Electric car: a tool to reduce environmental impact. To purchase or to share it?

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Abstract

In this study an analysis of the electric family car's performances, its possibility of introduction into the automobile market and the evaluation of the economic suitability of electric car sharing have been carried out. Two options, car purchase and car sharing, have been compared using the operating cost per kilometre. The work forecasts the car fleet's trend from 2001 to 2020 for the city of Palermo analysing the known data from 1985 to 2000. The vehicle fleet's internal turnover has been simulated using a comprehensive model. This research has evaluated the environmental pollution's decrease determined by the introduction of electric cars in urban mobility. A simulation has been made to estimate the reduction of polluting emissions taking into account two different market penetration rate's scenarios (high and low).

1 Introduction

Road transport constitutes a major source of air pollution, and its share is expected to rise in the future because of the rising global demand for private mobility, if no policy to limit trasportation demand will be adopted (e.g. modal shift, alternative vehicles). It has been estimated that the cost for the Community due to disease caused by pollutant emissions (like respiratory or cardiovascular disease) is about 1.7% of GDP(Gross Domestic Product). The diffusion of electric vehicles could represent one of the possible strategies in order to reduce air pollution caused by road traffic in urban areas, thus realising a more sustainable mobility [1]. Electric car seems to be more suitable because its performances answer better to private transport's demand in urban areas where over 80% of urban trips are shorter than 50 km per day.

One of the main point of weakness of electric car is that its purchasing cost is still considered too high, and such vehicles, at a first sight, seems to be not

competitive. In another work has been demonstrated that, the electric vehicle's higher purchase price can be amortized within 9 years taking into account 10500 kilometres travelled per year for each vehicle (VKT) [2]. The average car fleet age's actual value for the urban area of Palermo is 9.5 years but the average VKT in the urban area is about 9240 [3].
To overcome this issue the study has compared the electric car sharing or purchase evaluating their economic suitability.
In the second part of the work it has been evaluated the environmental pollution's decrease determined by the introduction of electric cars in urban mobility (high and low scenario) using a comprehensive model.
The model has taken into account car fleet's growth rate, the replacement of old cars with new ones, the technology substitution and the scrappage rate.

2 Cost-benefit analysis of electric car sharing and purchase.

This analysis aims to compare, from an economic point of view, the individual use of an electric car owned or shared. Indeed, although the cost involved in buying and keeping a traditional car is widely known, the same cannot be said for electric cars that run on batteries, which are built according to specific functional, construction and legal requirements. Hence, an analysis of costs involved in the life cycle of vehicles is first and foremost a quality-oriented analysis, rather than a quantitative one, that is, it will be aimed at identifying the new kinds of fixed and variable costs which entails the individual use of these vehicles. In order to compare electric car sharing (ECS) versus electric car purchase (ECP), the study has taken into account their operating costs per year (OC).
To estimate the car sharing costs it has been considered the annual subscription rate to the car sharing club of 77.47 €, the hourly fare of 1.65 € and the fare per kilometre of 0.20 €. The total cost is dependent by a kilometric fare and by a hourly fare. So, it was necessary to determine the number of kilometres travelled per year for each vehicle and the average time spent to travel the kilometres considered. The average time was calculated taking into account data referred to the General Plan of Urban Traffic (PGTU) and considering the possibility of driving the electric car into the Limited Traffic Area and into the reserved lane [4]. The average speed obtained was 28 km/h. The OC per year for car sharing has been determined as follow:

$$OC_{CS} = FK \cdot VKT + HF \cdot \frac{VKT}{AS} + SR \,. \tag{1}$$

where: FK = fare per kilometre, VKT = kilometres travelled per year, HF = hourly fare, AS = average speed and SR = subscription rate.
The OC per year for a owned electric car has been obtained using the following equation:

$$OC_{CP} = \left\{ \frac{P - RV}{n \cdot VKT} + \frac{\left[(1+i)^n \cdot P\right] - P}{n \cdot VKT} + \frac{I + MVT}{VKT} + \frac{OM + EM}{VKT} + \frac{L \cdot C}{100} \right\} \cdot VKT \,. \tag{2}$$

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where: P = purchase price, RV = residual value, n = number of years gone by the purchase date, i = interest rate (2.5%), I = insurance cost, MVT = motor vehicle tax, OM = ordinary repairs, EM = extraordinary maintenance, L = € per KWh , C = consumption per 100 km and VKT = kilometres travelled per year.
The application was made considering an utility car used in the urban area and a devaluation rate for electric car equal to that of internal combustion car [2].
The purchase price, the insurance cost and the motor vehicle tax considered in the analysis are referred to the Fiat Seicento Elettra. Of course, the electric vehicle's purchase price includes the subsidies determined by the regulation in force. It was also considered a 50% reduction for civil liability's insurance cost and the absence of the motor vehicle tax for the first five years from the purchase like estabilished by the law in force.
According to the ECE urban cycle a vehicle runs for 9240 kilometres per year (35 km per day for 24 days per month for 11 months per year). As it's possible to see in fig. 1, if an electric car runs for 9240 km per year, the economic suitability of car sharing is obtained above the 13th year from the purchase.

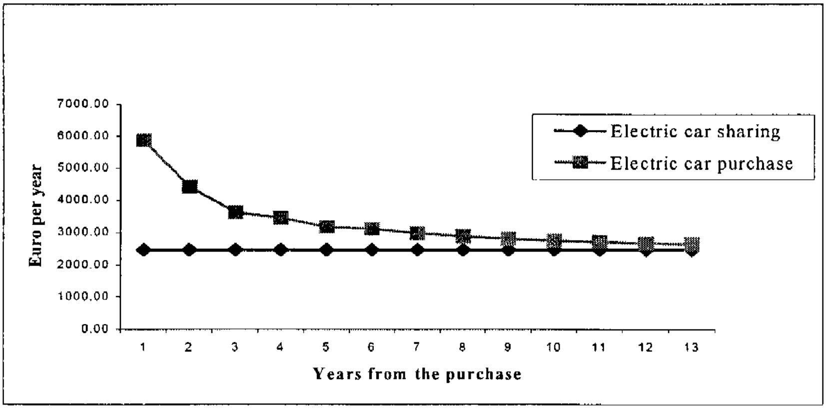

Fig. 1: OC related to 9240 VKT per year

The battery's average life related to the VKT per year has been calculated considering the car's range and the maximum and the minimum number of recharge cycles declared by the auto industry. The expected battery's average life is of 9 years considering 9240 VKT per year.
The electric car's life cycle is still undetermined, and it's really unrealistic to think that the battery could work after the 13th year. So, it's possible to affirm that with 9240 VKT per year car sharing is always cheaper than car ownership. It has been also compared the economic suitability of car sharing and car ownership considering a different number of VKT per year, different years spent from the purchase and the battery average life.
In fig. 2 could be noted the economic suitability of car ownership, after the 13th year from the purchase, is reached only if electric car runs for more than 10000 km per year.

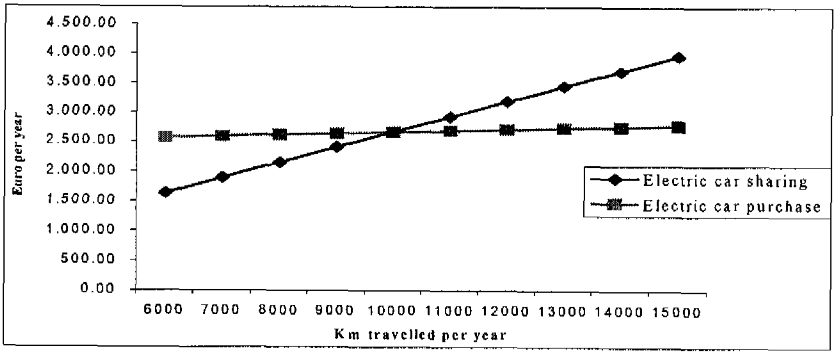

Fig. 2: OC at the 13th year from the purchase.

Fig. 3 shows how the cheapness of car sharing is obtained when the VKT per year are lower than 13000 km, with a car age of five years old.

It should be useful to remember that the average car fleet age is of 8.6 years in Italy, of 10 in Sicily and of 9.5 in Palermo [3], [5].

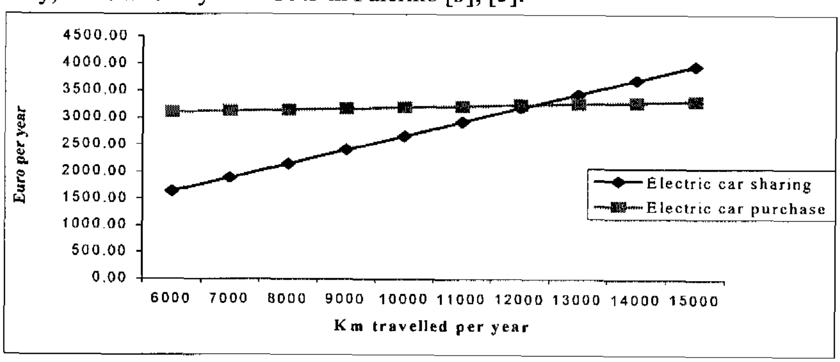

Fig. 3: OC at the 5th year from the purchase.

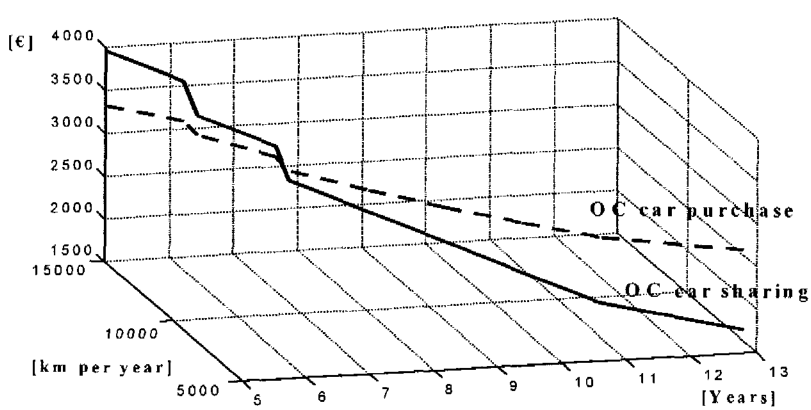

Fig. 4: Comparison between electric car sharing and purchase.

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Fig. 4 shows that the OC for car sharing and for car purchase vary according to the number of kilometres travelled per year. It should be noted the OC for car sharing is deeply decreasing when the VKT per year are reduced, instead the OC for car purchase is softly decreasing because it's also dependent from the residual value which is related to the years spent from the date of purchase.

3 Forecasting the emission's reduction.

The pollution's decrease determined by the introduction of electric cars in urban mobility is analysed by a model, in order to estimate car fleet trend and to forecast the air pollutant emissions. To estimate the car density (number of cars per citizen) it has been used a sigmoid function of time that better fits to the dynamic fleet evolution in different cases, such as: virgin car markets, booming car markets and saturated car markets [6]. The population forecast is necessary to obtain car fleet from the estimated car density. Thus, the population trend of Palermo was determined using the past data series since 1991 until 2000. This demographic projections were obtained by a linear regression with correlation coefficient $R^2 = 0.9614$.

The Gompertz's function used to estimate vehicle density is:

$$VD_i(t) = \frac{1}{e^{e^{M_i + b_i t}} + k_i}, \qquad k_i = -\ln(S_i). \tag{3}$$

where: $VD_i(t)$ is the vehicles density of type i (vehicles per 1000 population); t is the time in years (e. g. 0 for 1985, 35 for 2020); S_i is the saturation value: $S_i = \lim_{t \to \infty} VD_i(t)$; M_i, b_i are the parameters of the function. Coefficients M_i, and b_i are determined through a least squares error fitting procedure. The coefficient k_i represents the saturation value and it's calculated iteratively in order to achieve the best possible fit with historical data. The maximum value obtained for the correlation coefficient is $R^2 = 0.9433$ and the corresponding saturation value is S_i= 606 (cars/1000xpopulation). The car density forecast is shown in fig. 5, whose parameters are $M_i = -0.7511$, and $b_i = -0.1417$.

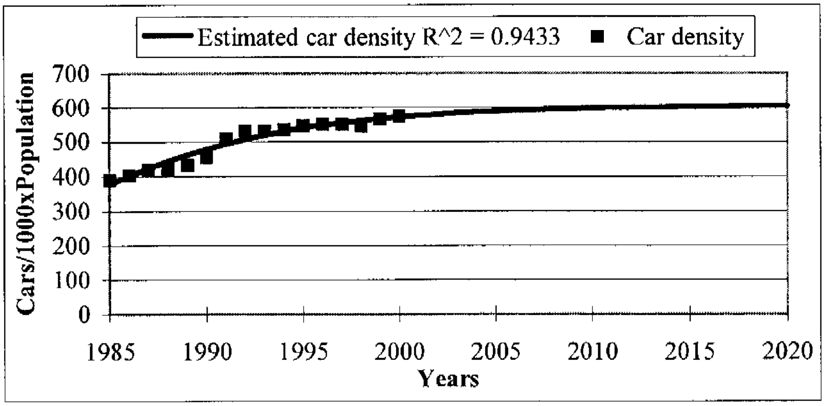

Fig. 5: Car Density Trend for Palermo

Once obtained the evolution of the car fleet (using the car density forecast and the demographic projections of Palermo), it's possible to determine its internal turnover, that is the rate at which old cars are scrapped and replaced by new ones. The estimate of internal turnover is really important, because new cars normally have emission standards stricter than the old ones, making use of new and cleaner technologies. In last years, the emission legislation in force for motor vehicle has become more strictly whether new or old cars. Thus, the replacement rate of car fleet affects directly pollutant emissions.
To calculate the car fleet's turnover for each year up to 2020, considering 1985 as the starting year, it has been used the following equation [6], [7]:

$$C_i(t) = C_i(t-1) - C_{si}(t) + C_{ri}(t) + C_{ei}(t). \qquad (4)$$

where: $C_i(t)$, $C_i(t-1)$ are the number of cars of type i, during years t and t – 1, respectively; $C_{si}(t)$ is the number of cars of type i, that were scrapped during year t; $C_{ri}(t)$ is the number of new cars of type i, that replaced old ones during year t; $C_{ei}(t)$ is the number of new cars of type i entering the market during year t without replacing old ones (causing market extension). The simulation of survival and scrappage rates is carried out with the aid of a modified two-parameter Weibul function with the following reliability function:

$$\varphi_i(k) = \exp - \left[\left(\frac{k + B_i}{T_i} \right)^{B_i} \right], \qquad \varphi_i(0) \equiv 1. \qquad (5)$$

where: k is the age of cars, expressed in years; $\varphi_I(k)$ is the presence probability of cars of type i having age k; B_i is failure rate for car of type i ($B_i > 1$, it increases with age); T_i is the characteristic service life for car type i. Last two parameters for Italian car market assume the following values: $B_i = 7$, and $T_i = 21$ [7]. To determine the number of cars scrapped for each year, the age distribution for the starting year (i.e., 2000) has been used as an initial condition:

$$CCi(0,k) = Ci(0) \cdot \Gamma_{0i}(k). \qquad (6)$$

where: $CC_i(0,k)$ is the number of cars of type i, and age k in the starting year; $C_i(0)$ is the total number of cars of type i in the starting year; $\Gamma_{0i}(k)$ is the fraction of cars of type i, and age k in the starting year.
For each consecutive year the number of scrapped cars of age k is:

$$CC_{si}(t,k) = CC_{si}(t-1,k-1) \cdot \left(1 - \frac{\varphi_i(k)}{\varphi_i(k-1)} \right). \qquad (7)$$

consequently the total number of scrapped cars in year t is:

$$C_{si}(t) = \sum_{k=1}^{T_i} CC_{si}(t,k) = \sum_{k=1}^{T_i} \left[CC_{si}(t-1,k-1) \cdot \left(\frac{\varphi_i(k)}{\varphi_i(k-1)} \right) \right]. \qquad (8)$$

where: $\varphi_i(k)$ and $\varphi_i(k-1)$ are the presence probability of cars of type i and age k and k-1, respectively. The number of new cars entering the market can be now calculated considering the two following cases:

$Ci(t) < Ci(t-1) \Rightarrow Cei(t) = 0$ and $Cri(t) = Ci(t) - [Ci(t-1) - Csi(t)]$,

$Ci(t) \geq Ci(t-1) \Rightarrow Cri(t) = Csi(t)$ and $Cei(t) = Ci(t) - Ci(t-1)$.

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This approach allows to determine the car fleet's distribution matrix for technology (Tab. 1).

Tab. 1. Distribution matrix for technology without Evs.

Year	Euro I	Euro II	Euro III	Euro IV	$C_s(t)$	$C_r(t)$	$C_e(t)$
2001	47.1%	15.9%	37.0%	0.0%	11.6%	11.6%	0.3%
2002	35.2%	15.4%	49.4%	0.0%	12.4%	12.4%	0.4%
2003	23.9%	14.9%	61.3%	0.0%	12.2%	12.2%	0.3%
2004	14.4%	14.0%	60.3%	11.3%	11.1%	11.1%	0.2%
2005	7.4%	13.0%	58.8%	20.8%	9.4%	9.4%	0.1%
2006	3.2%	11.6%	56.6%	28.6%	7.7%	7.7%	0.1%
2007	1.1%	9.9%	53.6%	35.4%	6.8%	6.8%	0.0%
2008	0.3%	8.0%	49.6%	42.2%	7.0%	7.0%	0.0%
2009	0.1%	6.0%	44.3%	49.6%	7.9%	7.8%	0.0%
2010	0.0%	4.1%	37.9%	58.0%	9.1%	9.0%	0.0%
2011	0.0%	2.5%	30.7%	66.9%	10.3%	10.2%	0.0%
2012	0.0%	1.3%	23.0%	75.7%	11.3%	11.2%	0.0%
2013	0.0%	0.6%	15.7%	83.8%	12.1%	11.9%	0.0%
2014	0.0%	0.2%	9.5%	90.3%	12.9%	12.8%	0.0%
2015	0.0%	0.0%	4.9%	95.0%	14.3%	14.1%	0.0%
2016	0.0%	0.0%	2.1%	97.9%	16.6%	16.4%	0.0%
2017	0.0%	0.0%	0.7%	99.3%	20.3%	20.1%	0.0%
2018	0.0%	0.0%	0.2%	99.8%	25.5%	25.3%	0.0%
2019	0.0%	0.0%	0.0%	100.0%	32.1%	31.9%	0.0%
2020	0.0%	0.0%	0.0%	100.0%	39.8%	39.5%	0.0%

The aim of the survey has been the estimate of the pollution reduction, obtained by two supposed substitution rate of heat engine car with electric ones equal to 10% and 20% from the year 2004, considering the technology evolution of internal combustion engine, before presented. The year 2004 has been considered the year in which the Euro IV technology is available. The analysis has taken into account car fleet's growth rate, the replacement of old cars with new ones, the technology substitution and the scrappage rate in order to envisage this two different electric car's market scenarios (high and low).

As can be noted in fig. 6 and 7 since 2019 the entire car fleet has been made up by cars with EURO IV technology and electric ones.

In the study the following pollutants have been analysed: hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO_x), sulphurous dioxide (SO_2), particulate matter (PM_{10}). Emission factors to estimate pollutant emission levels have been obtained taking into account mainly standard emission car's technologies that are already available. The emission factor levels for the internal combustion car are taken from the data base CORINAIR and from the emission model COPERT III [8], [9].

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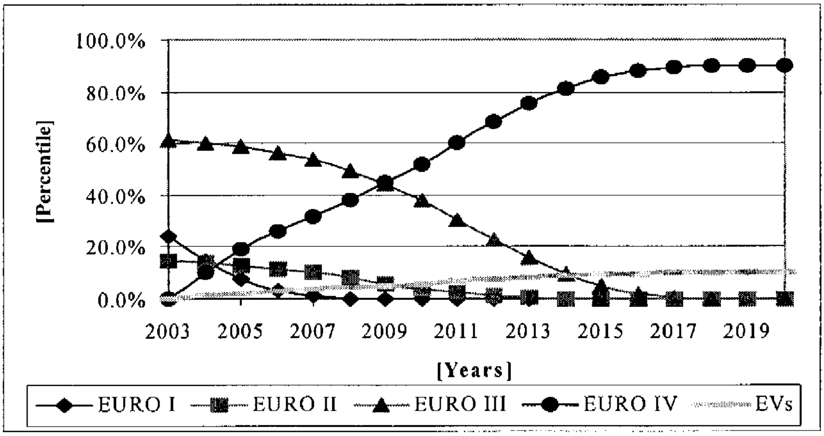

Fig. 6: Car fleet's evolution per technology - low scenario.

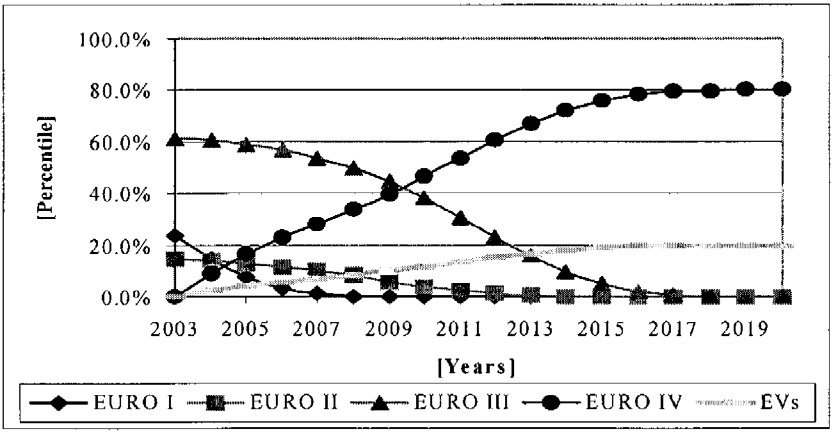

Fig. 7: Car fleet's evolution per technology - high scenario.

Once established emission levels for all the pollutant considered, a simulation has been carried on, where the car fleet has been divided according to the engine technology evolution; the trend has been determined considering the substitution rate; and finally the analysis has been built up imagining that the oldest technology will be replaced with a new one less pollutant. Data obtained have been used to estimate pollutant emission levels. This base case scenario has taken into account the car fleet's trend for the actual technology (without electric car) and 10000 kilometres travelled per year for each vehicle (see fig. 8).

In the base case scenario it should be noted a considerable decrease of nitrogen oxide (NO_x), hydrocarbons (HC) and carbon monoxide (CO) and particulate matter (PM_{10}) while carbon dioxide (CO_2) and sulphurous dioxide (SO_2) are softly decreasing. The reason of this general decrease is mainly dependent on the substitution of oldest cars with new ones less pollutant.

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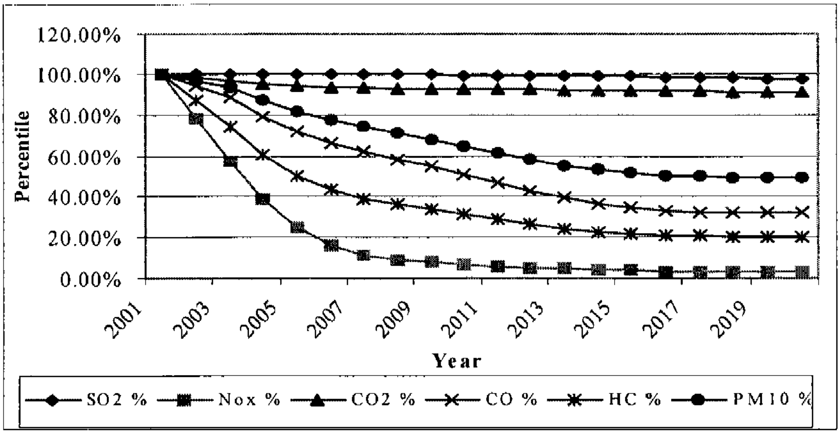

Fig. 8: Pollutant Emission's reduction - base case scenario

In table 2 the pollutant emission rate found for the year 2020 has been compared with that of 2004 for the base case, the low and the high scenarios. 2004 is the year in which we've envisaged the beginning of the market's penetration by electric car.

Tab. 2: Pollutant emission rate referred to base case scenario.

Year	SO_2	NO_x	CO_2	CO	HC	PM_{10}	Scenario
2004-20	-2.25%	-91.10%	-4.59%	-59.58%	-66.31%	-43.49%	Base
2004-20	-12.02%	-91.99%	-14.13%	-63.62%	-69.68%	-49.14%	Low
2004-20	-21.80%	-92.88%	-23.67%	-67.66%	-73.05%	-54.79%	High

The pollutant change emission rate values, expressed by percentage, were determined considering: the low scenario, with an electric vehicle's market penetration rate equal to 10% of new registered cars (fig. 6); the high scenario, with an electric vehicle's market penetration rate equal to 20% of new registered cars (fig. 7). The scenarios analysed are characterized by a decreasing rate of all pollutants (fig. 9). In particular, both in the low and the high scenarios it could be noted a relevant decreasement for SO_2 and CO_2. It should be underlined that the other pollutants are softly decreasing respect to the base case scenario because of the pollutant emissions' lowering allowed by the new technology Euro IV.

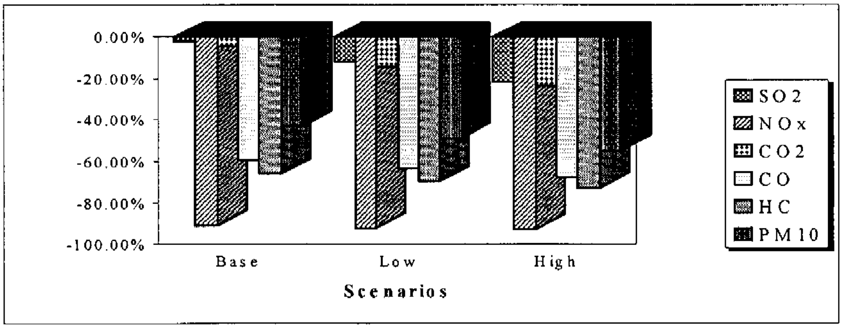

Fig. 9: Pollutant emission rate referred to base case scenario

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4 Conclusions

The cost benefit analysis has shown how the electric vehicle's purchase cost can't be amortized considering a VKT per year equal to 9240 km and it has highlighted the economic suitability of car sharing in urban areas. Thus, car sharing should be improved in order to allow *a door to door* service and to increase its demand and suitability.
The simulation model adopted has allowed to evaluate the environmental impact of electric car envisaging two different scenarios, taking into account the technology evolution and the car fleet trend for passengers.
The environmental policies in force concerning the pollutant emissions of internal combustion cars in the urban areas have yet reduced the environmental pollution. The study underlines how an urban transport policy based on car sharing should be addressed to reach a greater reduction of air pollution in cities.
Next purpose of this study will be to validate the scenarios proposed using data obtained by a SP analysis which will evaluate the car sharing demand, considering also the costs involved to assure a door to door service. Thus, car sharing should have similar characteristics of car ownership (availability, capacity, etc) and it should meet better consumer's requirements.
The simulation models presented have been made by software MATLAB^{R} and EXCEL.

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