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An evaluation of the hybrid car technology for the Mexico Mega City

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ABSTRACT

The introduction of hybrid electric vehicle (HEV) technology in the private car fleet of Mexico City is evaluated in terms of private costs, energy, public health and CO_2 emission benefits. In addition to constructing plausible scenarios for urban expansion, emission, car fleet, and fuel consumption for year 2026 and comparing them with a 2004 base case, a time series is built to obtain accumulated economic benefits. Experimental techniques were used to build a vehicle library for a car simulator that included a Prius 2002, chosen as the HEV technology representative for this work. The simulator is used to estimate the emissions and fuel consumption of the car fleet scenarios. In the context of an urban scenario for year 2026, a complex air quality model obtains the concentrations of criterion pollutants corresponding to these scenarios.

Using a technology penetration model, the hybridized fleet starts unfolding in year 2009 reaching to 20% in 2026. In this year, the hybridized fleet resulted in reductions of about 10% of CO_2 emissions, and yielded reductions in daytime mean concentrations of up to 7% in ozone and 3.4% in $PM_{2.5}$ compared to the 2004 base case. These reductions are concentrated in the densely populated areas of Mexico City. By building a time series of costs and benefits it is shown that, depending on fuel prices and using a 5% return rate, positive accumulated benefits (CO_2 benefits + energy benefits + public health benefits − private costs) will start generating in year 2015 reaching between 2.8 and 4.5 billion US Dlls in 2026. Another modernized private fleet consisting exclusively of Tier I and II cars did not yield appreciable results, signaling that a change in private car technology towards HEV's is needed to obtain significant accumulated benefits.

1. Introduction

According to official projections, Mexican oil exports are expected to cease in a decade [1]. Moreover, 80% of primary energy generation in Mexico is dependent on fossil fuels [1], and 30% of governmental income is based on revenues from the oil-industry monopoly Petróleos Mexicanos (PEMEX). This dependency on oil poses a direct challenge to the Mexican economy and its energy availability. Urgent energy savings programs, alternative energy generation and attractive policies to promote energy efficiency must be implemented to moderate an impending crisis.

Mexico already has an important automotive production and technological capabilities occupying the 10th place of cars output in the world [2]. At the same time the transport sector in Mexico consumes about 43% of energy [3], and the private car fleet is responsible for about 65% of transport fuel consumption in Mexico City [4]. These factors provide Mexico an important area of opportunity in energy and emissions savings in the transport sector by improving the automobile technology offered in the local market.

Several studies have been published evaluating and comparing the benefits of existing and future car technologies including the HEV's, Plug-in HEV's (PHEV's), and full electric. For example [5,6] use projected future scenarios for year 2030 and [7] for 2035, comparing energy and Green House Gas (GHG) emissions savings, whereas in [8] a portfolio of advanced cars including fuel-cell cars, and alternative fuels are used to project macroeconomic costs to 2030. Other studies like [9] show that Plug-in HEV's (PHEV) energy costs and GHG emissions could differ greatly depending on the energy supply system and the time of the day used for connection to replenish batteries. Costs and benefits of PHEV's, HEV's and conventional cars for years 2010 and 2030 are estimated for comparison.

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Our work is focused solely on comparing conventional cars used in Mexico City with established HEV technology, taking advantage of the experience and information already gathered in the American market. The comparison here is made in terms of operating fuel savings, private costs, CO_2 emissions, tailpipe emissions effect on air quality and its consequence on public health benefits. To get a better economical perspective, a time series is built depicting the evolution of the costs and benefits, determining when positive gains start to accumulate and their total amount reached in year 2026.

The use of a vehicle simulator such as ADVISOR [10] was favored over emission models such as MOBILE [11], MOVES [12], or IVE [13]. The reason was to better approximate the emissions and energy use of the Prius, our choice as the HEV technology representative. Its train power is shared by an electric motor and an internal combustion engine that is turned-on and off depending on the batteries' state of charge, current speed, requested torque and other parameters. Only a comprehensive vehicular simulator that includes all the elements and variables of a HEV power train, can account for these factors to obtain emissions and fuel consumption in traffic under varied urban conditions with high time and space resolution.

To obtain the emission factors, a Prius 2002 HEV and a sample fleet of cars without catalytic converter and Tier I and II vehicles in Mexico City were used. Three private car fleet scenarios were implemented: A base fleet for year 2004 (base-fleet), formed by 20% of cars without catalytic converter and 80% Tier I and II vehicles, and two future fleet scenarios projected to year 2026. One of these future fleet scenarios reaches 20% of Prius 2002 HEV's combined with Tier I and II car technologies (hybridized-fleet) in year 2026. The other fleet scenario contains only Tier I and II car technologies (non-hybridized fleet).

The emissions factors found for the car fleet scenarios are then used by an air quality model to obtain the corresponding geographical distribution of photochemical pollution over Mexico City. The main emission changes considered are HC's, NO_x and secondary $PM_{2.5}$ aerosol precursors. Two pollutants are used to compare the benefit on public health due to the emissions of the fleet scenarios: Ozone, whose surface concentrations reach values above the local norm (0.11 ppm for an hour a year) more than 58% of the days of the year [14], and secondary $PM_{2.5}$ aerosols. CO_2 emissions are used to estimate fuel savings and GHG benefits.

Due to the constant urban growth of Mexico City, the projections are placed in the context of a future urban scenario for year 2026. Air quality modeling estimated the portion of the population subject to the pollution reduction, thus increasing the accuracy of public health benefits. Across the board concentrations reductions were not used.

The base year for our study is 2004 and the results are projected to year 2026. According to a technology penetration model developed here, under certain conditions, this period allows time for an accumulation of 20% of HEV's in the Mexico City car fleet. In our scenario the HEV's start their introduction in 2009.

Although currently there are different types and brands of HEV's technologies in the market, our work is based on the Prius 2002. It uses a parallel-series power train specifically designed to optimize emissions [15]. The reasons for this selection as representative of HEV technology are threefold: First, in 2003 a Prius 2002 (then one of no more than 10 HEV's existing in Mexico City) provided by the National Institute of Ecology (INE) was used for on road and laboratory tests. Second, this car has similar although lower performance than the Prius 2004 model, the most popular HEV in the world. Finally, the Prius 2002 car was thoroughly simulated using ADVISOR and evaluated by National Renewable Energy Laboratories (NREL) [16]. This is a complicated task due to the complexities of the power train of the Prius 2002. The information provided by NREL played a key role in this evaluation. The Prius 2002 at our disposal used PEMEX-MAGNA gasoline sold in Mexico City. Thus, our measured emissions used for calibration are under real local operating conditions.

As mentioned, the Prius 2002 has a lower performance than the 2004 and 2009 models. For example, the Prius 2002 has a published gas consumption of 18 $km\,l^{-1}$ in highway and 21 $km\,l^{-1}$ in city while the Prius 2004 has 20.4 $km\,l^{-1}$ and 23.6 $km\,l^{-1}$ respectively [15]. Since both models have similar emission controls the better performance of the Prius 2004 has lower emissions than the 2002 model. This information, together with the fact that new hybrid technologies are under way such as the "two mode hybrids" [17], and the third generation Prius placed in the market in 2009 with even better gas mileage, renders our selection of the Prius 2002 as conservative.

A basic assumption to compare future scenarios is that traffic patterns will not vary with time. A projection of vehicular traffic to year 2026 would need a sophisticated traffic model that is currently out of our reach.

2. Methodology

The methodological framework of this research is shown in the flux-diagram of Fig. 1. It consists of two main stages: the first consists of processes modeling, designed to construct plausible technology penetration scenarios and vehicular simulations to obtain corresponding fleet emissions. This information, together with urban expansion data, is fed to an air quality model to obtain atmospheric concentration distribution variation of pollutants such as ozone and $PM_{2.5}$.

The second stage valuates the cumulative costs and benefits of the scenarios. It uses the geographical variations of the concentrations provided by the air quality model corresponding to each scenario to obtain exposure and health impact. Also, the calculated CO_2 emissions are used to estimate fuel and GHG benefits. A private cost is assessed using fleet size, composition, and differential costs of HEV's versus conventional cars based on the American market experience.

2.1. Technology penetration model for HEV's

Loosely based on GREET [18], a penetration model was built to estimate the year in which close to 20% of the total fleet could be conformed by HEV's in Mexico City. This model consists of three main components: first, the size of the private car fleet is estimated based on population growth for Mexico City. Secondly, a sales trend of HEV's based on the American market experience is established. Finally, the percentage of HEV's occupying the car fleet is calculated using the preceding steps with appropriate retirement rates.

To estimate the size of the private vehicle fleet for 2026 a simple bivariate Ordinary Least Square regression was used relating car ownership and population in Mexico City in this way. The natural log of the private vehicle fleet growth is strongly correlated to population growth ($R^2 = 0.91$, $F = 20.9$, $\sigma = 0.045$). The regression was estimated using four time periods between 1993 and 2007 shown in Table 1 obtaining the following model:

$$N = 350646\ \exp\{(1.07 \times 10^{-7})\,P\} \quad (1)$$

where N is the number of private cars and P the population. The corresponding motorization index for 2026 would be of 27% from the current (2010) of 18%. The growth rate of car fleet calculated this way falls near a medium scenario used to estimate energy growth of the transport sector in Mexico City [19].

We suppose that the hybrid car sales will start in Mexico City in year 2009. They will follow a similar but slower growth than the sales outlook for the American market considered in [20]; instead of 38% of HEV's sales for year 2030 we consider 34%.

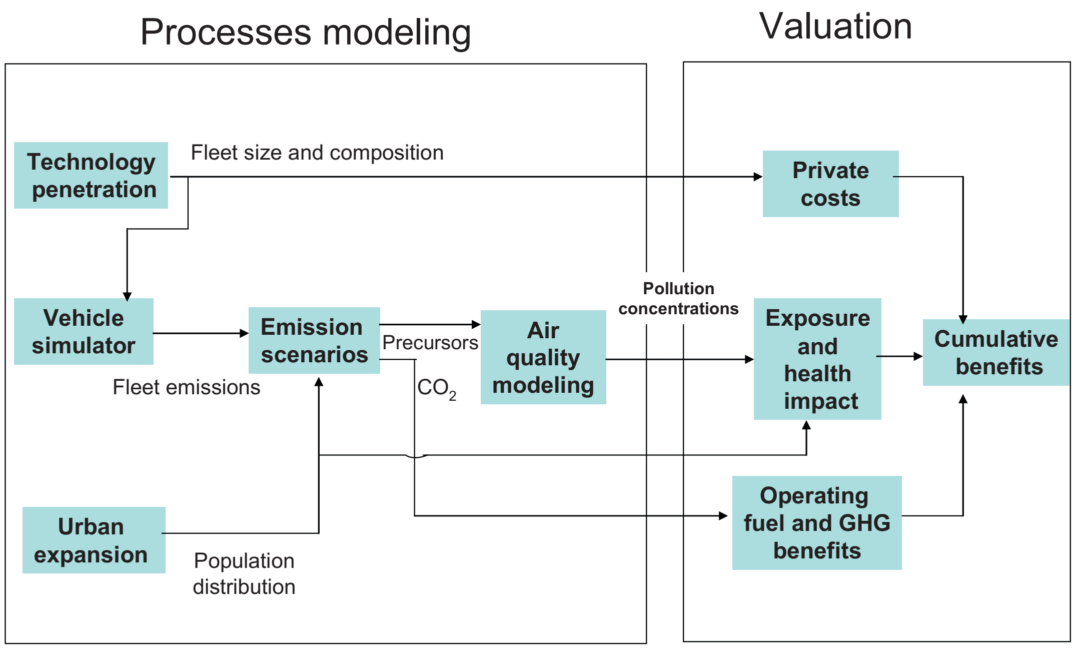

Fig. 1. Flux-diagram containing the stages and components of the proposed methodology.

To accomplish this, the following sales trend for HEV's was implemented:

$$s = -0.029y^2 + 2.29y - 1.036 \quad (2)$$

where s is thousands of cars sold and y is a year index starting with 1 for 2009. The trend in Eq. (2) is similar to the already registered in the US from year 1999 to 2008 [21]. This trend is challenging to follow, especially because of the different size of the markets. Nevertheless, the fact that this trend already took place shows that at least is feasible from the stand point of supply.

In our suppositions, for the first 10 years starting in 2009 a retirement rate of 2% a year for HEV's was considered, mainly because of accidents. After that, the HEV's reach a retirement rate of 5.8%, the same as the conventional fleet. Using Eq. (2), in year 2026 the penetration model shows that close to 20% of the total car fleet of HEV's could be achieved.

2.2. *Vehicular simulation*

In order to account for the complex power train of a HEV, the car simulator ADVISOR is used as described in [22,23]. All the fleet cars are synthesized in the simulator by building maps relating torque, RPM's and emissions and by specifying specific data of each car such as weight, aerodynamic drag coefficient, and type of transmission. These maps were obtained for each car using experimental techniques described in [23–25]. This procedure estimates the emissions of criteria gases such as NO_x, HC's, CO and CO_2 and other toxic gases like NH_3 with a temporal resolution of one second. It should be noted that vehicles in Mexico City account for 82% of NO_x, 34% of HC's, and 99% of CO emissions [14].

A basic statistical analysis comparing emission measurements on road and simulated emissions by ADVISOR of the car specimens can be found in [22,25], where it is also shown that, using the simulation process, emissions are obtained with high time and space resolution.

For the case of the hybrid car simulation we took advantage of the Toyota Prius 2002 simulation in ADVISOR obtained by NREL and experiments carried in the Engineering School of the Universidad Nacional Autónoma de México with this car model provided by INE. These experiments allowed measuring the emissions of a Prius 2002 using the local Pemex Magna gasoline, and adjust the performance of the simulated Prius 2002 in Advisor [24,25]. Overall the Prius 2002 simulated here has similar emissions than the one measured by NREL in Colorado, located in a comparable height as Mexico City.

The synthesized cars perform 14 residential, 22 arterial and 18 highway virtual driving cycles from 5:00 LST to 22:00 LST in ADVISOR. These cycles were obtained in Mexico City by [26]. The synthesized emissions for each fleet are calculated using a basic traffic model [24], and traffic activity also provided by [26]. From this information emission factors are obtained allowing the comparison between the three fleets.

Table 1
Vehicle fleet and population. Bold numbers indicate data from official sources. The other numbers are interpolated.

Year	Vehicles	Population
1993	**1,915,617**	15,901,808
1994	2,000,840	16,170,487
1995	2,086,063	**16,439,166**
1996	2,171,285	16,749,481
1997	2,256,508	17,059,797
1998	**2,341,731**	17,370,112
1999	2,359,199	17,680,428
2000	2,376,666	**17,990,743**
2001	2,394,134	18,170,435
2002	2,411,601	18,350,127
2003	2,429,069	18,529,819
2004	**2,446,536**	18,709,511
2005	2,587,921	**18,889,203**
2006	2,729,305	19,046,654
2007	**2,870,690**	**19,204,105**

2.3. *Urban expansion scenarios*

To put the results of this work in the context of Mexico City for year 2026, three future urban scenarios were obtained. As will be discussed, one of these urban scenarios is selected as the most plausible and used to obtain the emissions, pollution concentrations and public costs benefits. A complete description of this methodology is found in [27].

The urban expansion scenarios are obtained using a three-stage procedure:

First, a calibrated binary logistic regression model is used to predict observed urban expansion for the period from 1990 to 2000.The predictive variables used in the model include distance to main highways, job accessibility, socioeconomic characteristics of nearby urban areas, terrain slope and land use. The values for these independent variables correspond to year 1990. The calibrated model predicted observed urban expansion with 82% accuracy, and a Nagelkerke R2 of 0.43.

Secondly, coefficients of the calibrated model are used for a second regression using parameter values for year 2000 to obtain urban expansion probabilities for 2010 which are assumed to be similar for year 2026. This step also assumes that the individual effects of variables on urban expansion will remain constant in time.

Finally, forecasted population growth is assigned to new urban areas according to the urbanization probability estimated in stage two. Population is assigned according to three population density scenarios for each urban ring. Throughout the whole process the basic area unit used is the hectare.

The first urban expansion scenario (E1), assumes that population densities will remain constant. The second scenario (E2), assumes that densities will continue the observed trends, i.e., a decrease in density in the center city, a high increase in density in the inner urban ring, and slight density increases in the outer ring as well as in the city. In contrast, the third scenario (E3), assumes that expansion will be influenced by planning and suggests slight density increases in the city center and city fringes, while preserving current population densities in the inner and outer ring.

We consider that the second urban expansion scenario (E2) as the basis for this study since it follows current trends. It is the most pessimistic in terms of urban expanded area. This scenario forecasts an urban expansion of 55,842 ha for year 2026 at a mean urban density of 86 person ha^{-1}.

The estimated expansion under this scenario is shown in Fig. 2.

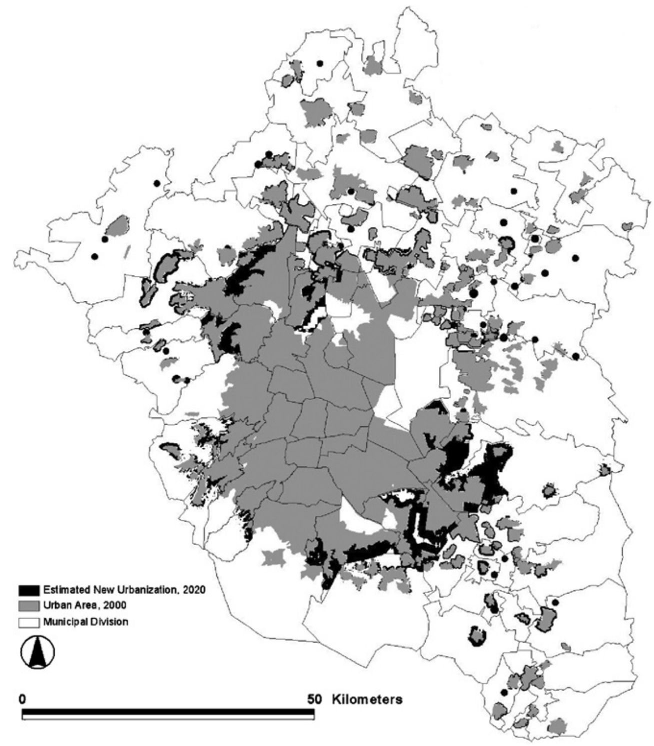

Fig. 2. Urban expansion scenario E2 obtained using the described methodology used by the air quality model.

2.4. Emission scenarios

The emission factors for the base, hybridized and non-hybridized fleets are obtained using the results of the vehicular simulation process described in Section 2.1 and the data from the urban expansion in Section 2.3. As mentioned, the projection year is 2026 and the introduction of HEV's represented by the Prius 2002 emissions starts in 2009.

The car specimens used for the fleets used for comparison are shown in Table 2. Also shown are the statistical weights assigned to each car to obtain the car fleets whose respective age histogram is shown in Fig. 3. Note that the base-fleet includes 20% of cars without catalytic filter (more than 11 years old in 2004). It was tailored to mirror the age histograms of cars in Mexico City for year 2004, according to the study by [26]. This histogram is skewed towards more modern cars due to governmental and financial policies of auto companies promoting the acquisition of new cars. The projected future hybridized and non-hybridized fleets contain Tier I and II cars only. The portion of conventional cars of these two projected fleets has almost identical age histograms.

Table 2
Specimen cars and weight factors used to obtain the three fleets.

Vehicle model	Weight factors			Year	Number of cylinders	Fuel injection and catalytic filter
	Base	Hybridized	Non-hybridized			
VW_Beetle Sedan	.030	.000	.000	1982	4	No
VW_Caribe	.040	.000	.000	1984	4	No
VW_Combi	.040	.000	.000	1985	4	No
Nissan_TsuruII	.060	.000	.000	1990	4	No
DODGE_SPIRIT	.070	.110	.130	1992	4	Yes
NISSAN_TSURU	.050	.110	.135	1995	4	Yes
HONDA	.070	.100	.125	1998	4	Yes
Ford_Explorer	.070	.100	.125	1999	8	Yes
GM_Monza	.070	.050	.065	2000	4	Yes
VW_Pointer	.070	.050	.060	2000	4	Yes
NISSAN_SENTRA	.030	.030	.045	2002	4	Yes
Chrysler_Voyager	.120	.070	.080	2002	6	Yes
GM_Chevy	.070	.050	.065	2003	4	Yes
VW_Beetle Sedan	.070	.050	.060	2003	4	Yes
FORD_ECO_SPORT	.050	.020	.030	2004	4	Yes
Chevrolet_Meriva	.040	.030	.040	2004	4	Yes
Ford_Fiesta	.050	.030	.040	2004	4	Yes
Prius 2002	.000	.200	.000	–	–	Yes

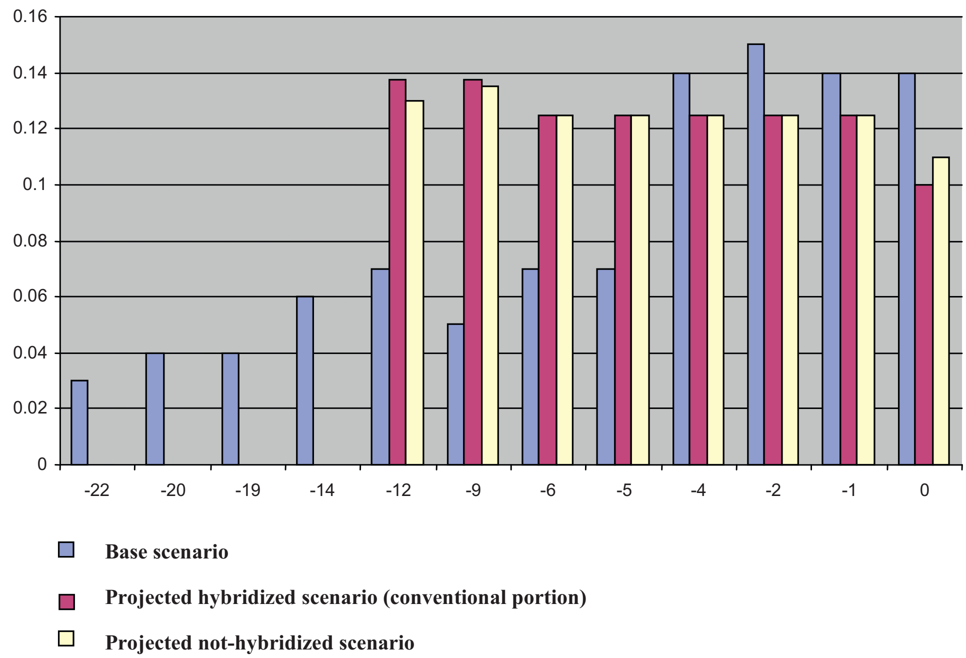

Fig. 3. Histogram of age percentage of the three car fleets. Both future hybridized and non-hybridized fleets contain only Tier I and II cars. The base case for year 2004 contains 20% of cars without catalytic converter.

Table 3
Age weighted average and number of cylinders for the vehicular fleet scenarios.

Weighted age average (years)			Number of cylinders		
Base	Hybridized (conventional portion)	Non-hybridized	Base	Hybridized (conventional portion)	Non-hybridized
6.12	5.14	5.02	4.52	4.68	4.66

Table 3 shows the age averages and number of cylinders for each car fleet scenario. There is a slight increase in number of cylinders with respect to the base case reflecting current trends. The average age of the conventional part of the hybridized fleet is similar to the non-hybridized fleet.

2.5. Air quality modeling

The air quality model used to obtain the geographical distribution of pollutants for the three emission scenarios is the Multi Scale Climate and Chemistry Model (MCCM). MCCM [28] directly couples meteorology and photochemistry. The model MM5 provides the meteorology and the photochemistry the RADM mechanism [29,30]. It contains 39 chemical species and particulate matter.

The emissions factors obtained for the respective car fleets were applied to the corresponding transport emissions of the inventory described in [31]. MCCM also includes a module for biogenic emissions. More details of the model and experience with MCCM in Mexico City can be found in [32–35]. The land use for the base and future urban scenario E2 of Section 2.2 are used by MCCM.

The meteorology and air quality data of a representative sample of 56 days for year 2004 was obtained. These days were selected using a uniform probability distribution. The basic statistics comparing concentrations of some representative pollutants for the sample days and year measurements by the local air quality network SIMAT are shown in Table 4. A good agreement between the statistics of the sample days and year values was found.

This day's sample was used by MCCM to model the base case for emissions and land use for urban scenario E2 of Section 2.2. The modeled concentrations with a resolution of 3 km are compared with measurements of the local meteorology and air quality network SIMAT. Table 5 shows a statistical comparison of measured and modeled ozone for the 56 sample days. In Fig. 4 is shown an example of typical time series of modeled and measured ozone for selected stations of the local air quality and meteorological stations (SIMAT). Based on data shown in Fig. 4 and Table 5, the conclusion is that MCCM captures with reasonable fidelity ozone concentrations in Mexico City.

In addition, $PM_{2.5}$ concentration variations due to the emission scenarios were calculated using concentration variations of precursor compounds. These are: ammonia (NH_4), NO_3, sulfur dioxide (SO_2), sulfate (SO_4), toluene aromatics, xylene aromatics, ethane and propane. The geographical distribution patterns for $PM_{2.5}$ are

Table 4
Basic statistics comparing measurements of the sample days and measurements for year 2004.

Variable	Observations	Mean (ppm)	SD	Min. (ppm)	Max. (ppm)
CO-year	8784	1.43	.81	.22	7.34
CO-sample	480	1.47	.85	.3	5.59
O_3-year	8784	27.97	28.26	1.65	150.39
O_3-sample	480	28.85	30.20	1.65	146.42
NO_2-year	8784	33.02	14.46	5.9	127.2
NO_2-sample	480	34.16	13.57	8.9	87.9

Table 5
Statistical comparison of ozone modeling results using MCCM and measurements for the 56 sample days. σ_p and σ_0 are the predicted (modeled) data and observed standard deviation respectively. RMSE is the root mean square error, RMSEs is the systematic root means square error, RMSEu is the unsystematic root mean square error. NGE is the net gross error; NB is the normalized bias, and Ic the index of agreement [36].

Station	σ_0	σ_p	$RMSE_s$	$RMSE_u$	RMSE	NGE	NB	Ic
Tacubaya	0.037	0.020	0.031	0.028	0.013	0.768	-0.495	0.729
Xalostoc	0.027	0.020	0.016	0.011	0.012	1.075	0.635	0.854
Merced	0.031	0.027	0.020	0.012	0.016	0.856	-0.146	0.904
Cerro de la Estrella	0.027	0.033	0.022	0.010	0.020	1.835	1.458	0.887
Plateros	0.037	0.033	0.022	0.011	0.019	0.790	0.081	0.921
Hangares	0.030	0.027	0.018	0.009	0.016	0.714	-0.094	0.882
Cuautilan	0.031	0.029	0.022	0.011	0.019	0.878	0.584	0.852
Tlahuac	0.027	0.017	0.024	0.019	0.013	3.280	3.113	0.709
Iztapalapa	0.030	0.029	0.018	0.006	0.017	0.670	0.192	0.899
Taxqueña	0.034	0.033	0.021	0.007	0.019	1.742	1.304	0.899

similar to the one shown for ozone. Even though particle emissions of gasoline cars are relatively low, their gas emissions may have a modest impact in the formation of secondary aerosols. It should be noted that aerosols models in general, including ours, underestimate secondary organic compounds formation for Mexico City [37].

2.6. Exposure modeling and health impact

To find the potential exposure Ψ of the population to the atmospheric pollutant concentrations, the results of the air quality model are matched with the population data of Mexico City using a GIS. The formula used is,

$$\Psi = \frac{\sum_{n=1}^{m}\sum_{i,j}\varpi_{i,j,n}c_{i,j}}{m\varpi_{\max}}, \qquad (3)$$

where $\varpi_{i,j,n}$ and c_{ij} are the population and concentration in the 3 km cell i, j and $\varpi_{\max}$ is the maximum population in the region of interest.

The values obtained for Ψ are used in conjunction with epidemiological studies to estimate avoided cases of mortality, respiratory hospitalizations, asthma emergency room visits, restricted activity days, and school loss days due to the reduction in atmospheric concentrations of ozone and of $PM_{2.5}$ aerosols. Ozone exceeds the local norm 58% of the days [14].

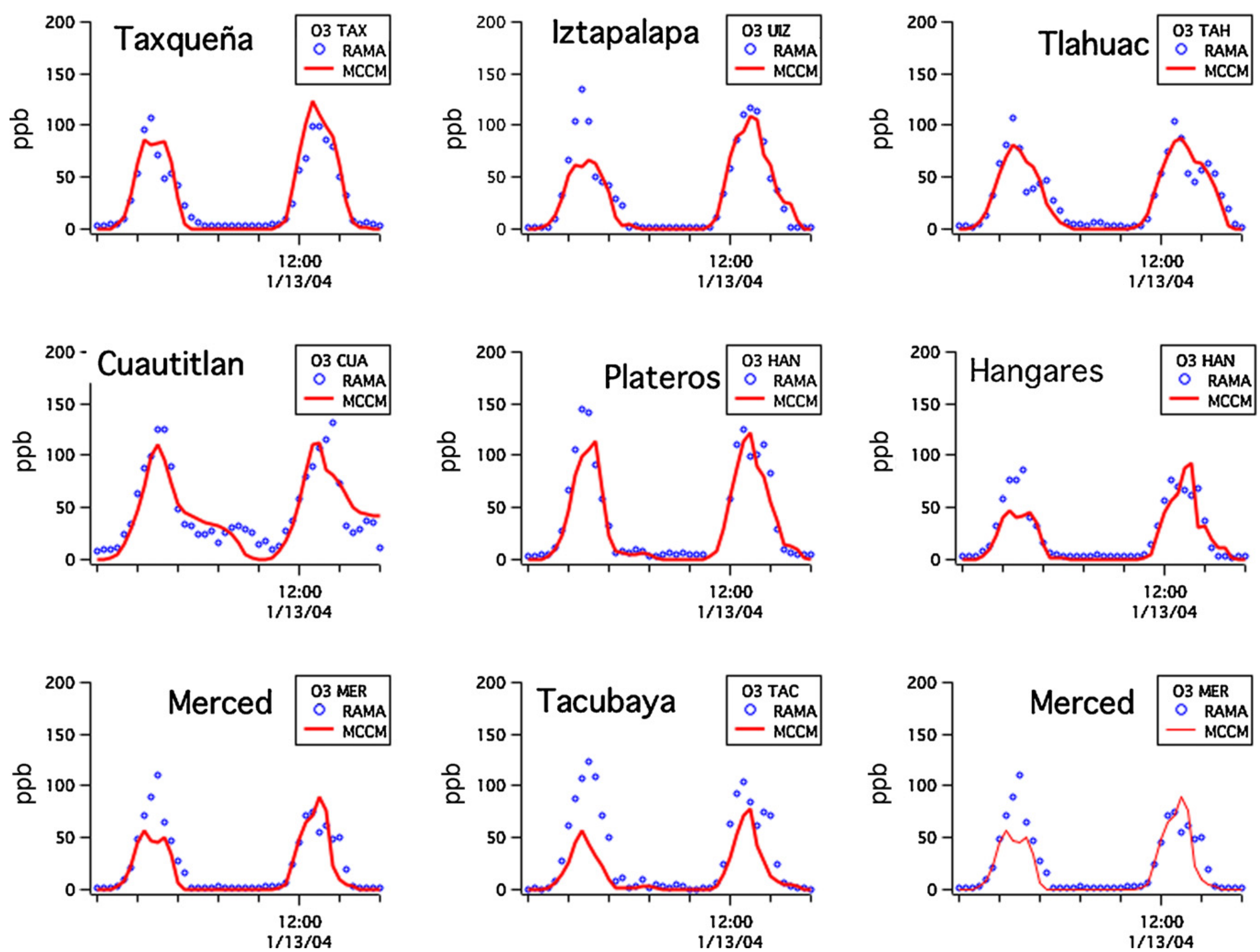

Fig. 4. Time series of modeled (MMCM) and observed ozone concentrations in ppb's at some selected stations of SIMAT, for January 12th, 2004.

Much uncertainty exists as to the correct concentration response values to estimate health impacts, especially if response functions for other countries are applied for Mexico City. To contend with this situation in the case of ozone, we follow [38]. There the response functions and their uncertainty bounds were derived from local and international literature [39–41]. For $PM_{2.5}$ case the response functions used are from [42,43].

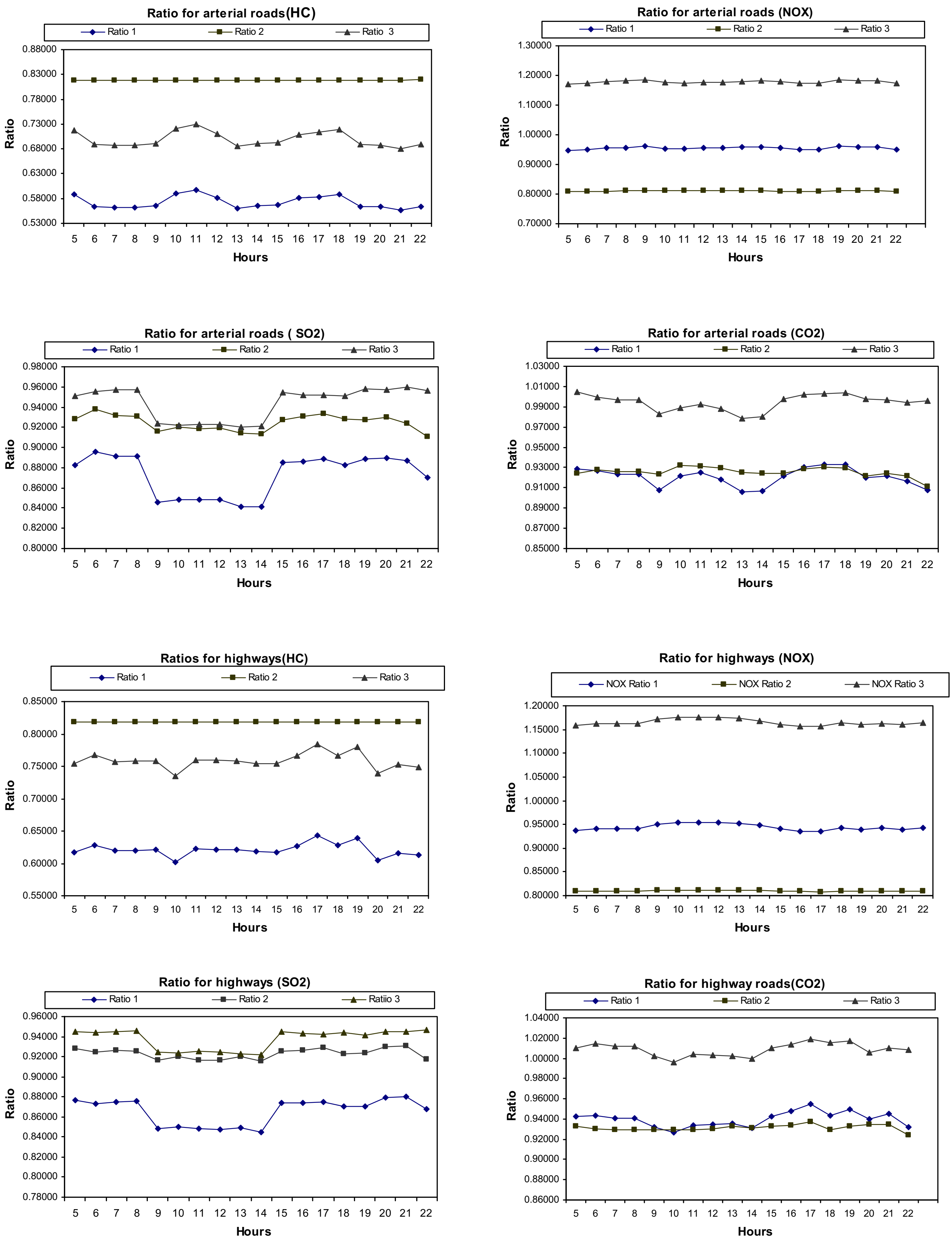

Fig. 5. Ratios 1, 2 and 3 of HC's, NO_x, CO, CO_2, SO_2 for residential, arterial and highways.

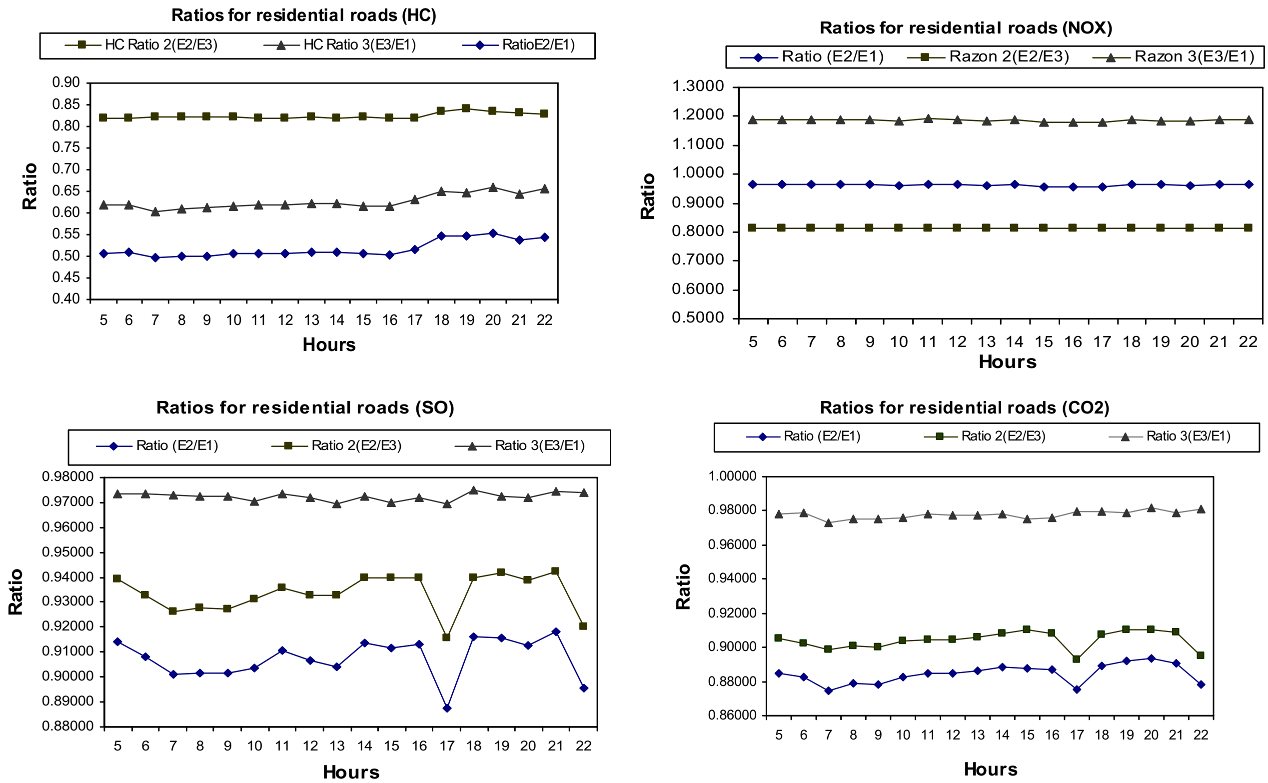

Fig. 5. (*Continued*)

2.7. Private costs and operating fuel benefits

To obtain a time series of the private costs is assumed that excess cost incurred in acquiring a HEV car vary linearly with time. It starts at 4,500,00 US Dlls at year 2009 finishing at 2,500,00 US Dlls at year 2035, as considered by [7]. Using [44] it was also considered the final car value after a maximum of 10 years, based on the MSRP for a Hybrid Ford Escape and an average depreciation schedule for that vehicle. We did not incorporate a residual value of the batteries at the end of life of the HEV, since a large degree of uncertainty exists in the battery market, and secondary markets have no experience incorporating these end-of-life batteries.

The fuel consumption time series was calculated using the penetration model of Section 2.1 to obtain number of conventional cars and HEV's each year, together with CO_2 emissions using ADVISOR.

It is important to note that the accumulation of private cost and benefits (public health, CO_2 and fuel) follow different finite arithmetic series. If the cost per unit for year j is denoted by c_j^u, and n_j is the on road number of HEV's in year j, the total accumulated cost C_m for year m is

$$C_m = \sum_{j=1}^{m} n_j c_j^u, \tag{4}$$

whereas the accumulated benefit for year m, B_m, must be calculated according to

$$B_m = \sum_{j=1}^{m} \left(\sum_{i=1}^{j} n_i \right) b_j^u, \tag{5}$$

where b_j^u is the benefit per unit for year i. This is because the benefit for year j is $(\sum_{i=1}^{j} n_i) b_j^u$ and is due to the sum of HEV's in operation introduced in current and previous years. Since the coefficient of the benefit series in Eq. (5) is larger than the one for the cost series in Eq. (4), its growth rate is also larger. Therefore, benefits accumulate faster than costs.

3. Results

3.1. Emission results of the fleet scenarios

To compare the emissions produced by the base, future hybridized and non-hybridized fleets of HC's, NO_x, SO_2 and CO_2, three ratios were obtained:

- Ratio 1: Hybridized emission scenario/base emission scenario.
- Ratio 2: Hybridized emission scenario/non-hybridized emission scenario.
- Ratio 3: Non-hybridized emission scenario/base emission scenario.

In this way Ratios 1 and 2 will be less than 1 if the hybridized emissions are lower than the base and non-hybridized scenarios, respectively. Ratio 3 will be less than 1 if the emissions of the non-hybridized are less than the base scenario.

Fig. 5 shows the emissions time series from 5:00 to 22:00 LST for these ratios. Hourly variations depend on motor stress, battery use in the case of HEV's, traffic activity and fleet composition. Ratio 1 has lower values than Ratio 3. Therefore emissions corresponding to the 20% hybridized-fleet have the lowest emission values. This is especially true during hours of higher traffic and on the residential roads because the HEV has better gas consumption on urban driving than on highway conditions, opposite to the conventional case.

Note how Ratio 1, that compares the emissions of the 20% hybridized with the base-fleet, indicate savings in HC's of 45%, 5% in $NO_{x,}$ 45% in CO, 12% in SO_2 and 10% in CO_2. Ratio 2 shows that the 20% hybridized-fleet emissions save about 18% in HC's, 20%

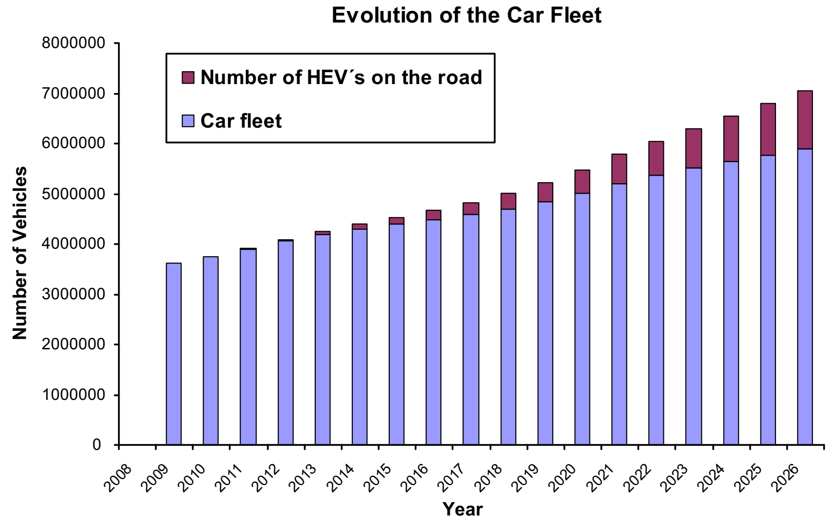

Fig. 6. Evolution of the hybridized-fleet using the proposed penetration model.

in NO_x, 18% in CO, 9% in SO_2 and 9% in CO_2 with respect to the non-hybridized fleet.

Ratio 3 shows that the non-hybridized fleet with respect to the base fleet saves about 33% in HC's, 33% in CO and 6% in SO_2, but there is an increase of 16% of NO_x and there is almost no difference in CO_2 emissions. We see that, from the two projected car fleet scenarios, only the 20% hybridized-fleet saves CO_2 and NO_x emissions and has the greatest emissions savings overall.

3.2. Penetration model and fuel consumption results

Under the suppositions of the penetration model, Fig. 6 shows the evolution of the hybridized-fleet. About 20% of HEV could be on the road in year 2026.

In Fig. 7 is shown the time series for daily fuel consumption in liters for the base-fleet and hybridized-fleet. To obtain fuel consumption, saving factor of 10% in CO_2 emissions obtained in Section 3.1 is rolled back using the percentage of HEV's in the fleet. By year 2026, while the base-fleet reaches 65 million liters the hybridized-fleet uses 55.5 million liters. Fig. 7 shows that the base-fleet consumption trend is slowed as more hybrids enter the market.

3.3. Air quality results

Based on the emission scenarios results, a comparison of surface ozone concentrations of the hybridized and non-hybridized fleets is discussed in the context of urban scenario E2 of Section 2.2.

In the left panels of Fig. 8, are shown the typical results of the variation percentage of surface ozone concentration between the base and the 20% hybridized scenario. On the right, are shown the results of the variation percentage between the base and the non-hybridized scenario. The formula used is

$$Pv = (C_b - C_f)(t)_i \, (C_b(t)i)^{-1} * 100 \qquad (6)$$

where P_v is the percentage variation, $C_b(t)_i$ and $C_f(t)_i$ are the concentration of base and future scenarios respectively at time t on the ith surface cell. The size of the cell is the same as the resolution of the innermost MCCM domain of 3 km.

It is evident that the largest concentrations percentage variation is when a transition to a 20% hybridized-fleet has been accomplished. This scenario provides about 7% reduction in mean diurnal ozone concentrations whereas the non-hybridized does not provide significant reductions. Moreover, the reductions due to the

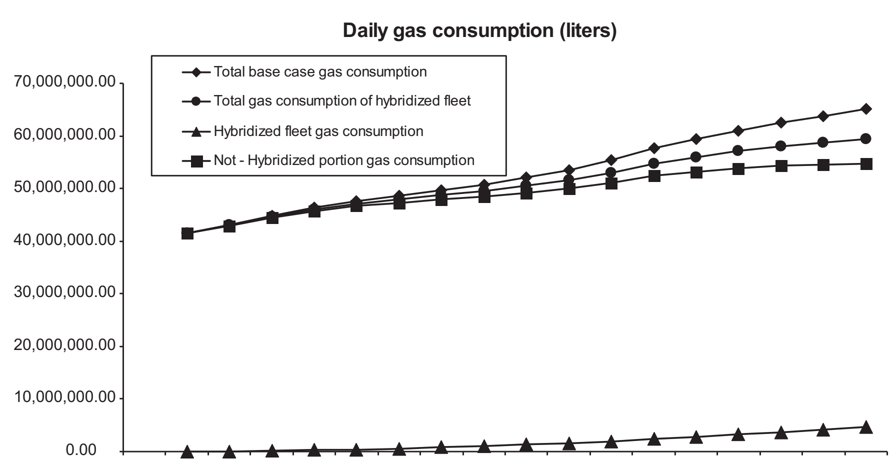

Fig. 7. Time series of the daily fuel consumption for the base-fleet and hybridized-fleet. Also shown is the consumption of the hybridized and non-hybridized portion of the hybridized fleet.

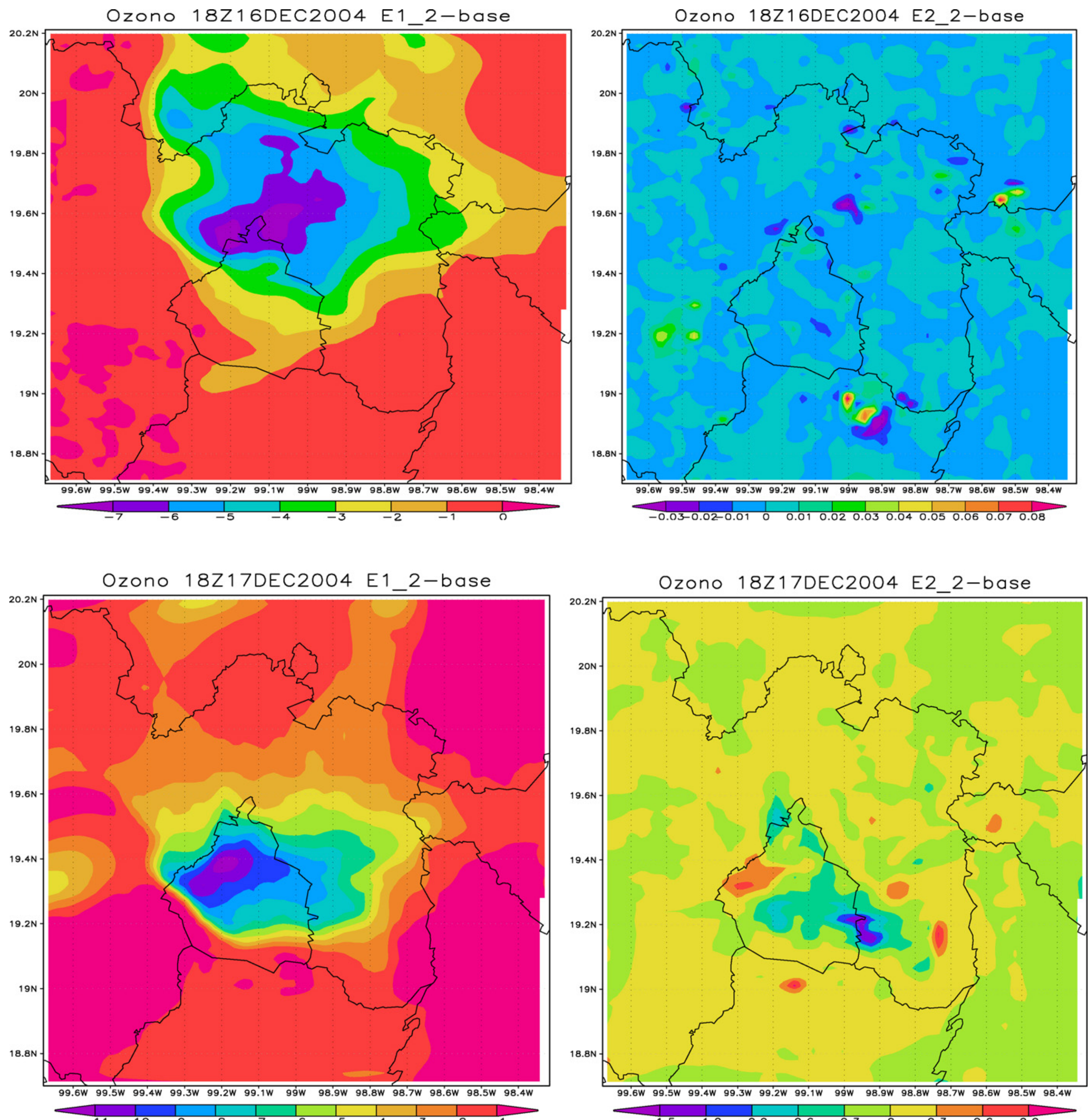

Fig. 8. Typical geographical location of the percentage of diurnal variation of ozone concentrations. On the left panels is shown the variation percentage between the base and the projected hybridized scenario, and on the right the variation percentage between the base and the non-hybridized scenario. These modeling results are based on meteorology of the 16th and 17th of December 2004 with urban scenarios for 2026.

hybridized scenario are found on the most populated areas and on the southern mountains, whereas the reductions of the non-hybridized scenario are spotty and small.

In Fig. 9 is shown the time series of ozone concentrations on a point where the largest variations for each case of Fig. 8 were found. Note that the hybridized scenario provides substantial (∼15%) peak reductions whereas the not hybridized are small. This is because of the reductions in HC's and NO_x in the 20% hybridized case.

The estimated variation of $PM_{2.5}$ concentrations due to changes in emissions between base fleet and non-hybridized fleet is a reduction of 0.015 $\mu g\,m^{-3}$ or 0.3%. This reduction is negligible. Between the base and hybridized scenario there is a modest reduction of 0.18 $\mu g\,m^{-3}$ or 3.4%. Typical geographical location of $PM_{2.5}$ concentration reductions is shown in Fig. 10. The $PM_{2.5}$ reductions geographical distributions follow similar patterns as the ozone reductions.

Experiments with the air quality model revealed that only when 10% of fleet hybridization is attained that discernable reduction of ozone and $PM_{2.5}$ takes place. From then on, an almost linear reduction of corresponding concentrations is assumed.

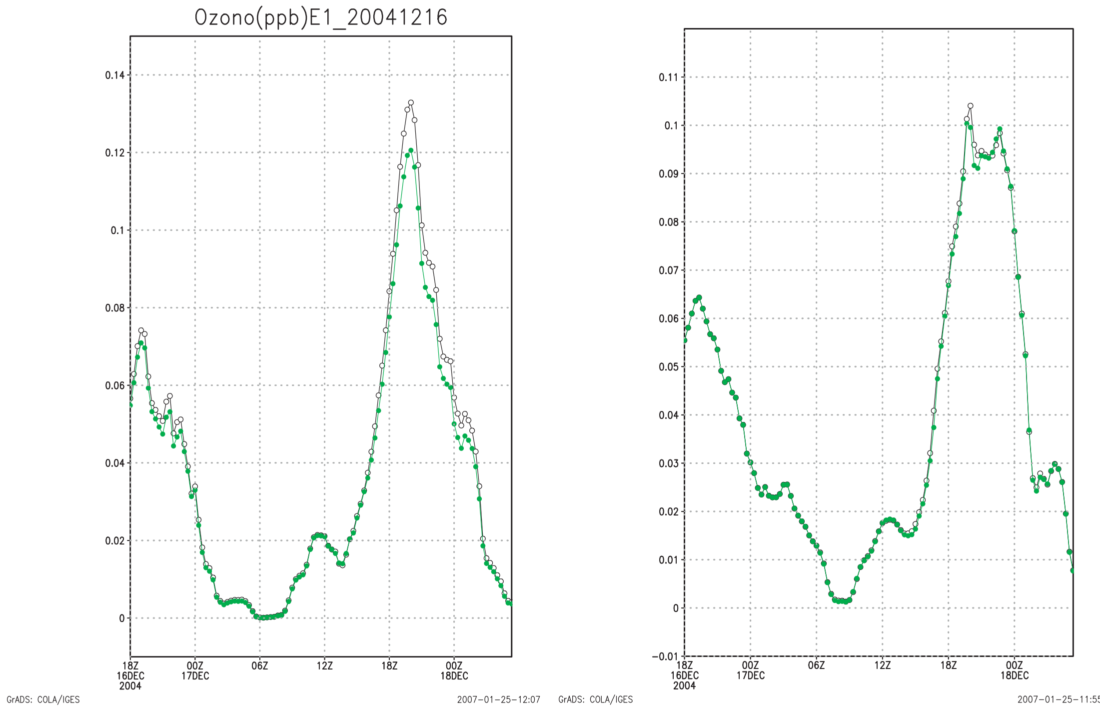

Fig. 9. Time series in ppb's of ozone concentrations on points of maximum percentage variation of Fig. 8. Left panel shows the base (dark line) and projected hybridized scenario (light line). Right panel displays the base (dark line) and projected non-hybridized scenario (light line).

3.4. Valuation results

First, monetary values are used to estimate the benefits of the hybridized scenario for year 2026 and then these results are rolled back to obtain a time series that allows estimating the accumulated benefits from year 2009 to 2026. As shown in Table 6 and air quality results in Section 3.3 the base and non-hybridized scenarios are similar, so the benefits valuation is performed only between the base and hybridized case.

Tables 7 and 8 show the yearly monetary health benefits results for ozone and $PM_{2.5}$ reductions for year 2026. The ozone and $PM_{2.5}$ reductions are concentrated in the most densely populated areas of Mexico City where about 25% of the total population is affected.

Table 9 shows the fuel savings, health and CO_2 benefits together with local and global benefits between the base and non-hybridized versus the hybridized case for year 2026. Results shown in Table 6 are used to estimate CO_2 and fuel reductions. It is considered that the transport sector in Mexico City emits 20,480,000 Tons of CO_2 per year [14] and that 65% of the fuel consumption is by private cars. To obtain a CO_2 benefit it was considered that the reduction of a Ton of CO_2 pays 10.0 USD by the carbon market [45]. The fuel benefit was calculated based on current value of gasoline (November 2010) per liter of regular grade gasoline in the Mexican market of about 0.8 USD per liter. Note that since the fuel benefit is large, the confidence intervals from health benefits can be ignored.

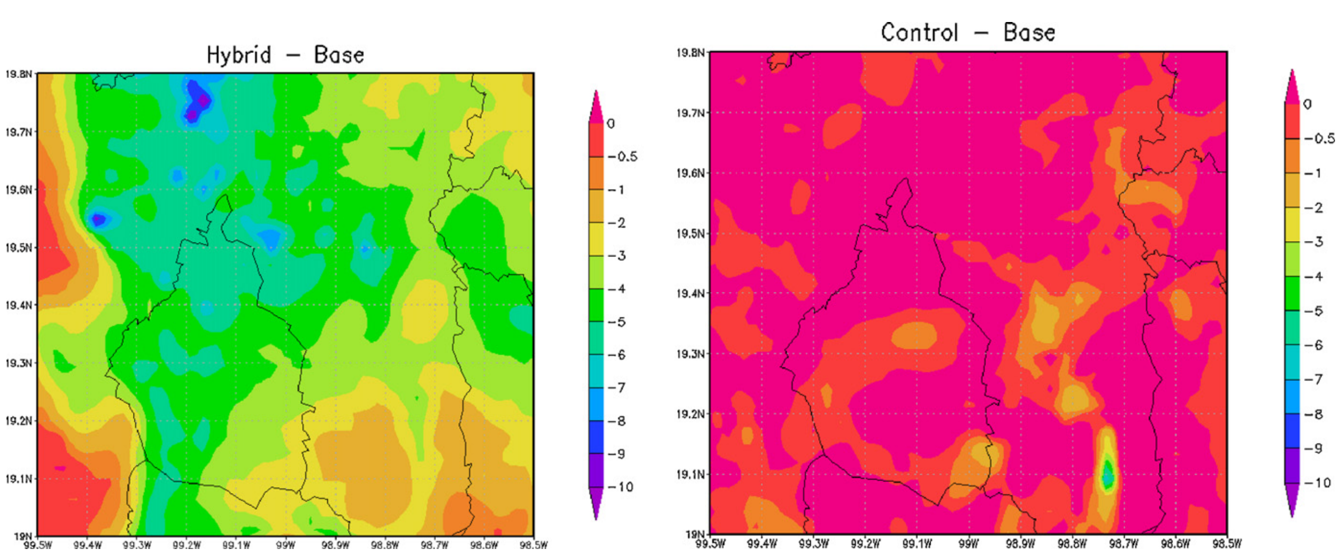

Fig. 10. Typical geographical location of the percentage of diurnal variation of $PM_{2.5}$ due to reductions in precursors. On left comparison of the hybrid and base case scenarios and on right non-hybridized and base scenarios. These modeling results are based on meteorology of the 17th of December 2004 with urban scenarios for 2026.

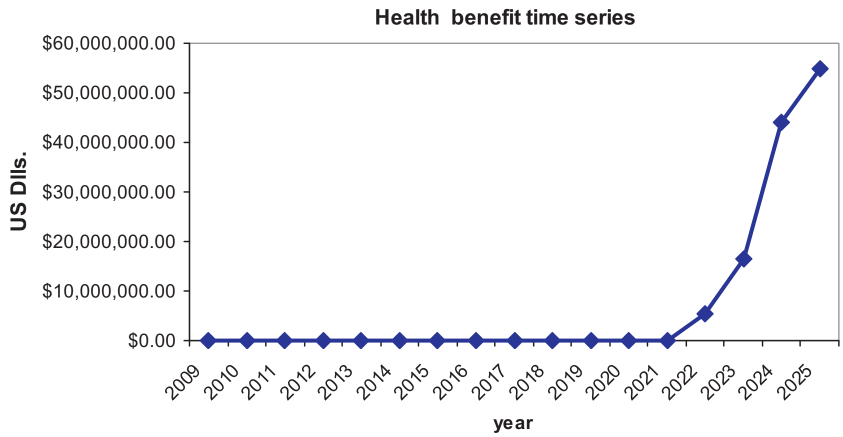

Fig. 11. Constructed time series for health benefits (ozone + $PM_{2.5}$).

Table 6
Emission ratios for the three scenario fleets. The weighted average takes into account that 36% of trips are on residential roads, 44% on arterial and 19% in highways.

	HC's	NO_x	CO	SO_2	CO_2
Ratio 1: Hybridized fleet/base fleet					
Residential	0.516	0.962	0.516	0.907	0.884
Arterial	0.572	0.955	0.572	0.873	0.920
Highway	0.621	0.943	0.621	0.866	0.940
Weighted average	0.555	0.945	0.427	0.875	0.901
Ratio 2: Hybridized fleet/non-hybridized fleet					
Residential	0.824	0.812	0.824	0.933	0.904
Arterial	0.818	0.811	0.818	0.924	0.925
Highway	0.818	0.810	0.818	0.923	0.931
Weighted average	0.812	0.803	0.812	0.912	0.910
Ratio 3: Non-hybridized fleet/base fleet					
Residential	0.626	1.186	0.626	0.972	0.977
Arterial	0.699	1.178	0.649	0.944	0.994
Highway	0.758	1.165	0.786	0.937	1.008
Weighted average	0.677	1.166	0.660	0.943	0.980

Now the time series for all the economic parameters are obtained. For health benefits the corresponding value for year 2026 is rolled back by considering that, as shown by the air quality results for the non-hybrid scenario, no appreciable changes in air quality will be attained until the hybrid-scenario reaches 10%. Therefore the health benefit is considered zero until year 2022. In year 2023 the health benefits start growing as shown in the time series of Fig. 11 until 55 million US Dlls are attained matching Table 9 for year 2026.

The CO_2, fuel benefit and private costs time series are rolled back using the fuel consumption and penetration model results of Section 3.2. In Fig. 12 shows a time series starting in year 2009 of net benefits (CO_2 benefit + fuel benefit + health benefits − private costs) with 5% of return rate for the 2009–2020 time period, using 1.0, 0.8 and 0.6 US Dlls per liter of gasoline.

According to our scenarios positive returns will start generating after 2012, and will reach between 502 million to 837 million US Dlls in year 2026. In Fig. 13 are shown the accumulated benefits.

Table 7
Ozone health benefits results between the base and non-hybridized versus the hybridized scenario for year 2026. In parentheses the lower and higher estimate specifying a 95% confidence interval.

	Affected population	Avoided cases ozone	Monetary value (USD)	Benefits (USD/year)
Mortality	5,364,448	46 pp (23:69) (pp:pp)	300,000	13,839,471 (6,919,736: 20,759,207)
Respiratory hospitalizations	5,363,448	177 (59:136)	2,111	199,096 (124,435:286,200)
Asthma emergency rooms visits	1,877,557	58 (36:80)	317	18,426 (11,516:25,336)
Minor restricted activity days	3,384,967	177,888 (72,773:283,004)	12	2,134,662 (873,271:3,396,052)
School loss days	1,437,672	728,059 (230,094:1,133,299)	12	8,736,704 (2,761,128:13,599,587)
				Total: 24,928,359 (10,690,085:38,066,382)

Table 8
$PM_{2.5}$ health benefits results between the base and non-hybridized versus the hybridized scenario for year 2026. In parentheses the lower and higher estimate specifying a 95% confidence interval.

Health Impact	Affected population	Avoided cases	Monetary value (USD)	Benefits (USD/year)
Cardiopulmonary mortality	12,735,958	57 (20:97)	300,000	17,114,160
Lung cancer mortality	12,735,958	7 (2:13)	300,000	2,228,454
Infant respiratory mortality	375,547	0	1,300,000	0
Infant sudden infant death syndrome	375,547	0	1,300,000	0
Chronic bronchitis	12,735,958	155 (0:1,926)	52,000	8,055,938
Minor restricted activity days	18,532,452	197,892 (159,3342:236,443)	12	2,374,708
Work loss days	11,592,987	21,022 (17,891:24,152)	13	273,280
				$30,046,540 (8,053,600:136,232,491)

Table 9
Valuation in million USD/year between base versus the hybridized scenario for year 2026.

Fuel savings	Health benefits (ozone + $PM_{2.5}$)	CO_2 benefits (Global benefit)	Local benefits (fuel + health benefits)	Local + global benefits
439.5	55	15.6	464.5	480.1

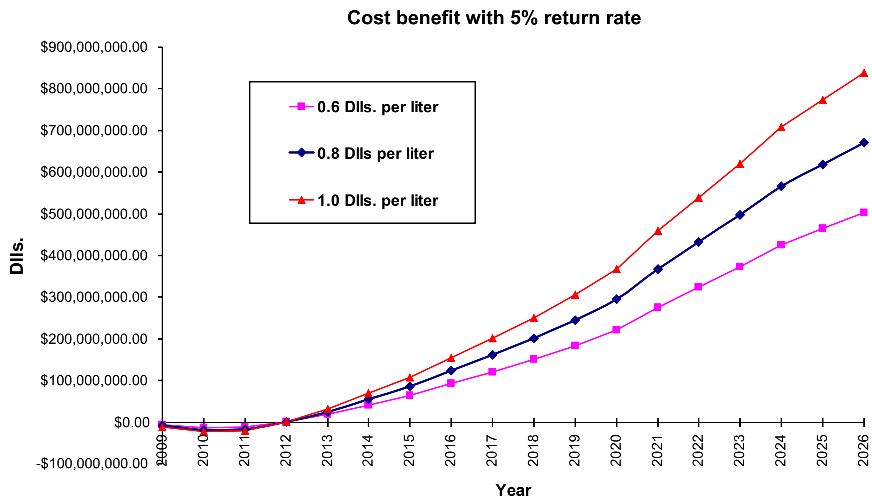

Fig. 12. Cost benefit time series with 5% return rate using gasoline prices of 0.6, 0.8 and 1.0 USD per liter.

They will become positive until year 2015. In year 2026 they are expected to be between 2.8 and 4.5 Billion US Dlls depending on gasoline prices.

4. Discussion

Compared to the base case, only the hybridized-fleet resulted in meaningful energy, public health and CO_2 benefits. The energy savings were the largest, but public health plus CO_2 benefits amount to 50% of the private costs around year 2026.

The benefits due to air quality improvements are concentrated in densely populated areas (slower traffic) where close to 15% reduction in ozone concentration peaks was obtained. This is so because the internal combustion engine (IC) of the HEV is turned off part of the time and accelerations after a stop are aided by the electrical motor. In general the IC of the Prius starts when it reaches about 30 km h^{-1}. Without this aid, the IC in a conventional car is in a region of high torque and low RPM's and therefore relatively high emissions are produced. Relative to idling, acceleration emissions in gram per second vary by a factor of 5 or 10 depending on pollutant [46]. When the IC of the Prius 2002 is on, the RPM's variations are, by design, mostly concentrated in an optimal emissions range.

As shown in Table 6 the 20% hybridized-fleet reduced the NO_x emissions in about 5% with respect the base fleet whereas the non-hybridized fleet incremented these emissions in about 16%. This is because we included the effect of the air conditioning (AC) that was turned on in ADVISOR when the ambient temperature rose above 20 °C during the virtual cycles. When AC is on, the IC of a conventional car has an extra load of about 2 KW. In a Prius the batteries run the AC. If the IC of the Prius 2002 is turned on to charge the battery, it is maintained in an optimal RPM range to maintain low emissions. The reductions in NO_x with the AC on in the Prius 2002 are in agreement with [16]. This may not be the case for other HEV's where AC is run by the IC directly, compromising NO_x emission improvements.

It should be stressed that our sample fleet contains Tier I and II cars. A comparison with an exclusively Tier II fleet was not possible since the contents of sulfur in the Mexican gasoline does not allow for a proper functioning of this car technology regarding emissions.

The CO_2 savings and therefore gas consumption of about 10% in 2026 of the private transport sector depends highly on traffic conditions. If traffic speeds in Mexico City are reduced, the saving ratios may increase, especially if more efficient HEV's already in the market are introduced.

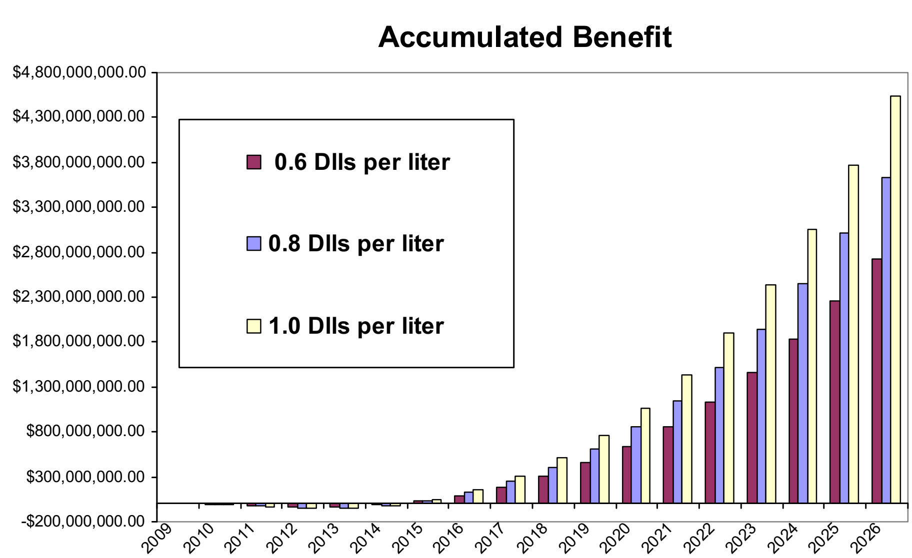

Fig. 13. Time series of accumulated benefits using gasoline prices of 0.6, 0.8 and 1.0 US Dlls.

The fact that the non-hybridized fleet did not provide important improvements in ozone and $PM_{2.5}$ shows that modernization of the car fleet as considered here, with present gasoline quality will not be an effective control strategy. The current conventional car technology has already provided most of its potential. Only the introduction of new car technologies, such as HEV's, can effectively reduce pollution and provide energy savings. At the same time, policies to reduce the fleet of old private cars, mostly present in the city periphery, and to promote fleet renewal should be reinforced, not to allow fleet aging.

Under the suppositions of this work, the hybridization of the car fleet will start positive returns in year 2012 and accumulated positive returns will start collecting in year 2015 depending on gasoline prices. This means that HEV introduction program should be considered as medium to long range. The larger the time horizon the larger the benefits. HEV availability, as well as aggressive inducements to acquire these cars must take place.

This study on HEV technology did not take into consideration production environmental and energy costs but in [47] is shown that the energy cycle of HEV's is comparable with conventional and other car technologies.

Acknowledgments

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Glossary

AC: air conditioning
ADVISOR: advanced vehicle simulator
GHG: Greenhouse effect gas
GIS: Geographic Information System
GREET: Greenhouse gases, regulated emissions, and energy use in transportation model
HEV: hybrid electric vehicle
IC: internal combustion engine
INE: National Institute of Health, Mexico
IVE: International Vehicle Emission Model by International Sustainable System Research
LST: local standard time
MCCM: Multiscale Climate and Chemistry Model
MOBILE: An emission factor model of the Environmental Protection Agency, USA
MOVES: Motor Vehicle Emission Simulator, an emission factor model of the Environmental Protection Agency, USA.
MSRP: Manufacturer's suggested retail price
NREL: National Renewable Energy Laboratories of the Department of Energy, USA
PEMEX: Petróleos Mexicanos, Mexican oil state monopoly
PHEV: plug-in hybrid electric vehicle
$PM_{2.5}$: particulate matter with equivalent aerodynamic diameter of less than 2.5 μm
RPM: revolutions per minute
SIMAT: automatic environmental monitoring system, Mexico City
US DLLS: United States Dollars