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The usefulness of air quality monitoring and air quality impact studies before the introduction of reformulated gasolines in developing countries. Mexico City, a real case study

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Abstract

Urban air pollution is a major environmental problem in several developing countries in the world. This phenomenon seems to be related to the growth of both the urban population in large cities and the number of old and poorly maintained car fleets. The expected rise of population in the next century in countries which suffer from lack of capital for air pollution control, means that there is a great potential for the worsening of the air quality. The worldwide promoted policy to phase out lead in gasolines has not proved to be an adequate option in improving the environmental quality. Mexico City Metropolitan Area (MCMA) represents a case in which the introduction of reformulated gasolines in an old car fleet has given as a result the reduction of the airborne lead levels but has worsened the ozone concentration of its urban atmosphere. This paper critically analyzes the chronological evolution of the ozone air pollution problem in MCMA after the successive occurrence of several changes in the formulation of low leaded and unleaded gasolines. It also presents evidences of the usefulness potential of air quality monitoring activities and air quality impact studies on the definition of realistic fuel reformulation policies of developing countries.

Keywords: Ozone urban air pollution; Reformulated gasoline; Mexico City

1. Introduction

Despite the introduction of several air quality management strategies, monitoring trends show that nitrogen dioxide, ozone, suspended fine particles and carbon monoxide in urban areas of developing countries are increasing (WMO, 1997). Rapid industrial growth and population increase are likely to lead to patterns of motorization that resemble those of the industrialized countries. Transport is the principal source of emissions to air in most countries, and the scale of emissions in the most polluted urban areas means that action in the transport sector is unavoidable to address air quality problems. Another reason to take actions on this sector is that due to the expected increase in size and population in megacities, projections for transport are quiet alarming in terms of their potential impact on the environment (Gilbert, 1997).

However, it has been observed that governments of developing countries have been copying air pollution control strategies implemented in developed countries instead of building up their own strategies in accordance with their economical and political situations. Switching from leaded gasoline to unleaded gasoline is the most representative example of one of these strategies. This paper attempts to show evidences that there is not a single "solution" in air quality problems throughout the world because of the strong dependence concerning local factors. We are taking the air pollution problem of Mexico City Metropolitan Area (MCMA) as an example

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of the usefulness of air quality monitoring data in recognition of the failure of a strategy.

2. Background

In the last few decades, urban development and growing industrialization have been the cause for air pollution to become a major issue in some developing countries around the world (Mage et al., 1996; WHO, 1997). Introduction of unleaded gasoline in high income per capita countries has been the guideline for developing countries to reduce the emissions of primary pollutants such as lead from exhausts. However, this change in gasoline formulation has not been accompanied with the associated substitution of the old car fleet by a new one equipped with the system controls required to prevent the emission of more reactive compounds, because of the dependence on political and economical implications (Onursal and Gautan, 1997). Lead levels in some urban atmospheres have now been falling for several years but there are new problems on the environmental agenda, as a consequence of the lack of knowledge of the relationship between fuel composition and vehicle emissions (Bravo et al., 1989; McGinty and Dent, 1995).

Research performed throughout the 1960s, 1970s, and 1980s have concluded that impact of vehicle emissions upon ozone formation depends upon both mass and reactivity of the emissions (NRC, 1991). Furthermore, it has been found that the average emission rate and the reactivity potential of the hydrocarbons in the exhaust depend on the age distribution of the in-use vehicle fleet, the control systems in use, the number of kilometers driven per year, the magnitude of emissions for a given age, the rate of deterioration of emission controls and the gasoline composition (Calvert et al., 1993). Fleet age has a dominant effect on car emissions: the older the fleet, the higher the average emissions.

As the name implies, unleaded gasoline or reformulated gasoline (RFG), is a refined petroleum product whose composition is similar to leaded gasoline. These properties of gasoline that have been considered to reformulate the fuel to decrease lead, exhaust mass emissions or atmospheric reactivity, include: reduction or elimination of lead content, limits on benzene, use of oxygenated additives and limits for a number of previously uncontrolled components and properties (Walsh, 1991). Attempts to reformulate gasoline have generally been carried out with parallel efforts to keep octane ratings constant. When doing this, it is often not possible to vary the individual fuel components independently; if one component is decreased or removed, it must be replaced with others to maintain octane value (Leal-Santa Ana, 1992; Calvert et al., 1993).

RFGs have been introduced into limited markets, particularly, those that have both photochemical smog problems and rich economies. The latter because the cost to renew the car fleet and the cost of the RFGs. The potential for using RFGs is relatively new, and their compositions could evolve further. Also, it needs to be determined to what degree automobile control systems and fuels can be matched to lower emissions. In fact, the possibility of reducing total vehicular emissions of hydrocarbons (HCs) and nitrogen oxides ($NO_x = NO + NO_2$) by using different blends of reformulated gasolines is still explored (Treiber et al., 1998).

3. Mexico City Metropolitan Area: a real study case

In Mexico, 76.7% of the population live in urban areas. Mexico has three mega cities with population ranging from 1.5 to 8.0 million; MCMA alone has more than 18 million people. It is expected that this urban region is going to be one of the 20 largest urban regions of the world by the year 2015. At the present MCMA is ranked fifth after Tokyo, Shanghai, Jakarta and Beijing (Gilbert, 1997) and suffers serious problems of air pollution (Table 1). Gilbert (1997) suggests that MCMA must be considered as the urban region that may have the worst ozone air pollution in the world.

More than 30,000 industrial establishments are located in the MCMA. There are 12,000 commercial/service facilities utilizing combustion processes (restaurants,

Table 1
Air quality in 10 largest urban areas, based on a subjective assessment of monitoring data and emissions inventories (adapted from Gilbert, 1997)

Megacity	SO_2	TSP	Lead	CO	NO_2	O_3
Bangkok	*	***	**	*	*	*
Beijing	***	***	*		*	**
Jakarta	*	***	**	**	*	**
Los Angeles	*	**	*	**	**	***
Metro Manila	*	***	**			
MCMA[a]	*	***	*	*	**	***
New York	*	*	*	**	*	**
Seoul	***	***	*	*	*	*
Shangai	**	***				
Tokyo	*	*		*	*	***

***Serious problem: WHO guidelines exceeded by more than a factor of two.
**Moderate to heavy problem: WHO guidelines exceeded by up to a factor of two; short term guidelines exceeded on a regular basis in some places.
*Low pollution: WHO guidelines normally met; short term guidelines may be exceeded ocassionally.
[a]MCMA air quality modified by the authors after reviewing recent data of air quality of the region.

bakeries, hotels, etc.) and a large number of non-combustion sources such as dry cleaning, printing and solvent use facilities.

By 1993, the transportation sector was estimated to have 2.6 million private vehicles, 56,500 taxicabs, 7500 buses, 54,500 collective transport vehicles, 196,000 gasoline-fueled trucks, 60,000 diesel-fueled trucks, including railway and airport facilities. All these activities require fuel. Approximately 20 million liters of gasoline and diesel, 1.8 million liters of low-sulfur fuel–oil and 310 million cubic feet of natural gas are consumed each day (Streit and Guzmán, 1996). Table 2 shows the estimated annual emissions by 1994. Daily emissions together with local topography and meteorological conditions in this region result in the trapping of air and build-up of pollutant air to create exceptionally high concentrations of ground-level ozone (Bravo et al., 1994). High altitude of the MCMA (2240 m.a.s.l.) combined with both high ozone levels and exposure time doses, have aggravated many of the health effects, particularly those related with respiratory system (Calderón-Garcidueñas et al., 1992; Fortoul et al., 1995).

As shown in Table 2, vehicles are the largest source of pollutant emissions in the MCMA. The large contribution of the transport sector has been attributed to various factors, including:

- lack of stringent pollution control standards for vehicles in the past;
- unfavorable fuel properties, including high sulfur content of diesel and gasoline, and unnecessarily high volatility of leaded and unleaded gasolines;
- rapid urbanization, resulting in increased demand for road transport;
- localized traffic congestion, producing "stop-go" driving conditions.

Rapid economic growth in the 1960s, 1970s and early 1980s, together with severe economic problems which started in the mid-late 1980s and collapsed in the mid 1990s, are reflected in the age structure of the vehicle fleet. By 1990, the estimated median age of the fleet was around 10 years. However, it has been suggested that after the Mexican economic crisis of 1995 the median age has been risen to around 12 years. There is not necessarily a link between vehicle age and poor maintenance. A number of older non-catalyst vehicles and a substantial fraction of "new" vehicles equipped with catalytic converters (i.e. taxicabs and minibuses), are in poor mechanical conditions, building up an important fleet of "super-emitters". Between 50 and 70% of total mobile-source emissions are produced by high-use commercial vehicles such as trucks, taxicabs and public collective transportation (minibuses).

In the last 15 years, the MCMA has suffered a variety of difficulties in controlling automotive emissions. Although officials identified the problem and took action, they have been politically hastened to adjust to the real scale of the technological and economical situation. From the start, PEMEX, the Mexican oil monopoly, was pressured by non-governmental groups to eliminate lead from gasolines because of the high levels of lead observed in the air of the MCMA (Bravo, 1987). Airborne lead levels greater than 3 $\mu g\,m^{-3}$ were currently observed prior 1986. In the mid-1986, PEMEX had to reduce the lead content of leaded gasolines sold in MCMA from 3.5 ml tetra ethyl lead/gal ("Nova" gasoline with 80 octanes) and 0.1 g Pb/gal ("Extra" gasoline with 92 octanes) to 0.5–1.0 ml tetra ethyl lead/gal ("Nova Plus" gasoline with 81 octanes) and 0.05 g Pb/gal ("Extra Plus" gasoline with 92 octanes), respectively (Leal-Santa Ana, 1992). Nevertheless, due to technological limitations, PEMEX had to reformulate gasolines by rising the content of high alkyl isomers and alkyl aromatic fractions (PEMEX, 1987).

Although not supported with an air quality impact study, this reduction in tetra ethyl lead content brought the expected reduction in the atmospheric lead levels. The annual mean concentration of airborne lead went down from 2.5 $\mu g\,m^{-3}$ in 1986 to 1.5 $\mu g\,m^{-3}$ in 1987 (Bravo, 1987). However, an unexpected impact on the air quality emerged. Combustion of gasolines formulated mainly with isomers, alkyl aromatic hydrocarbons, olefins and short isoparaffins produce highly reactive HCs such as ethylene, propylene, butenes and others such as alhylbenzenes. As a consequence, ozone levels increased disproportionately in relation to the levels of this oxidant observed before the introduction of these "new" gasolines. Fig. 1 shows how after the introduction of RFGs, the ozone has become the "real big" air pollution problem in the MCMA.

Table 2
Estimated annual pollutant emissions in the MCMA in 1994 in ton yr^{-1}

Source category	PM	SO_2	CO	NO_x	HCs	Total	%
Industry	6385	26,051	8,696	31,520	33,099	105,724	2.9
Commercial/service	1077	7217	948	5339	398,433	413,014	11.7
Transport	18,842	12,200	2′348,497	91,787	555,319	3′026,695	85.4
Total	26,304	45,468	2′358,141	128,646	986,841	3′545,383	100

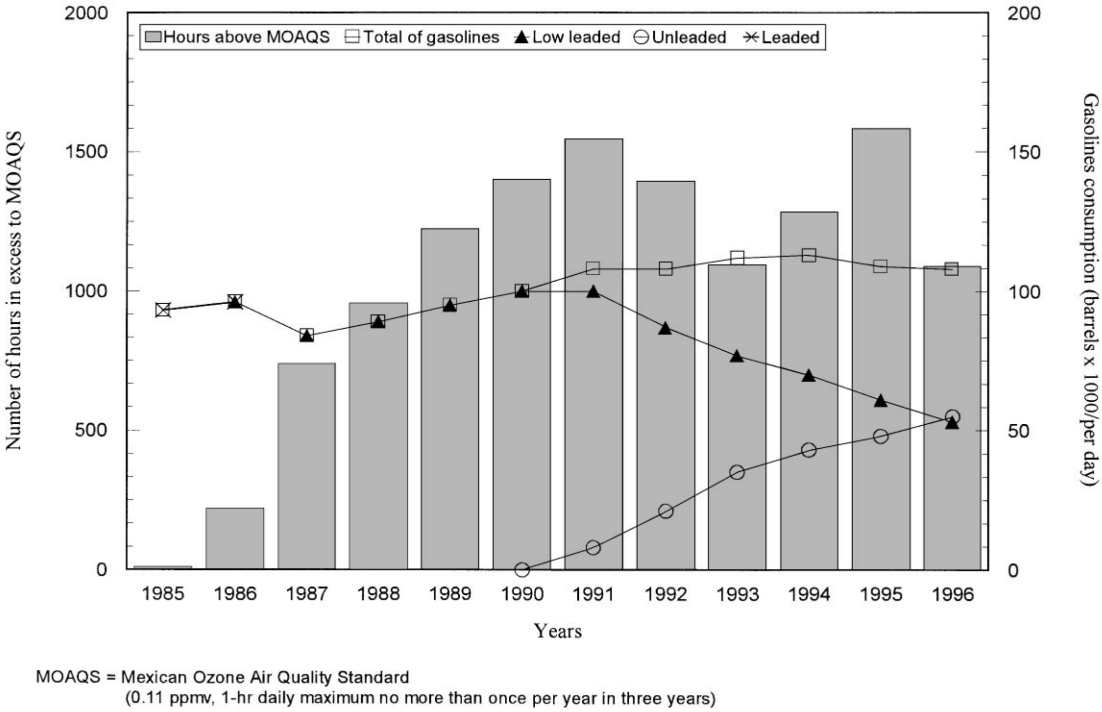

Fig. 1. Annual hours in excess to Mexican Ozone Air Quality Standard at the University of Mexico Monitoring Station and annual average of daily consumption of gasolines in Mexico City Metropolitan Area between 1985 and 1996.

In November 1989, in a further political move by the Mexican authorities to reduce atmospheric carbon monoxide and hydrocarbon concentrations, two new RFGs containing 5% of MTBE were introduced in MCMA (Leal-Santa Ana, 1992). Once again, this action was performed without an air quality impact study and a new change in HCs reactivity was observed. Formaldehyde and ozone concentrations were monitored before and after the introduction of these oxygenated gasolines by Bravo et al. (1991). Their results showed that the noon formaldehyde peak observed prior to the addition of MTBE changed to the morning-traffic hours. This was associated to an increase in the emissions of formaldehyde from mobile sources. The ozone data also showed that the time of occurrence of the O_3 peak concentrations did not change but there was a definitive increase in ozone concentrations in mid morning and evening. The above led to conclude that the introduction of MTBE in gasolines used by a nearly old non-catalyst fleet, increased levels of formaldehyde in MCMA and gave place to an increase in photochemical activity.

In 1990 Mexican government declared its policy to move towards adoption of USA emissions standards for all vehicle classes. This forced policy was adopted both, to improve air quality by decree and in anticipation of the by then proposed Free Trade Agreement with USA and Canada. New passenger cars and light-duty trucks sold in Mexico had not been subjected to stringent exhaust emissions standards until the 1991 model year (Table 3). However, 1991 standards were such that they could be met even without the use of a catalytic converter or other advanced emission control technologies. The 1991 and 1992 car models constituted a transition period during which more stringent emission standards were established making necessary to install catalytic converters, but not the advanced control systems required on USA vehicles.

In order to adjust to this mandate, PEMEX introduced the "Magna Sin" gasoline which was another "new" different RFG of higher octane, unleaded grade, with specifications very similar to USA unleaded regular. At the end of this year, the low leaded "Nova" gasoline (0.2–0.3 ml tetra ethyl lead/gal) and the unleaded "Magna Sin" gasoline (0.01 g lead/gal), both containing 5% of MTBE, were the only gasolines sold in MCMA. However, the differential pricing between both gasolines encouraged misfueling catalyst-equipped vehicles with leaded gasoline – a practice that destroys the effectiveness of the catalyst and greatly increases HCs reactive emissions. This practice was commonly observed in catalyst-equipped vehicles destined for high-use applications such as taxis and minibuses. The large differential pricing also

Table 3
Mexican emission standards (new vehicles)

Model year	Exhaust emissions ($g\,km^{-1}$)		
	HCs	CO	NO_x
1975	2.5	29.2	Not regulated
1976	2.1	24.2	Not regulated
1977	2.6	24.2	2.2
1988	2.0	22.2	2.3
1990	1.8	18.0	2.0
1991	0.7	7.0	1.4
1993 on	0.25	2.11	0.62

acted to discourage purchases of new catalyst-equipped vehicles. Meanwhile the ozone levels kept growing as well as the gasoline sales (Fig. 1). The increase in the gasolines sold was attributed to an unexpected growth of the old vehicle fleet as an economical response of the public to the official program "a day without a car" in which all non-official vehicles were prohibited from operating on one workday per week. Because of the lack of a good public transportation system in the MCMA, this program led people to buy older cars.

After 1991, a stabilization on sales of RFGs was observed. The consumption of leaded gasoline started to decrease and the unleaded gasoline began to increase but no sustained benefits on air quality were observed. By 1993, the exceedences to the ozone air quality standard showed a decrease. Two possibilities have been attributed to this phenomenon. One of these was attributed to a relative increment of newer catalyst-equipped cars and the other to a meteorological anomaly observed in this year in central Mexico. However, contrary to official expectations, the ozone levels once again rose until 1995, when a reduction and stabilization in exceedences to the ozone air quality standard was observed. It must be mentioned that the quarterly average airborne lead concentrations after 1993 have gone down to values below 0.8 $\mu g\,m^{-3}$ in MCMA, almost half of the Mexican lead air quality standard of 1.5 $\mu g\,m^{-3}$.

Nevertheless by 1993, PEMEX was required to perform air quality impact studies for every new gasoline plant project by the Export–Import Bank and the World Bank, in order to obtain the financing for construction. The objective of these studies was to evaluate the benefit of the proposed new gasolines on air quality of MCMA. Several analytical and modeling studies were performed by the Mexican Petroleum Institute (IMP) on both, the expected emissions of the primary pollutants CO, NO_x and HC from a composite catalyst and non-catalyst fleet, and the ozone potential of such emissions from a series of gasoline mixtures. Although the whole results of such studies were not available to the public domain, PEMEX claimed that their "new" leaded and unleaded gasolines would reduce the emissions of the primary pollutants on both catalyst and non-catalyst cars. However, economical and political pressures, led PEMEX to adopt specifications of RFGs similar to those of USA (Table 4). Although PEMEX has made an effort to reach the quality of RFGs of the USA, the relatively high content of sulfur in Mexican gasolines, has diminished to some extent, the potential benefits of such reformulated gasolines because of the known bad effects of sulfur on catalytic converters.

On the other hand, the economical crisis of Mexico at the end of 1995, brought about a reduction in the purchasing power of the public to buy new cars. It is estimated that by 1997 the 65% of the total fleet were non-catalyst pre-1991 model cars. In addition, the lack of regulations to check in-use emission controls favored the growing of the "super-emitters" fleet. Next, in spite of all the above technological limitations and environmental consequences, in 1998 the sale of low leaded gasoline was pulled off of the market of MCMA. Since this year, two "new" unleaded RFGs ("Magna" and "Premium") are sold in this megacity. The difference between both RFGs, apart from the octane number, seems to be the paraffins and isoparaffins content because the olefinic and aromatic content seems to be the same (see Table 4). According to PEMEX, these RGFs are fulfilling the top international specifications. However, ozone levels still remain high, as illustrated in Fig. 2, which shows the ozone concentrations recorded along a typical week of July 1998, at a smog receptor site of the MCMA.

The environmental impact of ozone air pollution along the last 15 years in MCMA, also has had a large hidden cost. Margulis (1992) quantified the health effects of pollutants in this megacity by means of standard dose–response curves. This author calculated the economic costs of pollution, by integrating the average individual costs associated with the levels of each pollutant. The estimated total annual cost related to ozone pollution was US$ 102 million per year. On the other hand, important effects of ozone air pollution on tree vegetation surrounding the MCMA have been observed since 1985. The *Abies religiosa Schl.* trees in the Desierto de los Leones Forest, located downwind from MCMA, nowadays show a significant reduction in their vigor, manifested by a considerable loss of branches and leaves which eventually leads to their death (Alvarez et al., 1998).

4. Discussion

One challenge of RFGs as clean fuels has been how their composition may improve air quality of urban regions. Unfortunately, there have been few detailed published studies about the air quality impacts of RFGs

Table 4
Comparison of characteristics of reformulated gasolines for Mexico and USA

Parameters	PEMEX Magna Sin NOM-086[a] 1995	USA Federal ASTM D-4814 1993	CARB[b] June 1996	PEMEX Premium[c] 1998	PEMEX Magna[c] 1998
Vapor pressure, psi	6.5–8.5	Max. 7.8 Denver	6.8 max	6.5–7.8	6.5–7.8
Distillation temperature (°C)					
10% (maximum)	65	70	—	—	—
50%	77–118	77–121	93 max	—	—
90% (maximum)	190	190	143	—	—
Final boiling temperature (°C)	221	225	—	—	—
Sulfur (% weight) (maximum)	0.10	0.10	0.003	0.05	0.05
Lead, kg m^{-3} (maximum)	0.0026	0.013	—	—	—
Octane (R + M)/2 (minimum)	87	87	87	92	87
Aromatics (% vol) (maximum)	30	—	22	25	25
Olefins (% vol) (maximum)	15[d]	—	4	10	10
Benzene (% vol) (maximum)	2	—	0.8	1.0	1.0
Oxygen (% weight)	1–2	—	2 min	1–2	2 max

[a]Official standard for Mexico since 1995.
[b]California Air Resources Board.
[c]Source: Centro de Estudios del Sector privado para el Desarrollo Sustentable (1998) "Normatividad Ambiently Emisiones Vehiculares en México", México, DF, Septiembre.
[d]Since January 1998, the maximum % vol changed to 12.5.

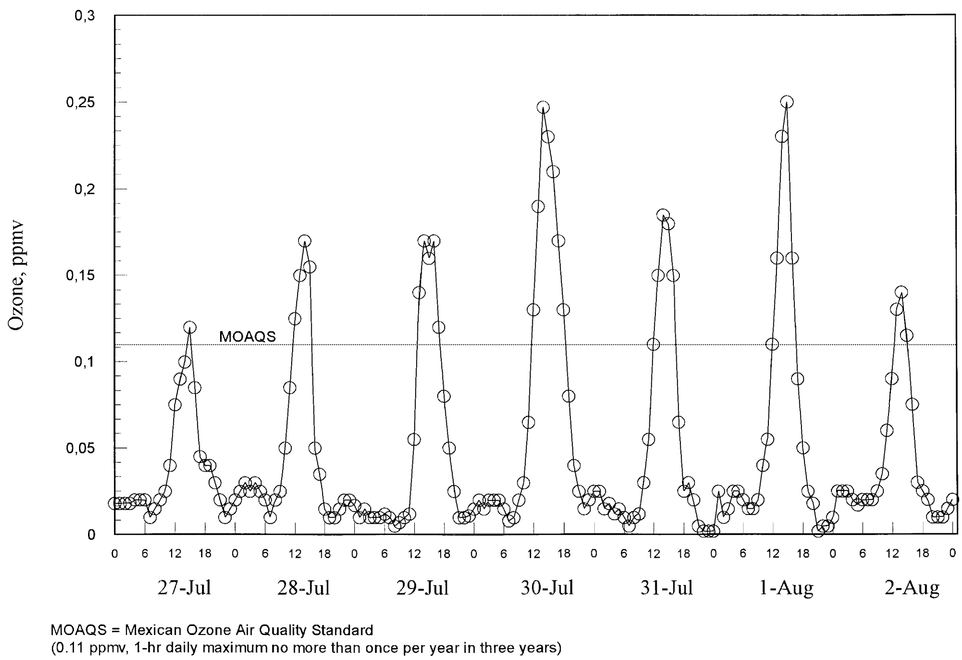

Fig. 2. Hourly ozone concentrations recorded at the University of Mexico Monitoring Station for the period 27 July–2 August, 1998.

(McGinty and Dent, 1995). Two of the most interesting studies about the predicted impact for variation in gasoline composition are from the Auto/Oil Air Quality Improvement Research Program (Koehl et al., 1991; Hochhauser et al., 1991). One of these studies includes the results of testing the effects of varying fuel compositions on emissions composition and quantity, and the modeling of the changes in air quality that would accompany the use of the various fuels. The results showed that changing fuel composition could have an effect on air quality, due to the change of mass emissions of HC, NO_x and CO, as well as the reactivity of the HC. Also, the results of modeling for future year simulations predicted that peak ozone concentrations would be reduced only from about 1% to 3% in response to gasoline changes. Similar effects have been observed in MCMA.

The lesson learned on hastening the change of fuels and vehicular technology in countries with economical problems such as Mexico, indicates that far from taking away air pollution problems as has happened in developed countries, there have emerged other problems even more difficult to solve. For the above reasons, developing countries should make a thorough evaluation of the potential environmental and economical implications related to the change in fuel composition. A good and honest air quality impact study may prevent a serious damage to the air quality of an urban region. On the other hand, substitution of leaded gasolines by RFGs requires the adoption of various expensive measures. However, international organizations such as the WHO/UNEP are insisting developing countries to phase out lead in gasolines within short terms (Mage et al., 1996). But, if the lead pollution levels present in a region do not exceed local and international air quality standards, why force developing countries to unleaded fuel policies?

5. Concluding comments

Policy decisions at governmental level are often made for political expediency reasons without a basic understanding of the effect of the proposals. This has become more frequent with the advent of vociferous environmental lobbies who generate heated public debates in which it becomes difficult to introduce scientific objectivity. This is particularly true for developing countries where decisions are frequently taken over without testing for compatibility with local environmental and economical conditions. A living lesson of the latter is MCMA, where the hastened introduction of reformulated unleaded gasolines have resulted in the worsening of its air quality. Introduction of RFGs requires a radical change in the vehicular fleet in order to be successful to improve the air quality. Otherwise, severe photochemical problems may arise. However, the costs and times associated with such air pollution control strategies are incompatible with the economy of the majority of the developing countries.

Although alternative fuels as methanol, ethanol, reformulated gasoline, liquefied petroleum gas and liquefied natural gas may be used in the most seriously polluted areas of the world as an option to improve air quality, the usefulness to perform well documented air quality impact studies, as part of the policy to change the use of leaded gasolines, will never be out of place. The experience of MCMA should be taken as an example for other developing countries that are moving toward the use of RFGs.

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