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Considerations on CO_2 and Pollutants Emissions of Modern Cars

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Abstract. The European Union is pursuing the path of the decarbonization, with a stronger commitment than other countries, involving all the energy sectors. This paper is focused on the transportation sector. From a bibliography review, several solutions are proposed by the automotive manufacturers to meet the limits of emissions. Besides the Electric and Plug-in Hybrid Vehicles, the Internal Combustion Engines are obtaining positive improvements. Based on these considerations, the effect of the modernization of the Italian fleet of passengers cars is here proposed and assessed.

INTRODUCTION

In the last decades, to contrast the greenhouse effect, the politicians of the European Union (EU) have undertaken the way of the decarbonization for the member states, by stating ambitious targets. In 2014 the European Council introduced three binding targets (1). By 2030 a 40% reduction of greenhouse gas (GHG) emissions compared to 1990 is foreseen, as well as a 27% share of renewable energy sources (RES) and an increase of the energy efficiency of 27% with respect the Business-as-Usual (BAU) energy demand. In 2016 a legislative proposal, "Clean Energy for all Europeans"(2), was presented and adopted in November 2018 with the 32% binding EU target for RES by 2030 instead of the 27%.

To achieve these ambitious targets, all energy sectors are involved. This paper focuses on the transport sector. Based on a bibliographic review, the current situation of the automotive sector is presented and a possible guideline is proposed, considering that, in addition to greenhouse gas emissions, the transport sector is regulated by increasingly stringent pollutant emission limits and by new types of approval procedures. In particular, the Italian fleet is analyzed by considering its use according to the age of the vehicles.

This paper is organized as follows: (i) Europe's impact on global GHG emissions, starting from an overview of the global GHG emissions and energy requirement, focusing on the transportation sector; (ii) Actions in the road transportation sector; (iii) Impact of emissions from recent passengers cars, considering the evolution of the approval legislation; (iv) Possible solutions to control emissions, for CO_2 emissions with literature approaches, for NOx and PM by presenting an assessment for a possible scenario.

EUROPE'S IMPACT ON GLOBAL GHG EMISSIONS

The CO_2 emissions represent about 65% of the GHG emissions in the world (3). The CO_2 emissions of the EU-28 correspond to 10.4% of the world CO_2 emissions. In EU-28, the main contribution is given by the energy industry sector. All contributions for both the GHG and CO_2 emissions are reported in FIGURE 1.

The evolution from 1995 to 2016 of the energy consumption of the EU-28 is reported in FIGURE 2. It can be noted that the main changes are related to the consumption of solid fuels and renewables. *Renewables* and *gases* are the two sources showing a significant increase in share.

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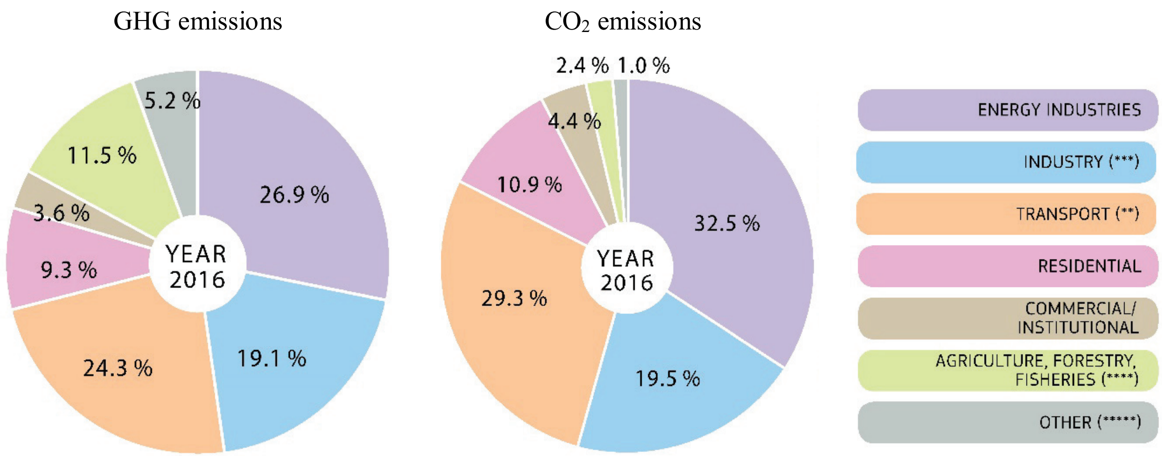

FIGURE 1. GHG (on the left) and CO_2 (on the right) emissions by sector in EU-28 (4)

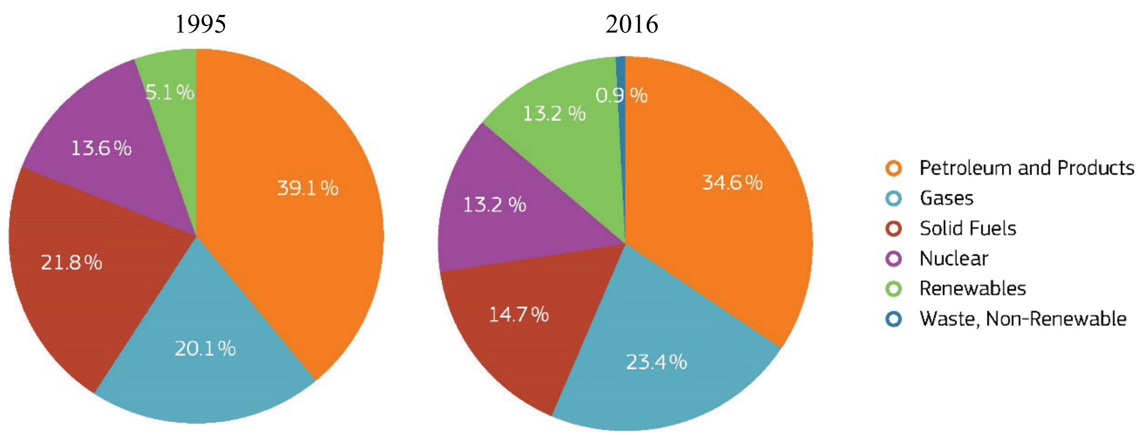

FIGURE 2. EU-28 energy consumption: on the left the energy mix related to 1995 for a total of 1678.8 Mtoe; on the right the energy mix related to 2016 for a total of 1639.0 Mtoe (5)

Focusing on the contribution of the transport sector on GHG emissions, FIGURE 3 shows a continuous increase. In particular, civil aviation shows the highest increase, while the only decreasing one is railway, but it did not consider the emissions related to electricity production. The major contribution is given by road transportation.

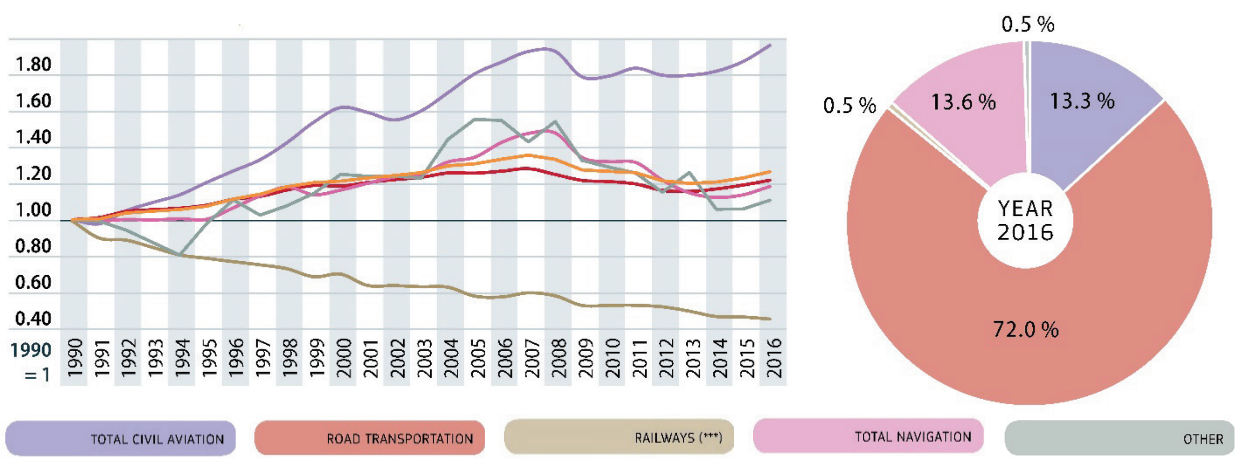

FIGURE 3. GHG emissions from transport EU-28 by mode: on the left the trend normalized to 1990 and on the right the shares (%) of the transport mode (4)

Analyzing in depth the road transportation mode (FIGURE 4), it can be observed that the largest contribution comes from cars. In this case, GHG emissions and CO_2 emissions are practically the same, because the main source of GHG gas is the CO_2 obtained by the combustion of fossil fuel. From shares reported in FIGURE 4, it can be computed that the European cars contribute for about 0.9% of the global GHG emissions. Nevertheless, the targets of the EU are the most ambitious in the world. In the report of the ICCT, the target of the EU have been compared with the others in FIGURE 5. The European Commission stated (6), that, from 2021, the EU fleet average emission target for new cars will be 95 g CO_2/km. This emission level corresponds to a fuel consumption of around 4.1 l/100 km of gasoline or 3.6 l/100 km of diesel. The target of 130 g/km was phased in between 2012 and 2015. A phase-in period will also apply to the target of 95 g/km. In 2020, the emission targets will apply for each manufacturer's 95% least emitting new cars from 2021 to the full fleet.

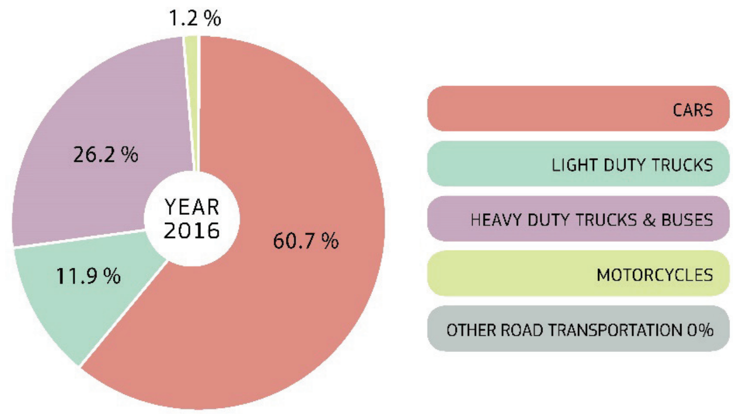

FIGURE 4. Share (%) of road transport emissions of the EU-28 (4)

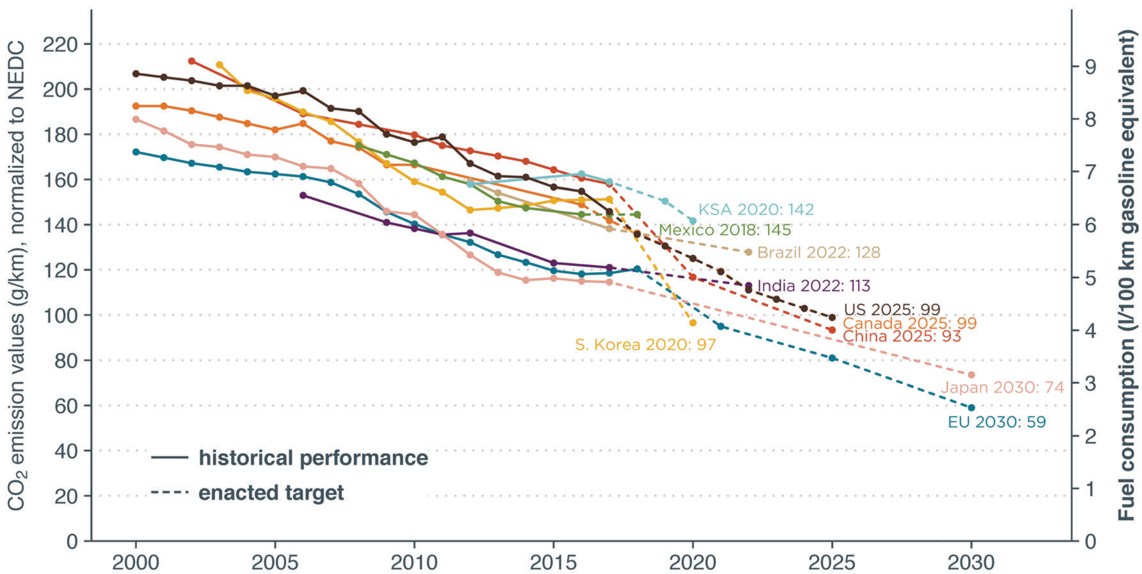

FIGURE 5. The target set in the world for CO_2 emissions and fuel consumption for passenger car, normalized to NEDC (7)

The European Parliament and the Council on 17 April 2019 set CO_2 emission performance standards for new passenger cars. From 2025 the average emissions are reduced by 15 % of the target in 2021. From 2030 the average emission is reduced the 37.5% of the target in 2021 (8).

ACTIONS IN ROAD TRANSPORT SECTOR

The European target to reduce 60% of the GHG emission from the transport sector has been presented in 2011 (9). The 2016 European Strategy for Low Emission Mobility proposes actions concerning technology neutrality (10). To reduce emissions, the automotive industry has undertaken several strategies, such as: downsizing of turbocharged engines, stop/start systems, hybrid solutions, engines with high geometric compression ratio and with Atkinson cycle (11–14). For instance, in June 2019 a Spark Plug Controlled Compression Ignition (SPCCI) technology was introduced, the world's first commercial gasoline engine with compression ignition, obtaining 132 kW (180 HP) and 96 gCO_2/km (15,16). Another approach to controlling emissions is the adoption of lightweight strategies (17). For the heavy-duty applications, other options are additionally considered, like the Waste Heat Recovery technologies, the Thermo-Electric Generator (TEG), the Organic Rankine Cycle (ORC) and Electric Turbo-Compound (ETC), that could be extended to light-duty application and passengers cars, obtaining CO2 saving of around 4% (18).

Electric vehicles (EVs) are recently proposed by many automotive companies. Even considering GHG emissions due to electricity production and to manufacturing processes, studies have indicated that EVs can reduce CO_2 emissions (19,20). The assessment of the cost-effectiveness of EVs in the European Union Member States until 2050 is proposed in (21): the work concludes that EVs will start to be cost-effective by 2030, but only if their costs drop 30% below the value currently expected.

An alternative with a high level of electrification is the Plug-in hybrid electric vehicles (PHEVs) that can assure a certain range capacity with a lower amount of batteries than pure EVs. A recent study deeply analyzes PHEVs (22). The study shows that PHEVs recharged from renewable electricity can noteworthily reduce well-to-wheel CO_2 emissions of passenger cars, but electric ranges should not exceed 200 to 300 km since battery production is CO_2-intensive. Based on the PHEV fleet simulation, the authors calculate the annual well-to-wheel CO_2 savings over a vehicle lifetime of 12 years, with recharging by different electricity generation modes, compared to a 130 gCO_2/km conventional vehicle. The results show that only charging electricity from renewable energy generation (2 gCO_2/km), natural gas power plants (99 gCO_2/km), and the current German mix (117 gCO_2/km) real savings can be achieved. In all other cases, the energy-intense battery production and the CO_2 content of the electricity assumed for recharging lead to higher well-to-wheel emissions than for a conventional vehicle. The studies compare the energy mix of other regions. In particular, the CO_2 emission factors of France, Sweden, and Norway are close to renewable generation (10 gCO_2/kWh), the average U.S. electricity generation is slightly above the German mix (585 gCO_2/kWh), and China's electricity generation shows specific CO_2 emissions comparable to hard coal (835 gCO_2/kWh).

EVs have also been evaluated for heavy-duty road transport (23) and it results that, in this sector, the pure battery electric trucks seem unable to fulfill user requirements in long-distance road freight due to limited range and long recharging times. Pure battery electric trucks or plug-in hybrid diesel trucks could be used in city and distribution logistics. GHG can be reduced along the highway with the electric trucks powered by overhead lines, so-called trolley trucks or catenary hybrid trucks. Authors report that, from the perspective of the energy system, trolley trucks constitute an additional and inflexible electricity demand. Moreover, all major European countries should invest billions of € in standardizing this option.

From the literature emerge some concerns about a massive diffusion of EVs. A wide diffusion of EVs will increase the need for electricity, and the generation and distribution networks should be able to meet the requirements. A study, focused for Finland, highlights the necessity of the investments for the network (24) and concludes that EVs may cause significantly higher load changes and the load capacity can be exceeded.

The batteries for EVs and PHEVs contains rare earth elements. A recent study (25) reports some concerns about the demands for Neodymium, Dysprosium, Cerium, Praseodymium and Lantanium in China, in addition to Cobalt. The paper concludes that for the successful development of automotive electrification in China, related policies and plans regarding the supplies of different types and quantities of rare earth elements should be urgently established. Moreover, although the discovery and exploitation of mines of new rare earth element can be effective in providing a sufficient supply in the short term, the development of substitute materials and recovery technologies could address the demand for rare earth elements in the long term. These statements could impact for the rest of the world since the Chinese industry is the main producer of batteries.

The European Automobile Manufacturers Association (ACEA), European Association of Automotive Suppliers (CLEPA) and IndustriAll release a document (26) in which declare that they are in favor of setting new and ambitious emission limits for the post-2021 period as a step towards achieving the EU's climate goals. The three organizations underline that the new standards should be economically and technologically achievable, and investment security for the industry has to be guaranteed. Since the decarbonization of road transport can be achieved with different pathways, technologies and solutions, technological neutrality is essential to underpin Europe's manufacturing leadership. The document reports a warning about the risks of imposing a binding mandate, especially as its achievement would depend on factors that are outside the control of the car sector, such as energy supply, charging infrastructure, consumer acceptance (related to range and affordability), public subsidies and access to raw materials.

IMPACT OF EMISSIONS FROM RECENT PASSENGERS CARS

Besides the GHG impact, cars have an impact on air quality. Passenger cars have been regulated by the European emission standards since 1992 with EURO 1, and they evolved to 2017 with EURO 6d-Temp. In 2014-2015 it was found that some vehicles from well-reputed carmakers do not respect the emission limit in real driving conditions (27,28). In particular, cars tested with Portable Emissions Measurement Systems (PEMS) did not respect the EURO 5 and EURO 6 NOx limits, contrarily to their previous approval. In 2016, the so-called Real-Driving Emissions (RDE) on-road test procedure with PEMS was introduced in the Euro 6 emission legislation. In 2017, the WLTC (Worldwide harmonized Light vehicles Test Cycle) replaced the NEDC (New European Driving Cycle) (29).

Recent studies and data are available on the emissions of modern cars. The outdated diesel cars are responsible for the high impact on the Particulate Matter (PM) and nitrogen oxides (NOx), especially in large cities. Eight European cities have been studied with a validated model for NO_2 concentration (30). It was found that a reduction in the on-road NOx emissions of Euro 6 diesel cars can decrease the regional and urban NO_2 concentrations and therefore the frequency of exceedances of the NO_2 air quality standard. High NO_2 fractions in the NOx emissions of diesel cars tend to increase the urban NO_2 concentrations only in the proximity of concentrated road traffic typically found on artery roads in large cities like Paris and London.

The evolution of energy consumption and emissions on the road transportation sector is proposed in (31). The study applies to Portugal for the period 2010–2050. It concludes that, due to a delay in the impact of technology improvements (slow fleet turnover), internal combustion engine (ICE) technologies determine the energy consumption and emissions results of short-term scenarios. Alternative technologies are more effective in producing results in the long-term. In a work of 2018 (32), the scenario for the next 15 years in Portugal reports that the transportation sector will continue to be dominated by fossil fuels.

A recent study (33) observed that cleaner vehicles complying with post-Euro 6 emissions standard are important at reducing pollutants (by up to −27%); this happens at the same time as the economy is improved by 0.5–1.1% and employment by 0.22%, i.e., tackling the issue of transportation is synergic with the economy.

Recent test results (34) show that real-world emissions are substantially reduced by successive levels of Euro 6. Since the level of cleanness of modern cars, the non-exhaust Particulate Matter (PM) emissions are the main responsible for PM emissions. A dedicated study reports that the total PM10 emissions and PM2.5 emissions are almost equal between the PM emission from EVs and from ICEVs (35).

Data of October 2018 (36) from tests of the approval authorities show that 270 diesel modern cars are below the RDE NOx threshold (168 mg/km) and that the vast majority of them are below the RDE NOx threshold in force from January 2020 (80 mg/km) as shown in FIGURE 6.

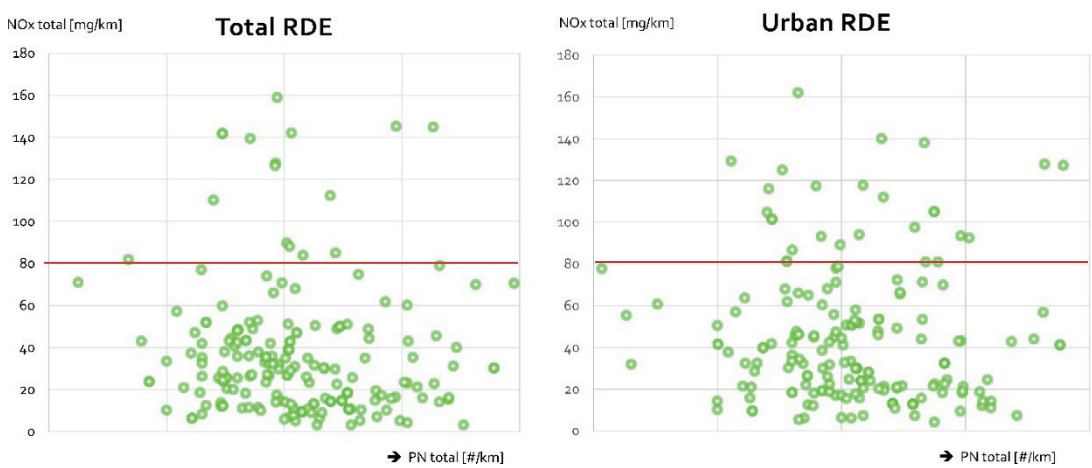

FIGURE 6. Latest approval test results for 270 RDE-compliant diesel vehicle types (36). *Below the red line all the tested cars that respect the future limits.*

POSSIBLE SOLUTIONS TO CONTROL PASSENGERS CARS EMISSIONS

From the literature, it appears that the ICEVs will circulate in the next decades (37), and they could not be close to their abandon. Due to this consideration, some options are proposed below, not excluding the ICEVs in controlling the CO_2 emissions. In particular, for CO_2, solutions available in the literature are reported. For the other two pollutants that deserve more attention, NOx and PM, the author proposes an analysis focused on Italy.

CO_2 Emissions

The CO_2 emissions from ICEVs are determined by fuel consumption, and it is strictly dependent on the energy efficiency of the engine. However, improving energy efficiency could be not sufficient for the CO_2 saving effect since the weight plays a significant role. In the last decades, the choice of customers has brought to an increase of the size of cars sold in Europe. As reported in (38), biofuels will remain the most important alternative to fossil fuels until 2030. Concerning alternative powertrains, the potentials for market penetration and CO_2 reduction of battery electric vehicles and fuel cell vehicles up to 2030 are very limited (1%).

In a work dedicated to the study of the reduction of the CO_2 emissions from cars in the European Union (39), results suggest that bringing transportation under the EU Emission Trading Scheme (ETS) should be considered as an alternative to the CO_2 standard limits. The advantage of an emissions trading system is that it searches out the cheapest way to reduce emissions. If it is more expensive to reduce emissions from cars, it can reduce emissions elsewhere. Efficient regulation of CO_2 emissions will improve the feasibility of far-reaching emission reduction goals in Europe. Even if the current EU ETS is mostly related to electricity and energy-intensive industries, it would be feasible to extend it to transportation fuels. Such an expansion could involve completely integrating the transport sector, or it could—at least temporarily—consist of a parallel trading scheme with a gateway as done for aviation. In order to incentivize abatement measures along the fuel chain while considering transaction costs, the most suitable choice of regulated entity for private transport would be the fuel providers. With emissions trading that covered transportation fuels, the currently targeted EU-wide emission reductions would be achieved at a lower cost, and in the long run, it would bring a growing sector under a fixed cap.

NOx and PM Emissions

The type-approval limits for passengers cars regulate the emissions of carbon monoxide (CO), the total hydrocarbon (THC), non-methane hydrocarbons (NMHC), nitrogen oxides (NOx) and particulate matter (PM). The latter two attract particular attention. They are mainly challenging for diesel cars, but as demonstrated by the data reported in FIGURE 6, these engines can respect the standard emissions.

In this section is proposed a possible impact with the limited cost for the final customers that could speed up the achievement of the improvement of the air quality.

Based on Italian data updated to 31 December 2018 (40), it is assessed the contribution of each emission class of vehicle to the total emission of the Italian car fleet. In Italy, there are more than 39 million passenger cars. In TABLE 1 are reported the type-approval limits for passengers cars from the Euro 0 to Euro 6 category. These values have been used in this work to determine the emissions for the various type-approval classes. The emissions of the passengers cars approved before 1993 (Euro 0) are considered to have the same standard emissions of the ones approved in the period 1993-1997 (Euro 1), even they could emit more than that standards.

TABLE 1 Type-approval limits for passengers cars for each category

From year	Type-approval	CO g/km		HC g/km		NOx g/km		PM g/km	
		Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel
	Euro 0	2.72	2.72	0.97			0.97*		0.14
1993	Euro 1	2.72	2.72	0.97			0.97*		0.14
1997	Euro 2	2.2	1	0.5			0.7*		0.08
2001	Euro 3	2.3	0.64	0.2	0.56	0.15	0.5		0.05
2006	Euro 4	1	0.5	0.1	0.3	0.08	0.25		0.025
2011	Euro 5	1	0.5	0.1	0.23	0.06	0.18	0.005	0.005
2015	Euro 6	1	0.5	0.1	0.17	0.06	0.08	0.005	0.005

*also includes HC

TABLE 2 shows the allowances for each emission class and their fuel supply. For simplicity, the cars with dual-fuel are grouped in the category with the fuel supply of the base engine (diesel or gasoline).

TABLE 2. Car fleet in Italy in 2018

Type-approval	Year of compulsory road registration	Allowances	Gasoline fuel supply %	Diesel fuel supply %	Usage factor
Euro 0		9.5%	84	16	0.5
Euro 1	1993	2.6%	82	18	0.5
Euro 2	1997	9.5%	76	24	0.5
Euro 3	2001	13.6%	48	52	0.5
Euro 4	2006	28.4%	54	46	0.5
Euro 5	2011	18.1%	43	57	0.75
Euro 6	2015	18.3%	47	53	1

It can be noted that the age of the Italian fleet is high and therefore, there are many cars on the road that comply with less stringent emission limits. To assess the emissions from each regulatory class, the specific type-approval limits have been considered in accordance with TABLE 1. In order to consider the effect of the age on the utilization of the cars, it is account for their average annual distance with the Usage factor reported in TABLE 2. This assumption is based on the observation that the less cars circulate, the more they manage to age, as indicated in (41). In practice, cars over 9 years old cover on average almost half the distance covered by those ones of a year. For range between 1 and 9 years has been introduced a Usage factor of 0.75. The results of the analysis are reported in FIGURE 7. They are obtained calculating the numbers of cars that belong to each type-approval category knowing their allowances. The amount emissions for each category is determined by the specific emission of each pollutant.

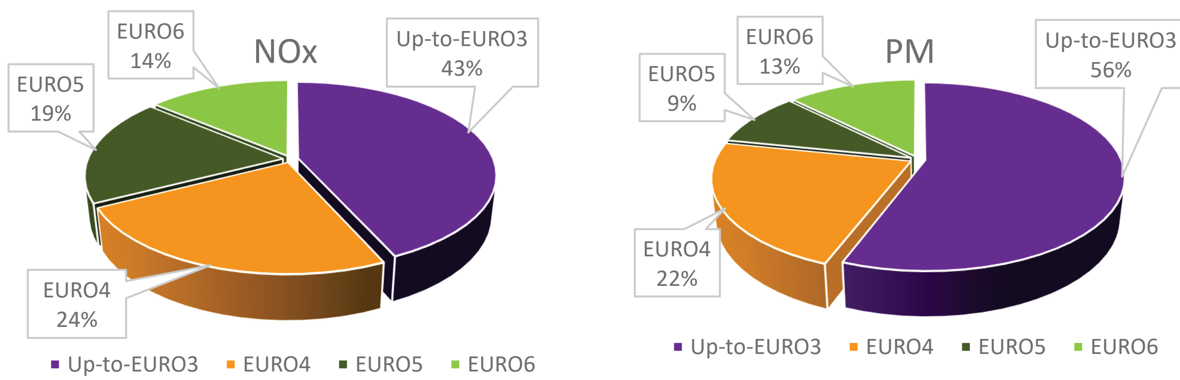

FIGURE 7. Share of emissions of NOx (on the left) and PM emissions (on the right) for each emission class of vehicle

The results show that the oldest cars are the ones with the highest environmental impact, even adopting a conservative approach that considers a lower annual mileage. By this consideration, it can be supposed that a modernization of the current Italian fleet can bring to positive effects. In order to evaluate the effect, it is supposed that for the future all the cars would be substituted with Euro6-cars maintaining the same usage factor. The results are reported in FIGURE 8.

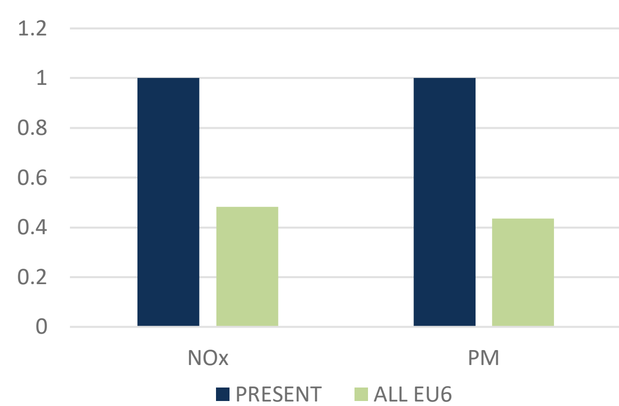

FIGURE 8. Emissions of the current Italian fleet (blue) and in case all cars would comply with Euro6 type-approval (green)

FIGURE 8 shows that the modernization of the circulating fleet can decrease the NOx of about 52% while the PM of 56%. Due to the new procedure for the approval with the RDE, these values are more reliable. Can be noted that the improvements could be even larger than ones presented since the old cars were type-approved without the RDE procedure. It can be worthy of note that the modernization of the fleet gives a positive contribution also to the CO_2 emissions. As reported in FIGURE 5 in 2016, the specific emissions were already under 120 g/km. Moreover, considering that automakers are constantly improving the efficiency of their engines, and that the currently sold fuel in Italy contains the 6.5% of biofuels and that in the next years it will contain the 10% of biofuel, this means that the CO_2 from fossil fuel is and will be even less.

CONCLUSIONS

The paper proposes a picture of the current state of emissions from passenger cars. Both CO_2 and pollutants (NOx, PM) have been considered. Based on a literature review, possible solutions are proposed. It can be summarized that:

- EVs are effective for urban application because, in this context, lower investment for infrastructures are required; the number of batteries needed for these applications is relatively moderate for the mileage required.
- In the calculation of the life cycle assessment, EVs and PHEVs are penalized in terms of emitted CO_2 due to the production of current-technology batteries: more batteries higher the emissions of CO_2.
- The EVs are not expected to have a large share of the market within a few years; their success is related to the investment for the infrastructures and the price of electricity might be an uncertainty for the consumers.
- ICEVs are constantly improving their efficiency, and biofuels can play an important role to limit the CO_2 emissions from fossil fuels, they could tackle the issue of transportation in synergy with the economy
- The European cars contribute to CO_2 emissions for less than 1% of the global GHG emissions. Bringing transportation under the EU Emission Trading Scheme (ETS) is an alternative to the CO_2 standards that is worth considering. If it is more expensive to reduce emissions from cars, emissions can be reduced elsewhere. With emissions trading covering transportation fuels, the currently targeted EU emission reductions would be achieved at a lower cost.
- Modernization of the Italian fleet of passenger cars, even considering the less usage in function of the age, can reduce the emissions of pollutants significantly and can give a positive contribution to CO_2 emissions.

Further investigations will be included in future works, like the role of public transport and other players in the transport sector, future technologies, a more accurate estimation of the Usage factor, and the effects on CO_2 emissions due to the decline in diesel car sales.

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