to $1.70 \cdot 10^9$ km with an increase of 6.8% on total travelled distance by all circulating vehicles, even if their total number is increased by a 4.1%. This increasing trend of travelled kilometres can be explained considering that the transition from a simulation to another is linked to a fleet renewal; indeed, in the ten years that separate the two simulations, older vehicles were scrapped in favour of newer ones. This fleet renewal has consequences on driving mileages, because usually an old vehicle is maintained only when the owner needs to realize short transfers, while when longer transfers are regularly needed, the older vehicle is often upgraded to a newer one. This habit is reflected in average yearly driving mileage, which is progressively increased (see Appendix B at page 94). Again, this increase is in line with the trend for years 2010, 2013, 2016 and 2019 obtained in another study.

Figure 3-10 shows the mileage distribution between the different categories, which is very similar in shares to the fleet composition of Figure 3-9. It is similar also to the mileage distribution observed for 2019 simulation in Figure 3-2.

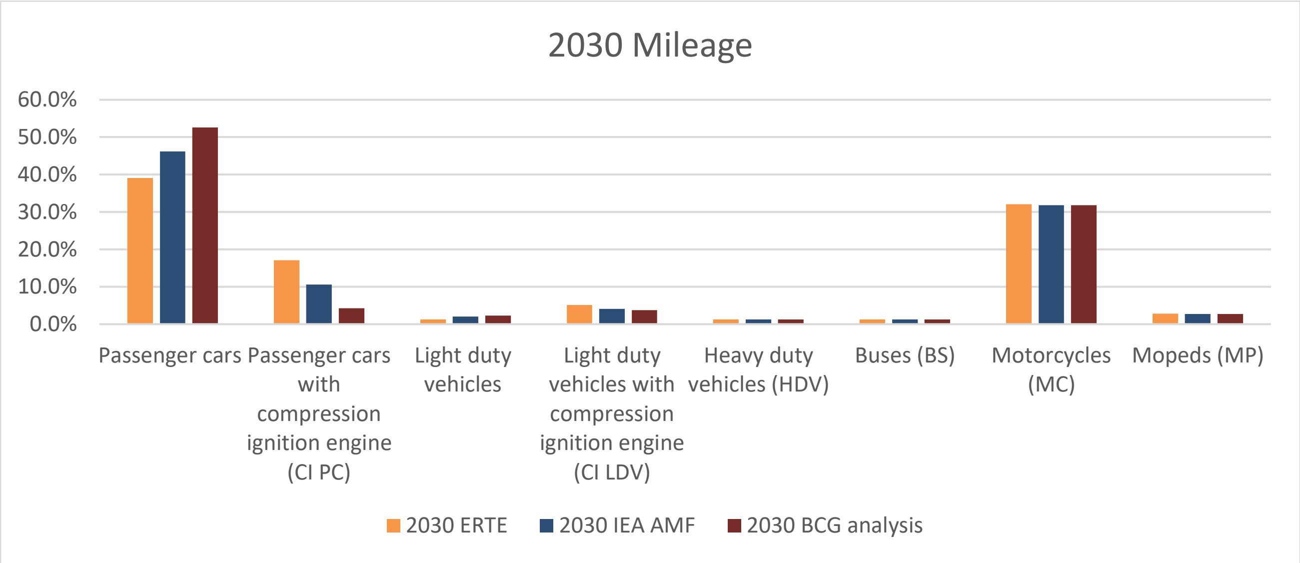


Figure 3-10: 2030 mileage distribution

As for previous simulation, the distributions of CO, HC, NO_x, NO_2, PM and CO_2 will be analysed. It is interesting to start directly from total emissions, evaluating the variation from 2019 data. The overall emitted pollutants in the year 2030 are the following:

Table 3-3: 2030 fleet total direct emissions

	CO	HC	NO_x	NO_2	PM	CO_2
Total 2030 ERTE emissions	1.7E+09 g	2.2E+08 g	1.3E+08 g	2.6E+08 g	3.4E+07 g	2.6E+11 g
Hot emissions share	64.9%	43.5%	88.8%	100.0%	100.0%	95.0%
Cold emissions share	35.1%	56.5%	11.2%	0.0%	0.0%	5.0%
Total 2030 IEA AMF emissions	1.713E+09	2.244E+08	1.366E+08	2.641E+07	3.405E+06	2.619E+11
Hot emission share	64.9%	43.5%	88.8%	100%	100%	95.0%
Cold emission share	35.1%	56.5%	11.2%	0.0%	0.0%	5.0%
Total 2030 BCG Analysis	1.864E+09	2.401E+08	1.270E+08	1.952E+07	3.715E+06	3.217E+11
Hot emission share	62.6%	41.3%	86.0%	100.0%	100.0%	95.7%
Cold emission share	37.4%	58.7%	14.0%	0.0%	0.0%	4.3%

Table 3-4: 2030 fleet total in-direct emissions

	CO	HC	NO_x	NO_2	PM	CO_2
Total 2030 ERTE emissions	4.639E+06 g	1.569E+06 g	5.423E+06 g	5.423E+05 g	1.189E+05 g	1.485E+10 g
Percentage	0.264%	0.682%	3.483%	1.570%	3.224%	4.938%
Total 2030 IEA AMF emissions	6.600E+06	2.233E+06	7.717E+06	7.717E+05	1.690E+05	2.114E+10
Percentage	0.384%	0.985%	5.348%	2.839%	4.728%	7.468%
Total 2030 BCG Analysis	2.568E+06	8.684E+05	3.002E+06	3.002E+05	6.592E+04	8.223E+09
Percentage	0.138%	0.360%	2.309%	1.514%	1.743%	2.493%

Table 3-5: 2030 Total Fleet (Direct + Indirect) Emissions

2030 Total (Direct+Indirect) emissions	CO(g)	HC(g)	No_x (g)	NO_2(g)	PM(g)	CO_2(g)
2030 ERTE emissions	1.756E+09 g	2.301E+08 g	1.557E+08 g	3.453E+07 g	3.686E+06 g	3.008E+11 g
2030 IEA AMF emissions	1.720E+09	2.267E+08	1.443E+08	2.718E+07	3.574E+06	2.830E+11
2030 BCG Analysis	1.867E+09	2.410E+08	1.300E+08	1.982E+07	3.781E+06	3.299E+11

Table 3-6: 2030 Total Fleet (Direct + Indirect) Emissions with reference to 2019 scenario

2030 Scenario with reference to 2019 Ratio	CO	HC	No_x	NO_2	PM	CO_2
2019 Scenario	5.232E+09 g	1.058E+08 g	6.177E+08 g	1.361E+08 g	2.270E+07 g	3.259E+11 g
2030 ERTE Scenario/2019	0.336	0.218	0.252	0.254	0.162	0.923
2030 IEA AMF Scenario/2019	0.329	0.214	0.234	0.200	0.157	0.868
2030 BCG Analysis/2019	0.357	0.228	0.210	0.146	0.167	1.012

These are the total (direct + indirect) emission ratios obtained with the reference scenario of 2019. For the scenario of 2030 ERTE with reference to 2019 scenario the ratio's obtained for CO is 0.336 and for hydrocarbons the ratio is 0.218. When it comes to the nitrogen emissions of NOX and NO2 the ratios are 0.252 and 0.254, for PM the ratio obtained with reference to 2019 scenario is 0.162 and for carbon dioxide 0.923. Similarly, for the scenarios of 2030 IEA AMF and BCG Analysis the ratio's will be obtained with reference to the 2019 scenario. As you can see the table 3-5 ratios for 2030 IEA AMF scenario for CO, HC, NOX, NO2, PM and CO2 are 0.329,0.214,0.234,0.200,0.157 and 0.868. Same for 2030 BCG Analysis the ratio's obtained with reference to 2019 scenario are 0.357, 0.228, 0.210, 0.146, 0.167 and 1.012.

Comparision of 2030 ERTE, 2030 IEA AMF and 2030 BCG Analysis with the reference scenario 2019:

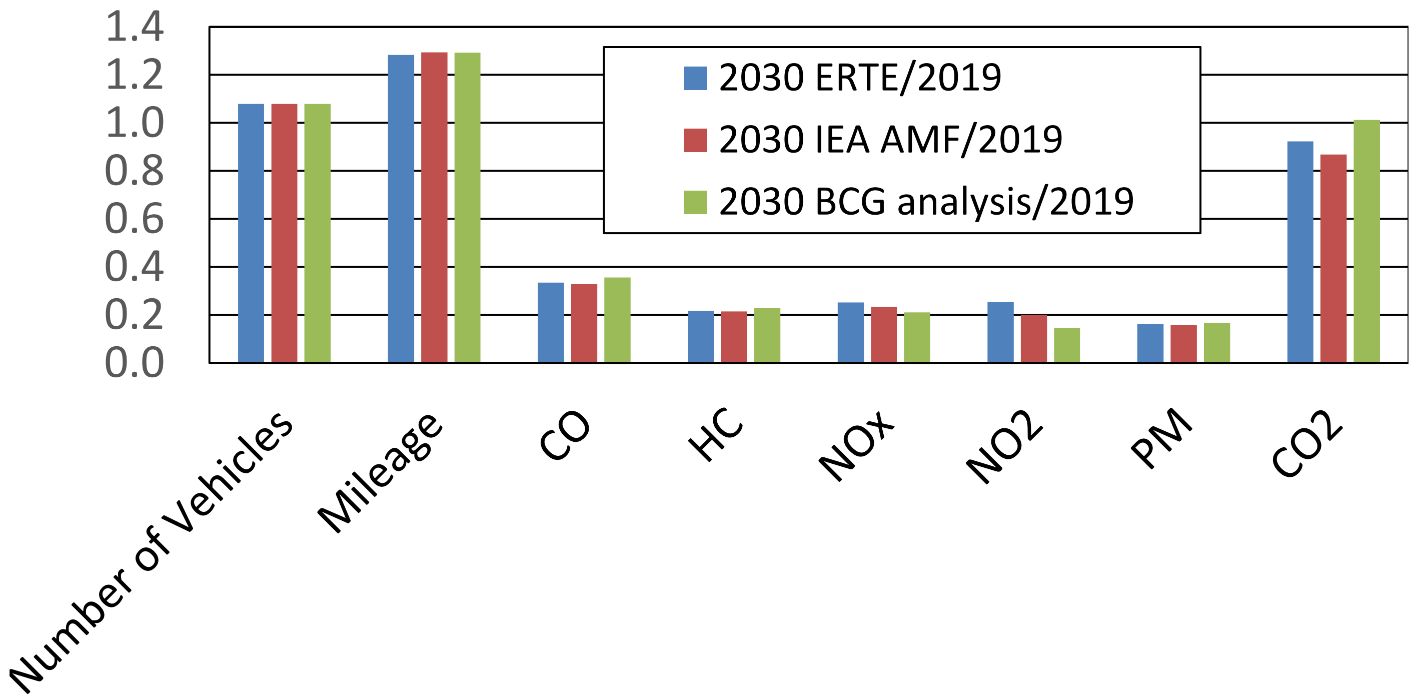


Figure 3-11: comparison of 2030 scenarios with reference scenario 2019

In the above figure represents the comparison of 2030 scenarios of 2030 ERTE, 2030 IEA AMF and 2030 BCG Analysis with the reference scenario of 2019. All the chemical pollutants are reduced (CO, HC, NO_X, NO_2, PM). Reduction of CO2 are also observed but with a lower benefit if compared to the other pollutants.

CHAPTER 4: CONCLUSIONS

In the previous pages, legislative scenario and emission control issues was presented in Chapter 1, PROGRESS model was introduced and explained in Chapter 2 and finally the analysis of Italy vehicular fleet characteristics and emissions was performed and presented in details in Chapter 3. The results of this analysis are promising, as PROGRESS model has shown that the continued improvements on vehicular emission control has a significant impact on the air quality inside urban areas.

The total pollution released from road transport sector was calculated thanks to PROGRESS, both for present (2019) and for future forecasted (2030) scenarios. From this analysis descends that manufacturer efforts in the struggle against pollutants emissions are rewarded by a decrease of chemical pollution, that in four years reached notable improvements, for example -13.2% of NOx and -29.3% of PM. However, this reduction came with some drawbacks, as post-treatment devices and engine emission control strategies became so complex and expensive, approaching the technological limits of these components. For this reason, these techniques are not sufficient, as an example most of car manufacturers are planning to cease the production of diesel passenger cars in next years, because they are too polluting to comply with future Euro regulations for what regards NOx and PM. For this reason, in order to comply with the future legislations for chemical pollutants and for carbon dioxide, the only possible way seem to be the adoption of hybrid, electric vehicles and fuel cell vehicles.

The analysis made through PROGRESS allowed also to validate the potentialities of hybrid, electric and fuel cell passenger cars, showing how much they are promising and less polluting than

their gasoline and diesel counterparts, being so the key to reach the compliance with both Euro legislations and future CO_2 limits. However, hybrid and electric are two technologies still in development, characterized by some drawbacks respect their gasoline and diesel counterparts. Furthermore, in the market only integrations on passenger cars are currently available on a large scale, while other vehicle categories are running late, and only two- wheelers and buses are starting to be equipped with electric powertrains. Anyway, they are still considered like exceptions to their conventional counterparts, and not like real alternatives to internal combustion engines.

So, hybrid and electric powertrains must be sustained with further investments, which have to be extended also in the other vehicle categories, in order to obtain global adoption of this technology throughout all the vehicular fleet, reducing drastically environmental pollution, achieving a better air quality, especially inside the urban areas. So, further efforts from vehicle manufacturers are necessary, to fight worldwide pollution and to reduce health problems of the population.

As final remark, hybrid and electric vehicles are the milestone in the conflict against urban areas environmental pollution, but this change must come not only from the sector of public and private mobility. Extended efforts also in energy production and residential heating are required, as they are, alongside with road mobility sector, some of the most pollutant activities in urban areas. Therefore, a global environmental benefit can be obtained only acting simultaneously in more directions.

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