ENERGY AND INFRASTRUCTURE POLICIES FOR MITIGATING AIR POLLUTION IN MEXICO CITY

by

Juan Alberto Leautaud
Bachelor of Science in Civil Engineering
Universidad Iberoamericana, A.C. (1993)

and

César Pérez-Barnés
Bachelor of Science in Chemical Engineering
Universidad Nacional Autónoma de México (1992)

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Signature of Co-Author________________________________
Department of Civil and Environmental Engineering
January 31, 1997

Signature of Co-Author________________________________
Technology and Policy Program
January 31, 1997

Certified by ________________________________
Professor Fred Moavenzadeh
Thesis Supervisor
Director, Technology and Development Program

Accepted by________________________________
Professor Richard DeNeufville
Chairman, Technology and Policy Program

Accepted by________________________________
Joseph Sussman
Chairman, Department Committee on Graduate Studies

Submitted by:
Juan Alberto Leautaud
César Pérez-Barnés

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THESIS ABSTRACT:

The purpose of this study is to use the systems dynamics methodology to analyze the dynamic interactions between the transport sector and ozone pollution levels in Mexico City. Pollution by ozone is a persistent environmental problem with serious health effects for the population. In 1995 ozone concentration levels exceeded the safety norm 132 days of the year affecting 9 % of the population and resulting in health costs over US $100 million.

Government policy strategies have been successful in the mitigation of other pollutants such as lead and sulfur oxides. However, they have had limited results in the case of ozone. Since 1990 the government has insisted in the implementation of command and control policies that face the problem in a static an isolated manner. The most recent government program acknowledges the dynamic nature of the problem. Nonetheless, it has so far failed to produce a tool able capture this dynamics and derive policy implications from them.

A systems dynamics model was developed based on two dynamic hypotheses that captured the congestion and the transport supply dynamics of the city. The model estimates the demand for different transportation mode choices following the disaggregate mode choice modeling methodology. It tracks the emissions of each of the modes as a function of fuel qualities and engine and emissions control technologies. And finally it estimates the resulting tropospheric ozone concentration by interpolating a relationship between ozone and its precursors (NO_x and hydrocarbons) concentration levels on a particular day with unfavorable meteorological conditions.

Four main conclusions arise from this work. First is that current public policy analysis tools are insufficient to capture the dynamic interactions in the city. Second, there is no a priori benefit in choosing either command and control or economic incentives instruments since both showed instances of policy resistance behavior. Third, the removal of the transit restrictive program, "day without a car" would have a substantial impact on ozone concentration reductions with manageable short term consequences. Finally, results suggest that it is improbable to achieve dramatic reductions of ozone concentrations within the next 20 to 25 years.

<u>Thesis supervisor:</u>
Professor Fred Moavenzadeh Director, Technology and Development Program

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PUBLIC POLICY IMPLICATIONS OF AIR POLLUTION

The characteristics of economic development determine to a large extent the way in which natural and environmental resources are used. In Mexico, the development model has favored industrial growth with intensive energy consumption as well as the expansion of urban centers. Both industrialization and urban growth are substantial in determining the demand for environmental resources.

At least part of Mexico's economic growth has depended on the supply of raw materials at low costs. In particular for energy and fuels, often prices have not reflected the total operational, let alone the environmental and societal costs. This puts a high pressure on the environmental resources.

As an aggravating factor, environmental management is relatively new in Mexico, which implies that the institutions in charge of environmental policy do not yet have sufficient experience, nor have they defined with sufficient clarity their objectives, to be effective in their purpose. Other times these authorities have to battle with others whose objectives are ones of shorter term and thus get more relative weight in the decision making process.

Air pollution is an extremely important problem in Mexico City as dangerous levels have been reached and sustained by certain pollutants, in particular ozone (O_3) and particles (TSP). Even though it is clear that environmental management policies are needed and demanded by the population, urban air quality is a complex problem that depends upon different factors such as fuel prices and qualities, industrial development and growth and increasing transport requirements among others. It is not always clear which is the correct way about how to design and implement environmental policies.

A continuing debate exists in environmental economics concerning the merits of two control strategies: Command and control regulations (CAC) and Market based or economic incentives (EI). The CAC or regulatory approach is based on the issuance or enactment of orders by a government agency in order to regulate pollution emissions, by binding polluting agents to do (or not to do) something. It is known in the United States as the application of the "Best Available Control Technology" (BACT). The regulations can also cover the following issues:

- Pollution discharge bans related to pollution concentration measures or damage costs
- Limits in terms of maximum rates of discharge from pollution source
- Specification of inputs or outputs from a given production process

Economic instruments are those which affect the agents' private costs and benefits, and in principle, encourage the economically rational polluter to change its behavior by balancing less payments (of, for example, a pollution tax) against increased costs incurred in curtailing pollution discharges. Early economic work in the field of pollution control showed, given certain assumptions, that the most efficient or most cost effective way to achieve a particular level of environmental quality is through the imposition of economic incentives instruments. [1]

However, when we introduce criteria such as distributional equity and/or ethical considerations (for instance, the concept of charging a fee as a license to pollute is not unanimously accepted as ethically correct), then the case becomes less clear cut. [2]

Following is a brief overview of the environmental management implications of various air pollution problems, both on a global and on a regional scale.

Command and Control strategies: Stratospheric Ozone depletion

Ozone has a double role in environmental problems. While it is a harmful pollutant in the low atmosphere or troposphere, in the stratosphere (high atmosphere between 15 and 35 Km) it serves as a filter for ultraviolet solar light. The stratospheric ozone layer serves as a natural shield by absorbing radiation with wavelengths in the 280-320 nm range that can be harmful to biological organisms. [3]

Ozone is produced by the photochemical decomposition of a molecule of oxygen

$$O_2 + h\nu \rightarrow 2O$$

In turn, the highly reactive Oxygen atom combines with O_2 and forms Ozone

$$+ O_2 \rightarrow O_3$$

Ozone, in turn, can be destroyed by absorbing another photon that breaks it into an oxygen molecule and atom.

$$O_3 + O + h\nu_2 \rightarrow O_2 + O$$

Thus, UV radiation gets absorbed by the formation and destruction of ozone.

Chlorofluorocarbons, such as CFC-11 ($CFCl_3$) are chemical products that are extensively used in compression and refrigeration systems, as well as in aerosol propelents foaming agents. Unlike most chlorine containing species, CFC's are virtually inert at tropospheric level, which is one of the properties that make them useful products.

CFC's have long enough tropospheric lifetimes to eventually reach the stratosphere. There, under the high energies of UV radiation, they liberate chorine atoms from the

CFC's molecule. In turn, Cl atoms are attracted to the ozone molecules. As a result of this process, ozone decomposes in a chain reaction that alters its formation-destruction cycle and leads to a concentration reduction.

Concern about the diminishment of stratospheric ozone began almost two decades ago. Molina and Rowland (1974) [4] proposed that human activity played a major role in O_3 depletion via the release of CFC's. In 1978, the United States banned the use of CFC's as propellants in aerosol sprays. Concrete evidence of the dramatic decrease in stratospheric ozone over the polar regions was first obtained in 1985, when a team from the British Antartic survey reported that average ozone concenrations were decreasing by 60%. The current Antartic Ozone hole is a region between 12 and 25 Km in altitude depleted of O_3 as a result of the degradation of ozone by chlorine, which is released into the atmosphere through human production of CFC's.

An important political reaction stemed from these discoveries. The Viena Convention for the Protection was created in 1985 under the sponsorship of the United Nations. In September 1987, in Montreal, the worlds largest producers of CFC's agreed to reduce production up to 50% by the year 1998. This turned the Montreal protocol into one of the most successful international environmental policy agreement in history. Furthermore, it presented an example of the successful application of a command and control regulatory strategy.

The Montreal protocol still leaves at least two reasons for concern. First, the residence time of CFC's and other halogen carrying substances makes further reductions necessary. Most experts agree that 85% of production must be eliminated only to stabilize atmosferic conditions to current levels.

Second, some countries with CFC production capacity have not signed the Montreal Protocol, or even the Viena Convention. Of this group of countries the two largest are China and India.

The CFC's policy success was heavily dependant on the significant amount of scientific evidence about the cause and effects involved and the affordability of replacing CFC's.

Economic instruments or market strategies: Acid deposition

One example of a successful economic incentives mechanism is the creation of tradable emission permits for SOx emissions. An interesting aspect of market strategies lies in that they set an acceptable standard of pollution (in the same spirit as the command and control approach does), but they leave the polluter the flexibility as to how to adjust to this standard. This mechanism has been in place for SOx emissions since the 1970's US Clean Air Act and has been expanded under the New Clean Air Act of 1991.

Acid Rain refers to the low pH precipitations that have been observed in certain industrial regions, particularly in northern Europe, the U.S. and Canada. It received widespread public attention through the 1980's, due to concern about its effects on freshwaters and their associated fisheries, forests, structures and materials, human health and crops. Acid deposition refers to the direct deposition of acidic substances from the atmosphere and has caused the acidification of some lakes and streams, and a consequent loss of fish populations, specially in soft water lakes in acid sensitive regions such as the northeastern United States and Southern Scandinavia. Severe forest damage has been attributed at least in part to acid deposition, specially in central Europe. Many questions about acidic deposition remain unanswered, in particular, the quantitative relationship between acid deposition rates and changes in surface water chemistry.

The largest contributors to atmospheric acid deposition are sulfuric acid (H_2SO_4) and nitric acid (HNO_3). Most of the acids are emitted to the atmosphere in the form of precursors, typically sulfur oxydes (SOx) and nitrogen oxides (NOx), which can be further oxidyzed in the atmosphere to form acids, in particular sulfuric acid H_2SO_4) and nitric acid (HNO_3). The sulfur oxydes originate from sulfur-containing impurities in fuels, notably coal and residual fuel oils. Nitrogen oxydes have two sources; they originate from nitrogen containing impurities in fuels and as the product of reaction between atmospheric oxygen and nitrogen at elevated temperatures in fuel burning equipment, such as industrial boilers, stationary power plants, and automobile engines. In addition to their roles as acid precursors, both SOx and NOx are toxic and irritating

In any case, different regulation approaches tend to converge on taxing the emission of acid deposition precursors in amounts equal to the cost of avoidance. In the case of regulated industries like electricity generation, succesful control policies of precursors like SO_x have included internalizing the costs of removal and charging them, at least partially, to the final consumers and the creation of tradable permits. The internalization of environmental costs is charged to the final consumer by allowing tariff levels that ensures a return over the cost of capital to the utility. The tradable permits system ensures that the precursor emission levels within a region stay within stablished standards by the use of bubbles.

Bubbles, introduced in 1979, are perhaps the most famous part of the US tradable permits system. A bubble is a hypothetical aggregate limit for existing sources of pollution. Within the limits of the bubble, firms are free to vary sources of pollution so long as the overall limit is not breached. Instead of using the CAC approach, the regulator can then issue permits for discrete amounts of pollution and allow firms to trade. This means that the permits will have a market value since they can be bought and sold and that these permits will be traded because the marginal cost of emission reductions can be different for every firm.

The polluting plant would then pay a certain amount to the non polluting plant, this has at least a double benefit. On one hand, the polluting plant incurs in a less intensive cost than by the addition of the equipment, on the other hand the non polluting plant can afford to invest in scrubbing technologies that are cleaner than the standards. Overall, this system provides greater flexibility to utilities at the same level of environmental impact.

Permit trading is the central feature of acid rain control in the US. In 1994, Mexico approved the creation of a market of exchangeable permits for the control of sulfur bioxide in inmobile sources (Norm 086). The objective is to control SO_2 emissions by means of an exchangeable permit market and a period of three years has been allowed for operations to begin. During that time, markets have to operate in designated bubbles. The bubbles, in turn, are stipulated as a function of the seriousness of the local emissions problem. One of these bubbles comprises the Federal District and surrounding urban municipalities.

Uncertainty and complexity: Greenhouse gases and climate change

Greenhouse gas emissions and their impact on climate represent another problem with an important international dimension and thus an added level of complexity. However, in this case, both the amount of cause-effect uncertainties and the substitution costs are much higher. Additionally, there are important obstacles to a successful economic incentives approach. This makes it a much less tractable problem from the policy maker's point of view.

If the earth had no atmosphere the average temperature on its surface would be well bellow freezing point (about-19 C). A number of gases -water vapor, carbon dioxide (CO_2), chlorofluorocarbons (CFC's), methane (CH_4) and nitrous oxide (N_2O)- in the earth's atmosphere absorb infrared radiation and act as a blanket which helps trap the heat absorbed through the atmosphere and re-emitted from the earth's surface. The consequence is that total amount of radiation striking the earth's surface is increased, so the average temperature of the surface is increased.

Economic activity (especially over the last 150 years) is increasing the rate of emissions and the concentration of green house gases in the atmosphere. The "greenhouse" analogy has been used because like glass, water vapor and CO_2 in the atmosphere is transparent to visible light (from the sun) but relatively opaque to infrared radiation being re-emitted by the earth's surface. Hence, a greenhouse is a very efficient structure for retaining solar radiation as heat. Industrialization has resulted in the intensive exploitation of fossil fuels (coal, gas, oil) for production and transportation. Burning fossil fuel releases CO_2 to the atmosphere, the concentration of which has risen by 33 percent since 1800. Agricultural and industrial activity generates other greenhouse gases, methane, nitrous oxide and CFC's.

According to the IPCC (Intergovernmental Panel on Climate Change), a body set up in 1988 to investigate global warming, the increases in greenhouse gases in the atmosphere will result, on average, in an additional warming of the earth's surface. Although the problem is not fully understood and thus no prediction can have a reasonable degree of certainty, it is widely accepted within the scientific community that there will be some temperature rise on the average.[5]

Green house gases already in the atmosphere may have caused the temperatures of the Earth's surface to rise between 0.9° C to 3° C, of which, according to some measures, only about 0.5° of which have been felt so far.

The actual size of this temperature rise, its rate of increase and its distribution around the globe are subject to considerable uncertainty. This is because our climate is controlled by two complex systems, the atmosphere and the oceans, which themselves are interrelated. But a majority of climatologists now seemed to be agreed that a further increase in the global mean surface temperature of the earth of between 2° and 5° can be expected within the next hundred years if human produced green house gas emissions double over the same time period.

Since global warming will not produce uniform effects (gains and losses) across all countries, getting political agreement on targets and the allocation of emissions reductions among countries will be difficult. Then there is the free rider problem. If global warming is reduced all countries will benefit regardless of whether they participated in the agreement and incurred the abatement costs. The potential existence of free riders means that any protocol must have built-in incentives for cooperation. This involves transferring resources-finance, technology, information- to the countries not cooperating. A CAC approach in the form of a restricting regulation will probably induce the affected agents to circumvent it.

Given these factors, economic incentive instruments-taxes and tradable permits- need to be considered. How effective is a pollution tax likely to be in reducing emission levels or rather, how high will the tax have to be set in order to be effective? That depends upon the elasticities (relative responses) of the relevant demand and supply curves. If demand for the product is highly elastic (responsive) to price and consumers can easily move towards purchasing adequate substitutes then, imposition of a pollution tax is likely to be effective. Examples of such cases might include domestic cleaning fluids which contain zinc and thereby cause contamination of waste water. Because there are many non-zinc cleaning products available if a pollution tax increases prices of polluting brands, consumers are likely to move to non-polluting alternatives.

The effectiveness of a pollution tax is likely to be much lower where demand is inelastic (unresponsive) to price changes and/or there are few suitable substitutes available. In the absence of available substitutes, the power of a tax to reduce pollution can be limited by consumers' willingness to carry on purchasing high quantities of the relevant goods even in the face of higher prices. Carbon taxes upon fuel are likely to face such problems as:

- How the permits are going to be allocated at the start of the scheme
- How large countries with massive CO_2 emissions may influence price and make the market less competitive

- How enforcement may be ensured by all participants.

One of the major difficulties in the implementation of pollution taxes are the implications for any single nation unilaterally imposing such taxes upon its own economy. If one country imposes a pollution tax on its own industries then the taxed companies will be put at a disadvantage compared to foreign competition, so that domestically produced goods will be less attractive than imports. This means that a Carbon tax is likely to be introduced on a significant scale only if it's introduced by a number of countries acting together.

Such concerted action will require some form of international agreement or treaty. However, the Greenhouse problem is difficult to regulate because:

- There are no end-of-pipe technologies
- Damage effects are anticipated but scale and severity are highly uncertain
- There is a time lag between pollution emission and environmental impact

AIR POLLUTION PROBLEM IN MEXICO CITY

Air pollution problem

Environmental degradation by air pollution in Mexico City is a complex multidimensional problem in terms of the diversity of pollutants, the diversity of sources and the interrelation between them. Air quality depends on the volume of pollutants emitted, their physicochemical behavior, and the processes (meteorological and anthropogenic) that determine their fate in the environment.

The first level of complexity is that urban air quality degradation is not related to only one pollutant as in the above cases. It rather deals with a variety of species that are harmful to human health. Some of them are direct emissions (lead, particles, etc.), others are the species that form part of chemical reactions whose end products are harmful ($NO_{x,}$, Hydrocarbons). Many have both characteristics (NOx, SOx, HC)

Here are some of the most relevant pollutants in urban spaces which cause a particular interest on Mexico City:

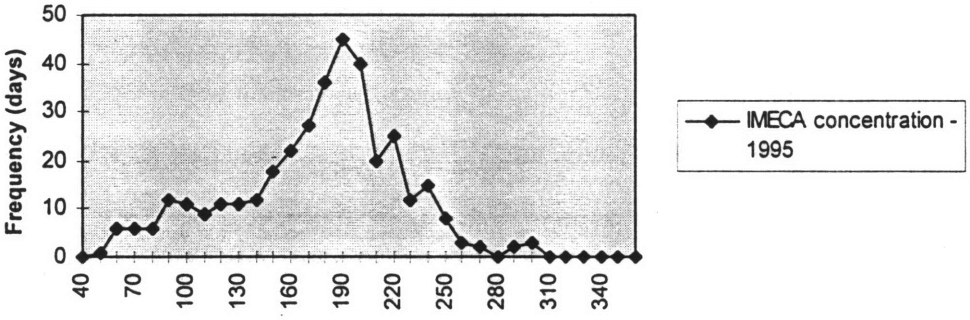
Ozone

Ozone is the best known of urban atmospheric pollutants. At ground level, ozone is associated with lung irritation and plant damage and has a serious destructive impact on forestry and agriculture. Ozone also causes the degradation of many materials such as rubber. This effect is behind the cracks in rubber objects after extended exposure.

Ozone is not an emitted pollutant. It is but the product of intermediate photochemical reactions. We will explain this process with further detail in the next section. What is worth mentioning here is that Ozone is clearly the biggest atmospheric problem in Mexico City, in terms of the number of days out of the norm and number of people exposed.

Recently, the health hazards created by high ozone concentrations have reached almost alarming levels. In 1995 the median daily value for the IMECA index was approximately 200 points. Following is the distribution of ozone levels during 1995

Histogram of IMECA concentrations - 1995



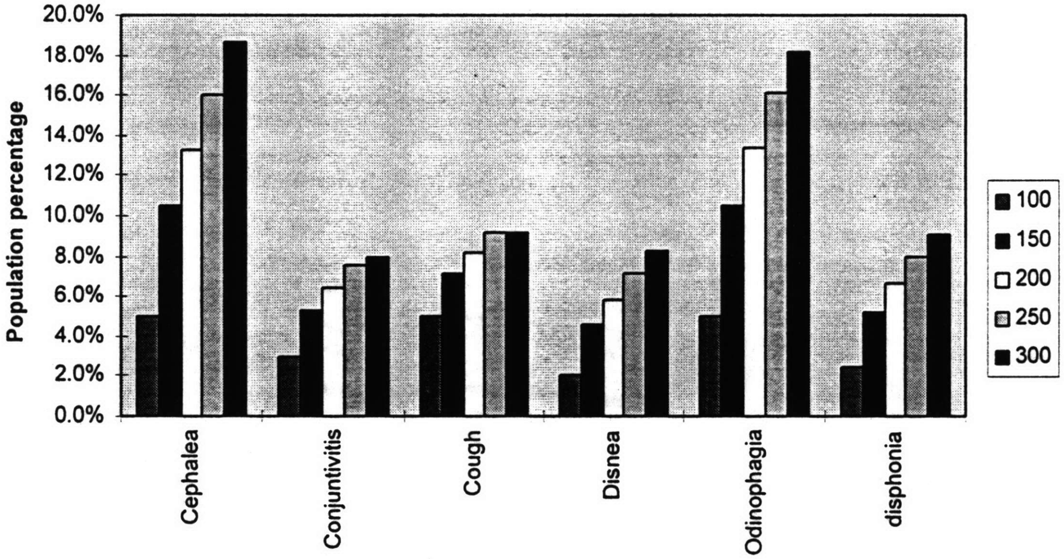
The Mexican Index for Air Quality (IMECA for its initials in Spanish) is used for measuring air pollution in Mexico City and it measures concentrations of pollutants on different scales, combining these measurements to form an index. Five pollutants are monitored daily: Ozone (O_3), total suspended particles (TSP), volatile organic compounds (VOC), Carbon monoxide (CO), and nitrogen oxides (NO_x). An IMECA level of 100 is considered to be within international standards of safety in terms of health, visibility and ecology and is equivalent to concentration levels defined in the table below. An IMECA level of 300 indicates extreme pollution conditions for which advice includes avoiding going outdoors.

IMECA Values for Ozone concentrations	
Ozone concentration	IMECA equation
0 - 0.11 ppm	909.090909 * $C(O_3)$ + 5
0.11 - 0.60 ppm	816.326350 * $C(O_3)$ +10.20409

Pulmonary effects observed in healthy humans exposed to typical urban ozone concentration include a decrease in respiratory capacity, bronchial constriction and pain. Extra pulmonary effects include hematological, neurological, hepatic cardiovascular and endocrine effects.

Even though the latency period of the symptoms can be short, exposure to high ozone levels has immediate effects on the health of the population.

Presence of health effects at different IMECA concentrations



On average, it is estimated that when pollution levels reach the 200 IMECA index value, approximately 9% of the population suffers pollution related health problems. In 1995 there were 132 such days.

Carbon monoxide

Carbon monoxide (CO) is a toxic gas produced during fuel combustion. The presence of CO may also affect the atmospheric mixing ratio of other gases by competing for oxidant species (such as the hydroxyl radical OH) thereby decreasing the oxidation rate of the other gases.

Even though CO levels in Mexico City seem to be under control, there are two points that ought to be mentioned. The first is that even though measurements at the analysis stations which show acceptable levels, many people are exposed to much higher concentrations in streets with heavy traffic and in public vehicles.

Second is that the EPA determined 9 ppm for a moving average of eight hours as the air quality norm, whereas the mexican standard is 11ppm for an eight hour moving average. Recent studies suggest that this concentration levels may have serious health consequences for pacients with a delicate heart condition.

Particles

Particles can be formed by a great variety of substances. The ones that have a natural origin are composed principally of soil, and occassionally they are originated by a biological process (vegetal and animal debris, spores etc.). Particles from combustion processes are generally ashes and atomized particles from the fuel. They have a very limited participation in the photochemical processes but they represent the most important agent in urban visibility reduction.

The air quality indicator used to evaluate atmosferic particle concentration are PST (Total suspended particles) and PM10 (< 10 micrometers). The former refers to the totality of particles in the atmosphere. The latter is an indicator that represents the fraction that can be inhaled and have health consequences. Particles represent the second most important problem of atmospheric pollution in Mexico City in terms of the number of people affected and the number of days in which the norm is exceeded.

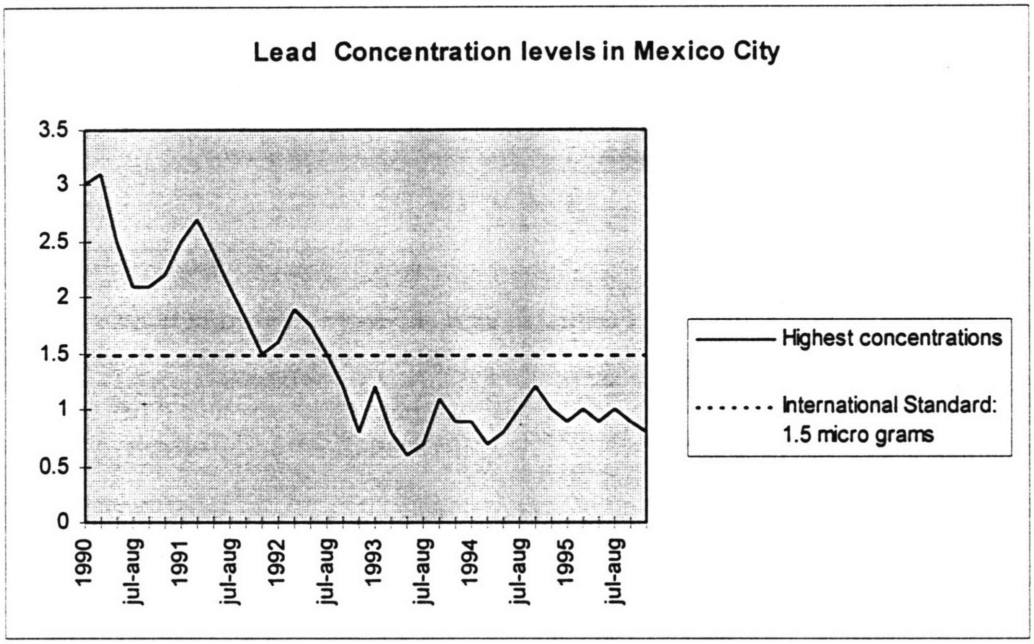
% of Observations over the standard (1986-1995)

Year	PST	PM10
1986	39.8	
1987	37.0	
1988	39.8	39.6
1989	29.9	46.0
1990	45.1	33.6
1991	61.5	5.0
1992	46.9	8.3
1993	16.1	19.0
1994	13.2	16.0
1995	15.6	12.6

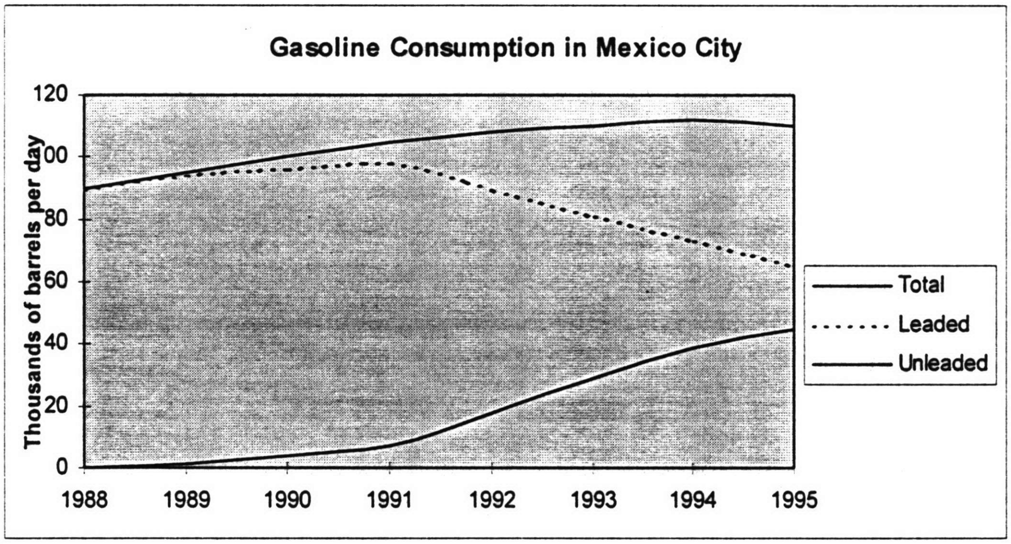
Lead

Lead has been used in the form of organic compounds such as lead tetraethyl as an octane agent in gasolines. It can be one of the constituents of particles in suspension. Its main emission source is automotive combustion. Another common source are mills. Lead is highly toxic when ingested and is accumulated in teeth, bones and the circulatory system.

Lead concentrations have been dramatically reduced as a result of several gasoline reformulations.



During the early eighties, gasoline contained an average of 0.9g/l of lead, by 1986 it went down to 0.09g/l. Additionally, non-leaded gasoline went from being 2% of the market in 1989 to a 44% in 1995. [6]



Sulfur Oxides

Sulfur oxides are produced by the oxidation of sulfur in fuels, especially coals and residual fuel oils, and as discussed in the first section, are responsible in large part for acid rain. Sulfur in fuels usually occurs as organic (R-S) or as pyrite (FeS_2). Sulfur oxides are also formed from the refining of the ores of the many metals that occur in the form of metal sulfides.

Sulfur oxides are a harmful agent as they irritate the respiratory system when inhaled. Sulfur aerosols are three to four times more irritating than SO_2 when inhaled.

From 1990 the government has achieved substantial progressive reductions in the levels of sulfur in gasolines and diesel. Current sulfur contents are equal to US EPA standards for Diesel (500 ppm max.). However gasoline sulfur content is still very high (500 ppm vs. 339 EPA 95 and 40 ppm CARB 96).

As was mentioned above, in 1994 a market of exchangeable permits for the control of sulfur bioxide in inmobile sources was authorized. This is the first attempt to implement a tradable permits control strategy in Mexico.

Pollution by Ozone in Mexico City

Health effects and costs to society

The relationship between the incidence of death and estimates of exposure to ozone, sulfur dioxide and suspended particles (TSP), has been researched by Santos Burgoa [7]. This analysis shows a positive and statistically significant relationship between mortality and the levels of ozone, sulfur dioxide and TSP registered the same day and even two days before.

Attempts to quantify the costs of deaths and diseases have also been carried out. Margulis (1992) values morbidity related costs of ozone at more than 100 million dollars per year. Combined morbidity ozone, lead and TSP costs are 100, 130 and 360 million dollars respectively. [8]

This thesis will concentrate in the ozone control policies in Mexico City since it is the pollutant that is most frequently not within accepted norms and one that affects virtually the totality of the population and a sensitive political problem in itself. It should be pointed that particles are extremely harmful pollutants, which means that although current norms are seldom breached, the damage cost is considerable.

There are two levels of complexity regarding tropospheric Ozone formation. The first one is the atmospheric chemical process by which ozone is created. The second is the diversity of sources of ozone precursors and their very different structural behavior.

Tropospheric ozone formation: process and sources

Complexity of the atmospheric chemical process

One of the first atmospheric chemical cycles to be documented in detail involves the production of high levels of ozone in the Los Angeles Basin in California. This cycle is ubiquitous in polluted air in any urban areas. The set of all possible reactions that occur is exceedingly complex. However, the two general reaction cycles in the formation of tropospheric ozone involve nitrogen oxides and other non methanic hydrocarbons. Both interact, although in different ways, with molecular oxygen to produce ozone and thus are called ozone precursors.

The O_3-NOx cycle can occur without the presence of Hydrocarbons. However the cycle is enhanced in its presence. The species involved are nitrogen dioxide (NO_2) nitric oxide (NO), molecular oxygen (O_2) and Ozone (O_3). Of these species, the only one that absorbs light is nitrogen dioxide, which is a brownish haze sometimes visible over urban areas.

Ozone is formed as the result of the fotolithic dissociation of NO_2

$$NO_2 + hv \rightarrow O + NO$$

$$O + O_2 \rightarrow O_3$$

Ozone is capable of reoxidizing NO by the following thermal (dark) reaction

$$NO + O_3 \rightarrow NO_2 + O_2$$

When the atmosphere is illuminated, tropospheric ozone levels increase until the rate of ozone destruction equals the photochemical production rate of ozone. During the night ozone levels decrease since only the dark reaction can take place.

The ozone formation during the day takes place in the presence of nitrogen oxides, which come from fuel combustion in the transport and industrial sectors. If this was the only reaction there is no way by which there could be levels of ozone higher than the NOx levels.

However, ozone concentrations measured in urban areas commonly exceed the concentrations predicted by the reactions of the O_3-NOx cycle. This reflects the fact that other oxidants are reoxidizing NO to nitrogen dioxide without consuming ozone. This oxidants are hydrocarbons that form free radicals that allow the oxydation of nitric oxydes without consuming ozone. The first reaction of this cycle is the the creation of a free radical R. (i.e. CH_3, C_2H_5 etc.)

$$\text{Hydrocarbons} + OH \rightarrow R + H_2O$$

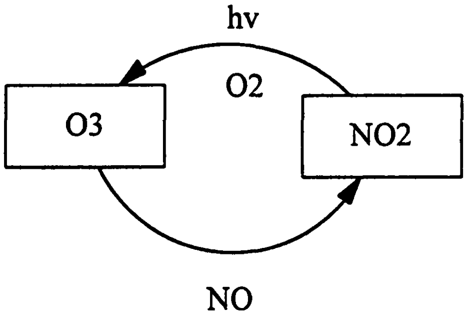
This free radical contains a free electron and reacts with an oxygen molecule from the air to form a peroxide radical (RO_2)

$$R + O_2 \rightarrow RO_2$$

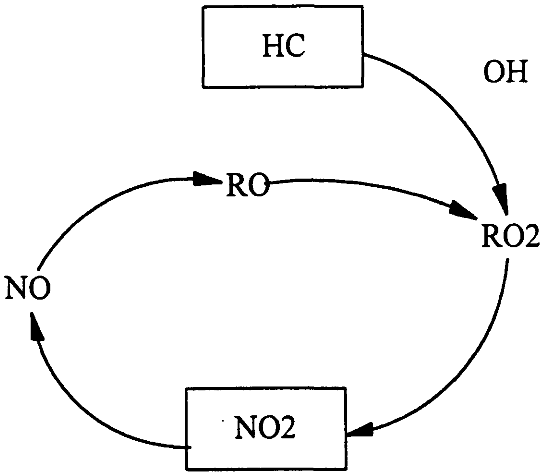
The peroxide radical reacts with NO to produce nitrogen dioxide:

$$RO_2 + NO \rightarrow RO + NO_2$$

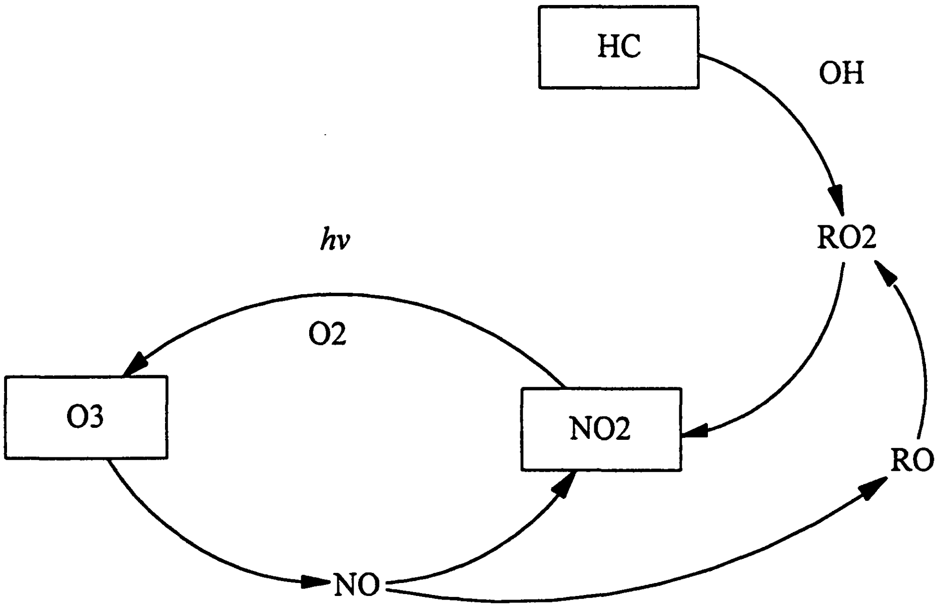
This increased level of NO_2 will induce a higher ozone formation rate. A simplified cycle can be illustrated in the following way:



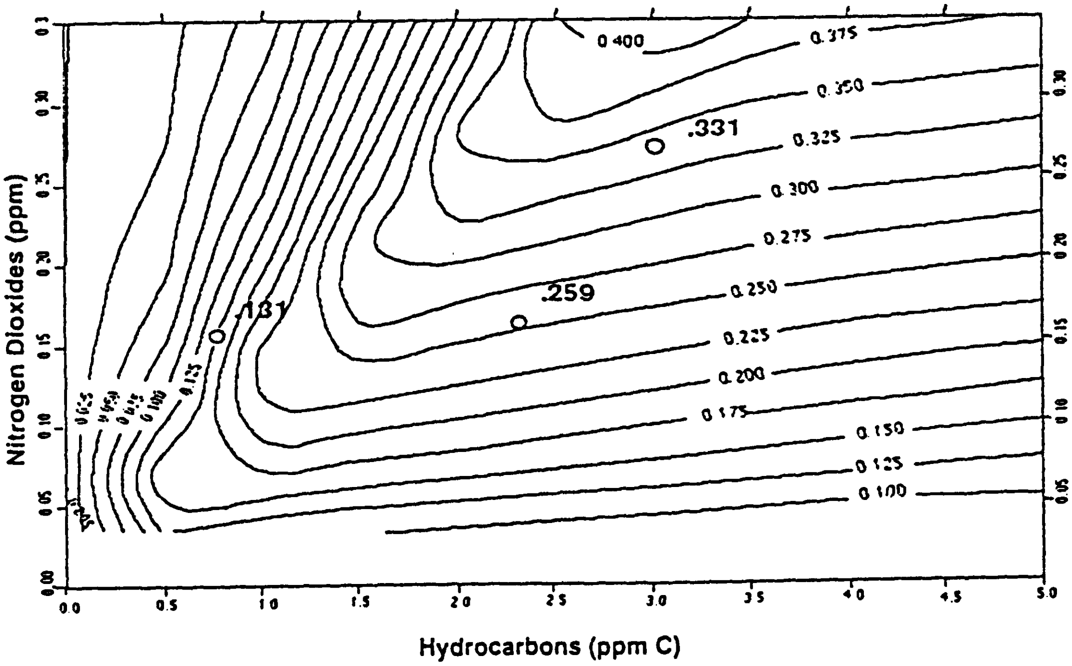
This is the primary ozone producing process, which is the NOx-O_3 cycle. Now suppose that we introduce hydrocarbons, the result will be the following NO_2 producing cycle.



This is just one of the possible pathways by which hydrocarbons can be oxydized, there are many more and the reactivity and reaction kinetics of the different species will vary. A simplified cycle would be:



Thus, one of the effects of introducing hydrocarbons is to accelerate the nitric oxide (NO) oxidation to NO_2.which in turns reacts in the light to produce more ozone. Given that the NO and free radical reaction is also a cyclic process itself, any source of free radicals will increase the reaction velocity of the cycle and, in the same way, any reaction that eliminates free radicals will slow the ozone production velocity. This makes the cycles very sensitive to the ratio of HC/NOx.



Isopleth showing the relationship between the HC and NO_x concentrations and the resulting peak ozone concentrations. The isopleth was created for conditions existing on February 22, 1991. Points indicating base conditions and conditions existing with two estimates of emission reductions are shown.

Source: [9]

The formation of ozone depends thus on NOx and Hydrocarbons in a very non linear way. For example, it has been observed that under certain conditions (low HC/NOx), an increase in NOx will result in a destruction of ozone. In these conditions, nitrogen oxides (NO and NO_2) remove free radicals that would otherwise react with the HC to eventually produce more ozone. This behavior is known as NOx inhibition effect.

A successful strategy to control tropospheric ozone levels has to rely on a policies that take into account the relative presence of the two main precursors, NOx and HC

Complexity in terms of pollutant sources

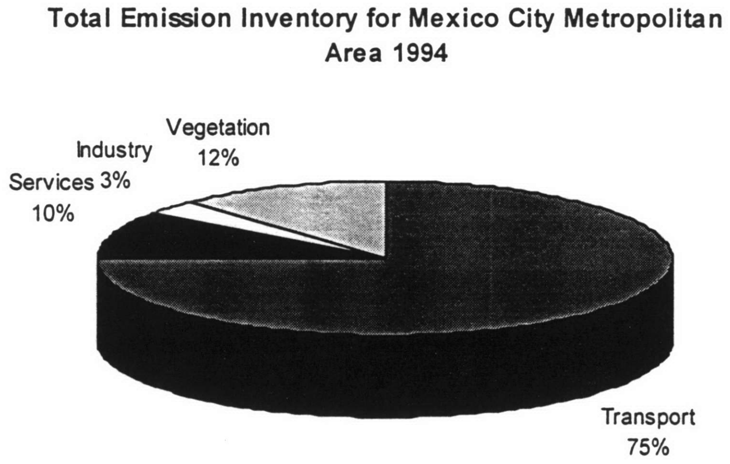
Virtually the totality of the NOx and HC emissions are related to fossil fuel utilization. The Energy balance of Mexico City is thus closely related to the emissions inventory, that is, to the total quantities of pollutants emitted over the metropolitan area. This reflects the dependency of emissions upon energy consumption.

Energy Consumption by Sector in the Mexico City Metropolitan Area (% of total consumption)

	Transport	Thermoelectric Generation	Industry and Services	Others	Total
Gasoline	41				41
Diesel	12				12
Fuel Oil					
Gasoil			2		2
LPG	3		7	10	20
Gas		9	15	1	25
Total	56	9	25	11	100

Source: [6]

The asymmetry between private benefits and public costs poses difficult problems to urban pollution control. An example is the very different nature of fuel burning agents in the metropolitan area. These include industrial, commercial and service facilities as well as mobile sources related to the public and private transport sector.[6]



Gasoline and Diesel in the transport sector hold both the largest share of both energy consumption and pollutant contributions (NO_x, HC, CO). On the other hand, electricity generation, services and industry are activities that use fuel oil, gas oil, LPG or gas as fuels and significant contributors of NO_x and SO_x.

Emission Inventory 1994

Mass % by Pollutant

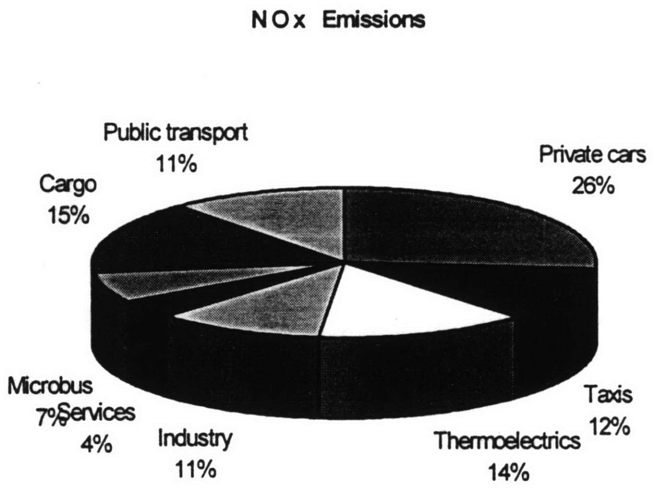
	PST	SO_2	CO	NO_x	HC
Industry	1.4	57.3	0.4	24.5	3.2
Services	0.2	15.9	0.1	4.2	38.9
Transport	4.2	26.8	99.5	71.3	54.1
Vegetation and Soil	94.2	0	0	0	3.8
Total	100	100	100	100	100

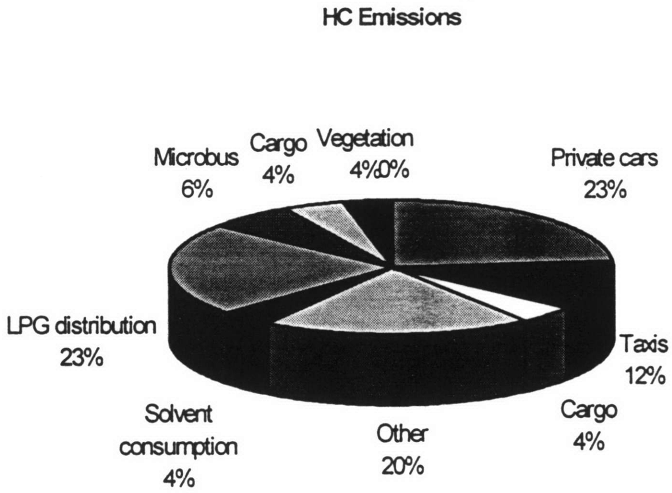
Even if fuel qualities have been improved in the past years there is still room for improvement.

COMPARED GASOLINE QUALITIES			
	Pemex Reformulated Magna	US	
		EPA 95	CARB 96
Sulfur (ppm max.)	500	339	40
Aromatics (%vol. max.)	25	32	25
Olefins (% vol. max.)	10	10.55	6
RVP (psi)	7.8	7.6	6.9
Benzene (% vol. max.)	1	1	1
Octane (R+H)/2	87	87	87
Oxygen (%weight)	1.5	3.1	2
Lead (g/gallon)	0.01	0.05	0.05

Source [19]

As we mentioned above the problem that causes greater concern among the population regarding atmospheric pollution in Mexico City is high Ozone levels. Therefore, a successful control strategy has to start with a detailed accounting of the main ozone precursors (HC, NO_x).





Source: [6]

Sources of ozone precursors can be grouped into fixed and mobile. As shown in the above graphs, the transportation sector, particularly private cars, is the largest contributor to HC and NO_x emissions. [6]

Stationary sources

Industrial

Industry is the highest contributor of SO_2 emissions and is a large NO_x contributor. It is the second sector in importance in terms of total emissions. Furthermore, emissions are concentrated in a small fraction of the plants.

In 1994 there were more than 30,000 industrial facilities. Of those, 4,623 contributed almost the totality of industrial emissions (96%). The chemical and metal industries are the largest contributors. This is mostly due to the use of outdated technologies and the lack of control equipment. In general, industrial emissions in Mexico stem from the lack of control or from the use of outdated equipment in combustion processes (NO_x emissions), the use of high sulfur fuels (although decreasing rapidly) and the use of solvents.

Industry Grouping in Mexico City according HC and NO_x Emissions Levels 1994

Group	*Emission range*	*# of facilities*	*% of facilities*	*HC Ton/y*	*NO_x Ton/y*	*HC+NO_x Ton/y*	*% emissions vs. Total Industry*
A	>6	466	10.08	23,194	30,342	53,536	96
B	>12	289	6.25	22,476	29,473	51,949	93
C	>18	228	4.93	21,936	29,045	50,981	91
D	>60	94	2.03	19,595	26,546	46,141	83
E	>90	74	1.60	19,064	25,768	44,832	80
F	>120	56	1.21	17,721	24,954	42,675	76

Source [6]

This way of ordering the industrial sources of emissions would suggest that implementation of CAC policies may be viable and not very costly given the reduced number of players.

Services

Services include hotels, hospitals, dry cleaning, kitchens etc. Here again, emissions are created by the combustion of different fuels (LPG, gas, diesel). However, recent studies by Rowland and by the Mexican Institute of Petroleum show that there is a strong concentration of highly reactive ozone precursor hydrocarbons, particularly propane, isooctane and butane, as well as olefin components throughout the Mexico City atmosphere.

These hydrocarbons are not usually found in combustion emissions in the service industry. Recent evidence presented by Rowland et al. (1995) [20] suggests that they come from unburned LPG which used as domestic fuel in Mexico and may be responsible for as much as 30% of ozone levels in Mexico City. Mexican LPG composition has a predominance of highly reactive hydrocarbons (C_4 and Olefins). LPG lead containment as well as its reformulation to reduce the reactive hydrocarbons could thus translate into important ozone reductions.

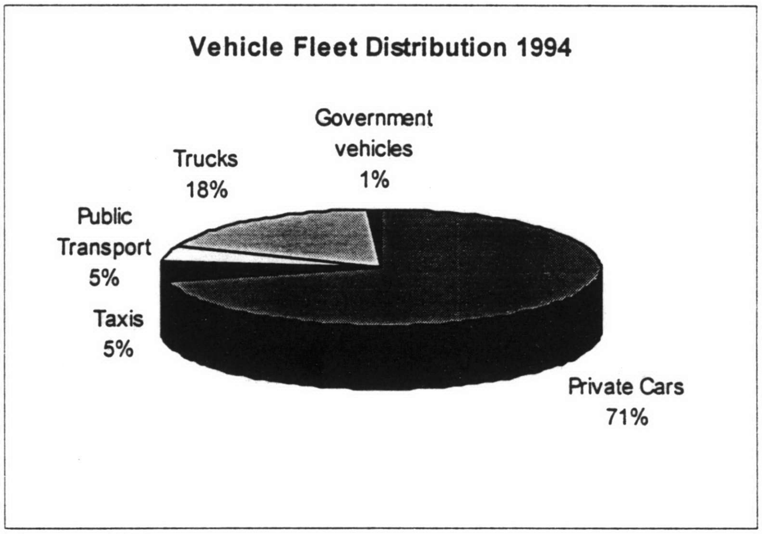
Other than the LPG leakage activity, HC emissions in the service sector come from the aged combustion equipment of many service establishments.

Other

In general, other stationary sources contribute roughly 20% of the Hc emissions and a negligible part of NOx emissions. However, their impact as a source of other pollutants ought not to be downplayed. For instance, the highest sources of particles emissions in the metropolitan area are erosion and dusts suspensions that come from paved and unpaved regions in the city. Soils contribute to more than 90% of particle emissions and vegetation brings 5% of HC.

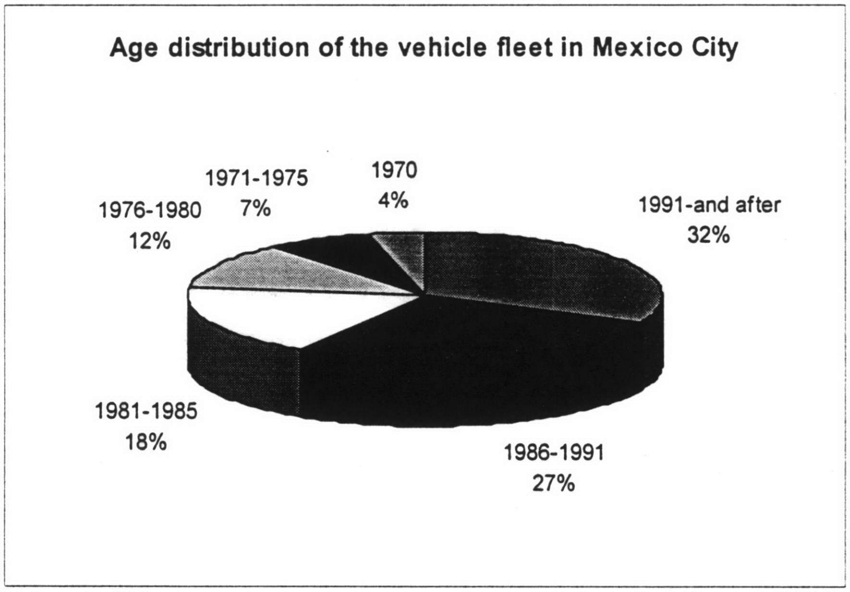
Mobile sources

The intensive fuel consumption of the transportation sector makes it the largest emission contributor in the metropolitan area. The vehicle fleet has persistently grown during the last years at rates of approximately 10% per year. The vehicle fleet has today between 2.5 Million and 3 Million vehicles.



Source: [6]

Private Cars represent the largest portion of the vehicle fleet. However, they represent a very heterogeneous composition in terms of age, combustion efficiency and emission contribution.

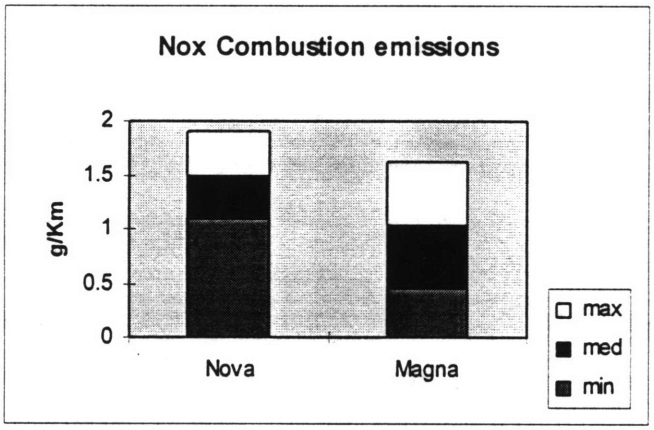


Source: [6]

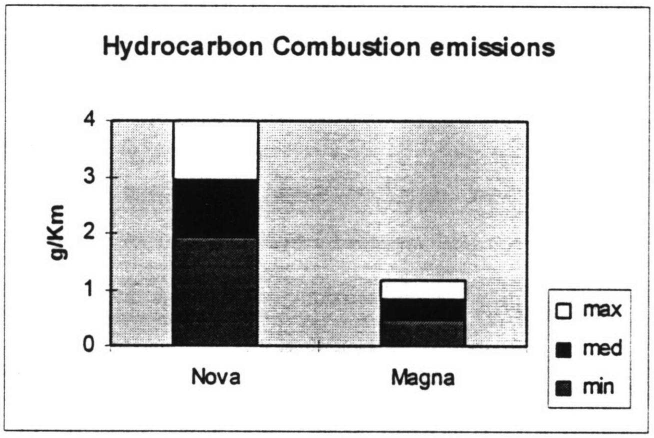
The high growth in the vehicle fleet brings about several problems. First, it represents an increase in emissions related to combustion since there will be an enhanced trip activity. This translates into an increase in both NOx and HC emissions. Second is that even without combustion activity, that is, even without an increased amount of trips, HC emissions levels would increase due to the evaporation component of such emissions.

NOx emissions are a result of the oxidation of both organic nitrogen impurities in fuel and nitrogen from the air. oxidation of atmospheric nitrogen (N_2) is most pronounced during high temperature combustion (which is desirable from the stand point of combustion efficiency).

Hydrocarbons are released to the atmosphere in two ways. First as a product of incomplete combustion: some fraction of the fuel is unburned and emitted to the atmosphere without being oxidized. Following are some measurements from a 1996 study from the Mexican Institute of petroleum (IMP). The study measured the combustion emissions of 35 Mexico City cars in order to estimate total NO_x and HC combustion emissions. [9]

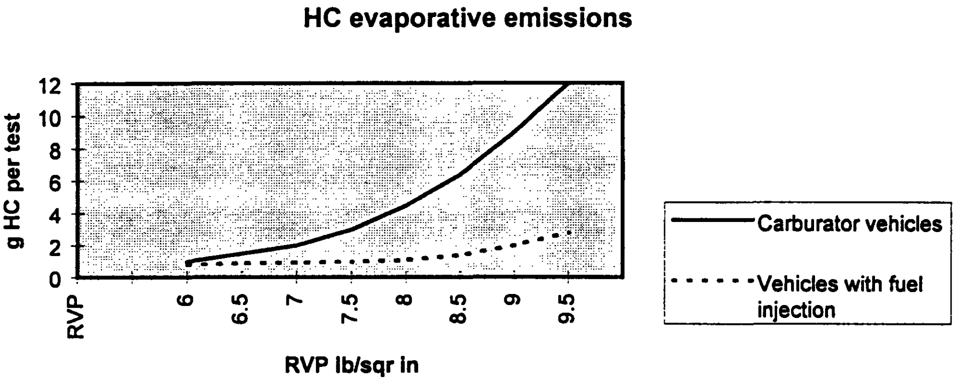


Source: [10]



Source: [10]

Since hydrocarbons are volatile organic compounds they evaporate at relatively low temperatures even in the absence of combustion activity. In gasolines, this volatility is controlled by the Reid Vapor Pressure (RVP) which is a measure of the surface pressure it takes for a liquid to evaporate. A light hydrocarbon has a very high vapor pressure. Heavier hydrocarbons like gas-oils, will have nearly a zero vapor pressure since it will vaporize very slowly at normal temperatures. From the same IMP study we obtain a relation between RVP and evaporative HC emissions:



Source: [10]

It is clear that lower technological standards have a great impact on HC evaporative emissions.

There is high uncertainty regarding HC in gasoline vehicles in terms of the contribution of evaporative emissions. Most estimations of HC emissions consider the unburned fraction of fuel that is emitted after combustion, but a recent reconciliation between the emissions inventory and air quality shows a severe underestimation on HC emissions. Recent studies have estimated evaporative emissions as being up to 70% of total vehicular emissions. [9]

In any case, NOx and HC contribution by private cars is much larger than the mobility demand it satisfies when compared to other transport modes. Currently there are 36 Million trips person per day within the metropolitan area. Private vehicles satisfy 21.4% of them. However, emissions for this mode of transport correspond to 35% of NOx and 46% of HC. This makes private cars an environmentally inefficient way to satisfy mobility demand.

From an energy point of view, private car gasoline consumption represents the highest energy consumption in the transport sector. Each trip person per day made on private car consumes nineteen times more energy than a bus trip, nine more than a pesero, sixty two times more than the subway (metro), and 94 times more than railways.

Even if environmentally inefficient, private car transportation has proved to be an extremely inelastic transport mode in Mexico City as well as in other cities. Private car transportation is very unresponsive to demand side management instruments. Research by Swait and Eskeland (1995) estimated the responsiveness of the demand for different transport modes demand to demand management instruments for the city of Sao Paulo [11]. Their research suggests that, in Sao Paulo, automobile transportation is the most inelastic transport mode in terms of trip cost and travel time.

A different research piece by Eskeland (1995) estimates the effects that the ""No Circula"" regulation had on the automobile transport mode demand. The results of the model are that the regulation, after a period of six months, actually increased total driving. In terms of gasoline consumption, the model results indicate that, had the demand not been subjected to a structural shift at the end of 1989, demand would have been lower in all but in the two first quarters of the regulation.

Was there a way to predict this policy resistance response from the system beforehand?. If so, what would be the analysis tools required that would be able to capture it? This questions lead us to examine the available analytical tools that have been developed to design and implement current environmental policies.

The Mexican authorities have invested a significant amount of resources to improve their understanding of different aspects of the air pollution problem in Mexico City, with impressive results in some occasions. However the dynamic interactions between the system and the policies that affect them has not, in our opinion,
been sufficiently explored.

APPROACH TO THE PROBLEM

Recent efforts and limitations: PICCA

The Mexican government has sponsored and undertaken intensive research efforts in the area of air pollution. To this day, research efforts have included econometric analyses of gasoline and car consumption, mobility and trip surveys, definition of emission inventories and state-of-the-art meteorological and photochemical simulation models as well as health impact studies and cost evaluating of pollution effects. All of these tools have been used to derive environmental policies.

In November 1990 several government dependencies established PICCA (Integrated Program Against Atmospheric Pollution). It constituted the first joint public effort on the part of the government to face the problem in a multidisciplinary and integrated manner.

The PICCA program not only announced a set of policies to be implemented immediately, but also set forth a wide spectrum of actions and research projects to be completed within the following 4 years.

Tools and policies for mitigating air pollution in Mexico City

Tools used to derive Policies	Policies
Econometric analysis for gasoline consumption	"Day without a car" program
Econometric analysis for car purchases	Fuel quality initiatives
Mobility / trip analysis (1994)	Public transport infrastructure additions
Emission inventories	Private industry and services
Photochemical model	Research and communication
Meteorological model	Reforestation
Multi-attribute decision analysis for control Strategies	

Since October 1993, the use of Diesel Sin, with a sulfur content of 0.05%, was made mandatory in the metropolitan area. Additionally, heavy fuel oil was eliminated and replaced by industrial gas oil with a maximum sulfur content of 2%. Similarly, vehicles sold after 1991 are required to use unleaded gasoline (Magna Sin). Furthermore, the lead content of Nova gasoline was reduced by 92%. Finally, LP gas was introduced in more than 25,000 public transport and haulage vehicles thereby reducing their emissions by 90%.

There has also been considerable investment in infrastructure projects that can be grouped into two categories:

-Road and Transport improvement, which includes the resurfacing of 1,750,000m^2 of road, the expansion of the Metro and the substitution of the collective transport systems (peseros, which are Volkswagen vans) for Microbuses with emission control systems
- Investments to eliminate or reduce emissions, which included the closing of the *18 de Marzo* oil refinery, total shift to natural gas as a burning fuel in the two thermoelectric plants that operate in the Metropolitan area and in 365 large industrial plants

In the transportation sector, one of the most visible policies proposed in the PICCA was the "Hoy No Circula" Program or "Day without a Car". The program banned each car from driving a specific day per week. It was presented as a temporary regulatory measure aimed to alleviate congestion and pollution problems and counted on people to use public transportation systems or to resort to car pooling in order to compensate for their mobility supply reduction.

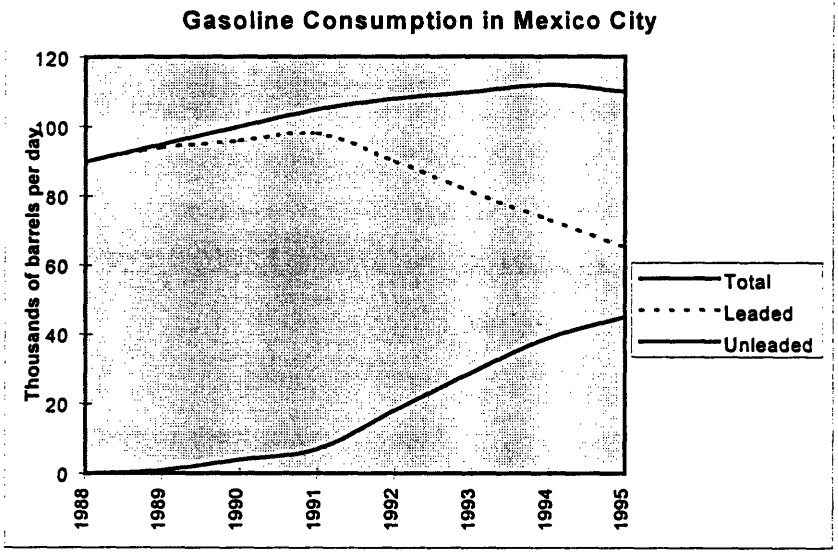
The regulation has been controversial to say the least. It has been criticized for being inefficient and unfair. Inefficient in the way most rationing devices and/or command-and-control regulation mechanisms are inefficient. Unfair because it will be particularly costly to some and easily avoided or circumvented by others.

But an even stronger issue brought up against this measure is that substantial evidence (Eskeland 1995) [12] supports the view that the regulation is actually counterproductive. Some have circumvented the ban by purchasing additional cars, many times older and with lower technical standards, and might have ended up increasing their driving. Even if the conclusion that aggregate car usage was increased is rejected, one may see the small reductions as evidence that the rationing scheme resulted in high compliance costs for many households.

Finally and more importantly, if that compliance strategy involved acquiring a used car with lower technical standards it would result on increased pollution. There would be increased NOx and HC emissions resulting from less efficient combustion (even if the car usage remains constant), but HC emissions would also augment as a consequence of an enlarged vehicle fleet. This dynamic is explored in greater detail in chapter 3.

The failure of the Day without a car program suggests that the problem of air pollution in Mexico is dynamic in nature, more so if policies aim to affect users' preferences. In fact, the observed behavior after the implementation of the program fitted the classic definition of policy resistance almost perfectly. In light of this finding, we believe that one of the areas of opportunity to enhance the understanding of the problem lies in the field of system dynamics.

Results of the "No Circula Program"



Gasoline consumption stayed constant

Private car fleet augmented by 500 000 used vehicles (20% of the fleet) in one year.

On average this vehicles are 10 times more pollluting than a new car (in HC's)

Source: [6]

Current status: ProAire

In 1995, the government presented its new 4-year plan to fight air pollution in the Mexico City metropolitan area. This plan was given the name of Pro-Aire. In it, the government follow through some of the studies it had proposed in the PICCA and proposed new policies geared towards mitigating air pollution.

This Policies were grouped into the following four objectives:

- Clean Industry: Emission reductions by added value unit in industry and services
- Clean vehicles: Emission reductions per Km
- Efficient Public Transport and new urban order

- Ecological recovery

In order to reach these goals, the program has defined seven strategies:

- Addition and upgrade of new technologies in services and industries
- Addition and upgrade of new technologies in vehicles
- Fuel upgrade and substitution
- Upgrade of Public transport system
- Economic incentives
- Industrial and vehicular inspection controls
- Environmental information and education
- Social participation

On a lower level of aggregation, there are more than 80 instruments and policies planned to be implemented. However, even if in some of the strategies and individual projects the economic incentives approach is mentioned and sometimes analyzed, there is still a concentration on attempting a "technological" solution and an insistent confidence on command and control instruments.

As mentioned above, environmental administration in Mexico has principally used command and control instruments in air pollution. This strategy has left many gaps in terms of environmental legislation, particularly in the definition and enforceability of an environmental economic instrument. Furthermore even if it is a government responsibility to maintain environmental standards, it is not always clear which government agency is in charge. All of this makes the implementation of economic instruments a difficult issue.

Finally, the policy-designing tools are limited in capturing dynamic interactions between public policies and the urban system. These limitations translate into two major policy shortcomings: staticity and isolation.

Tools and limitations in the fight against air pollution

Tools	Limitations	
	Static	Isolated
Econometric analysis for gasoline consumption		x
Econometric analysis for car purchases		x
Mobility / trip analysis (1994)		x
Emission inventories	x	
Photochemical model		x
Meteorological model		x
Multi-attribute decision analysis	x	x

Policies that have static limitations assume their effects will take place in an environment which is constant over time. Thus, their effectiveness is limited to the extent other variables in the system remain constant. For example, banning 20% of the private cars from the streets every day will reduce private vehicle emissions by 20% only if no more cars are introduced into the current fleet and no additional trips are made by the original fleet. As more cars enter the fleet, the absolute effect of the policy is diluted, even though the relative effect remains constant and 20% of the cars are always at home.

On the other hand, policies that are assumed isolated ignore the effects of other policies implemented simultaneously. This fact makes the evaluation of their cost effectiveness extremely difficult. Additionally, the second order effects of certain policies might counter the desired effects of others.

Some progress has been made in understanding the problem, not only through the different tools that have been developed, but of equal importance, by the recognition of the city as a complex dynamic system which has dimensions that have still not been explored. The ProAire program recognizes explicitly that the urban space is an open and dynamic system which includes and inter-relates its environment, its markets and with the underlying organization of its most basic activities. The former include; public and private transportation, infrastructure capacity, spatial organization, land use legislation and other similar variables. Additionally, the city's system structure merges with the state of technologies, with its information systems, its rules of decision and with the culture and customs of its inhabitants.

Any attempt to design a policy that incorporates at least some of these levels of dynamic complexity requires a tool that rigorously analyzes the structure of the system. We believe that a systems thinking approach and, more specifically, systems dynamics modeling, can be helpful in understanding some of the relations between the structure of urban systems and their behavior.

SYSTEM DYNAMICS

Background And Overview

System dynamics is a relatively recent methodology developed in MIT by Professor Jay Forrester in the 1950's [13]. It attempts to describe the behavior of complex systems as a function of their structure. By structure we understand the elements related to the flow of materials and information as well as the ones (tangible and intangible) that dominate the decision making process within a social system.. The area of focus of systems dynamics is the behavior of systems that contain feedback loops. A feedback loop is a cause and effect relationship between at least two variables related in such a way that both are affected by each other's behavior. [14]

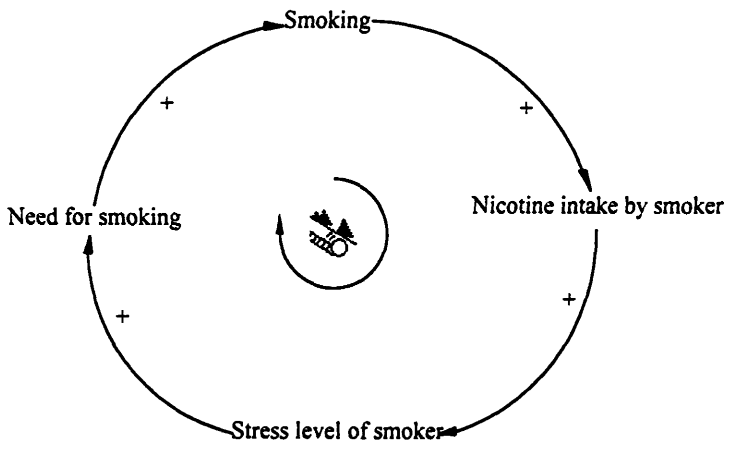
One of the fundamental notions behind system dynamics is that a rigorous systems thinking can be of great help when shaping our mental models. These mental models can be translated into a mathematical version and simulated in a computer program. This proves to be more reliable than an intuitive approach to evaluate the system's behavior. The sort model that is generated can easily have over 100 variables that are relevant to the problem, many of them related to one another in a non linear way. Human cognitive capabilities are not able to follow the implications of such systems.

Feedback loops have two possible polarities: positive, or reinforcing feedback loops and negative, or balancing feedback loops. A positive feedback loop feeds on itself to produce a change in every iteration that has the same direction as the change in the previous iteration. Hence, a positive feedback loop represents a system that is always growing or always shrinking. A typical example is a vicious cycle like smoking. Smokers are known to smoke more heavily when under stress. However, since nicotine generates anxiety, the more s/he smokes the more stress the person will feel and the more he or she will smoke.

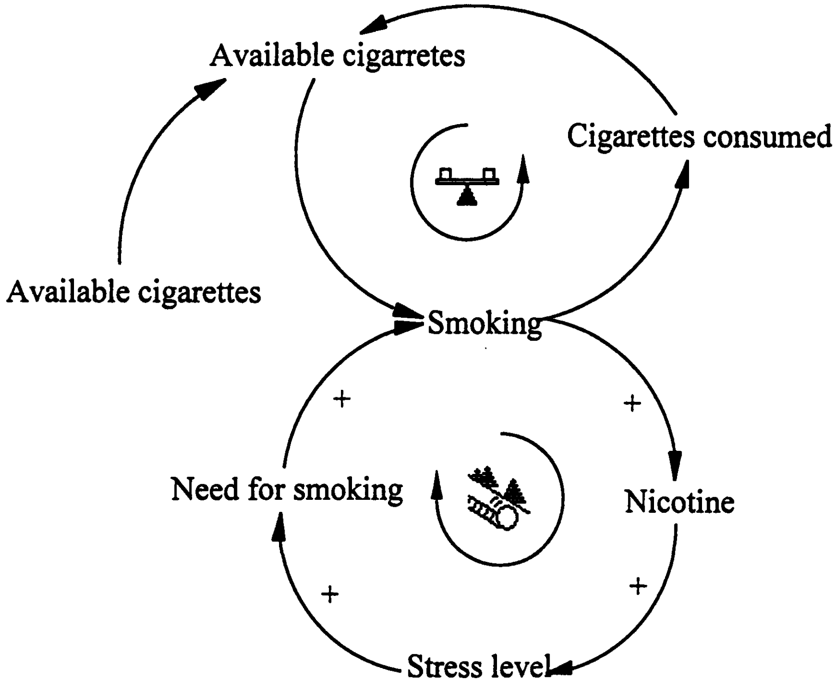
This dynamic is graphically captured in the figure below in which the arrows represent a cause effect relationship. The icon in the middle of the loop is a snowball rolling downhill and becoming bigger on its way, which is another example of a positive feedback loop. The plus or minus signs on the sides of the arrows represent the effect of the preceding variable on the next. A plus sign indicates that an increase in the cause variable produces an increase in the effect variable and, similarly, a decrease in the cause produces a decrease in the effect variable.

The opposite is true for the minus signs. An increase in one variable produces a decrease in the cause variable while reductions in one variable translate into increases for the next.

A positive feedback loop



A negative feedback loop illustrates the limits by which the system stops or balances its apparent limitless growth or decline. For instance, suppose the person above only had one pack of cigarettes available.



As the available cigarettes run out, the person will have to smoke less, namely zero when there are no more. This is a balancing loop because it imposes limits on the system's behavior, driving the system into equilibrium. In this example the equilibrium point is zero smoking and the cause is no more available cigarettes.

Since transportation activity is so relevant to ozone pollution levels in Mexico City, it would be useful to understand its interrelations. However, the totality of the transportation and air pollution dynamics of a city are not as easy to capture in a model and therefore the problem needs to be narrowed to some manageable level. This level must illustrate the problem and contribute to its solution at the same time.

Causal loops and Mexico City Air Pollution

Transportation and air pollution dynamics in Mexico City can be characterized as a feedback system. One of the dynamic parts in this system is transportation demand and its absorption by the different available transport modes.

For the purposes of our research we have divided the transportation supply in Mexico City into four major transport categories or modes: private cars (PC), taxis (TX), public vehicles (PubV) and subway (rail). Private cars include every motorized vehicle that has a single owner -person or household- and provides service exclusively to that owner. Motorcycles are included in this category for simplicity. Taxis include all vehicles registered as such in the Mexican department of motor vehicles. All other motorized vehicles which circulate at street level causing traffic and pollutant emissions are defined as public vehicles. Among these vehicles are buses, mini-buses, and "peseros" (i.e. gasoline fueled vans that operate as collective taxis). Rail refers to those transport means which do not produce emissions and/or do not circulate at the street level. All transportation needs are satisfied by one of these four modes based on their relative attractiveness, which is defined as a function of their travel cost and time.

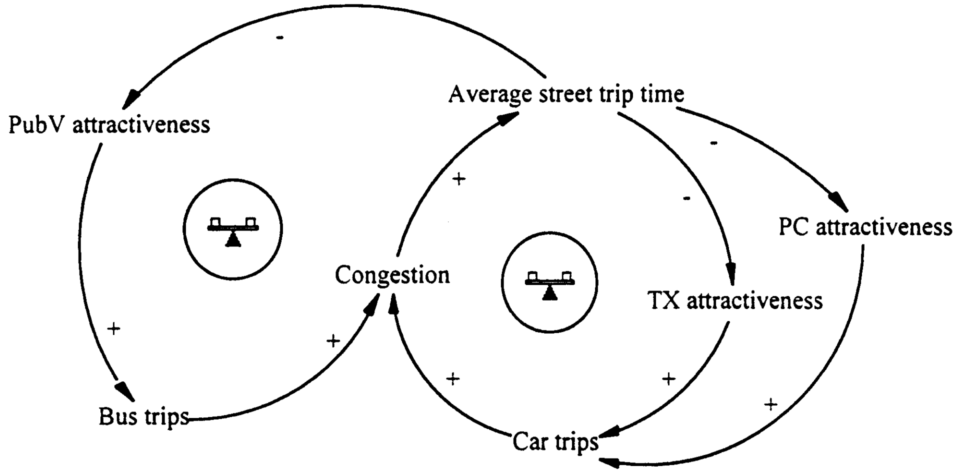
Including time as a measure of attractiveness for any mode of transport gives rise to the first dynamic we want to capture. Travel time for all transport at the street level is a function of distance and traffic. Trip distance can be assumed constant for the average trip in the city. However, traffic is a direct consequence of the number of vehicles in the street, which is in turn a consequence of the demand for private cars, taxis and public vehicles. Thus, we see that when people increase the use of their cars, traffic will grow and all transport at the street level will become less attractive due to congestion.

The figure shows the causal loop diagram for this dynamic. When the number of bus trips and car trips is higher congestion rises, and the average time for the trips made on vehicles at the street level is higher, thus making these modes of trips less attractive.

Even though all modes of transport except rail are affected by more traffic, it is important to note that the effect of increased time need not be the same for every mode in terms of their attractiveness.

As each mode of transport becomes less attractive, less trips will be made using that mode, which in turn will reduce congestion. Assuming this system existed in isolation, its behavior would converge towards an equilibrium point. There would be a given number of trips made in every transport mode such that increases in street traffic would make car travel undesirable relative to rail and less trips very attractive relative to rail. Traffic is thus captured as a balancing loop.

.- Congestion Balancing Loop



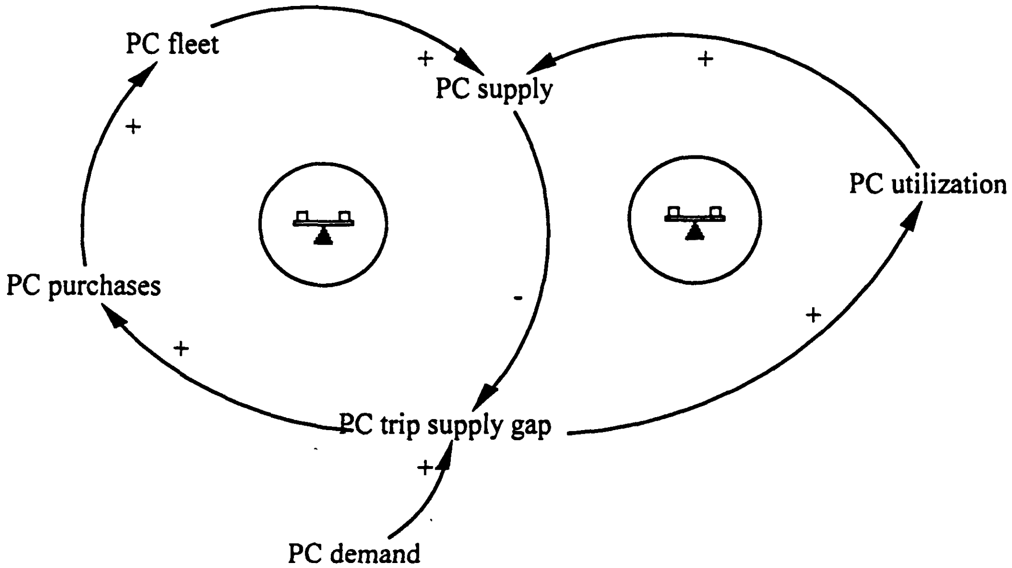
The system, however, is more complex than this. It exhibits a second dynamic which modifies the behavior of the simple structure pictured above. This second dynamic hypothesis deals with the supply for the different modes of transport. Specifically it considers supply to be the combination of a given mode's capacity and its utilization. For instance, the number of person trips made per day in private cars equals the product of the total car fleet and the number of trips per day that each car makes. This structure is analogous to the one for taxis, public vehicles and rail. Thus, changes in the demand for a given mode of transport may be met with changes in its utilization levels in the short term and with changes in the system capacity itself on a longer horizon.

This second dynamic is shown in the figure below, Transport supply loopset, which is a set of balancing loops whose behavior is to adjust utilization and capacity for every mode of transport just enough to satisfy each mode's trip demand.

In the case of private cars, as demand goes up, there is a growing gap between current supply conditions and the increased demand. The systems seeks to close this gap by raising utilization of the existing cars and by expanding the private car fleet. As supply is increased in this way, the observed gap relative to demand closes and the system returns to stable condition.

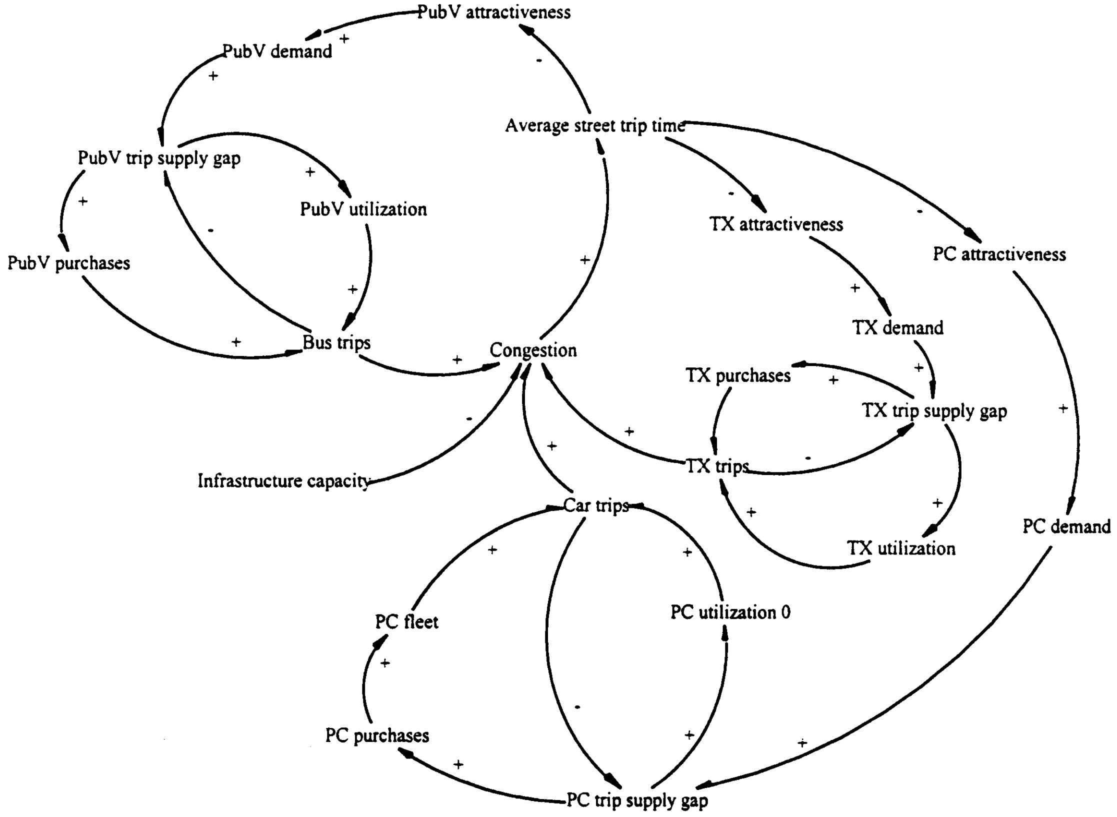
Because utilization can be adjusted faster than capacity and some modes react faster than others in either of these two dimensions, it is unclear at precisely which level each mode's supply will stabilize as well as the pathway by which it will reach equilibrium.

.- Transport Supply Loopset



Finally, the choice of transport mode and the way in which it is supplied eventually transform into emissions and air pollution, which is the problem at hand. Once combined, the full dynamic hypothesis become difficult to predict, albeit one can trace the effects that changes in some variables cause on others. Hence the need to build a model. The combined result coming from these dynamic hypothesis can be tested through computer simulations that can track the implications of the above structures. The results of this model are analyzed later in this chapter. The figure below shows the complete dynamic hypotheses to be captured in the system dynamics model.

.- Complete Dynamic Hypotheses



Modeling causal loops

The behavior of more complex causal loops such as the one depicted above are not easy to predict and understand by simple observation of the relationships among the variables. It is generally necessary to resort to computer simulations in order to determine whether a balancing loop dominates over a reinforcing one, what the time horizon is for this behavior, etc.

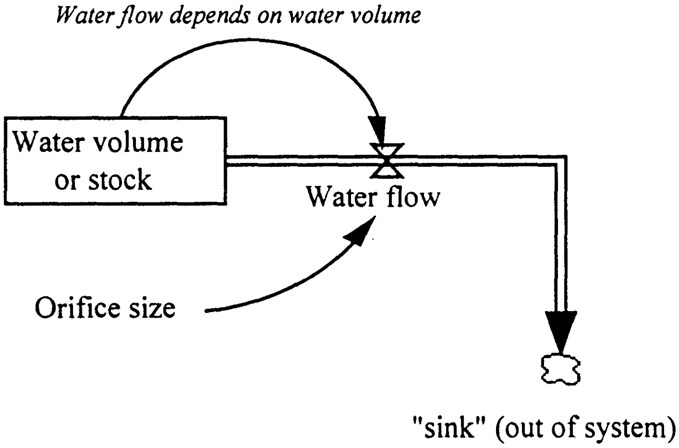
The model is not intended to be a perfectly accurate representation of reality. It is rather conceived as a flexible conceptual tool designed to contrast different hypothesis and , in general, to foster a more rigorous thinking about the dynamic implications of the problem. One of the virtues of this approach is to be able to illustrate if a set of assumptions can or cannot affect the behavior of the phenomenon of interest.

For the purpose of building an actual simulation model, the dynamic hypotheses captured in the causal loops are broken down in the actual variables that determine the behavior, rather than conceptual ones. Mathematical relations are established between these variables and then they are simulated over several time periods. The results for each time period are stored and can then be retrieved to compare the system's behavior under different scenarios.

The variables that comprise a system dynamics model can be basically divided into stock, flow and auxiliary variables. Stocks are variables for which a cumulative count is kept, while flows are variables that change the value of the stocks. All other variables are auxiliary. One example of such variable differentiation is a water tank with an orifice at the bottom. The volume of water inside the tank is a stock of which a cumulative count is kept, and the water flowing through the orifice is precisely a flow, which alters the level of the stock, that is the volume of water inside, at each point in time. The size of the orifice -which affects the flow of water- is an auxiliary variable.

Notice that this simple mini-system is already dynamic in nature. As water flows out from the tank and the volume contained decreases, the flow itself becomes less abundant because there is less hydrostatic pressure at the bottom. The water flow decreases its intensity as the tank is emptied, eventually reaching zero when the tank is empty. Thus, the volume of water inside the tank is a function of the rate at which water flows out and this rate is in turn a function of the volume of water inside the tank. The graphical representation in system dynamics for this simple simulation model is shown in the figure below.

.- A simple Systems Dynamics Model



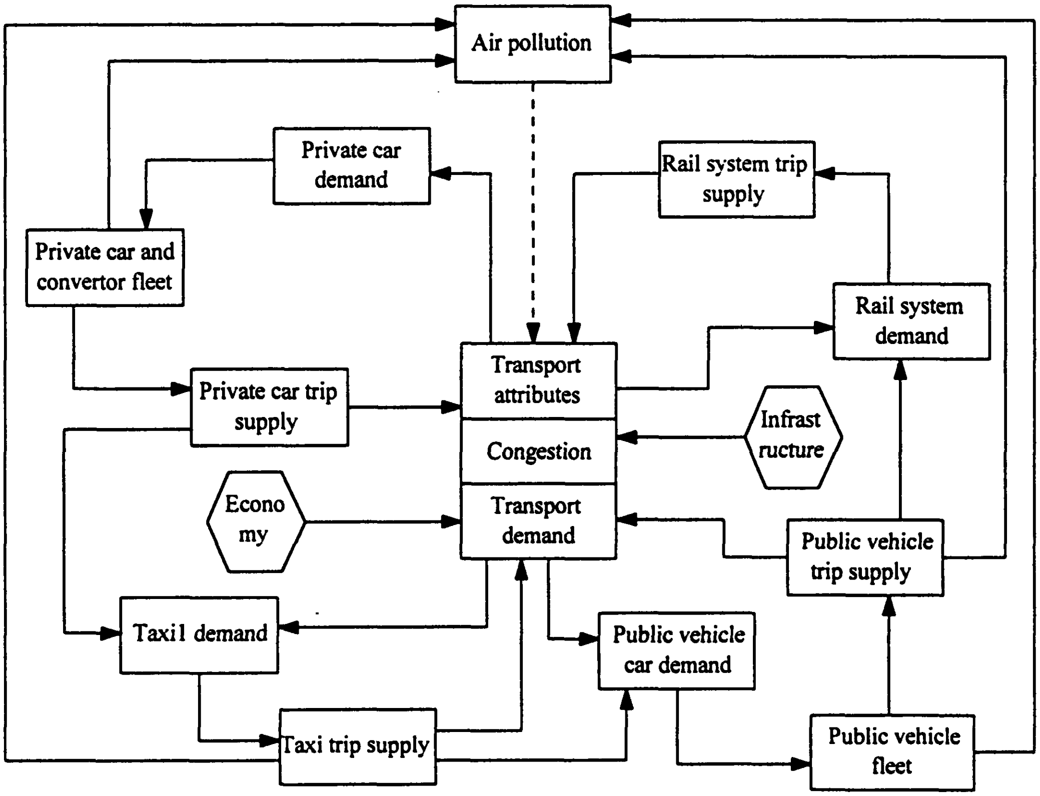
THE MEXICO CITY AIR POLLUTION DYNAMIC MODEL (APDM)

Model structure

In order to understand the dynamics which will arise from the stated dynamic hypotheses, we have built a system dynamics computer model. The model consists of 16 different "sectors", which represent different parts of the problem and are linked by several variables which make the behavior of one sector affect the behavior of other sectors.

The figure shows the basic model structure and its boundaries. Each labeled box represents one sector of the model, while the hexagons represent data which lies outside the scope of the model and is thus used merely as input in the simulations.

.- Model Structure



Model's time horizon

We determined 25 years as a convenient time horizon for the APDM. Simulations will start in January 1995 and end in December 2020 in monthly intervals from 0 to 300 months. Due to this time horizon, we will not calculate the values of every variable in daily intervals.

On one hand, the number of calculations needed to simulate 25 years day by day would be exorbitant. Further, the additional precision that could be gained with daily intervals will not provide any additional insights because the model seeks to understand the link between the system's structure and its behavior, not to accurately predict any quantity. Finally, because we intend to observe changes over these 25 years, the daily change fractions would be too small to handle; it would be like calculating the speed at which human hair grows in miles per hour.

Thus, month zero corresponds to January 1995, while month 300 corresponds with December of 2020.

Transport demand sector

This sector models the total transport demand for Mexico City proposing it as a product of the city's population and its mobility. Transport demand is defined in number of trips-person/day, i.e., one person making two trips is equivalent to two persons making one trip each. Mobility measures the number of trips per day that the average individual makes. It is modeled as a linear function of income per capita of the form:

$$M = \alpha + \beta * \text{Income per capita};$$

where α equals a fixed or base mobility constant and β equals the elasticity of trips-person per day to income per capita.

Hence , total transport demand in the city is given by the formula:

$$TD = \text{Population} \times \text{Mobility}$$

where:

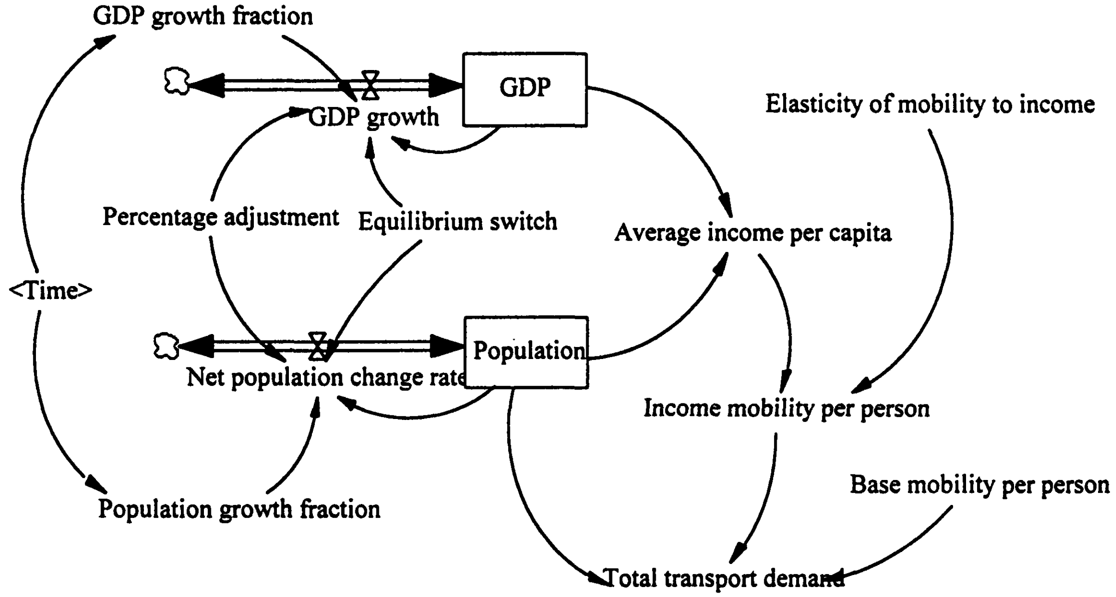
TD = transport demand
Population and mobility are as defined

As a proxy, we took the total number of trips-person per day during 1994 and assumed an intersect constant of one trip-person per day.

The resulting equation is a gross simplification in order to recognize that transport demand in the city depends on the population and income, rather than being a fixed quantity over time. It is not intended to be a precise prediction of this quantity.

We believe that any errors introduced by this technique will not alter our understanding of the structure of the system and will not affect our conclusions in terms of adequate public policies. However, the predicted transport demand should be read as nothing more than a qualitatively adequate number.

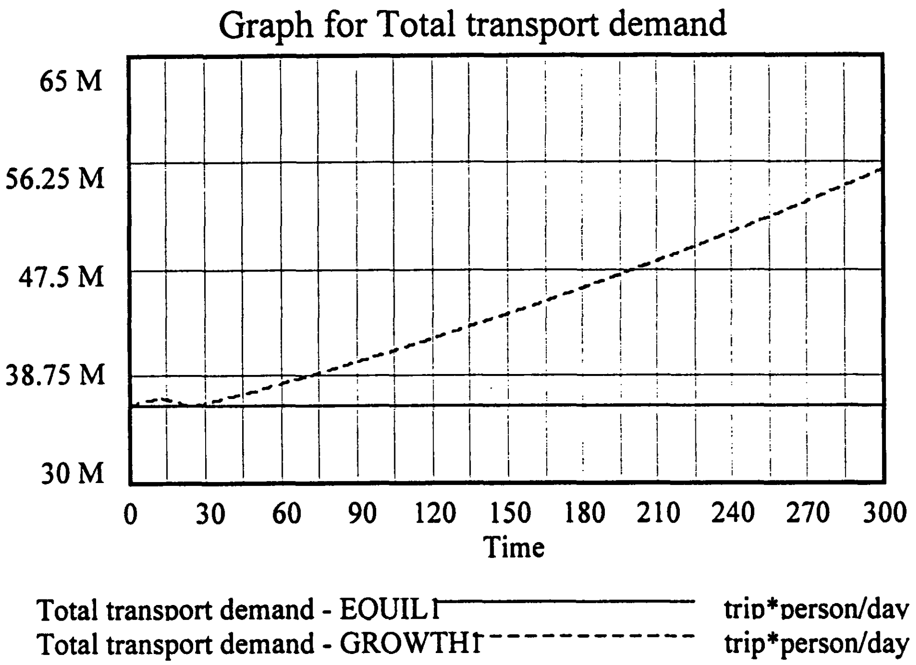
.- The Transport Demand Sector



The behavior of this sector in isolation is relatively easy to predict and understand. Total transport demand will remain constant as long as there is no growth in either population or income. As either population or income rise, there will be a corresponding surge in total transport demand. If we assume a population growth rate and a behavior for income consistent with historic values, we can compare the total transport demand of the "growing" city with a static scenario.

The data shown in the figure below is the monthly average of the number of trips-person/day, where month number zero is January 1995. Between 1995 and 2020, the two scenarios are labeled EQUIL1 and GROWTH1, respectively.

The system starts off at 36 million trip*person/day, which is the observed value in 1995, and then reflects the effect of the short growth and then of the recession. After 1997 (month 25) the sustained growth of the economy and the population translate into a solid growth in transportation demand.



The Congestion sector

The purpose of this sector is to capture the effects of traffic on travel time. Congestion level is defined as the peak utilization of the existing road infrastructure and it is assumed that there is an exponential relationship between congestion and travel time. Specifically, this relationship is of the form:

$$M = \text{Base trip time} * \varphi\ ;$$

where:

$$\varphi = 1 / (1 - \text{congestion}), \text{ and}$$

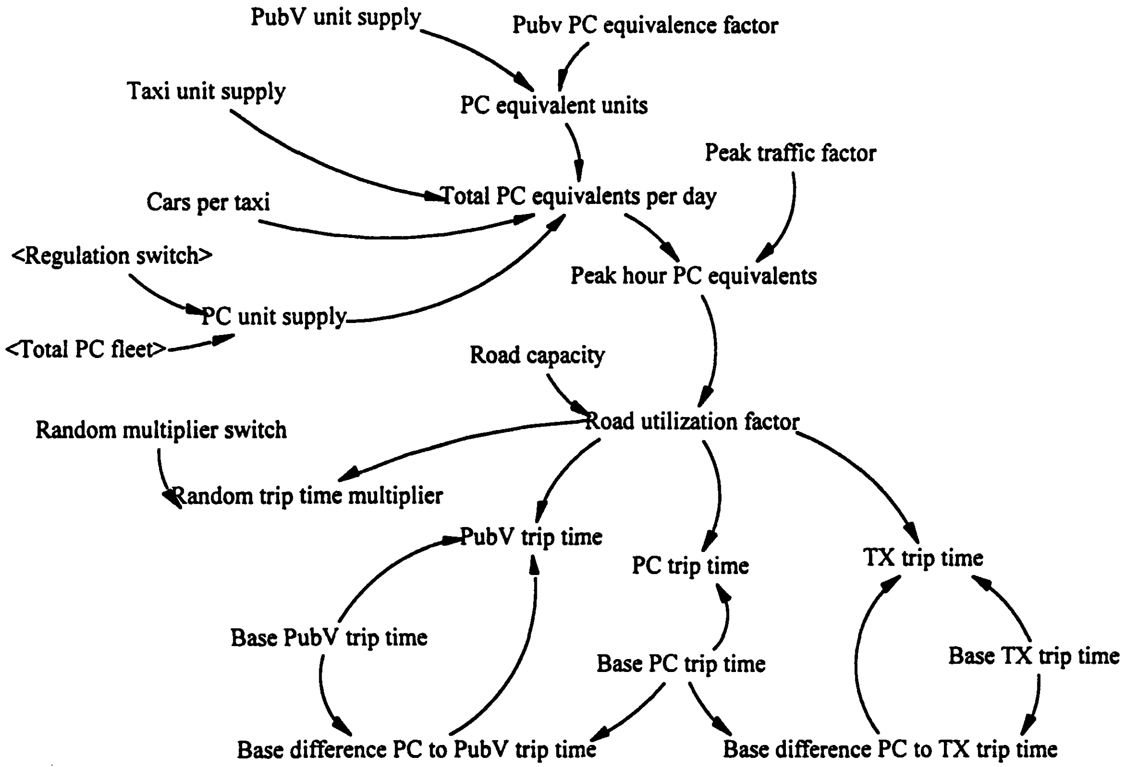
$$\text{Congestion} = \text{Total cars at peak hour} / \text{Road capacity}$$

Qualitatively, this relationship is widely accepted, although specific values for Mexico City were not available.

Again, because the aim of this model is not to accurately predict travel flows in the city but rather to illustrate the structural behavior arising from different policy alternatives, we have taken the scarce evidence available as a close enough proxy. In order to minimize the potential error we have assumed current utilization levels to be at 50% of capacity and have normalized the expected travel times around this point.

Regarding Base trip times, we established average times for all modes of transport from reduced surveys and used these times as corresponding to the assumed 50% utilization rate. Finally, we considered that the effects of traffic on travel time act only upon the in-vehicle times for taxi and public vehicles. Thus, a fraction of these times is constant regardless of congestion levels, while the remainder depends on traffic.

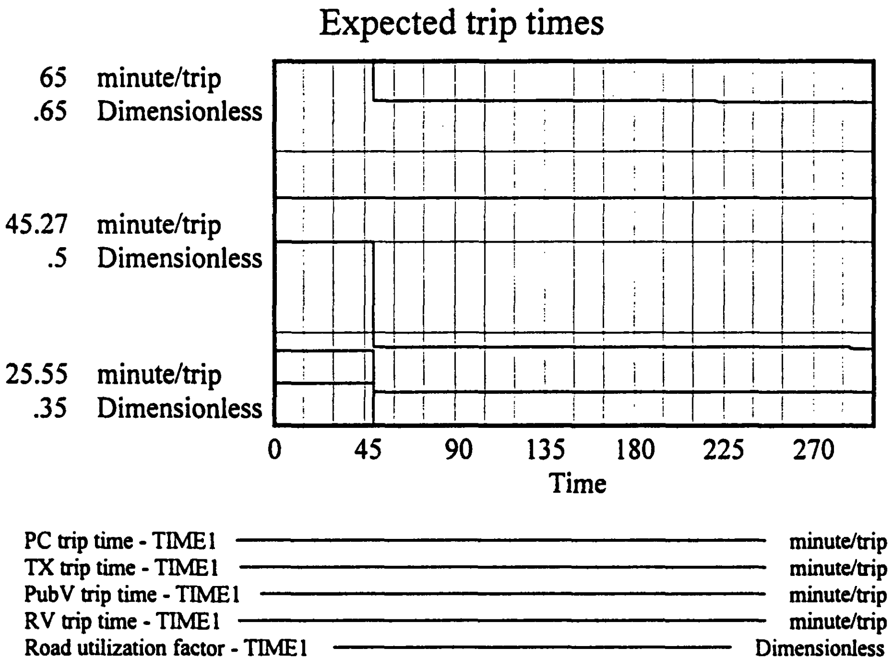
.- The Congestion Sector



Recent studies have shown that congestion is relevant to travel time not only in terms of its expected value, but also in terms of its uncertainty. Nagel and Rasmussen (1994) [15] have shown that at relatively low levels of congestion there is great uncertainty around the total travel time. As congestion rises still further, the uncertainty decreases because even though trip time increases it is easier to predict how long it will take to make a given journey.

The impact of uncertainty around the expected travel time can be quite significant, amounting up to 65% of the expected time at its peak with 11% congestion. At 50% congestion the variation of travel times is approximately 20%.

In order to test this sector we supposed that a second day without a car is put into effect. This would temporarily increase the PC unit trip supply and thus worsen congestion. The expected effect is that travel times for all surface transport modes will rise.



As expected, when a second day without a car is put into effect, the number of cars circulating decreases and with it traffic. Note how the congestion level drops from 50% to approximately 40%, which presumably will increase the attractiveness of street transport and generate more demand. This effect is not present because this is only a stand alone test of the sector.

The demand estimation sectors

Disaggregate mode choice modeling

In order to make an actual estimation of the number of trips-person/day for each mode it is necessary to look at measurable quantities such as time and cost.

The basic idea underlying this approach to travel demand modeling is that travel is the result of choices made by individuals. Further, this choice can be modeled in aggregate terms as the probability that one mode will be chosen over the others by a random traveler. As one mode becomes more attractive, the probability that it will be chosen for any given trip rises accordingly.

For the purposes of this model there are only four possible choice of transport modes: private cars (Pc), taxis (Tx), public vehicles (PubV) and rail. All of these have been defined earlier in this chapter.

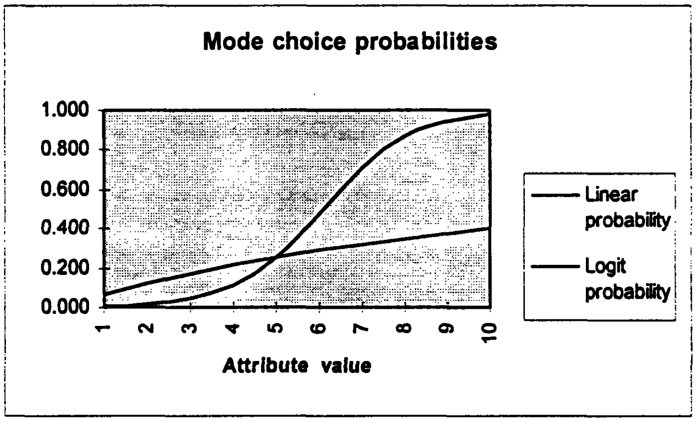
The variables affecting the outcome, i.e., the probability that an individual will choose one mode over others, are travel time and cost and a constant specific to each transport mode. In the case of rail travel there is also a saturation/mingling component. All of these variables translate into a utility component for each mode of transport which is then compared to the utility of other modes to determine the probability that a random person will choose a given mode.

Research by Horowitz, Koppelman and Lerman published in 1986 [16] presents a method of disaggregate mode choice modeling as an adequate approach to estimate demand for different modes of transport. According to this study, when using a multinomial logit model, the probability of one mode increases monotonically with the deterministic component of the utility of that alternative and viceversa. This distinction is important because the behavior of the relative probabilities is quite different under simple linear calculations. The figure shows the comparison of the probability behavior for transport mode *i* relative to its own attractiveness and assuming the attractiveness of other modes constant.

Under this approach, the probability that mode *i* will be chosen is defined as the exponential value of its attributes divided by the sum of the exponential values of all modes.

$$\Pr(i) = \frac{\exp(V_i)}{\exp(V_i) + \exp(V_j) + \exp(V_k) + \exp(V_l)}$$

Probability of mode *i*.



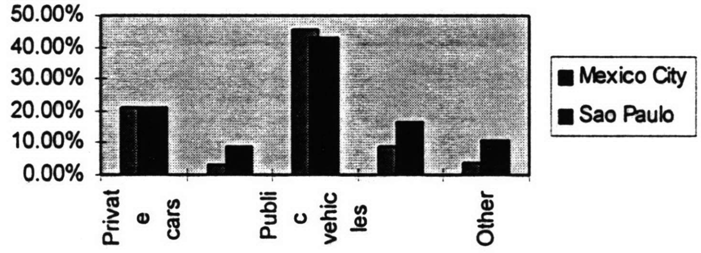
It can be seen that the probabilities of choosing alternatives 1 through 4 are equal when the deterministic components of the four alternatives' utilities are equal. Moreover, the choice probabilities are most sensitive to changes in the deterministic components of the utilities when these components are approximately equal and the choice probabilities are close to 0.25.

Modal attribute estimation

In order to obtain the attributes and utilities of the different modes of transport it is necessary to translate each of their average trip times and costs. However, because the statistical parameters needed to perform this translation are not available for the case of Mexico City, Research by Swait and Eskeland (1995) [11] on Sao Paulo, was used as an approximation. We feel that a city such as Sao Paulo resembles Mexico City more closely than other cities for which similar studies are available. Variables such as the city's population, its income and its travel distribution between modes lead us to this conclusion.

We compared the trip mode choice distribution of Mexico City and Sao Paulo, finding that they are remarkably similar. Even though the Sao Paulo study includes only the home-based work and non-work trips (leaving out the school and non-home based trips), its authors consider that this does not introduce substantive differences for the purposes of their research. Similarly, the Mexico data fails to include approximately 16.5% of the total trips which involve more than one mode. We feel that, ruling out private cars and taxis as multi-modal alternatives, these trips are divided in some fashion among buses, rail and other modes. It can be seen in the figure below that any additions to these transport modes could only bring Mexico City to a closer resemblance of Sao Paulo in this regard.

Trip mode choice - Mexico and Brazil



Before using the parameters from the Sao Paulo study, we decided to eliminate the socio-demographic effects included in that model because the corresponding Mexican data was unavailable for this study. Additionally, we assumed the transport mode of "auto passenger" to be equivalent to taxi trips in the case of Mexico. Finally, because the Sao Paulo parameters were obtained separately for the work and non-work trips, we weighted the coefficients by a supposed distribution in Mexico City between work and non-work trips of 72.5% and 27.5% respectively. This distribution was approximately observed in a study done by Mexican authorities in 1984.[16]

The relationship between a mode's attributes and its trip time and cost can be expressed then as:

$$A_i = \alpha_i + \beta_i * \text{Travel time}_i + \chi_i * \text{Travel cost}_i$$

where:

A_i = attributes of mode i

i = travel mode

α_i = alternative specific constant for mode i

β_i = travel time elasticity for mode i

χ_i = travel cost elasticity for mode i

Travel time = travel time for mode i measured in minutes per trip

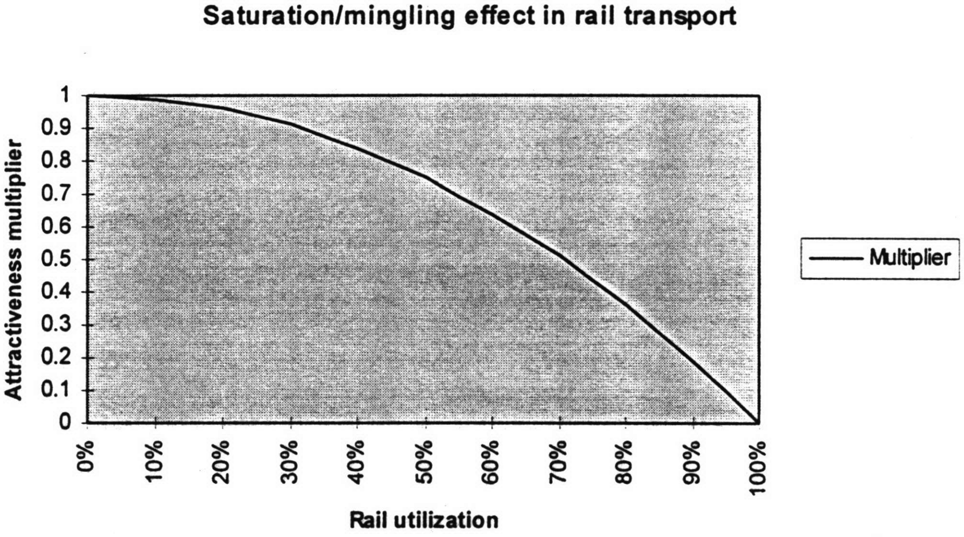
Travel cost = travel cost for mode i measured in US$/# min salaries

The resulting parameters are shown in the table below:

Travel mode	Alpha	Beta	Gamma	Travel time	Travel cost
Private car	3.8475	-0.0209	-0.1664	30.0	1.14
Taxi	1.7102	-0.0211	-0.4800	33.5	0.57
Public vehicles	5.6855	-0.0210	-0.2264	65.0	0.51
Rail	4.0134	-0.0183	-3.9671	50.0	0.04

One important difference between Mexico City and Sao Paulo is the rail system. While the Mexican rail system is almost exclusively a metropolitan subway system, Sao Paulo's railway system has less extensive urban coverage and includes a suburban train. This makes the crowding out effect in the Mexican rail more severe than that of Sao Paulo's, as there is more "competition" between travel modes for this routes.

We have included a "saturation effect" in the Mexican metro. Within this formulation, the attractiveness of rail transport decreases as its utilization rises because of the inconvenience of traveling nearly at full capacity.



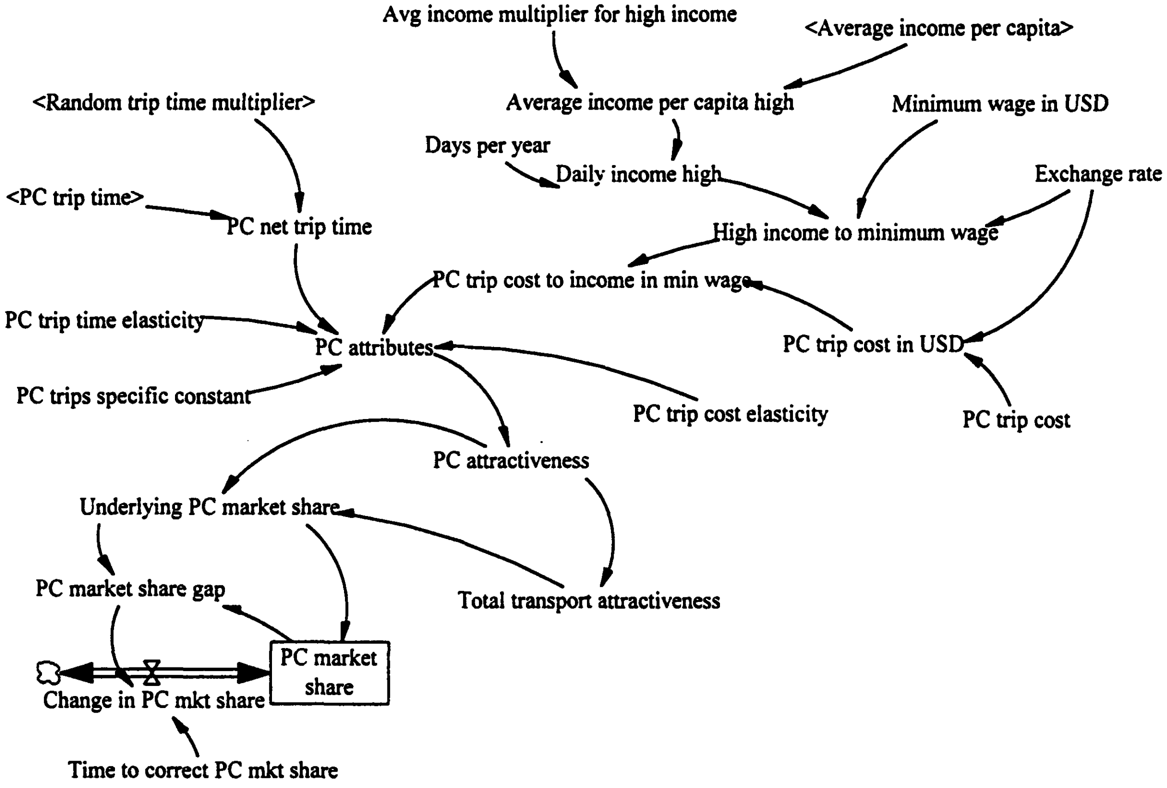
PC attractiveness sector

The PC attractiveness sector serves as a model for the attractiveness sectors corresponding to other transport modes. Each mode's sector incorporates the relevant travel time and cost into the attractiveness equation and calculates that mode's utility. Dividing that utility by the sum of utilities from all modes yields the mode's *underlying market share*. Actual market share is assumed to exhibit a lag relative to its underlying value, reflecting the fact that the actual trip demand for each mode does not react instantaneously to changes in time and cost.

In order to capture the time it takes for the population to internalize changes in travel time and/or cost as well as its reluctance to change their established transport mode, we have modeled actual market share as a stock. The time delay between changes in the underlying market share and the corresponding changes in actual market shares shows the inertia around information and decision making.

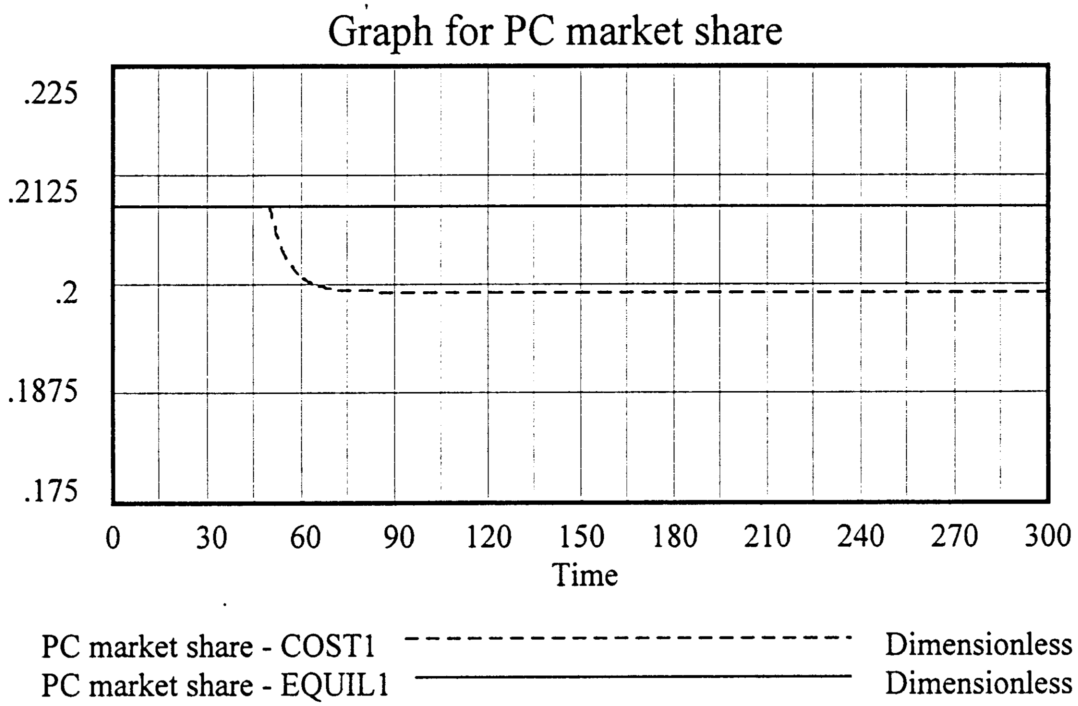
- PC attribute sector (typical for all modes)

.- PC Attribute Sector (typical for all modes)



Consider a change in the cost of private car average trip. As the cost goes up, the attributes of this mode will decrease and so will its utility relative to that of other modes. Thus, we can expect that its market share will eventually decline to a level in which the new demand exactly offsets the price increase. Similar effects could be seen in the behavior of other modes' attractiveness.

Effects of increasing the cost of a private car trip



The supply estimation sectors

Transport supply for every mode is modeled as the product of that mode's installed capacity and its utilization. For instance, private car trips per day are a product of the total car fleet and the number of trips per day that each car makes on average. Taxis and public vehicles have similar structures, while rail capacity is measured as the number of person trips per day it provides.

Each mode satisfies the demand it faces by adjusting either utilization or capacity. Utilization adapts to changes in demand within a relatively short time horizon, while capacity requires a longer period to adjust. A recent study done in MIT on the automobile recycling industry suggests that an appropriate time frame over which vehicle capacity can be adjusted is 66 months [17]. In absence of a similar time constant for the transport capacity utilization, we have proposed an average time of 12 months to adjust the utilization of capacity and verified this assumption with the author of the mentioned study.

Even though utilization can change within a much shorter time horizon than capacity, sometimes there are times in which the demand for trips demanded excess current utilization levels. These unmet demanded trips are cascaded down as "unmet demand" from private cars to taxis and then to public vehicles and rail. Thus, if there is a sudden rise in demand for private car trips, during the time it takes the public to adjust its utilization and/or build up the car fleet, the unmet private car trips will be added to the taxi trip demand. This pecking order for transport demand was established in a cost basis.

In order to address the fact that there are an infinite number of combinations of capacity and utilization levels that may satisfy a given transport demand, we assumed that the system is stress free when utilization levels are at their historical values. Thus, if at a given time there is an excess number of car trips being supplied relative to the demanded trips, the car fleet will adjust until such point at which utilization equals its historical target value.

The demand is a function of the number of person trips per day demanded and the average number of people per vehicle. This is relevant because while demand for public vehicles in person trips per day is far greater than that of private cars, the demand for public vehicle trips per day is significantly lower. We have assumed an average occupancy of 1.25 persons per trip in a private car and 25 persons per trip in a public vehicle.

The historical utilization as well as the average number of people per vehicle are shown in the table below.

Travel mode	People per vehicle	Target utilization
Private car	1.25	2.75
Taxi	1.25	6.95
Public vehicles	25	6.26
Rail*	1	0.50

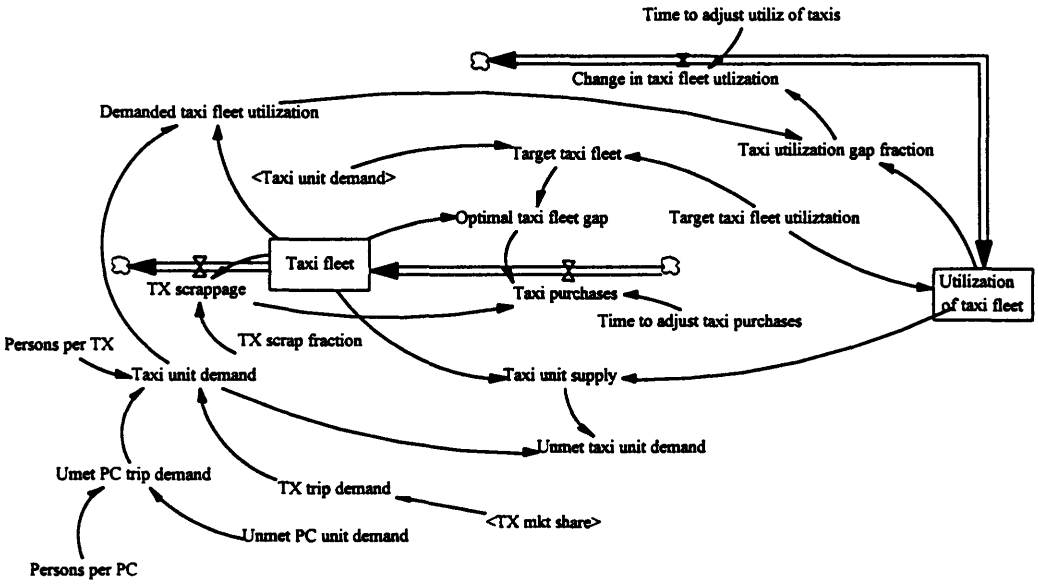
* Rail utilization is measured in percentage of current capacity

The figure bellow shows the structure of the taxi supply sector of the APDM, which is typical of other transport modes. Utilization and capacity are stocks in order to show that they cannot change instantaneously, even though their estimated values do.

We tested this structure by considering a sudden increase in the demand for taxi trip demand and holding everything else constant. We expected to see the increased demand being met by a higher utilization of the taxi fleet and, over a longer time horizon, to have the taxi fleet adjust to this higher demand.

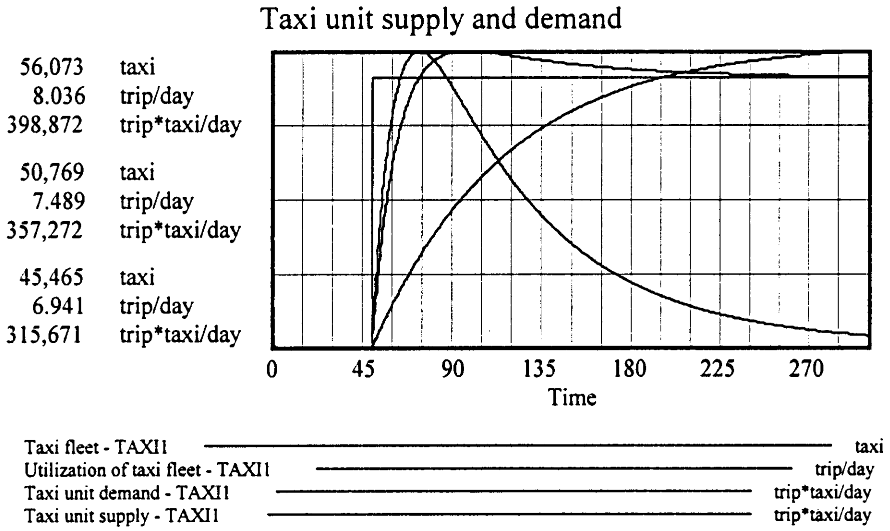
The taxi fleet increases through purchases done by private individuals. However, it can only decrease by natural scrappage during periods for which purchases are zero. not decrease symmetrically because we have assumed there can be no negative purchases - sales outside of the city. Thus, the taxi fleet decreases by natural attrition only.

.- Taxi supply sector



The figure below shows the behavior of the taxi fleet and its utilization as a response to a sudden increase in taxi trip demand.

Taxi unit supply and demand



As taxi unit demand rises at time 50, the system is driven out of its initial equilibrium. Taxi unit supply no longer matches demand and this gap generates pressure on taxis to provide more trips per day on one hand while on the other it generates a need for more taxis in the fleet.

The number of daily trips made by every taxi changes rapidly and can be observed by utilization rising steeply at time 50. However, this increased utilization is not enough to cover the additional demand and the taxi fleet increases as well, albeit at a slower rate. The product of these two variables -the taxi unit supply- starts rising as taxi supply attempts to meet the new demand.

At approximately time 75 -twenty five months after the demand shock- the taxi unit supply exactly equals taxi unit demand. However, the number of daily trips per taxi at this point is eight rather than seven, which was the value observed initially. Given that we have assumed seven trips per day as been the historical utilization level for taxis, we should suppose that utilization will tend to return to that level once demand has been met. For this reason, utilization starts declining at that point while the taxi fleet keeps growing.

Even though utilization starts declining, this decline is rather slow at first. Since the taxi fleet is still growing driven by the unsatisfied demand of previous months, the total supply of taxi trips overshoots past current demand levels. Each new taxi joining the fleet is providing slightly under eight trips per day and it will take time for the population and the taxi drivers to adjust their behavior patterns.

From a driver's point of view this dynamic is seen as only involving taxis. The increased demand could be generated by a policy such as the day without a car program, because in the short term, people will need to satisfy their transport needs. As more people want to use taxis as a transport means, taxi drivers will have to provide more trips per day in order to satisfy them. However, as taxis enter this era of bonanza with approximately 15% higher utilization gained overnight, it becomes very attractive for new people to acquire taxis and become drivers themselves. Soon, the taxi fleet starts increasing, with large numbers of taxis still on order in the hope of coming into service in time to catch the taxi boom.

At some point, new drivers have come into the market and the bonanza is over so the number of daily trips per taxi starts declining. However, there are still large numbers of taxis on order, awaiting to join the thriving taxi market and with each new taxi that reaches the street, utilization will have to drop even further because demand has already been met. Since utilization can change only so fast and no faster, the taxi market enters a phase of over supply.

The particular effects of over supply in the taxi market lie well outside the scope of this model and this research. However, we might very well suppose that at this point, average taxi fares will tend to fall thus making all drivers , old and new, worse off than they were before the "boom". At the very least, it would be prudent to take this effect into account when considering a policy such as the "day without a car" program.

Such is the usefulness of understanding a system's structure and behavior.

The car fleet sector

The two pollutant emissions to be monitored are Nitrogen oxides and hydrocarbons. In a gross simplification, it is the presence of these two pollutants and the effect of sunlight what forms tropospheric ozone. As discussed before, the relationship between ozone concentration and these pollutants is highly non-linear, which makes it necessary to keep track of them individually.

As mentioned in Chapter 1, private cars are by far the largest contributor to air pollution in Mexico City, contributing approximately 26% and 23% of N Ox and HC's emissions respectively. Therefore, it is useful to model their behavior in greater detail than other modes of transport.

In terms of nitrogen oxide emissions, it is useful to consider the effect of catalytic convertors. Cars equipped with catalytic convertors produce significantly less nitrogen oxide than those without them. On one hand, the convertors themselves reduce the emissions of HC's and N Ox per liter of fuel consumed. On the other hand, these convertors are technically restricted to use the higher quality "Magna Sin" gasoline.

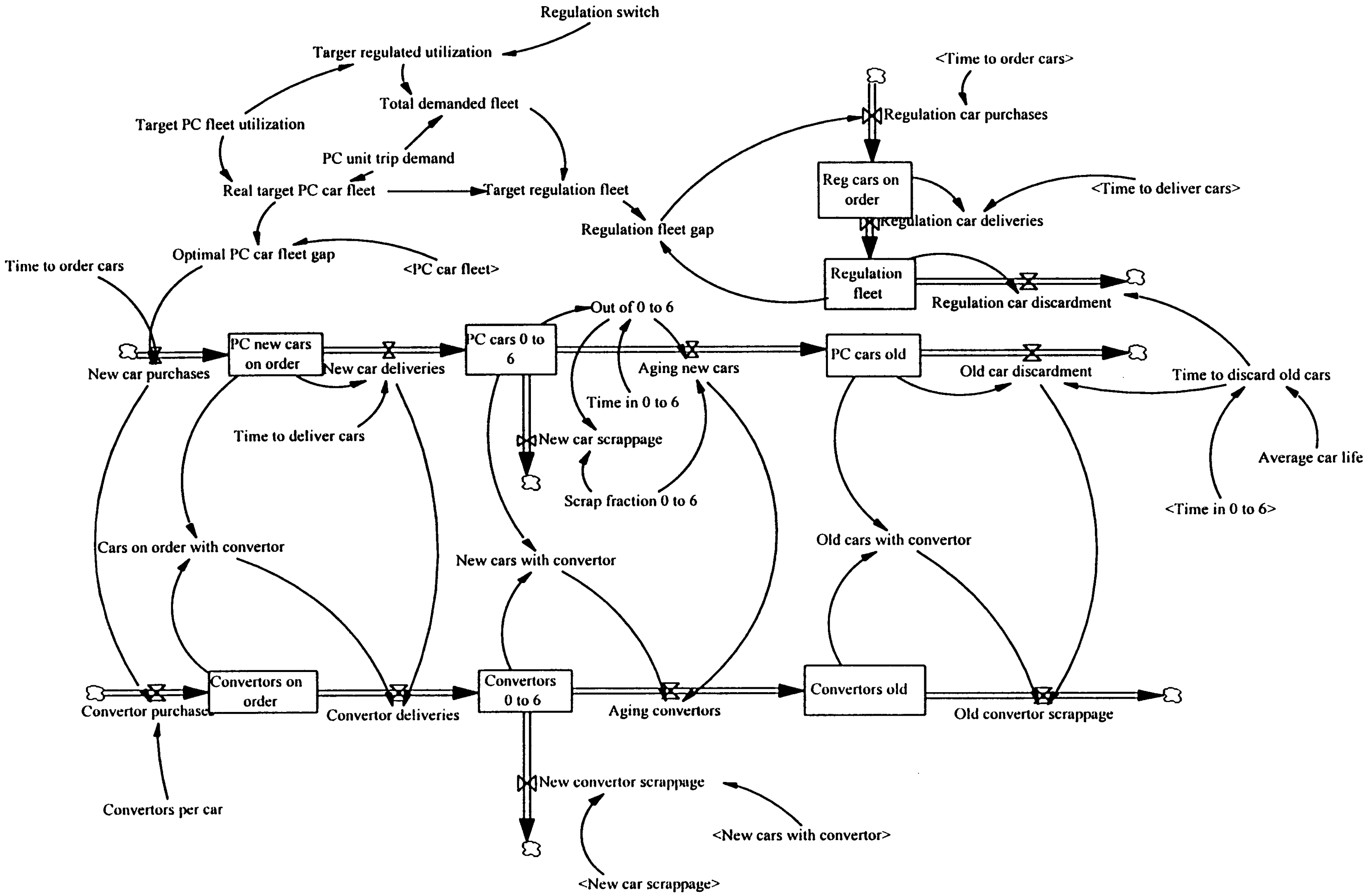
Hydrocarbon emissions from private cars are produced by combustion and evaporation. Emissions produced by combustion depend largely on gasoline quality and motor technologies such as catalytic convertors; emissions produced by evaporation hinge on the gasoline's RVP (vapor pressure). Most notably, evaporative emissions are independent of vehicle trips, they are related almost exclusively to the total car fleet and to its engine technology and maintenance level. .

In order to account for the different pollutant and emission types, the car fleet sector keeps a parallel track of cars and convertors. This division is an approximation of relative levels of engine technology including the different types of catalytic convertors and the presence of fuel injection systems. Moreover, the car fleet is divided into different age cohorts to reflect the effect of time on the efficiency of cars. Finally, this sector introduces the concept of the regulation fleet.

The need for a regulation fleet arises when the target utilization of the fleet is not the real utilization due to regulations such as the "day without a car" program. As a rough work-week approximation, a utilization of one trip per car per day (five per car per week) is reduced to 0.8 trips per car per day (4 per car per week). Thus, the car fleet needed to meet trip demand is increased. The regulation fleet is defined as the difference between the fleet that is actually needed to satisfy demand and the fleet that would have been needed in the case of full private car utilization. From historical evidence, we know that this regulation fleet resembles the second age cohort in its antiquity, with most of the cars missing a catalytic convertor.

The figure bellow shows the structure of the car fleet sector, including the convertor count and the regulation fleet.

.- The car fleet sector of the APDM

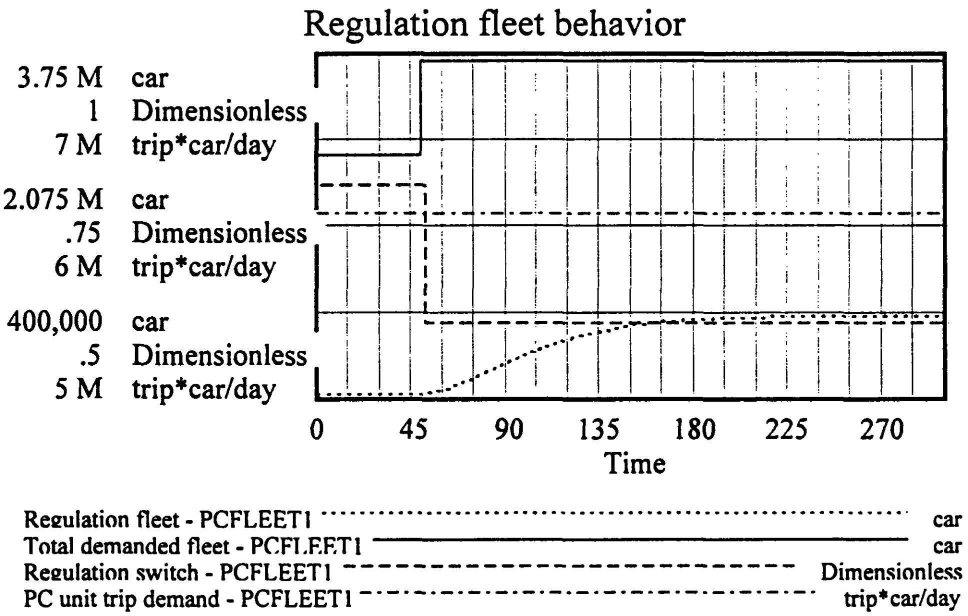


Regarding the behavior of this sector we have determined three main dynamics to observe:

- Regulation fleet responds only to changes in regulation.
- Fraction of cars with catalytic convertors increases over time (if no older cars enter the system)
- Normal car fleet responds slowly to changes in demand. (as a 1991 regulation forces new cars to include convertors)

In order to test the first dynamic, we supposed that the day without a car program is increased to two days per week, thus decreasing the regulation switch from 0.8 to 0.6. The result is that the target regulation fleet increases instantaneously which causes purchases and eventual deliveries of cars into the actual fleet. Figure 23 illustrates this behavior. We also simulated an increase in the demand for private car trips to test the behavior of the car fleet and the convertors against what we predicted.

Figure 23.- Regulation fleet behavior

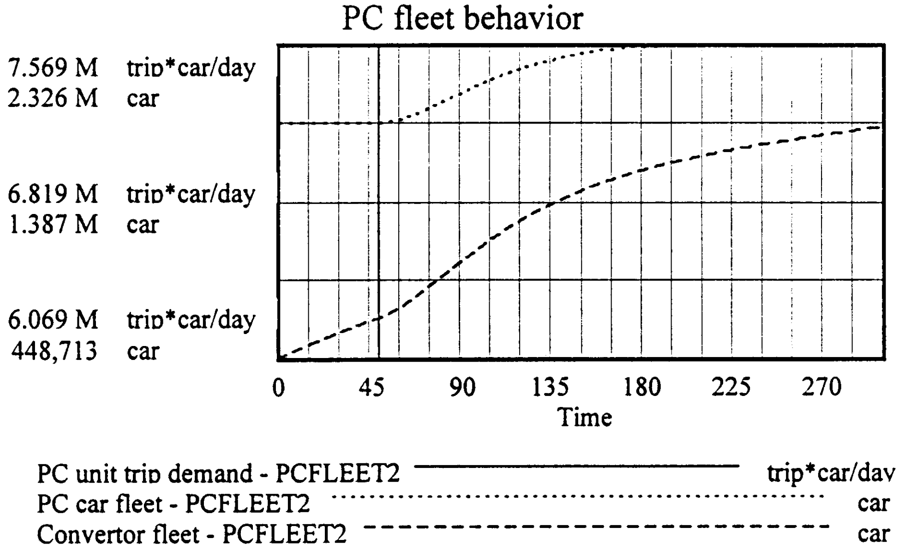


As the utilization of the private car fleet is effectively lowered from 0.8 to 0.6 (2 out of 5 working days without a car), the fleet required to meet the total demanded trips increases from approximately 2.6 million cars to 3.6 million, and the regulation fleet goes from just over 450,000 to over 1 million. This adjustment takes place over almost 180 months (15 years

Regarding the number of convertors per car and the normal car fleet, we simulated their behavior in response to a sudden increase in the demand for private car trips From 6 to 7.5 million trips*car per day.. The figure bellow shows the results for this simulation.

The figure shows that as the PC unit trip demand increases from 6 to 7.5 million, the car fleet (not including the regulation fleet) starts increasing to meet the new demand. Because new cars have to be placed on order and then delivered, the flow of new cars is slow at first, picking up over time and slowing down again as the new demand is met. The number of cars with convertor rises steadily as old cars without convertors go out of circulation and are replaced by new cars equipped with them.

- Normal car fleet and convertor behavior



The Air Pollution Sector

Emission sources

As discussed in chapter 1, this research is concerned with hydrocarbon and nitrogen oxides emissions as precursors of tropospheric ozone in Mexico City. Both hydrocarbons and nitrogen oxides emissions come from transport and other sources. In the case of hydrocarbons, transport emissions can come from evaporation and combustion while other sources include thermo electric plants, industry, liquid petroleum gas (LPG) leakages and vegetation. Nitrogen oxides are primarily a product of combustion and thus have no evaporative component in their transport sources. Thermoelectric plants, services and industry are other sources of Nitrogen Oxide emissions.

Ozone formation is a function of N Ox and HC concentration levels as well as the meteorological factors such as temperature, prevailing winds and thermal inversion. A recent study by the Mexican Institute of Petroleum (IMP) and the Los Alamos Research Center calculated the relationship between different ppm concentrations of hydrocarbons and Nitrogen Oxides and ozone concentrations in Mexico City. The data for this study were obtained in non-favorable atmospheric conditions observed in February 1991. We have assumed that the relationship observed at this time is constant over time, eschewing climatic effects.

After consulting with several people in this field, we concluded that the error that could be introduced by predicting ozone concentrations with data from the cited study is negligible for the purposes of this research. Moreover, the Mexican government has used the IMP/Los Alamos study to evaluate the impact of different public policies on ozone levels.

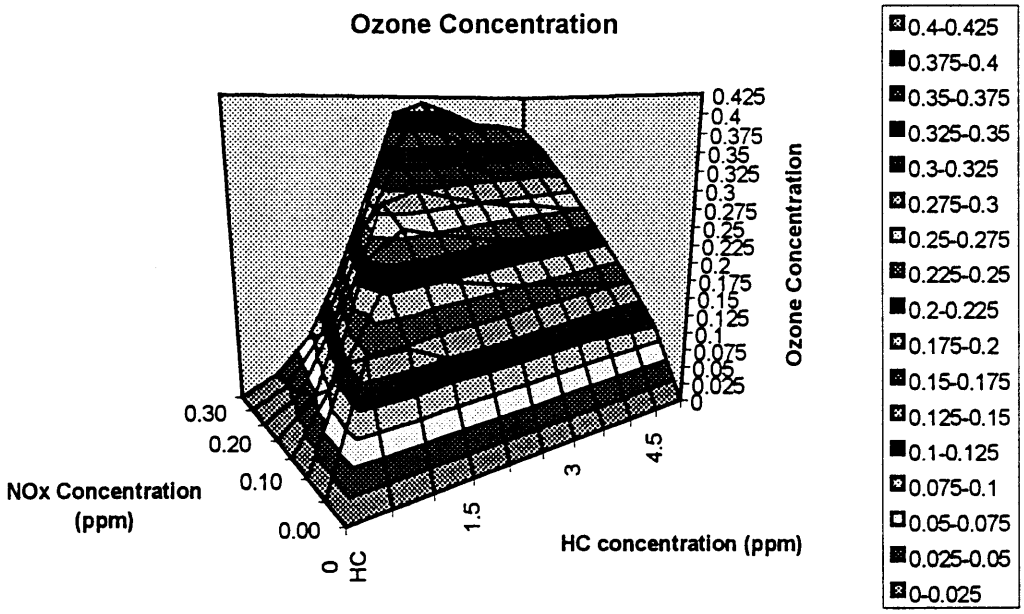
Nonetheless, it is important to note that the obtained ozone concentrations are not, nor do they pretend to be, precise estimations. The calculation of ozone levels using this

The relationship found by the IMP/ Los Alamos study between hydrocarbon and nitrogen oxide concentrations and ozone concentrations is shown in the figure 25.

Precursors concentration in the atmosphere

If Ozone levels can be estimated from hydrocarbon and nitrogen oxide concentrations, it is necessary translate their total emissions into concentrations in order to obtain ozone levels.

.- Ozone levels at different concentrations of HC's and N Ox's



If we assume a pollutant's concentration to be a linear function of its emissions and further assume that zero emissions equal zero concentration, all we need is to obtain a point that lies along this line in order to find the corresponding concentration for any other emission quantity.

point that lies along this line in order to find the corresponding concentration for any other emission quantity.

The Mexican government estimated the total HC and NO_x emissions from various sources including transport in 1994. Along with this emission inventory it also measured the average concentration of these pollutants for the same year. Thus we found that daily precursor concentration is related to emissions measured in tons per year by the approximate relationship:

$$C_{HC} = \text{HC emissions} / 675{,}215$$

for hydrocarbons and:

$$C_{NOx} = \text{NOX emissions} / 641{,}925$$

for Nitrogen oxides.

This, of course, is again a gross approximation. We realize that the relation between the volume of emitted pollutants and the atmospheric concentration of ozone is non linear since its highly dependent on meteorological conditions. We are also aware that when speaking about hydrocarbons we are talking about a whole family of volatile organic compounds, each of those with a very different reactivity. However, we consider that for the purposes of the present study considering a constant composition of hydrocarbons is a fair approximation

The figures bellow show the different sources of hydrocarbons and nitrogen oxides and how they are added to obtain total yearly emissions in the APDM.

Total hydrocarbon emissions are the sum of transport HC emissions and LPG leaks, freight, solvents, vegetation and other sources. Transport HC emissions are generated by private cars with and without catalytic convertors, taxis, buses, microbuses and "peseros", each of which has an evaporative and a combustion component.

In addition to the type of vehicle from which they come, emissions depend on the type of fuel burned. In this regard, we have identified Nova, Magna and Premium as the available gasoline types and diesel has a relatively weak presence in the transport fuel markets. Nova is the oldest gasoline type as well as the most polluting while Magna is an oxygenated gasoline which was introduced a few years ago in order to reduce vehicular emissions (particularly lead). Premium gasoline was introduced late in 1996. Due to the lack of available information regarding the Premium gasoline standards, we have assumed it to have California specifications.From the observed transport modes, only buses use diesel.

We have assumed that the consumption levels between unleaded (Magna) and leaded (Nova) gasoline are determined by cars equipped with catalytic convertors as opposed to cars without them. Catalytic convertors require the use of unleaded gasoline.

The new Premium gasoline will compete with the Magna (unleaded). We will simulate different scenarios for the consumption of each of these gasolines going into the future and adjust the emissions accordingly.

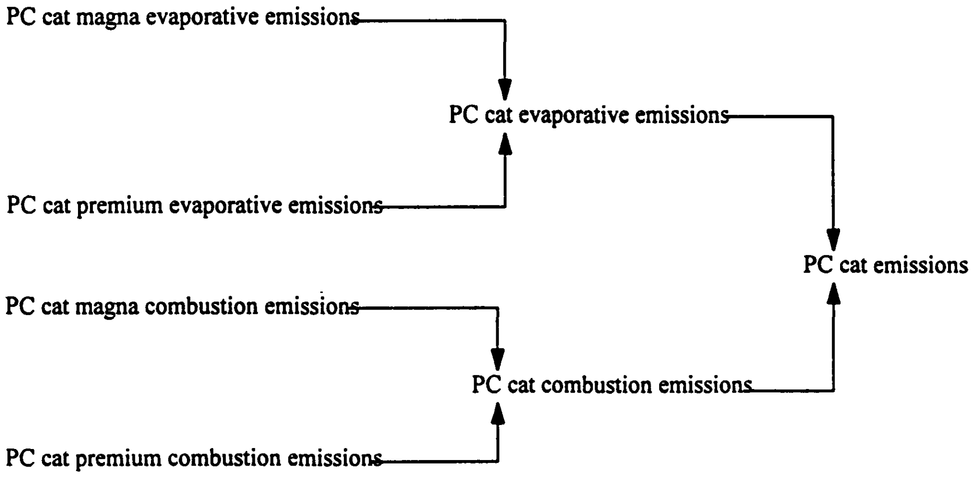
.- Emission analysis factors

Emission type	Vehicle type	Fuel type
• Evaporative	• Private car w/convertor	• Nova
• Combustion	• Private car w/o convertor	• Magna
	• Taxi	• Premium
	• Microbus	
	• Pesero	

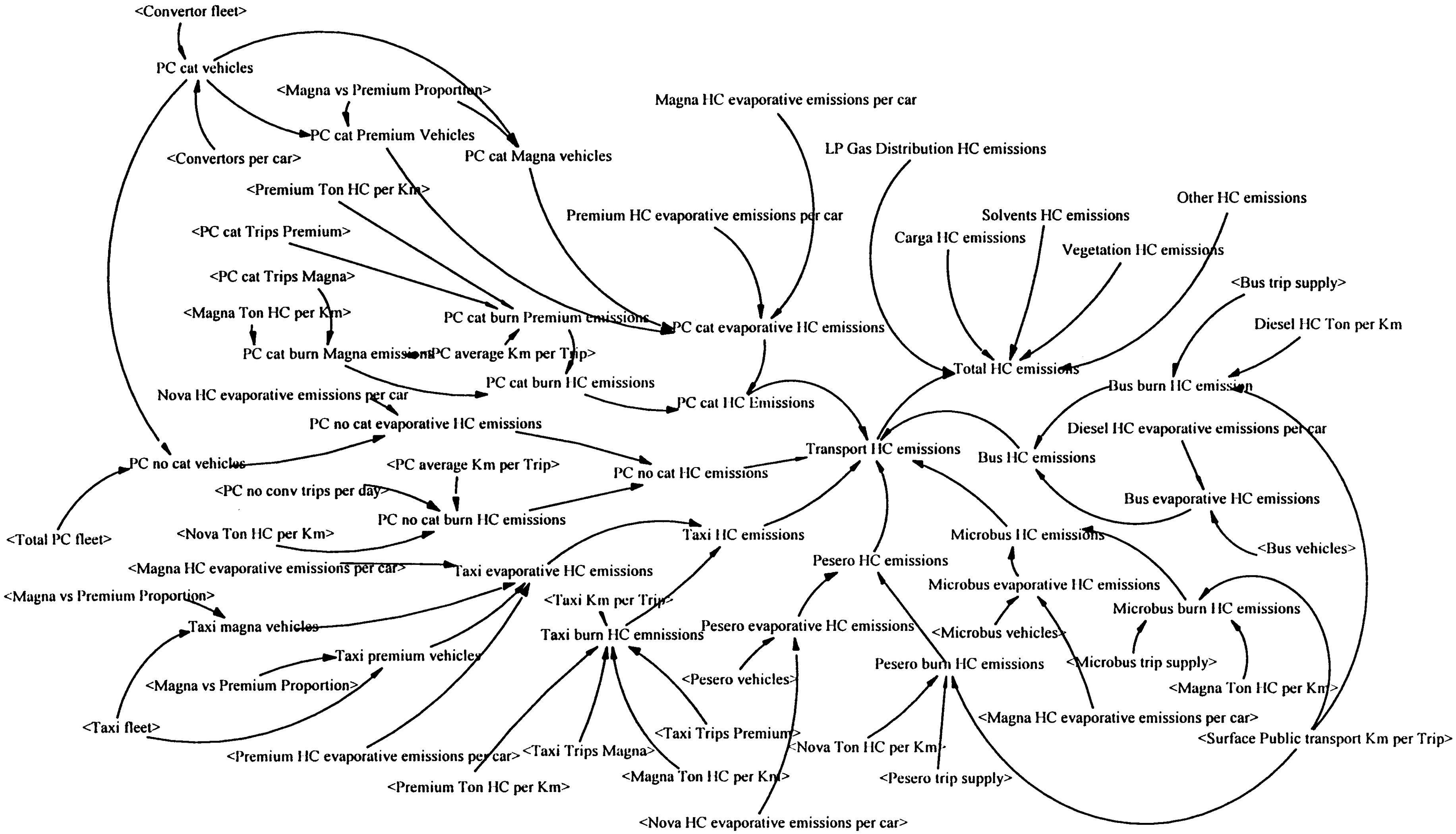
Hence, it is necessary to count the evaporation and combustion emissions of five different kinds of vehicles using three different types of fuels. Figure 28 shows the factors that have to be combined in order to account for all emissions.

As an example, Figure 29 shows the typical analysis tree for convertor-equipped private car emissions. Notice that some combinations such as evaporation emissions of Nova gasoline in cars with catalytic convertors are not possible and therefore not all emissions will use exactly the same analysis tree.

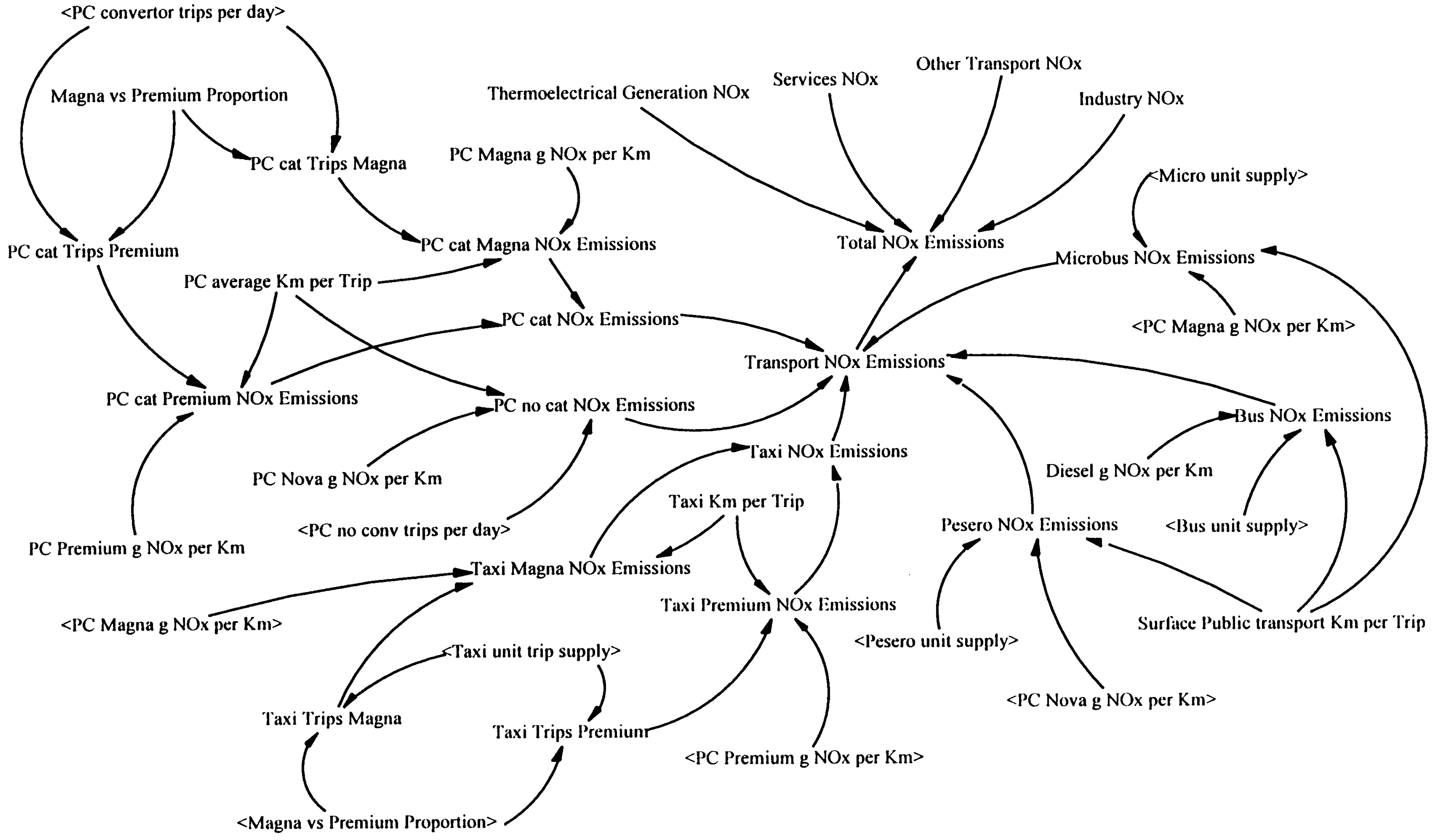
.- Typical analysis tree for evaporative emissions of private cars with catalytic convertors.



.- Estimation of hydrocarbon emissions



.- Estimation of Nitrogen Oxide emissions

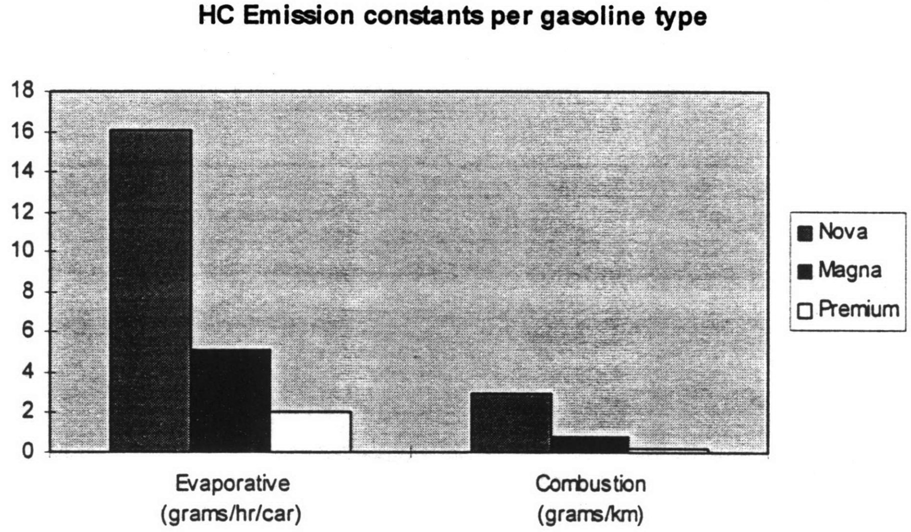


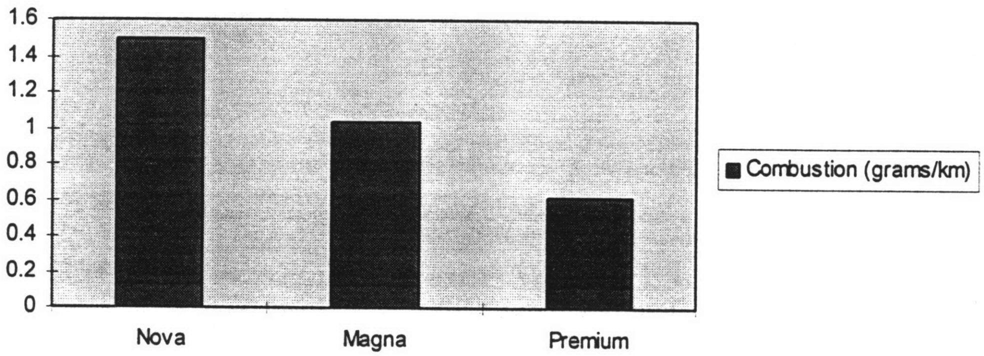
Evaporative emissions depend on the type of fuel used and the number of vehicles using it, regardless of their trips. Cars with catalytic convertors help are considered to prevent and contain the evaporation of gasoline from vehicles. Cars equipped with catalytic convertors (most of them with fuel injection technology) present much lower gasoline evaporation rates.

Emissions that are originated from combustion depend on the amount and type of fuel being burned and the type of vehicle burning it. The amount of fuel burned by any vehicle is a function of the number of trips it makes and the average distance of those trips, i.e., the number of kilometers traveled by that vehicle. Combustion emissions for each gasoline are modeled as the product of the traveled kilometers and a constant number of emissions per kilometer.

The constants corresponding to emissions by evaporation and combustion are expressed in grams of a given pollutant per hour per car and grams per Km respectively. They are shown in the the figure below:

.- HC and N Ox emission constants per gasoline type

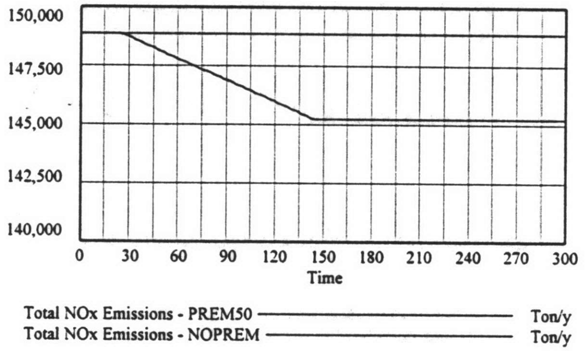


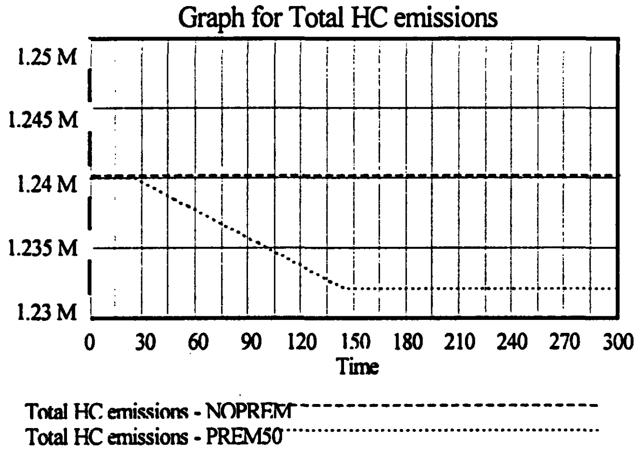

NOx emission constants per gasoline type

We tested the estimation of total hydrocarbon and nitrogen oxide emissions by assuming the new Premium gasoline starts penetrating the market in the beginning of 1997 and gains 50 percent of the unleaded gasoline market by the year 2007. This is an optimistic scenario since it is highly unlikely that: a) Premium gasoline achieves CARB standards, b) penetrates the market at such a rate. As we will see in chapter 3, the required investments in refining capacity would be enormous.

The resulting calculations for the total emissions of hydrocarbons and nitrogen dioxides is shown in the figure bellow

.- Premium gasoline penetration


Graph for Total NOx Emissions



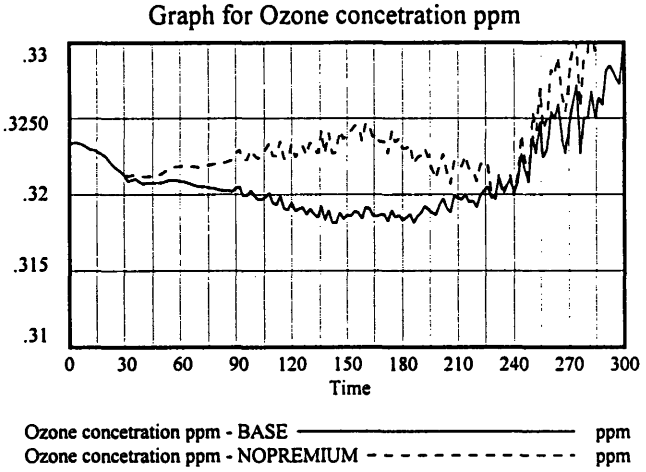
Ozone level estimation

Because of the non-linear relationship between ozone concentrations and levels of hydrocarbons and nitrogen dioxides, it is not appropriate to use a simple analytic expression describing a plane to calculate ozone concentrations. The values obtained by this analytical method differ from the graphically observed values by as much as 100% of the predicted level.

In light of this analytical limitation, we estimate ozone levels by interpolation of the available data. Ozone levels are interpolated on both the hydrocarbon and nitrogen dioxide axes and then averaged to yield the expected ozone concentration.

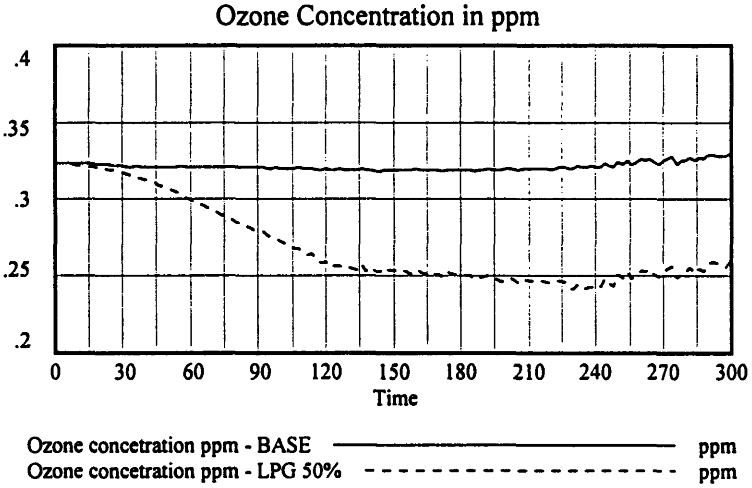
We tested the ozone interpolation by calculating the ozone concentrations arising from the scenario modeled for HC's and N Ox's earlier. As the Premium gasoline gains market share, the total emissions of both hydrocarbons and nitrogen dioxides are reduced, thus affecting the ozone levels. The results for this scenario are shown in the figure below.

.- Ozone concentrations when introducing Premium gasoline.



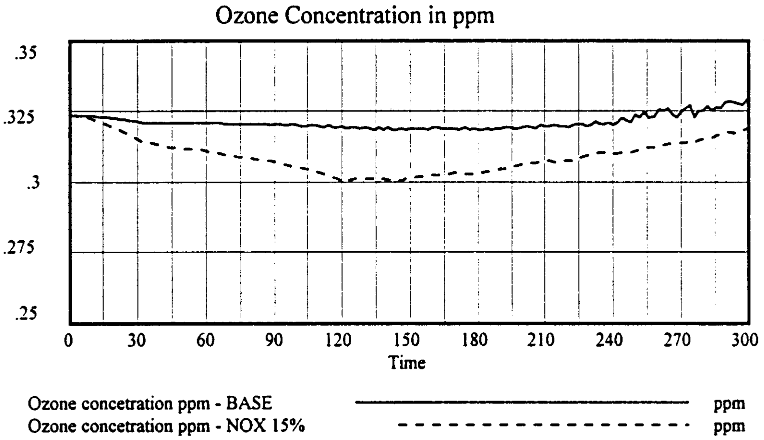
The non-linear relationship between concentrations of ozone and concentrations of HC's and NOx's can be better observed if we consider linear changes in one of the latter pollutants. For instance, if LPG handling leaks were reduced by 50% over the course of ten years, the corresponding reduction in ozone levels would be in the order of 18%, from 0.32 to approximately 0.26. The figure below illustrates this result.

.-Ozone concentration after reducing LPG HC's 50%



Even though the values themselves are only gross approximations, the relationship shown is very relevant when understanding the non-linear properties of ozone formation. More specifically, if we consider a similar reduction in the emissions of nitrogen dioxides of 15% over ten years, the corresponding reduction in ozone levels would be approximately 7%. Ozone levels would drop from 0.32 ppm to 0.26 ppm.

.- Ozone level after reducing NOx emissions 15%



Model integration

The behavior of each of the sectors described above is not the same when simulated in isolation than when simulated interacting with other sectors. For instance, the same external change may cause different reactions in supply and demand, or it may cause compounding reactions which amplify behaviors observed in isolation.

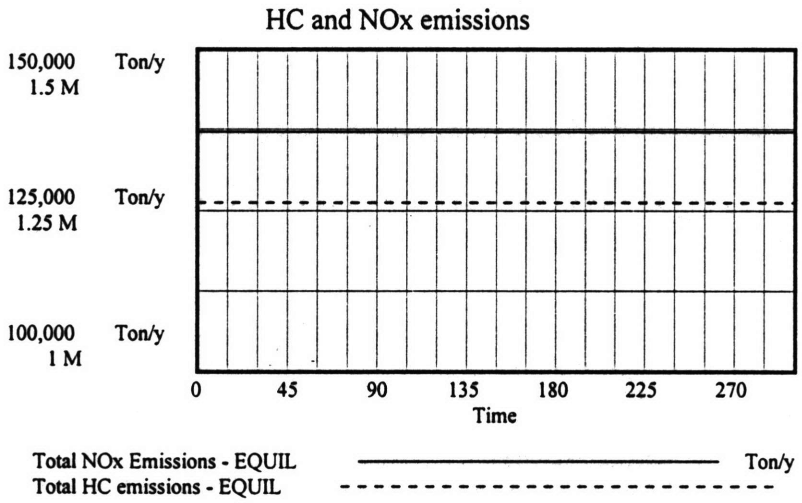
In order to provide the equivalent of a benchmark against which the dynamic effects of different policies can be compared, it is necessary to test the equilibrium of the model. In equilibrium, all stocks in the model remain constant. This implies that the flows into the stocks must exactly match the flows out of them. For instance, in equilibrium the car fleet will be constant and car purchases will exactly offset the natural scrappage of vehicles at the end of their average lifetime.

We tested the whole model in equilibrium and compared the results with the available data we had on total emissions for 1995. Not surprisingly, the vehicle fleets, number of trips, emission inventory and ozone levels simulated in the model for January 1995 were similar to their historical values. The table below shows how some of the critical model variables match historical values.

Variable	Units	Historical value	Simulated value
Total private car fleet	cars	2.5 M	2,222,162
Total HC emissions	ton / year	1,025,760	1.079 M
Total N Ox emissions	ton / year	128,646	137,132
Private car trips per day	car-trip/day	6.163 M	6.283 M
Taxi trips per day	taxi-trip/day	1.008 M	768,372
Public vehicle trips per day	pubv-trip/day	838,968	968,718
Subway trips per day	person-trip/day	4.217 M	3.265 M

As an example of the behavior of these variables in equilibrium (constant over time), the figure below shows total hydrocarbon and nitrogen dioxide emissions for this simulation.

.- Equilibrium emissions of hydrocarbon and nitrogen dioxide



It is not necessary to make great changes to variables such as total transport demand in the city in order to start analyzing the system's structure. In fact, just by adjusting the initial number of catalytic convertors to their real values, we uncover a basic and fundamental dynamic behavior.

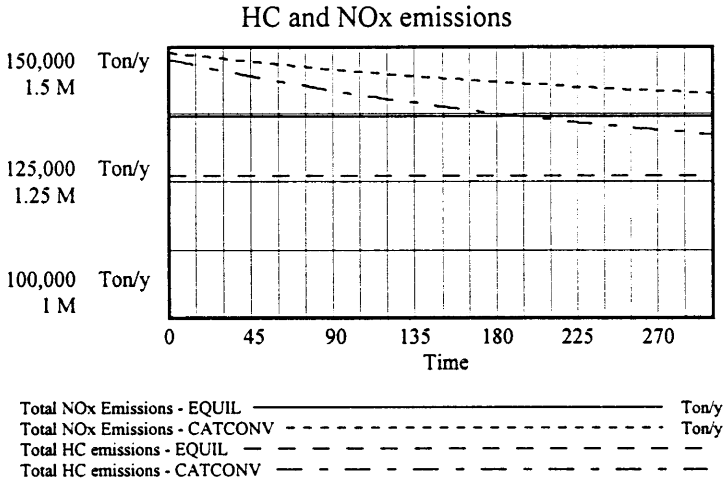
In equilibrium conditions, the model assumes no growth and no change in any policy during the simulation. Thus, flows like car purchases are only enough to cover the natural scrappage of the fleet, etc. However, because the old fleet going to scrap does not have catalytic convertors and the cars which are bought as replacement are equipped with convertors, the number of inefficient cars is constantly decreasing. This will happen until all cars in the fleet are equipped with convertors.

Observing hydrocarbon and nitrogen dioxide emissions, in a simulation where the number of cars equipped with catalytic convertors is increasing, we note that the results from the model do not resemble the equilibrium results. Even though neither the number of trips or vehicles change during the simulation, hydrocarbon and nitrogen dioxide concentrations do not remain in equilibrium but rather decrease over time. They start out at higher values because the number of private cars equipped with catalytic convertors in reality is much lower than the equilibrium condition.

Figure below shows the estimated HC and N Ox emissions compared to the growing number of convertors installed in the car fleet. Also plotted are the total catalytic convertors installed in the private car trips (Convertor fleet).

By tracing the causes of emissions back to the convertors we were able to identify the renewal of the private car fleet as the driver behind this behavior. Note that this behavior is due exclusively to the number of catalytic convertors; there are no changes in transport supply nor demand. The name of the simulation is CATCONV.

HC and NO$_x$ emissions and catalytic convertors



Additional dynamics included

Along the process of modeling our original dynamic hypotheses and researching relevant parameters for the simulations, we have run across behaviors and theories to explain them which have caught our attention. Specifically, we decided to include the variability that congestion levels produce on travel times and the effect of the average trip speed on the emissions per km of the different gasolines.

Together, these two facts may alter the behavior of the air pollution dynamics of Mexico City. Given that the average trip distance is virtually constant, a random oscillation of travel time translates into a random oscillation of average trip speed, which affects combustion efficiency. When cars reduce their average speed below a certain limit, the emissions per km of hydrocarbons rise dramatically. Such is the importance of these occurrences.

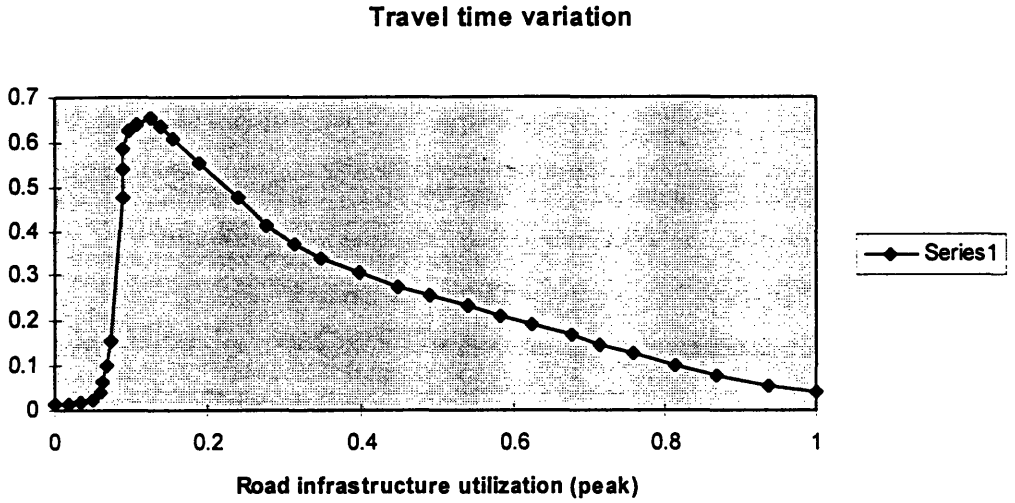
Earlier in this chapter we mentioned that at relatively low levels of congestion there is great uncertainty around the total travel time. As congestion rises still further, the uncertainty decreases until eventually it reaches zero when travelers are certain they will never reach their destinations.

The impact of uncertainty around the expected travel time can be quite significant. Nagel and Rasmussen estimate it at 65% of the expected time at its peak with 11% congestion. The figure shows the uncertainty of travel times corresponding with different road infrastructure utilization rates.

Thus, the trip time for a given mode of surface transport (Private cars, taxis and public vehicles) is an expected value depending on congestion levels. The observed trip times will oscillate randomly around their expected values, causing the average speed of these trips to oscillate as well.

We tested this dynamic with a constant congestion and found that travel times oscillate around their predicted values. Results are shown in the figure bellow.

Travel time variation Vs road utilization

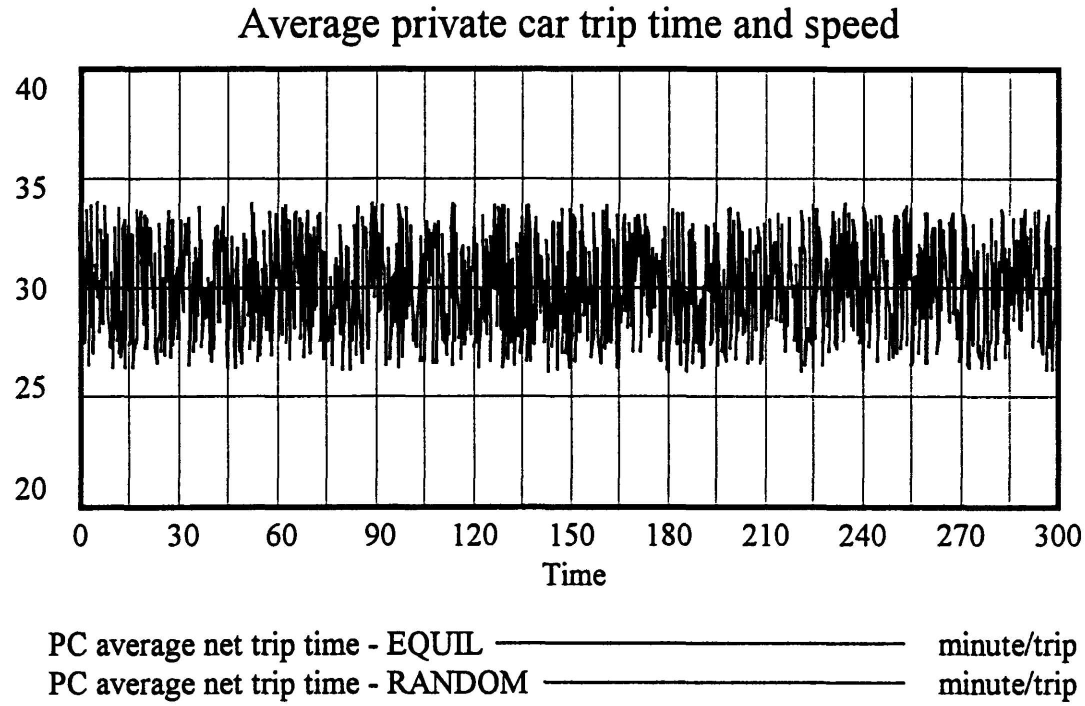


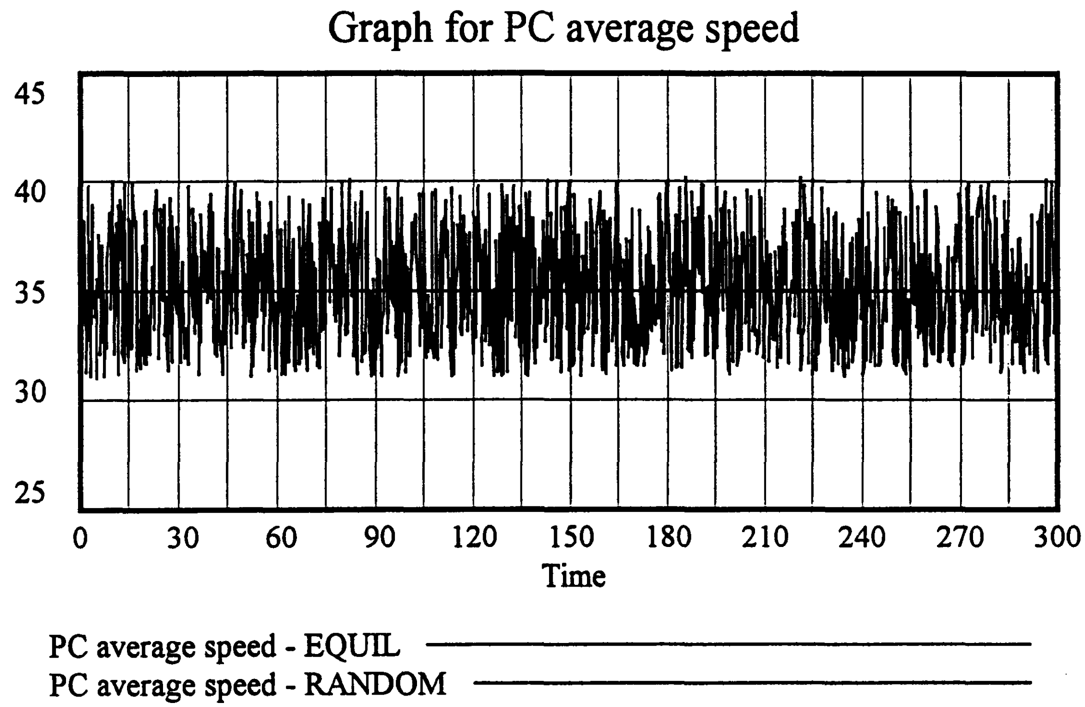
The following figure shows the travel times for private car trips at constant congestion levels. We can see that even though the expected travel time is constant at approximately 30 minutes per trip, the actual trip times move between 25 and 35 minutes randomly. We have plotted the corresponding average speed for this trips in the next graph. These speeds oscillate between 30 and 40 Km/h.

Even though the effect of speed on combustion efficiency is true for both hydrocarbons and nitrogen oxides, in the case of nitrogen oxides emissions increase only at very high velocities. Thus, the effect of reduced average speeds below a critical level is to increase hydrocarbon combustion emissions while keeping nitrogen oxide emissions unaffected.

Trip time uncertainty and speed-related pollution are the last dynamics included in the model. By simulating different policies under different scenarios these and other dynamic effects, we can test the robustness of our decisions.

Private car travel time and average speed.





Control settings

The dynamic effects or "control settings" for the model can be divided into policy controls, model structure controls, transit policy controls, infrastructure policy controls, and energy policy controls. As these variables take different values, the underlying structure and assumptions of the model adjust to reflect a particular view of the city and a particular policy. In this way, it is possible to simulate the same policy under different scenarios describing the city's inherent dynamics, thus testing the robustness of the policy in question.

For instance, the response of the system to a policy of increasing the use of rail transport might be different if increased demand is met with expansion or not. If subway utilization rises and causes further subway lines to be built, the system's pressure points will be dissipated by the construction. On the other hand, if subway utilization is met by a stringent construction budget, then a different system response will ensue.

The figure below shows the different scenario controls built into the APDM.

Model structure	*Infrastructure policy*	*Transit policy*	*Energy policy*
<Convertor equilibrium switch> <Speed pollution switch> <Random multiplier switch> <Symmetric cascade switch> <Demand equilibrium switch>	<Willingness to build and use rail capacity> <Road capacity> <Road tax to PC per km at full capacity>	<Regulation switch> <Subsidized car retirement>	<Magna vs Premium Proportion> <Pemex Magna substitution fraction> <Gasoline tax per km to PC>

a) Model structure

- Regulation switch refers to the day without a car program. At the start of the simulations its value is 0.8, as one out of every five working days cars are not allowed to make trips. Lifting the ban on the use of cars would be equivalent to a regulation switch of 1.
- Road capacity is a gross estimate of the city's road infrastructure capacity in terms of hourly vehicle throughput. A higher road capacity means a lower expected trip time and less uncertainty.
- Willingness to build and use rail capacity represents the economic, political and technical ability of the government to meet deficits of rail transport with new construction. This variable suggests a percentage of the rail deficit gap that the government will undertake to build.
- Subsidized car retirement refers to a program to retire old cars with outdated technologies and replacing them with new, more efficient vehicles. The policy assumes that the government retire a certain amount of old cars of the system and scrap them and would introduce the same amount of cars, with more efficient technologies, in exchange. The value of the switch is the number of cars retired at any given time.
- Convertor equilibrium switch allows the initial equilibrium simulation to return constant values for all stocks and flows in the model. For the sole purpose of achieving the mathematical equilibrium of the model, this switch changes the number of convertors installed in the fleet to equal the target equipment of the private car fleet.
- Speed pollution switch enables the model to capture the link between reduced average trip speed and increased pollution per km traveled. A value of 1 incorporates the effect.
- Random multiplier switch enables the model to capture the link between road utilization and average trip time uncertainty. A value of 1 incorporates the effect.

- Symmetric cascade switch changes the assumption of a given mode's transport surplus or deficit. When symmetry is assumed, unsatisfied demand flows into the next transport mode and excess demand takes away from the next transport mode.
- Magna Vs Premium proportion represents the share of the unleaded gasoline market that the present Magna gasoline will maintain in the face of the new competing Premium gasoline. This fraction does not have to be constant; any schedule of Premium penetration can be simulated.
- Demand equilibrium switch is linked to the estimation of total transport demand from GDP and population of the city. A value of zero sets demand growth to zero, thus setting this sector of the model in equilibrium.
- Gasoline Tax per Km to PC: simulates a gasoline tax by adding it to the operational cost of the vehicle.
- Road tax to PC per Km at full capacity: simulates a congestion tax by adding it to the operational cost of the vehicle and relating it to the road utilization factor..

By combining these scenario controls we will develop insight into the dynamics of the system and we will test the robustness of different public policies.

As en example of the use of this scenario controls, we ran a test simulation comparing the equilibrium scenario with one of the following characteristics:

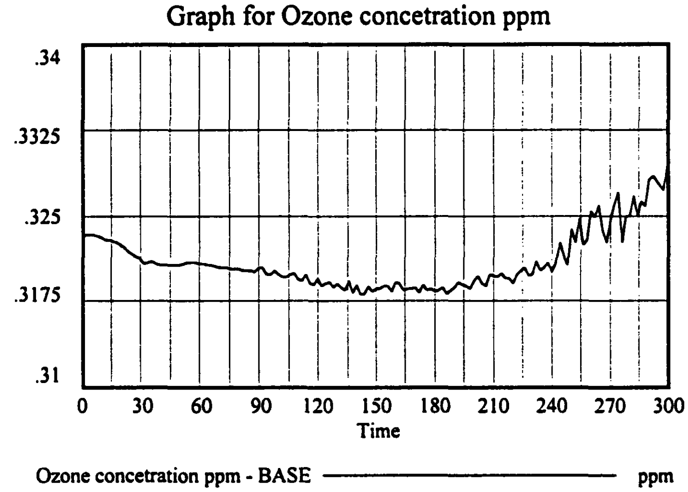
Scenario control	Value
Regulation switch	0.8 (constant)
Road capacity	1,515,940 trip-car / hour (constant)
Subsidized car retirement	0 (constant)
Pemex Magna substitution	0 (constant)
Gasoline tax per km to PC	0 (constant)
Road tax to PC per km at full capacity	0 (constant)
Willingness to buy and use rail	0 (constant)
Convertor equilibrium switch	0 (using observed convertors)
Speed pollution switch	1 (enabled)
Symmetric cascade switch	1 (enabled)
Random multiplier	1 (enabled)
Magna Vs Premium proportion	0 to 50% penetration in 10 yr.
Demand equilibrium switch	1 (growth)

It is nearly impossible to predict what the behavior of the model will be once it has been integrated and there are 13 control settings changing its conditions. It is at best unclear which dynamics will dominate and which will become relatively weaker. For instance, the growing number of catalytic convertors on one hand tends to reduce hydrocarbon emissions as well as nitrogen oxides, while the growth in the city's population and the GPD tend to increase these emissions. Similarly, increased traffic tends to reduce the average trip speed, thus increasing emissions while the presence of the new Premium gasoline tends to reduce them. Finally, the effect of the random component of trip times on emissions is unclear.

We have considered this simulation as the base case against which future simulations can be compared in order to evaluate their results Hence, the name of this simulation is BASE..

A look at the predicted ozone levels shows that under this scenario, long term ozone levels will be higher than what they are today. The figure below shows the predicted ozone levels.

Ozone levels in the first test simulation



At first glance we are able to form a mental model which explains the behavior of the system in very simple terms. The rate at which the city grows both demographically and economically produces more pollution than the combined effect of catalytic convertors purchased with new cars and the introduction of the Premium gasoline.

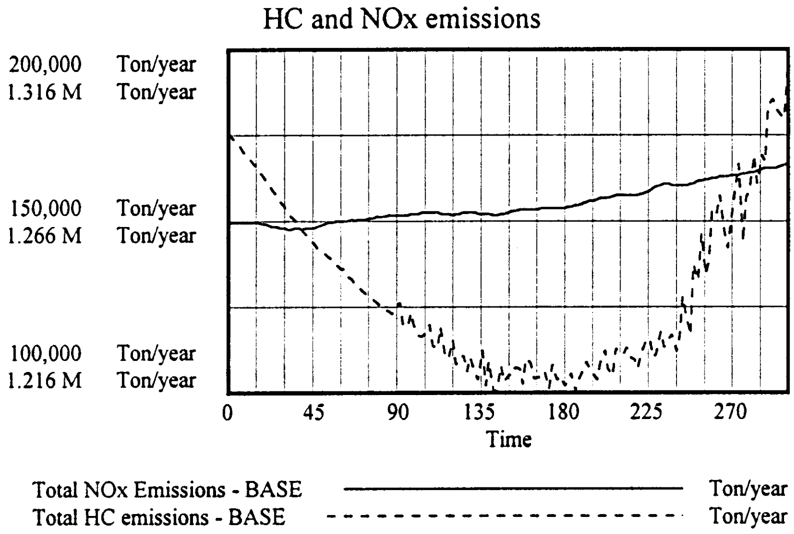
However, this mental model is not sufficient to explain the drivers behind this behavior. Would it have helped if the rail had been expanded?, Is the increased traffic causing vehicles to pollute more at lower speeds, or is it offset by the reduced attractiveness of higher trip times?

In order to understand the behavior of ozone levels in this simulation it is useful to trace its causes and identify the governing dynamics of the system.

The first step in tracing the causes of ozone is to look at emissions. This is important because of the non-linear relationship between emissions and ozone as well as because the emission inventories will further reveal the way in which the system's pollution is growing.

The figure below shows the hydrocarbon and nitrogen dioxides concentrations on the BASE simulation.

Pollutant concentrations

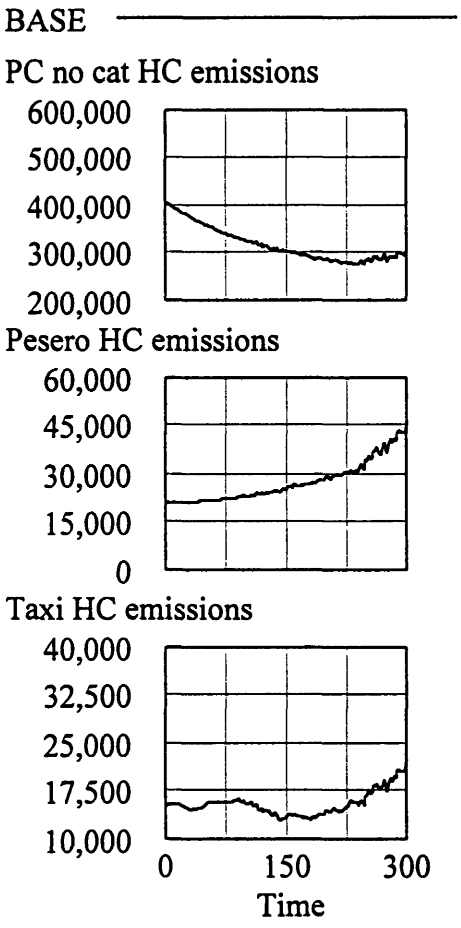


In this graph we see that the concentration level of both pollutants rises in the long term, albeit with slightly different behaviors. While nitrogen dioxide concentration is rising almost linearly, hydrocarbons look more like an exponential curve, showing an initial decrease and higher growth in future months. Additionally, hydrocarbon concentrations are much more volatile than nitrogen dioxide.

The volatility observed in the hydrocarbon concentration is due to the random component of trip time and average speed. As average speed oscillates around a mean value, so will the average efficiency of engines and thus emission levels. At the suggested level of road congestion, the uncertainty component of trip times seems to have a relatively low impact on pollution levels.

In this scenario, traffic is certainly more costly because of its delay costs (lost productivity) than because of it environmental impact by uncertainty. However, the environmental effect of traffic must not be disregarded, at least not until we have understood why hydrocarbon emissions rise faster towards the end of the simulation.

Some components of hydrocarbon emissions



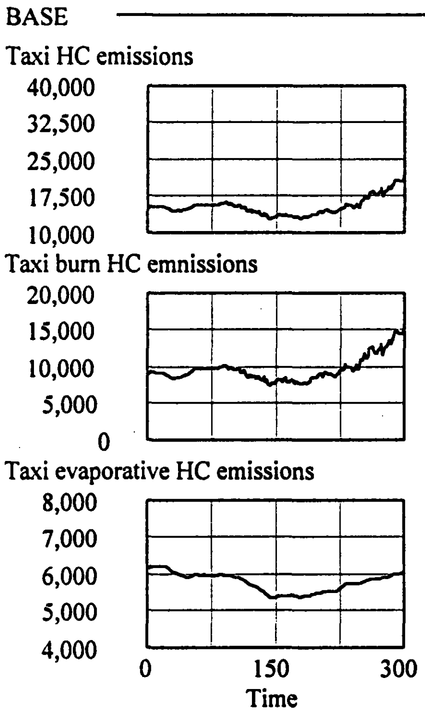
By analyzing the components of hydrocarbon emissions we see that al surface vehicles have increasing HC emissions with the exception of cars without catalytic convertors and taxis.

As cars without catalytic convertors are replaced with new cars, the number of such cars becomes smaller. Thus, emissions from these cars decrease because of a shrinking fleet.

This reduction is in fact offset, albeit no completely, by the increase of emissions from the growing fleet of private cars equipped with catalytic convertors.

Taxi emissions are driven by both evaporative and combustion emissions from taxis. This suggests that the behavior of the supplied taxi trips per day and the total taxi fleet follow the same pattern. The figure on the next page shows this fact.

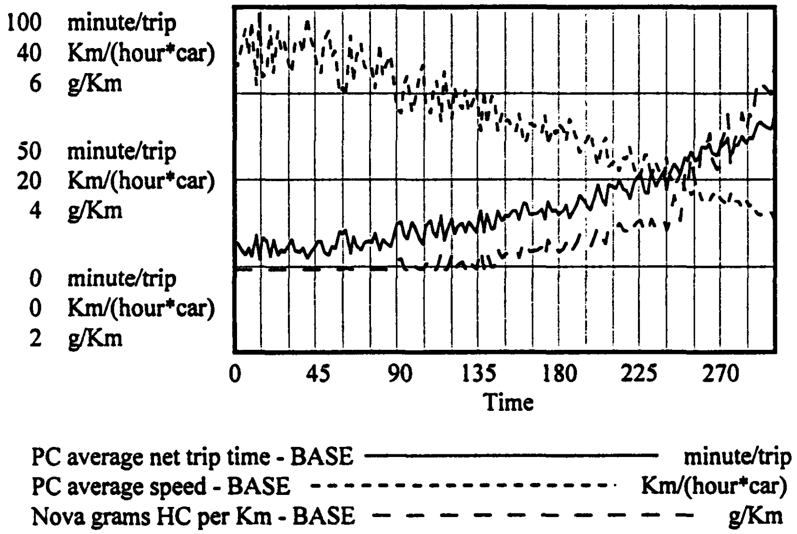
Regarding other transport sources, only the combustion component of emissions exhibits this growth pattern. Thus, we can now trace it to either the number of trips taken or the emissions per trip (which are affected by speed).



In the case of Private cars without catalytic convertors use Nova gasoline. The value of Nova gasoline emissions per km traveled can be compared with the expected travel time for private car trips and the average speed for those trips. As congestion levels rise in the city, the expected trip time for private car travel is higher and thus the average speed of the trip is lower. At lower speeds, engines -and particularly old engines- are less efficient and produce more emissions per km traveled.

Going back to the total hydrocarbon concentration, we see that although traffic does not pose a significant cost to the environment for the uncertainty it causes, it may cause significant problems at high road infrastructure utilization. Additionally, we see that mere congestion levels are not enough to divert the population from the use of the car. Thus the balancing loop resulting from the loss of attractiveness is, under this scenario, not strong enough to offset the efficiency loss of engines at lower speeds..

Average PC trip time, speed and related Nova emissions per km

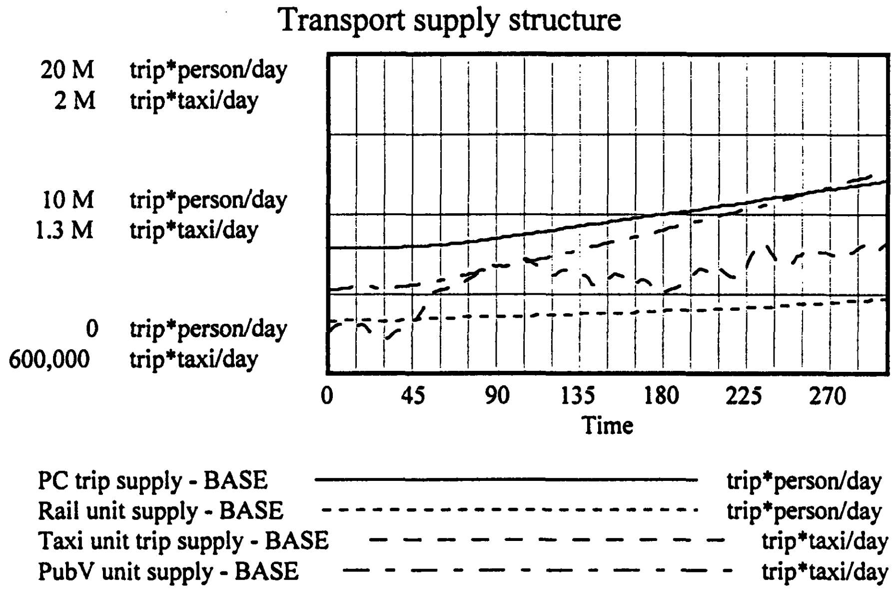


It is useful to understand the dynamics that increased traffic and travel times cause on the trip demand from the different modes. Although we would expect to see rail snatching a higher market share from the surface transport because of longer trip times, we find that they have the slowest growth. It is also interesting to note that taxis seem to be the most volatile mode regarding trip supply.

The trip supply for all modes of transport in the city is shown below. While private cars, public vehicles and rail generally follow the increase in the total demand for transport, taxi trips supply reacts very aggressively to the economic growth of 1997. The reason for this is the relative size of the taxi trip market compared to the private car trips.

As total transport demand starts increasing due to strong economic growth in 1997, all modes of transport are subject to increased demand. The additional trips demanded from the private car sector cause the population to increase its utilization of their cars and eventually to purchase additional cars. However, since automobile utilization cannot be adjusted overnight, there is a certain fraction of the demanded trips that remains temporarily unsatisfied by private cars and which are sought to be satisfied by the use of taxis.

Even though the unsatisfied trips are a relatively small fraction of the demanded private car trips, they are a massive demand shock to the taxi market. In other words, all those people who take time to arrange higher car utilizations (car pools, car sharing, etc.) in the face of increased travel demand will consider taxis as their first transport alternative. Because the taxi fleet is very small relative to the private car fleet, this residual demand from the private cars is overwhelming for taxis, even greater than the demand increase they face due to the city's growth.



Thus we see that policies which affect one mode may amplify or curtail their effects on other modes of transport, depending on the relative size of their fleets and utilization rates.

Sensitivity scenarios for the base case

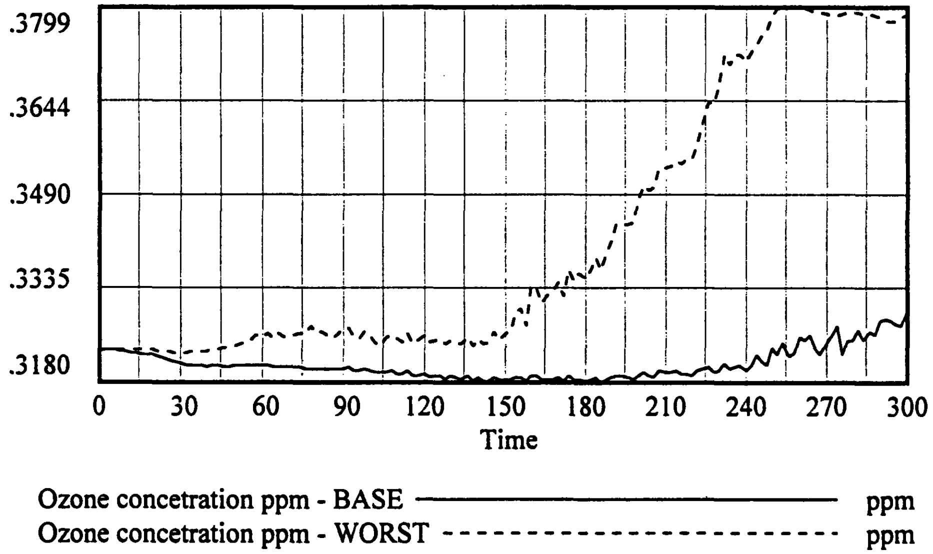
We have compared every proposed policy to our BASE case and judged its merit based on that comparison. This might give rise to some questions as to the validity of the BASE case and thus of the comparison itself.

We feel that the most relevant conclusions of the present study are of an structural, rather than a numerical nature. Therefore, the precision of a predicted ozone level for a particular scenario is not so important as the relative behavior of predicted ozone levels between a BASE case and a POLICY scenario. However, precisely because of the structural relationships between different policies and the BASE case it is valid to extrapolate the same relationships to different BASE cases. In other words, there is a valid discussion surrounding the base case.

The proposed BASE case for the APDM is an optimistic scenario of the city in terms of its growth and gasoline technology. Demographically, we have assumed to city to grow at a random rate oscillating tightly around 1.5 % annually. This translates into an estimated population for the year 2019 of 32 million people (including all of the metropolitan area). Regarding gasoline technology, the model assumes that the new Premium gasoline is introduced in 1997 and gains 50% market share from the currently used Magna Sin gasoline in 10 years.

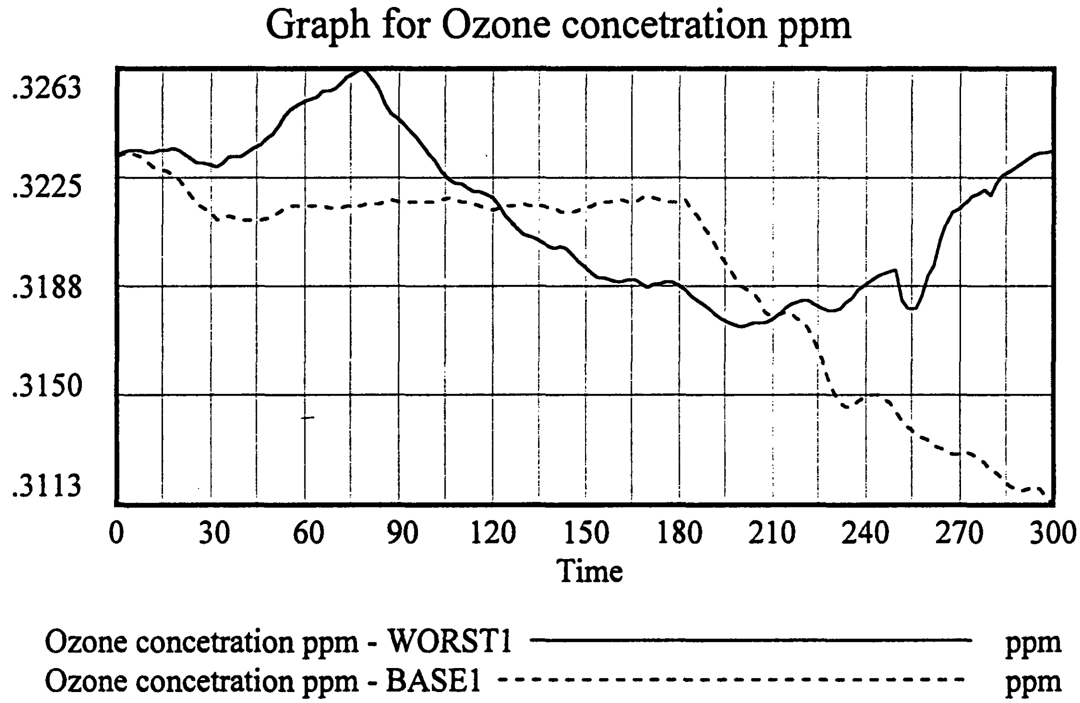
Under a pessimistic scenario, the city's population would grow at 3.5 % annually and the Premium gasoline would only reach a 10% penetration of the unleaded market. The differences between this BASE case with the optimistic view and the WORST case with the pessimistic view can be extrapolated for the results of the different policies.

Graph for Ozone concetration ppm

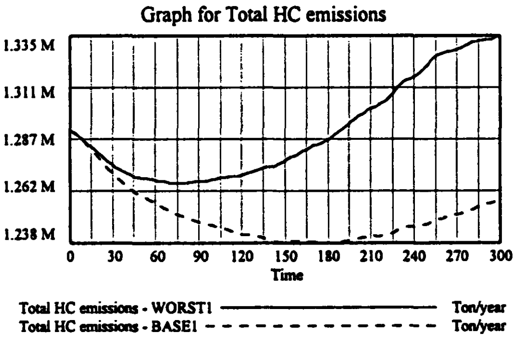


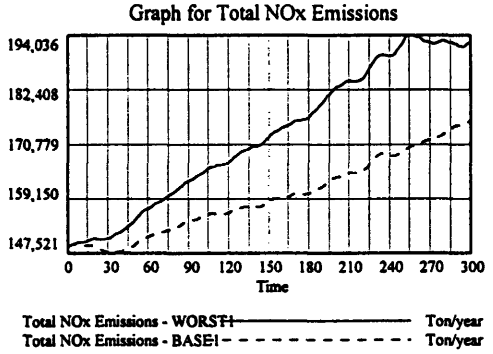
Finally, in order to qualify the difference between the BASE case and the WORST case, we have ignored the effect of reduced speed on air pollution, assumming that emissions per km remain constant regardless of speed. This only pretends to account for the fact that our present estimates for road capacity could also distort the expected results.

The same comparison is presented with the BASE and WORST scenarios labeled BASE1 and WORST1 respectively.


Graph for Ozone concetration ppm

A brief look at the hydrocarbon and nitrogen oxide concentrations reveals that the apparently erratic ozone movements are actually a product of the non-linear relationships between precursors and ozone levels.


Graph for Total HC emissions


Graph for Total NOx Emissions

Thus, regarding the BASE case for the simulations, there are two key points to consider. The first is that the effect of reduced speed on pollution is actually a critical variable and should not be taken lightly. The second is that, other things being equal, the distance between an optimistic BASE case and a pessimistic WORST case in not abysmal in terms of ozone levels, although it might make a great difference regarding the region of the ozone isopleths the city is at.

INFRASTRUCTURE POLICIES

Infrastructure And Urban Systems Behavior

Public policies regarding infrastructure are perhaps the ones that need to be best understood before being set. "The complexity of infrastructure systems arises partly from the interface between a relatively static arena which supports and constrains a relatively dynamic traffic of activities. The emergent behavior of the system depends on the detailed design of the arena and the collective behavior of the traffic using it. In the case of transportation the arena has a network structure and so its performance also depends on the connectivity of the network as well as its capacity."

A complete arena of infrastructure changes much more slowly than do the patterns of traffic using it. However, a network's capacity may in some cases be changed at a speed almost equivalent to that of the traffic that flows through it. This can happen by changing the efficiency with which traffic moves. Another way to change the performance of an infrastructure network is to alter the traffic patterns it supports. This implies changing the decision mechanisms that make individuals determine their use of the network.

Hence, there are three ways to alter the behavior of an infrastructure arena. The first is to change the physical underlying infrastructure, which is costly and time consuming as well as long lived and difficult to predict. The second way consists in improving the efficiency of traffic movement within the network, via signalization, usage regulations, etc. Finally, it is possible to affect the decision mechanisms of individuals and thus alter their usage of the network. This approach to change requires a deep understanding of the decision process of the individuals.

In this section we will test three infrastructure related policies geared towards reducing air pollution levels in Mexico City. The first simulation will consist of an aggressive policy of subway expansion, i.e., growing the physical network that supports the transport demand of the city. A second policy will deal with improving the efficiency with which traffic flows through the existing network. This scenario entails an enhancement of traffic signalization and the establishment of parking rules which will increase the effective throughput capacity of the road infrastructure. Lastly, we will consider the enactment of a congestion tax which will effectively increase the cost per trip to private cars in the city, thus shifting the travel mode decision of the population away from private cars.

Rail construction

In order to evaluate the results from this simulation we have compared its results to the ones obtained in the BASE simulation. Additionally, to be able to understand the effects of the suggested policy in isolation from other policies we have kept all model switches at their BASE values except the switch corresponding to rail building.

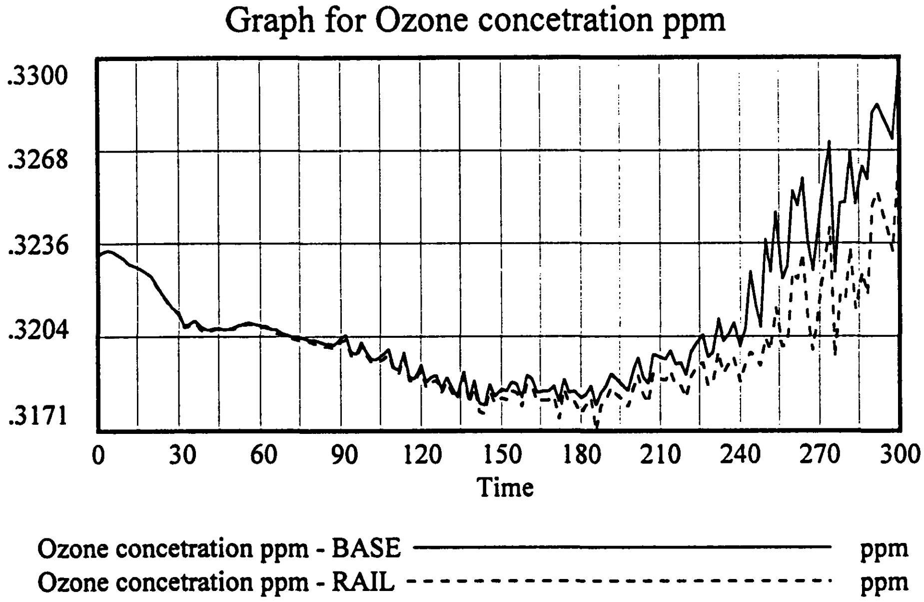
As it is explained in the model equations, the *Willingness to build and use rail capacity* captures the limitations faced by the city government regarding the provision of subway infrastructure. These limitations may be of a political, technical or economic nature and their combined effect is simplified as a percentage of the observed capacity deficit that is actually constructed by the government. Thus, when the switch is set to zero (such as in the BASE case) the subway infrastructure is assumed to be constant over time, regardless of the demand for rail travel.

This policy will be simulated under the name of RAIL and the value of the *Willingness to build and use rail capacity* switch will be set to one (100 percent of the capacity deficit will be tended to by the government).

The values for the different switches in the BASE simulation and the RAIL simulation are compared in the table below. We then present a discussion of the main findings of the simulation along with the structural insights developed and an evaluation of the robustness of the policy in terms of its impact and likelihood of success.

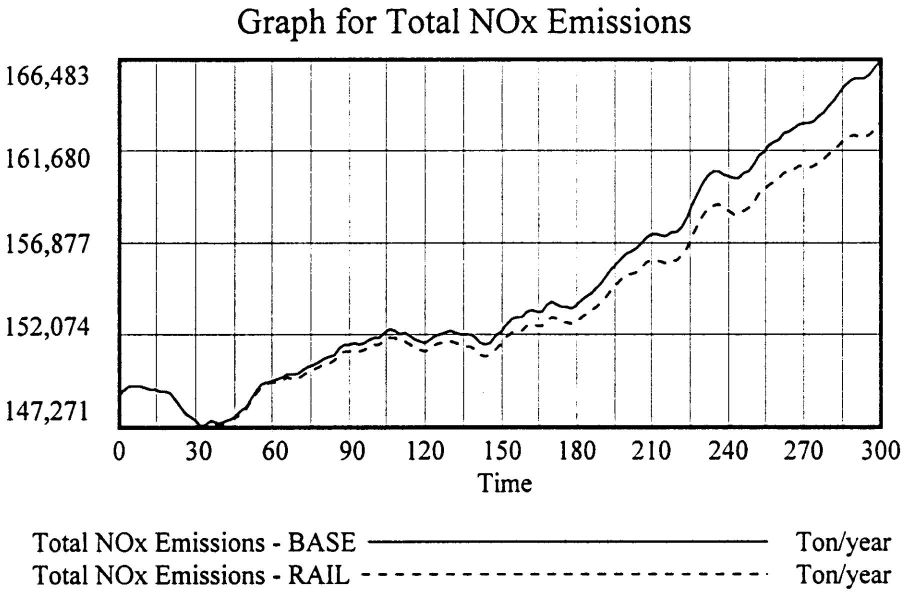
Switch	BASE Value	RAIL Value
Model structure switches		
Convertor equilibrium switch	0	0
Random multiplier switch	1	1
Demand equilibrium switch	1	1
Symmetric cascade switch	0	0
Speed pollution switch	1	1
Infrastructure Policy switches		
Road capacity	1,515,940	1,515,940
Willingness to build and use rail capacity	0	1
Road tax to PC at full capacity	0	0
Transit Policy switches		
Regulation switch	0.8	0.8
Subsidized car retirement	0	0
Energy Policy switches		
Magna Vs Premium Proportion	50% by 2007	50% by 2007
Pemex Magna substitution fraction	0	0
Gasoline tax per km to private cars	0	0

After running the simulation we found that there is little effect gained on ozone control by pursuing an aggressive subway construction program. Long term levels of ozone are almost identical to the base case, showing a behavior that is visually parallel.



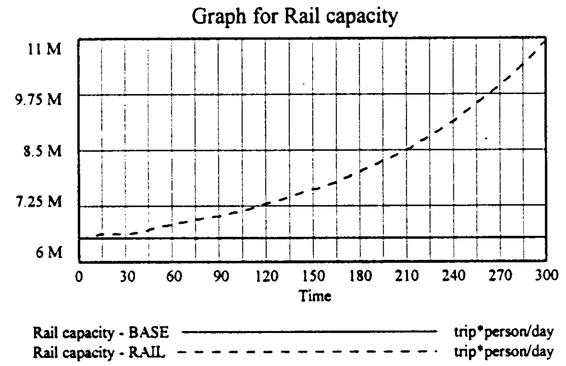
There are two questions to answer relative to the behavior of ozone levels in this policy. The first question is to explain why the long term reduction in ozone levels is only in the vicinity of 0.005 ppm, i.e., almost nil. A second question is why ozone levels seem to diverge in the long term even though they are virtually equal to the base case during the first 10 years of the simulation.

By observing the behavior of hydrocarbon and nitrogen oxides emissions for both simulations, we can discard the possibility of a non-linearity in the ozone function. We see that the emissions for both pollutants in the RAIL simulation hold the same relationship to the base case as the ozone levels. Even though there is a small reduction in the nitrogen oxide concentrations observed between months 35 and 155 (October 1997-october 2007), it is not matched by a corresponding reduction in ozone levels. This is in part due to the fact that the city's current HC to NOx ratio is related to a highly unfavorable region for NOx reductions, i.e., relatively large NOx reductions yield only marginal reductions in ozone levels. Additionally, the drop in nitrogen oxide emissions during this time is very small relative to the total NOx emission inventory.



Since the final ozone deviation cannot be explained by a non-linearity of the ozone-pollutants relationship, we must look back to more fundamental causes for the final value.

The most direct effect of the RAIL policy is to increase the capacity of the rail system. As demand for rail and all other modes of transport goes up, the utilization of the rail system increases, creating a pressure to build more capacity. In the BASE case, we have assumed that technical restrictions, political costs and/or budget constraints prevent the additional rail capacity from being built. Under the RAIL policy, however, the pressure on the rail system is relieved by expanding the capacity of the system. Thus, capacity expands constantly to meet the rising demand.

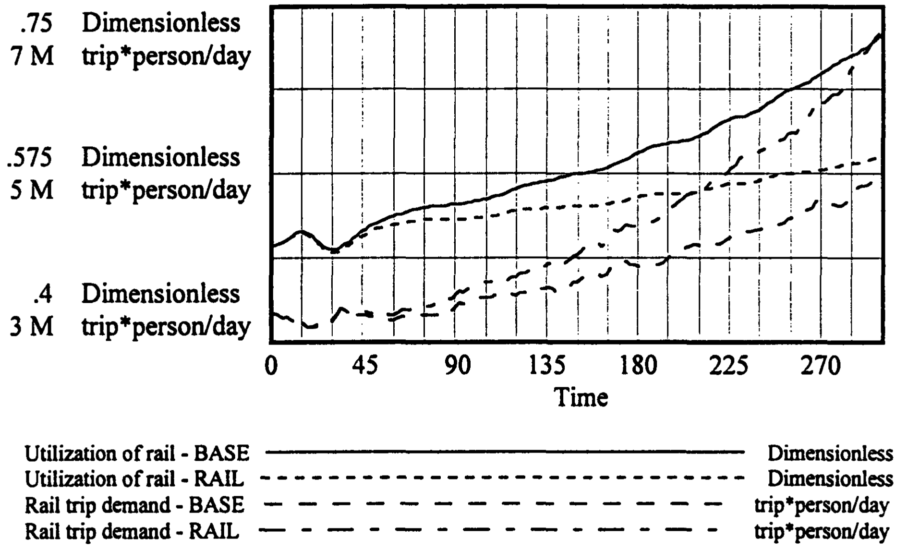


In the BASE case, rail capacity remains constant at approximately 6 million passengers per day. When implementing the policy of building to alleviate the saturation pressures, subway capacity expands to almost 11 million trips-person per day in 2019.

The increased capacity lowers the saturation of the subway, thus increasing its attractiveness as a means of transportation. As people's expectations of how saturated the subway system really is change, their demand for the service goes up. Each additional trip demanded from the subway means one less trip demanded from surface transports.

In general, the subway's market share is greater under the RAIL policy because lower utilization rates make it more pleasant to travel in the subway.

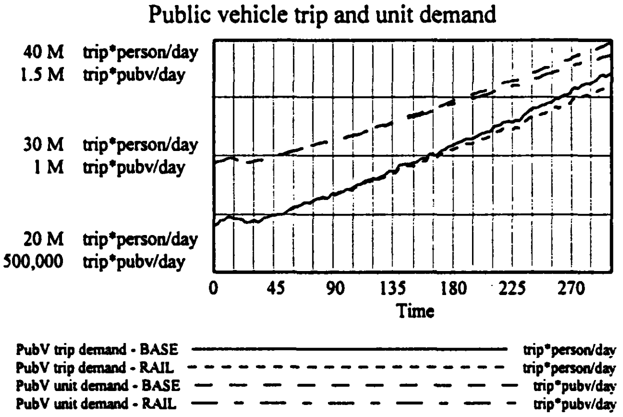
Utilization in the year 2020 under the RAIL policy is approximately 60%,compared to a BASE utilization of over 70% for the same year. This translates into a more attractive transport that is less crowded and creates a demand increase from slightly under 5 million trips in the base case to almost 6.7 million trips. A change of over 1.5 million trips-person per day.


Rail utilization and rail trip demand

This substantial increase in the demand for rail transport fails to accomplish a reduction in ozone levels because it only reduces surface transport trips (labeled Total street unit trips, including trips made by private cars, taxis and public vehicles) by approximately 400 thousand trips-engine per day. The reduction of the 1.5 million trips-person per day to a mere 400 thousand trips-engine per day can be explained by tracing the demand reductions in other modes that correspond with the increase in the demand for rail.

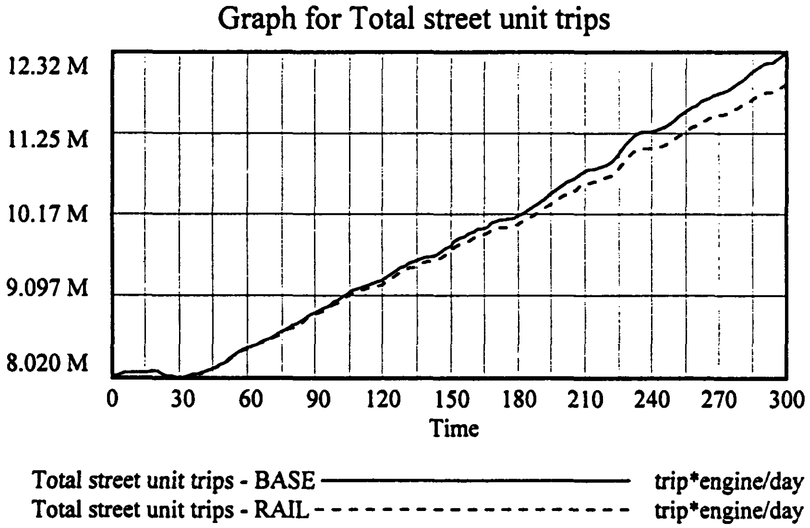
The main demand reduction takes place in public vehicle transport, which surrenders approximately 1.2 million of the 1.5 million trips-person per day won over by rail transport. In terms of overall market share, public vehicles lose over 3%, while private cars and taxis do not exhibit changes above the 1% threshold.

The number of people per vehicle in public transport is considered as the weighted average of passengers per bus, passengers per microbus and passengers per pesero. This average is approximately 25 people per vehicle during the simulation period. Hence, even though public transport "loses" 1.2 million person-trips per day to the more attractive subway system, its unit supply (the number of vehicle trips per day, as opposed to the number of person trips per day) need only be reduced by approximately 1.2 million ÷ 25 or 48,000 public vehicle trips per day.



The same dilution takes place in the trips taken from private cars and taxis, albeit in a much lower scale because the number of people per private car and taxi is only 1.25.

When we look at the combined unit supply of all surface transport, we find that even though rail has gained a total of 1.5 million trips, the aggregate reduction of vehicle trips of all surface transport is 400,000 trips vehicle per day.

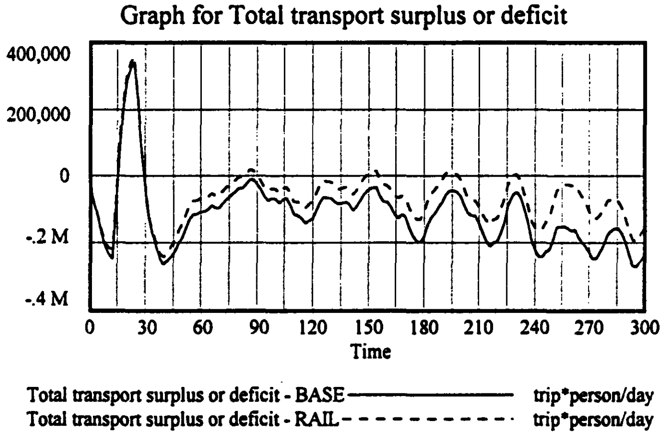


Having explained the reason for the bantam effect achieved in the long term ozone level, we can look into the divergent behavior generated by the rail policy.

This effect may be important because as we consider longer term horizons this divergence could generate more substantial ozone reductions if its trend continues. Thus, it is important to understand if this is a trend that can be extrapolated into the future with any degree of structural confidence.

From the analysis above we see that the divergence occurs at every level going back to the demand for unit trips from surface vehicles and rail. Thus we must search for the structure behind this behavior at a more fundamental level.

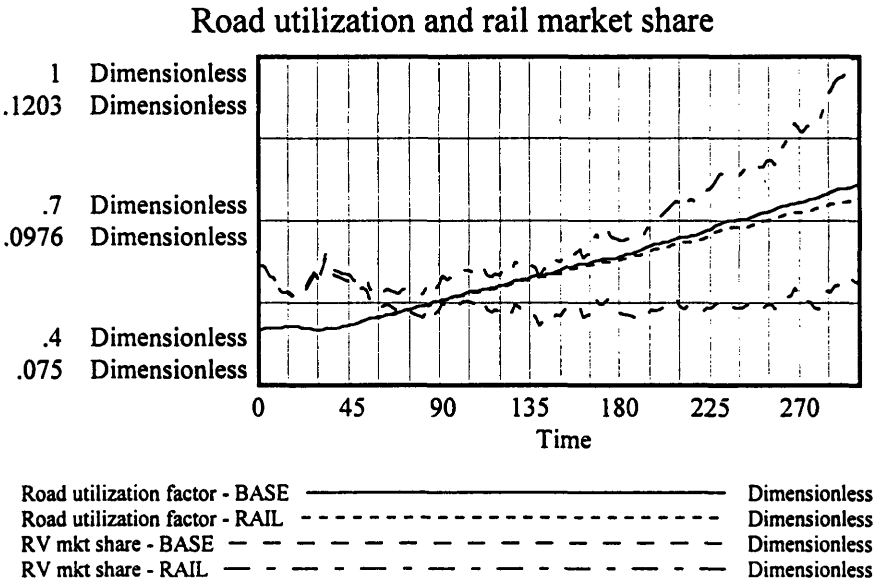
If we define Total transport surplus of deficit as the net difference between all transport supplied and demanded, we see that under the RAIL policy, the structural deficit of the system is lower and diverging from the deficit in the BASE case. The total long term variation between the deficits of both simulations explains approximately 70,000 person trips per day.



In other words, even though total transport demand is the same for both simulations, the structural deficit that the system needs to keep growing is less under the RAIL policy and diverges from the predicted deficit in the BASE case, especially towards the last years of the simulation. However, this divergence suggests an increased number of trips provided by the transport infrastructure of the city, which in general would generate more pollution, not less. Therefore, this is not the fundamental reason behind the divergence. It rather provides a dampening for the divergence itself.

The true reason behind the divergent behavior of the RAIL scenario is the congestion. As congestion levels rise far above their current levels (remember that road infrastructure was assumed constant), the expected trip time for surface transport trips rises considerably. As congestion becomes very severe, the increase in travel time shoots upwards and the attractiveness of all modes of transport except rail falls dramatically.

Hence, we see that the market share of rail transport tends to rise with congestion levels in a non-linear relationship.



Thus, it is traffic levels that are driving the growing importance of the subway in the long term transport supply.

The conclusions that can be derived from this policy scenario are that the long term effect (from current conditions and assumptions) of pursuing an aggressive rail expansion program are almost inconsequential in terms of ozone reduction. However, the policy shows the benefit of attracting a growing fraction of transport demand as the city's infrastructure becomes congested to the point of prohibitive travel times. In other words, an aggressive rail policy today may buy an escape valve for an over pressurized transport system tomorrow.

Road capacity enhancement

In the face of such a rapidly growing transport demand, particularly in the case of surface transport, it is of paramount importance to analyze traffic management alternatives as a means of reducing not only congestion but also pollution. However, road infrastructure policies are not always made taking all relevant dynamics into account. For instance, it must be considered that while improving a roads capacity reduces congestion and with it pollution, it also makes surface transport all the more attractive given the expected time reduction of its trips.

Again, in order to evaluate the results from this simulation we have compared its results to the ones obtained in the BASE simulation. Additionally, to be able to understand the effects of the suggested policy in isolation from other policies we have kept all model switches at their BASE values except the switch corresponding to road infrastructure capacity.

This switch represents the city's road capacity expressed in vehicle throughput per hour. Road utilization is estimated by comparing this capacity with the peak car equivalent trip demand every day. Since utilization is defined as the percentage of the road capacity that is used at peak time, as the road capacity is increased, the observed congestion levels will drop for a given number of car unit equivalents.

Car unit equivalents account for the fact that not all vehicles cause the same congestion in the streets. For the purposes of this research, we have defined private cars to be our measure of capacity and congestion. We have privately defined that one taxi is equivalent to one private car in terms of the congestion it generates, and that one public vehicle (including buses, microbuses and peseros) is on average equal to 2.5 private cars in the same scale.

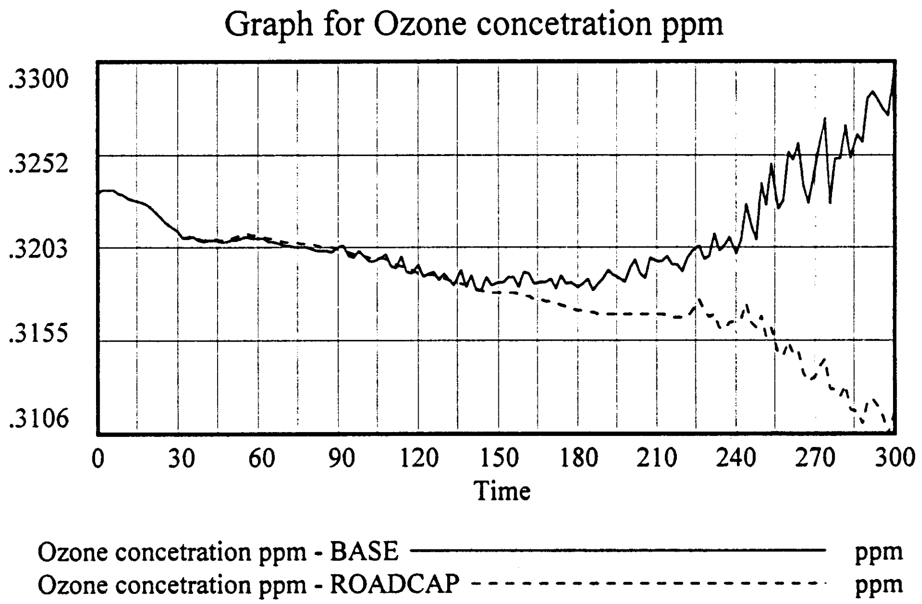
This policy will be simulated under the name of ROADCAP and the value of the *Road infrastructure capacity* switch will be set to grow from 1,515,940 private car equivalent trips per hour to 1,970,922 between January of 1997 and December of 2001. This represents a 30% increase in the throughput capacity achieved over the course of 5 years.

Switch	BASE Value	RAIL Value
Model structure switches		
Convertor equilibrium switch	0	0
Random multiplier switch	1	1
Demand equilibrium switch	1	1
Symmetric cascade switch	0	0
Speed pollution switch	1	1
Infrastructure Policy switches		
Road capacity	1,515,940	30% growth
Willingness to build and use rail capacity	0	1
Road tax to PC at full capacity	0	0
Transit Policy switches		
Regulation switch	0.8	0.8
Subsidized car retirement	0	0
Energy Policy switches		
Magna Vs Premium Proportion	50% by 2007	50% by 2007
Pemex Magna substitution fraction	0	0
Gasoline tax per km to private cars	0	0

The proposed increment in road capacity is a rough estimate of the result of three simultaneous policies: improved signalization and traffic control, improved road conditions and subsidized parking provision coupled with street parking limitations. The parking provision is assumed to be subsidized in order to isolate the dynamics generated by the road capacity expansion, not because we think a policy of this sort should be implemented. Because no formal study was made to derive this number, we have provided a small sensitivity analysis at the end of this section.

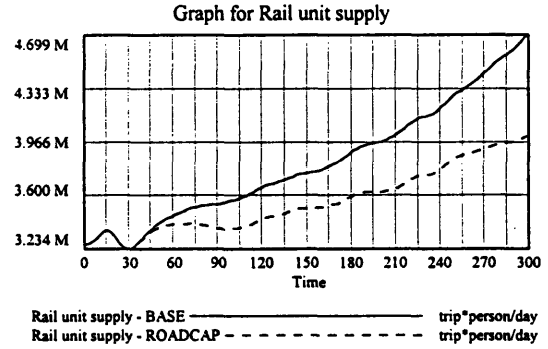
The values for the different switches in the BASE simulation and the ROADCAP simulation are compared in the table above. We then present a discussion of the main findings of the simulation along with the structural insights developed and an evaluation of the robustness of the policy in terms of its impact and likelihood of success.

The long term effect of the road capacity policy on ozone concentration is to reduce it by approximately 3.3%, or 0.02 ppm. The monthly average of the highest daily ozone concentrations drops from 0.33 ppm to roughly 0.31 ppm.



The two observed differences between this simulation and the base case the long term reduction in ozone levels and a lessened volatility in the short and long term.

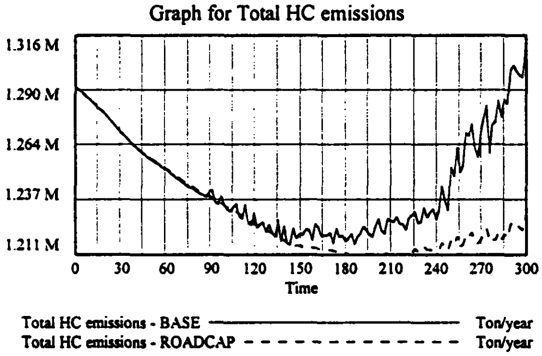
Regarding the long term reduction of ozone levels, they result from a set of interesting dynamics. On one hand, the total transport deficit decreases similarly to the rail policy, thus creating a higher supply of trips for a given demand. However, this increased supply is mostly provided by surface transport trips instead of rail. Additionally, the long term number of rail trips is less than the base case because its market share has a lower final value.



Hence, we must explain the final reduction in ozone levels even accounting for the fact of increased surface trips.

In order to explain this behavior it is useful to look at the emissions of the precursors of ozone. In the case of hydrocarbons, we see that the total emissions are almost identical to the BASE case until the year 2007 (month 145), at which date the ROADCAP emissions continue their downward trend while the BASE emissions start to rise.

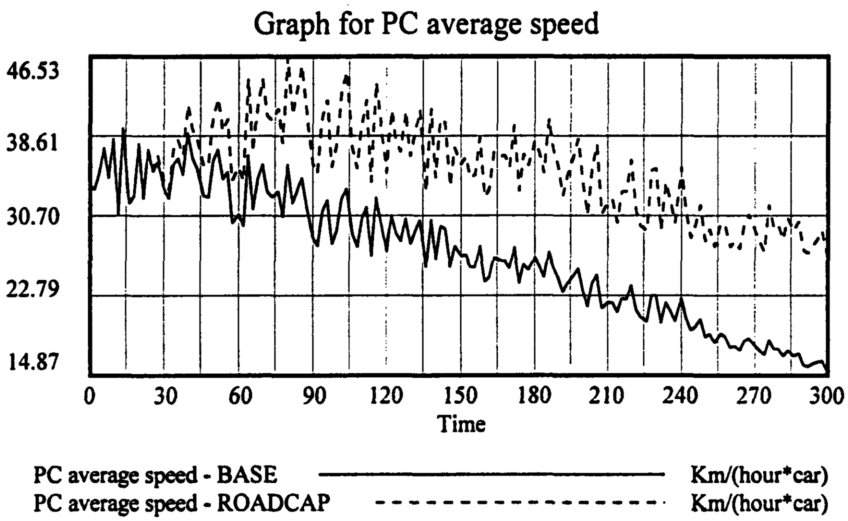
Afterwards, approximately 6 years later, in 2013 (month 130) the emission level starts rising again, but its levels fall well below the emissions of the base case.



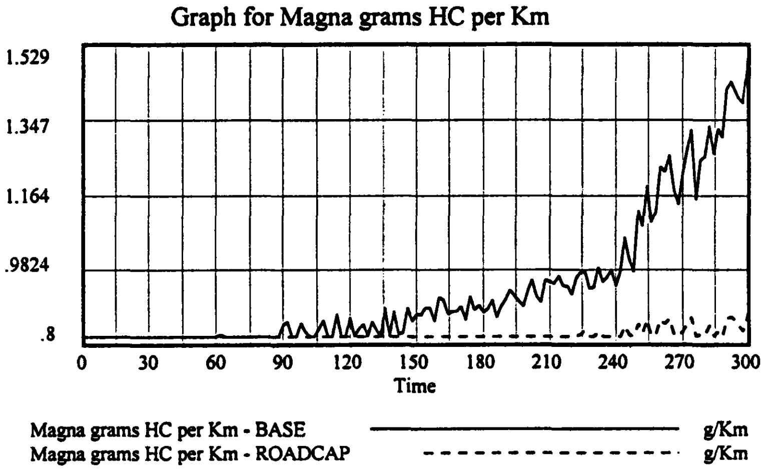
The comparison of Nitrogen oxide emissions shows a very different result. Given the increased supply of trips and the reduced market share of the rail, nitrogen oxides emissions reach a higher value when the policy is implemented and remain above BASE projections for the rest of the simulation and with a constant spread.

Since nitrogen oxides emissions per km are not affected by reductions in speed but hydrocarbons are, it seems logical to look at the average speed of surface transport. We observe that, as road capacity starts to increase with the improved signalization, the parking policies and the street paving program, the road utilization decreases, which causes the average time for surface trips to decrease, thus placing engines in a more efficient region of the hydrocarbon emissions to speed curve.

Since the effects of this curve are only felt at extremely low and extremely high speeds, increasing the average speed of surface trips from 36 to 46 km/hr in year five is hardly noticed.



However, as the growth in road capacity reaches its limit and the city keeps expanding, congestion starts to rise again and the average speed is again brought down. By the year 2020, the improved roads increase the average surface trip speed from 14 to 25 km/hr, thus reducing the hydrocarbon emissions per km significantly from their BASE case levels.



It is worthy to note that the emission reduction is only temporal because the average speed still decreases with the city's growth. Therefore, the true effect of the road expansion policy has been to delay the most harmful effects of saturation. The fact that hydrocarbon emissions keep going down during the period of increased average speed is due to the introduction of catalytic convertors into the fleet that will drive at the higher speed, thus achieving their full pollution containment potential.

The lower volatility of ozone levels in the short term is also caused by the effects of additional road capacity on speed. On one hand there is increased randomness around travel time due to the lower congestion levels. On the other hand, however, the reduction in the expected travel time offsets this and the average speed of the surface transport trips is not only lower, but also steadier.

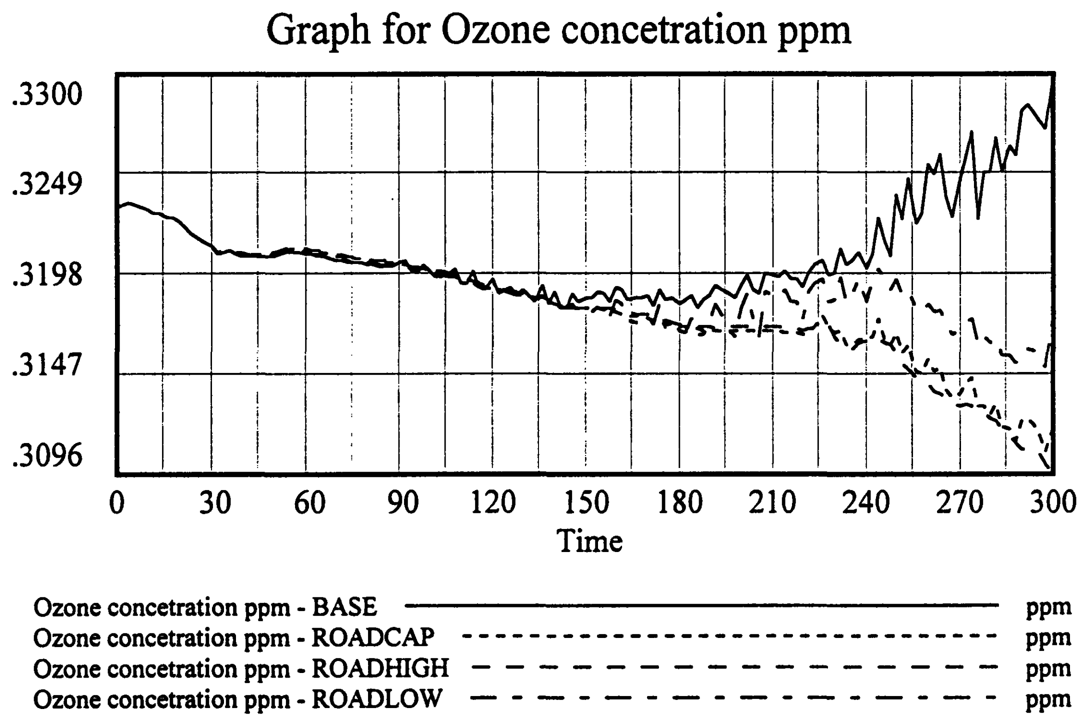
In other words, even though the volatility around the expected travel time is higher, the reduction of the travel time is faster than the volatility. Volatility increases from 12 to 20 percent of total trip time in year 2020, while speed is increased from 15 to 28 km/hr. While the increase in volatility is roughly 66%, the decrease in average speed is 86%. Thus the offsetting effect.

As noted earlier, the capacity addition to the existing infrastructure does not come from a detailed study but is rather a rough estimate. Therefore, we performed a sensitivity analysis of this policy to add to our understanding as well as provide some robustness to the policy analysis.

Under the same scenario, we modeled ROADLOW as increasing road capacity by only 10 over the same time horizon and ROADHIGH increasing it by 50%. The results below show that the nature of the system's response to the policy is roughly the same and approximately proportional to the magnitude of the increase in the road capacity for smaller additions only.

Generally, a lower addition to road capacity will yield a lesser ozone reduction and a shorter time before it becomes congested again. The opposite is not true for larger additions.

In the graph below we see that by adding 50 percent capacity ozone levels do not drop much further below their level corresponding to the ROADCAP scenario. The volatility with 50% addition is lower because of the same reasons and the time to congestion is also farther away in the future.



Congestion pricing

One option to internalize the environmental costs of congestion into the decision process of the population is to enact a congestion pricing tax. This tax would be charged on a per vehicle and per km basis only to private cars and would have a level tied to observed congestion. At higher congestion levels the imposed tax would be higher and viceversa.

It is worthwhile to note that the objective of this tax would not be to reduce congestion at peak traffic hours, thus flattening the transport demand curve of the city. In Mexico City, the transport demand curve is mostly flat due to the extreme saturation of the transport system. With the exception of the late night and pre-dawn hours, the traffic flows are relatively constant, ranging from a trough of about 6.5% of total transport demand at some hours and a peak of 8% at the worst moment.

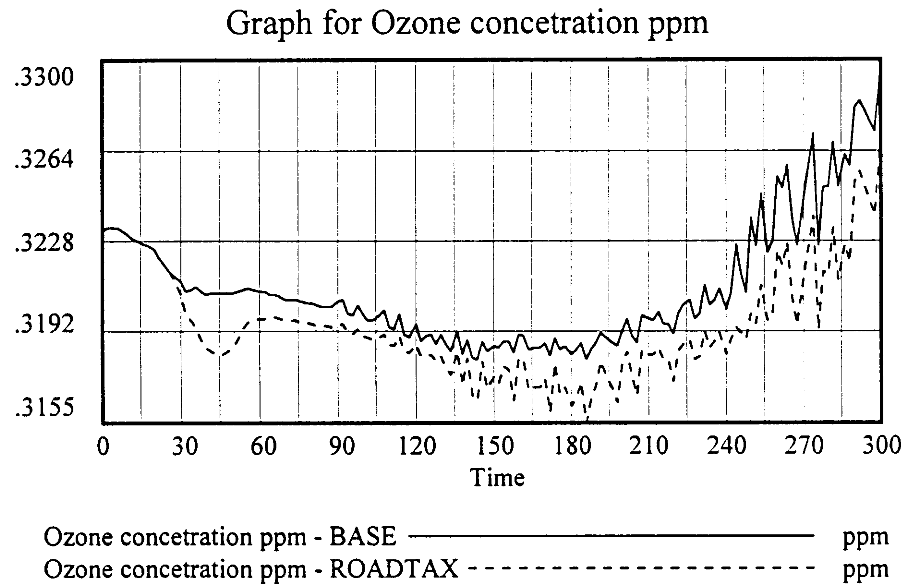
Given that the choice of transport mode is tied to the cost per trip the main purpose of this tax would be to tie the attractiveness of the private car to the environmental problems it generates. In effect, we are strengthening the loop that reduces private car demand when average time increases by charging a tax when average speeds are relatively low. We are attempting to make the effects of congestion on private car demand be felt two-fold.

In addition to the equity and social concerns raised in the first chapter of this thesis, such a tax would entail a significant political cost as well as an extremely difficult implementation. Politically, this measure would be unpopular, to say the least, and it would be difficult to find a regent of Mexico City willing to face this cost. Operationally, the implementation of this tax would require estimating congestion levels on a periodic basis and, more importantly, actually collecting the payment from every vehicle driving at the time of congestion.

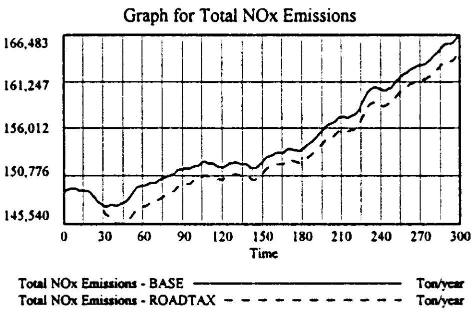
Under the assumption that these political and technical difficulties could be overcome, we have simulated this scenario by the name of ROADTAX. The tax is assumed to be directly charged to the cost of a private car trip and to be directly tied to the level of observed congestion. Under these assumptions, the simplest form of calculating the tax is to set an amount to be paid at full congestion levels and charge private cars the corresponding fraction according to peak congestion. For comparison purposes, the values of the switches of these simulation are shown in the table below:

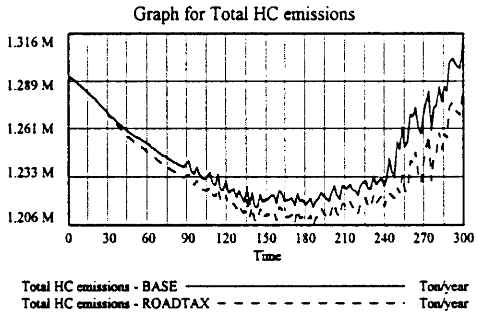
Switch	BASE Value	RAIL Value
Model structure switches		
Convertor equilibrium switch	0	0
Random multiplier switch	1	1
Demand equilibrium switch	1	1
Symmetric cascade switch	0	0
Speed pollution switch	1	1
Infrastructure Policy switches		
Road capacity	1,515,940	1,515,940
Willingness to build and use rail capacity	0	0
Road tax to PC at full capacity	0	$1 @full cap
Transit Policy switches		
Regulation switch	0.8	0.8
Subsidized car retirement	0	0
Energy Policy switches		
Magna Vs Premium Proportion	50% by 2007	50% by 2007
Pemex Magna substitution fraction	0	0
Gasoline tax per km to private cars	0	0

The results of this policy are quite disappointing. We see that ozone levels react to the implementation of the tax by dropping approximately 7.5% during the first 18 months (between January 1997 and July 1998) from 0.3207 ppm to 0.3187. However, even this small reduction in ozone levels is mostly lost within 8 months. The expected reduction at this time is on the order of 1%.



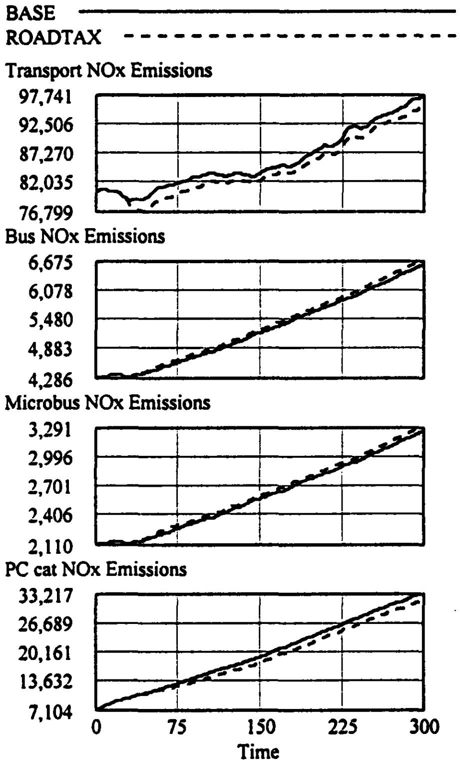
The behavior of ozone levels is driven by the emissions of nitrogen oxides. Whereas the total hydrocarbon emissions are slightly reduced by the ROADTAX policy, the emissions of nitrogen oxides fall initially but recover most of their previous level within 8 months.

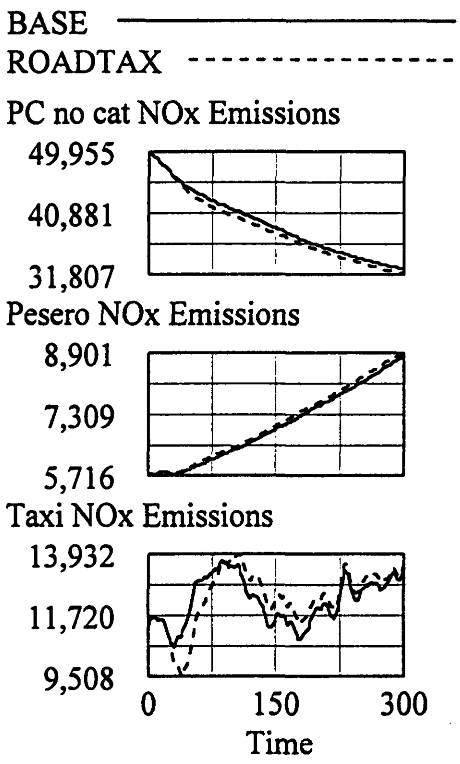




Nitrogen oxide emissions from fixed sources are assumed constant; their variable part lies in the transport component. Transport N Ox emissions come from every type of surface transport and they are tied to the number of trips made by each mode and its corresponding efficiency.

All transport modes show decreasing levels of nitrogen oxide emissions except taxis, whose emissions drop dramatically when the tax is enacted and then reach levels even above their BASE levels.



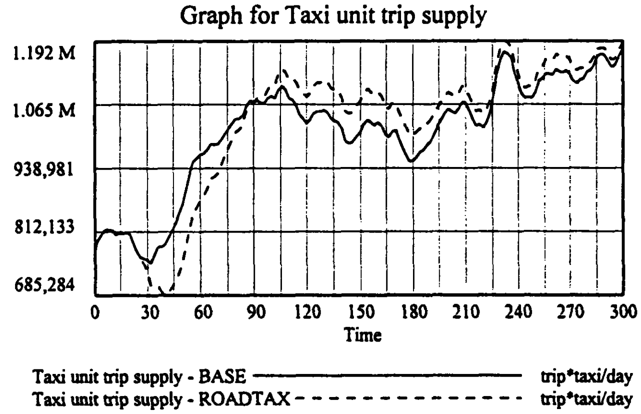


Nitrogen oxide emissions from private cars with and without catalytic convertors are reduced according to our expectations, albeit not by any significant amount. At the same time, emissions from public vehicles are increased due to the rise in their trip supply. This increment in public vehicle emissions is also relatively small.

In the case of taxis, emissions initially fall below their BASE value and then rise above it from where they start to converge towards the BASE scenario. The initial fall in taxi emissions is due to the change in demand for car trips. As the price per trip increases for private car trips, the unsatisfied portion of their demand shrinks. If the increase in the price is large enough the ensuing drop in demand will generate a negative unsatisfied demand. This means that demand levels have fallen below current supply but that given the time needed to change transport behavior there will be a period of adjustment in which there will be an oversupply of private car trips. The oversupply of private car trips takes away from taxi demand, causing the utilization of taxis to drop initially.

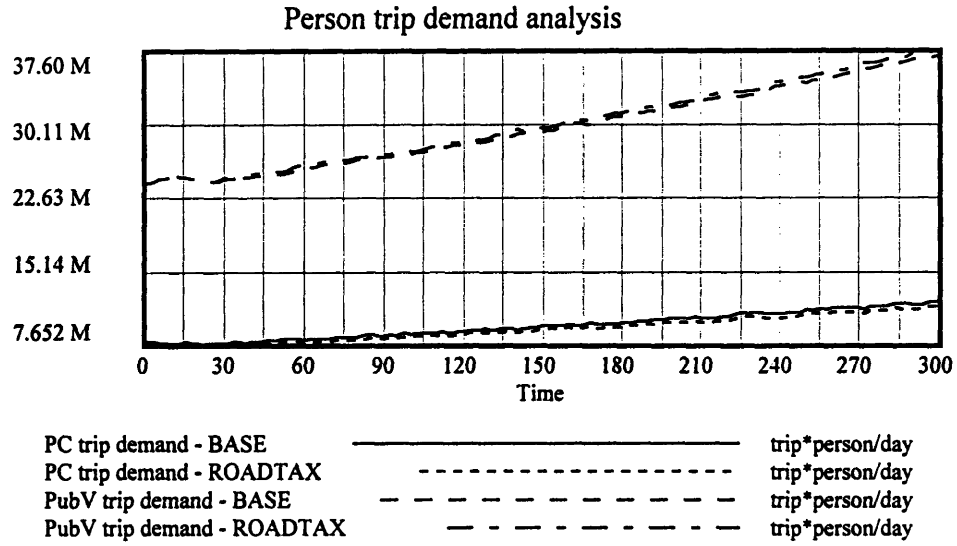
As private car supply adjusts to the reduced demand conditions, demand for taxis rapidly climbs. This rise is due to the recovery of their lost trips in part and to their increased market share, which is a fraction of the trips that private cars lost to high trip prices. When demand for taxi trips rises again, the utilization of the fleet starts rising as well as the fleet itself.

With more taxis making more trips per day in the streets the emission levels quickly return to the BASE levels and overshoot them because of the increased taxi supply.



It is important to note that the effect of this policy is not only insignificant and short lived, but that the little ozone reduction achieved is due to a second order effect on the taxi sector, not due to any fundamental change to the private car sector.

When compared to the demand for public vehicle transport, the demand for private cars remains virtually unaffected by this tax. It is only the abysmal proportion between the car trip sector and the taxi sector what causes such a dramatic effect. The fundamental dynamic reveals a private car public that is extremely inelastic to price when it comes to the use of their cars, particularly for work trips.



TRANSIT POLICIES

"Day without a car" extension

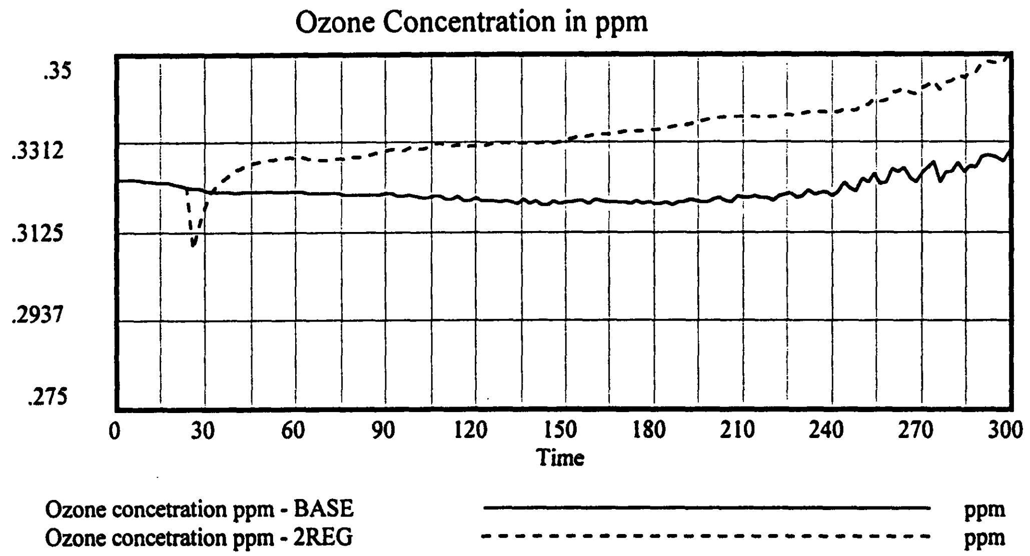
Even though the Mexican authorities are aware that the "Hoy No Circula" Program wasn't effective and was probably counterproductive, the Pro Aire program still considers the use of transit restriction mechanisms (i.e. permanence of the "Hoy No Circula", Double "No Circula" for days in which pollution is over the safe environmental norms) as a viable policy. There are mainly two reasons for this. First, there is the belief that a restriction of this kind would not be harmful if implemented only in emergency situations. Second, the authorities are concerned about the great environmental impact of deregulating.

The Mexican government thinks that given that the regulation resulted in an increase of the vehicle fleet, free circulation would bring suddenly a significant amount of private car trips to the streets and thus increased emissions as well as important transit problems.

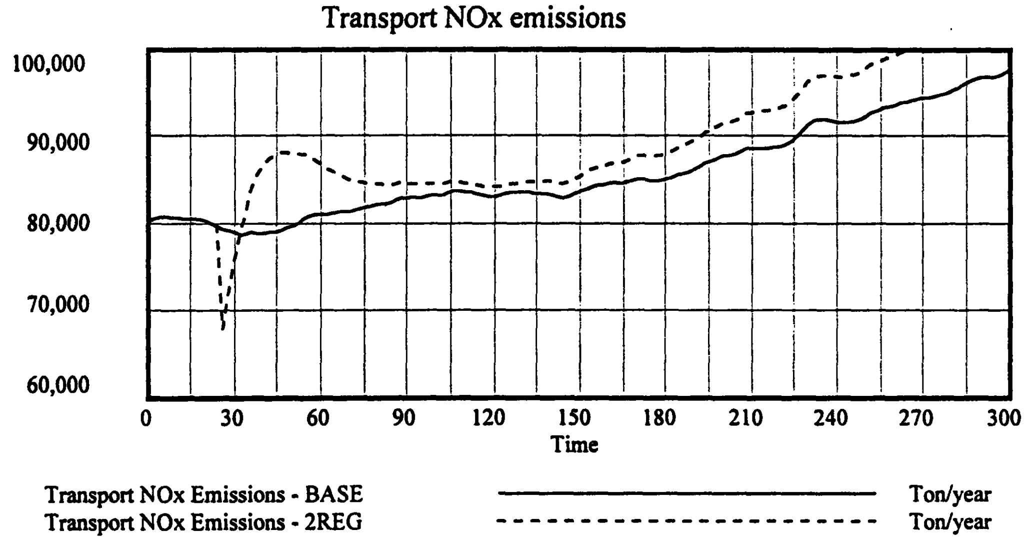
Following is a simulation of the implications of a "Doble No Circula" or "Two days without a car" program. The simulation results are compiled under the name 2REG. The parameters of the simulation are:

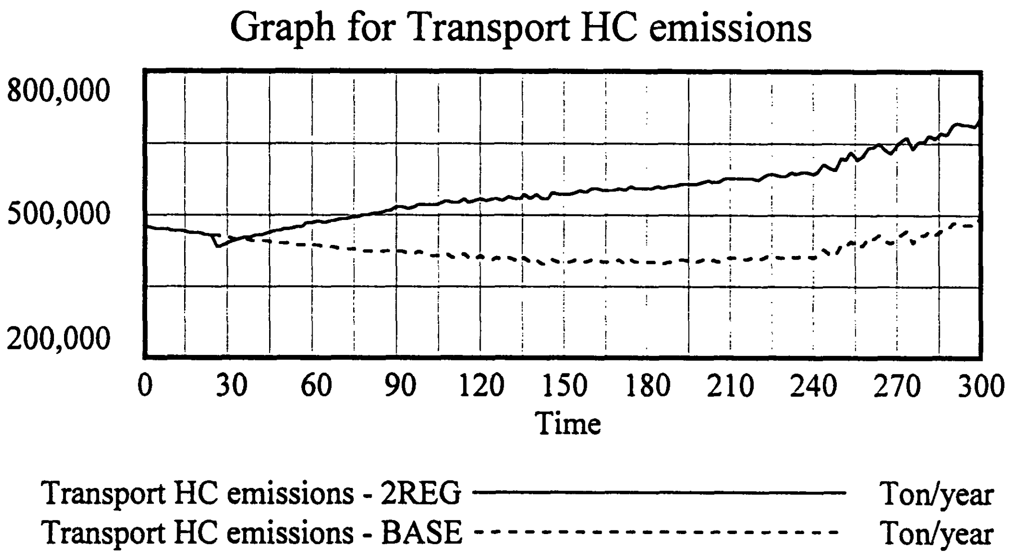
Switch	BASE Value	RAIL Value
Model structure switches		
Convertor equilibrium switch	0	0
Random multiplier switch	1	1
Demand equilibrium switch	1	1
Symmetric cascade switch	0	0
Speed pollution switch	1	1
Infrastructure Policy switches		
Road capacity	1,515,940	1,515,940
Willingness to build and use rail capacity	0	0
Road tax to PC at full capacity	0	0
Transit Policy switches		
Regulation switch	0.8	0.6 in 1997
Subsidized car retirement	0	0
Energy Policy switches		
Magna Vs Premium Proportion	50% by 2007	50% by 2007
Pemex Magna substitution fraction	0	0
Gasoline tax per km to private cars	0	0

The resulting Ozone levels obtained are:



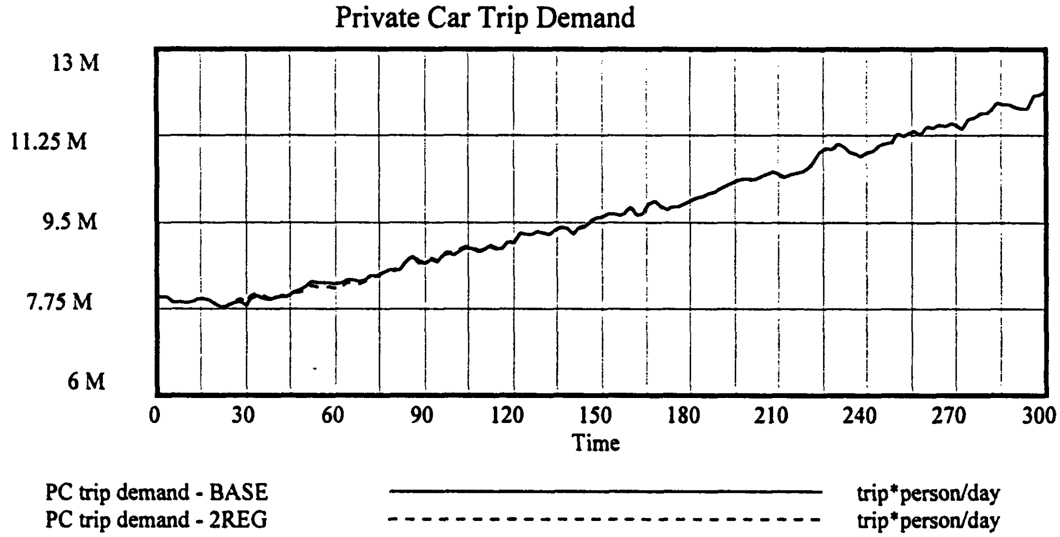
The dynamic shown here illustrates the policy resistance effect of the "No Circula Program". Initially, there is a reduction in the Ozone concentration level, this reduction lasts for a few months, but at time 30 the pre-regulation ozone concentration level is reached again. However, the effect does not stop there, concentration levels continue to increase. This comes as the result of the increase in transport emissions.

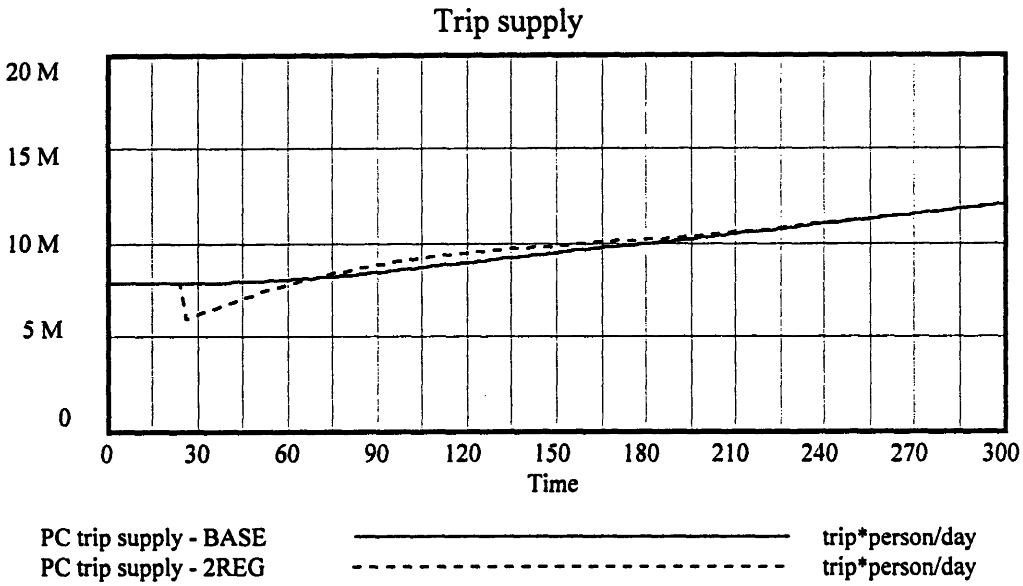




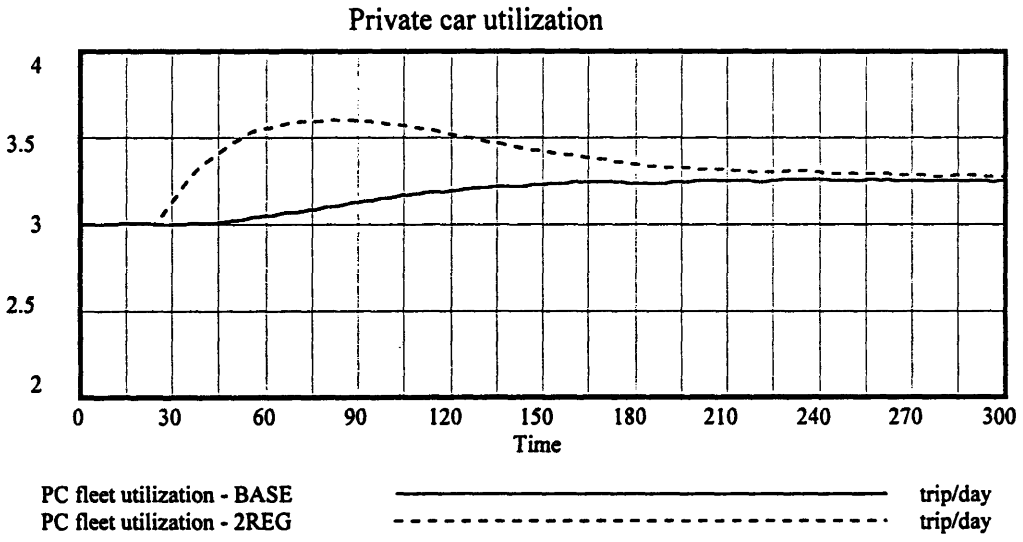
There is an increase in the emissions of both precursors. A NOx increase implies an increase in the number of trips by surface vehicles. The HC increase can be due to both, more transit and more evaporative emissions. We will examine the problem along these two lines.

First, we look at the model's output for Private Car demand and supply:



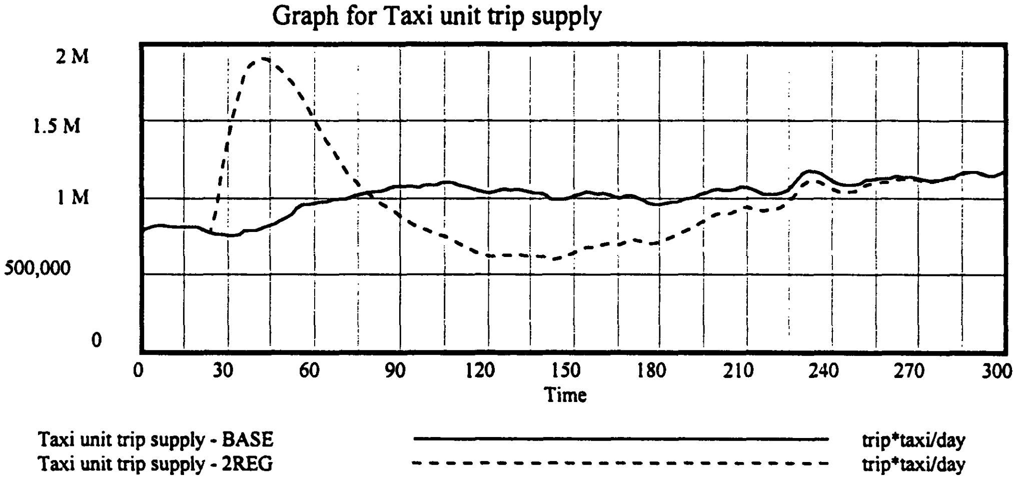


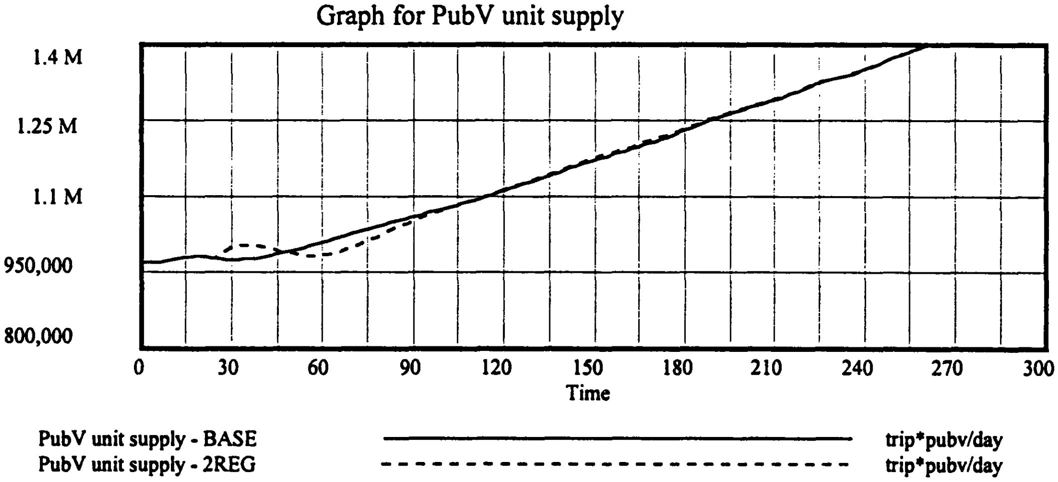
From the previous graphs it follows that the private car trip demand remains practically constant, while the supply is abruptly restricted. The system will cover this deficit and then overshoot its demand. The deficit is covered in the two following ways. First there is an increase in Private car trip utilization.



Private cars are going to be used more intensively in order to fulfill the demand. For example, households that have more than one car will make a more intensive use of one of the cars on the day in which the use of other is banned. When the trip demand is met, the utilization level tends to return to the pre-regulation level with a delay that can be interpreted as the adaptation time of the population to return to the previous use levels.

The second way in which the system adapts to the regulation-created trip deficit is by use of public surface transport and taxis.

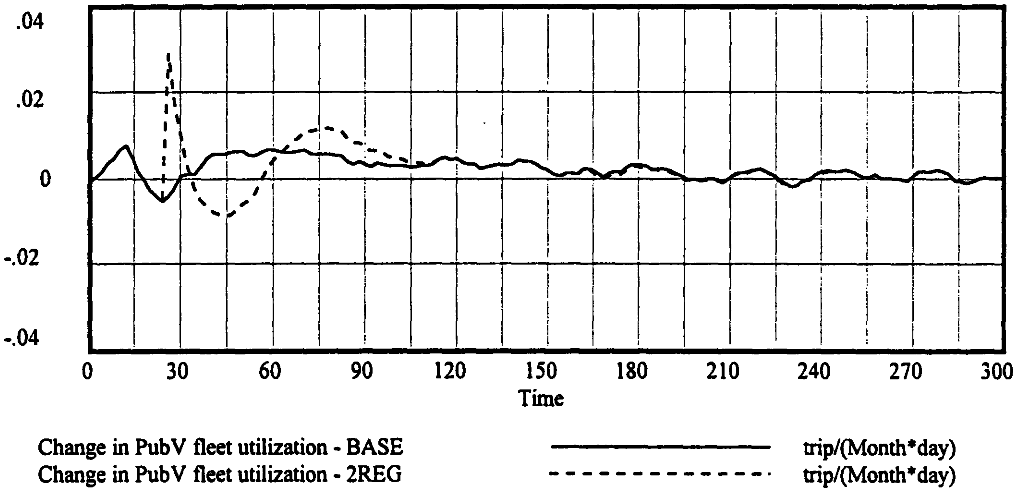




Besides an increase in private car utilization, the unmet Private car trip demand generates an increased usage of public transport and taxis. This trips increases plus the higher private car utilization are behind the NOx emissions and the combustion HC emissions.

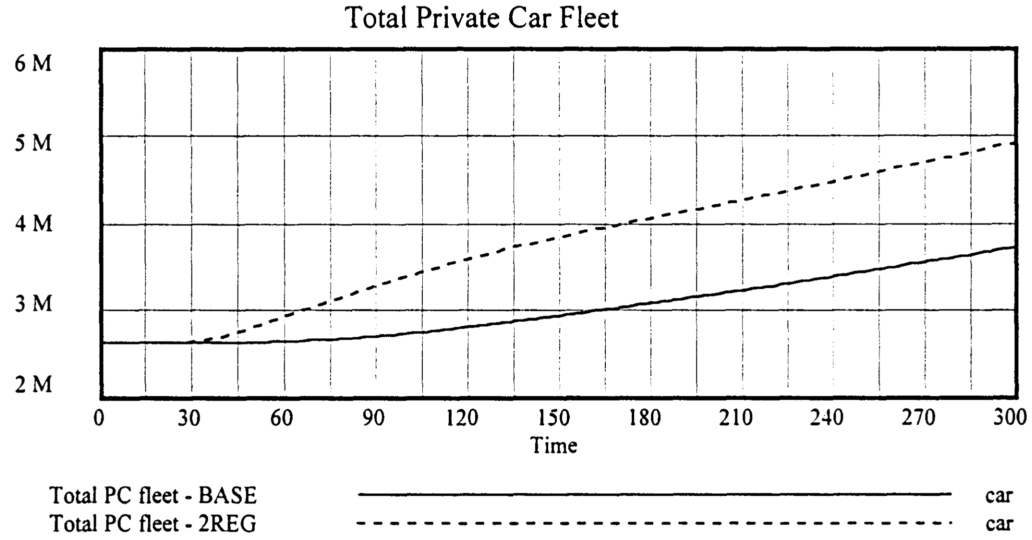
It is interesting to note that as trip demand is being satisfied (by increased car usage or car purchases), each transport mode decreases its use and undershoots the base case level. Again this undershoot comes from the times to change the utilization level of the particular transport mode.

Graph for Change in PubV fleet utilization



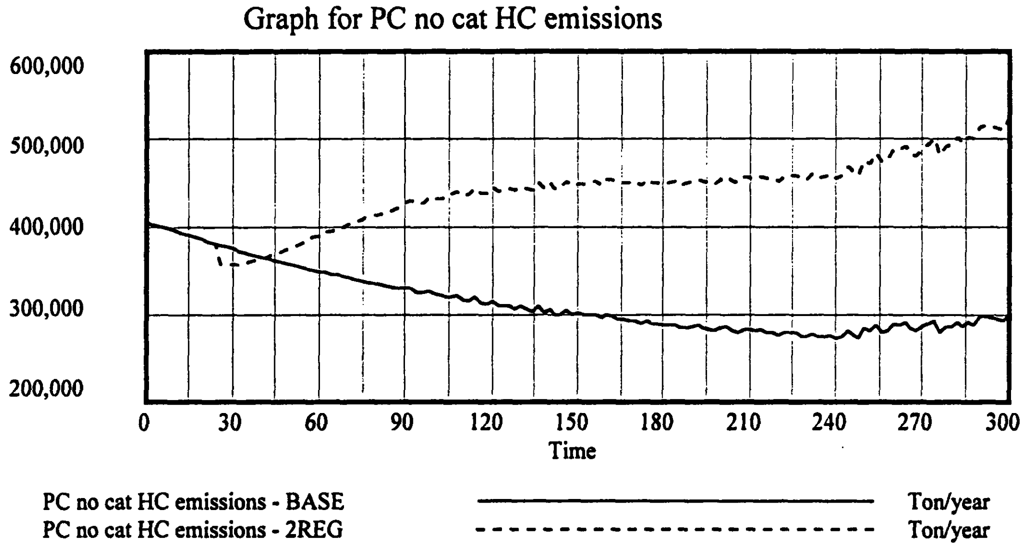
As showed in the above graph, the utilization rates are changed over time in order to fulfill demand. However, the change in the utilization level tends to 0 as the system has a base utilization level for every transport mode, and thus increases the fleet to compensate the demand deficit. At this point utilization becomes equal to base utilization and the change is 0.

The private demand trip deficit is fulfilled also by private car purchases. The private car fleet increases by purchases of new cars and by the acquisition of used ones. When the trip demand is satisfied, the fleet grows at a rate able to sustain the vehicle needs of the system at this lower utilization rate.



The increase in the private fleet has important effects in terms of evaporative HC emissions. These evaporative emissions occur regardless of the combustion process. The volatile organic compounds of the gasoline are evaporated at low temperatures and so they are present even when the car is stopped. New cars with fuel injection systems and catalytic convertors have fewer evaporative losses. Old cars with carburetors have the highest. Most of the cars purchased in Mexico City were used cars given the economic conditions of the country and that their purpose was to fulfill just a fraction of the demanded trips. The result is an older, more polluting fleet, both in terms of combustion and evaporative emissions.

This larger and lower quality fleet is a significant contributor of HC evaporative emissions.



It is interesting to note that there is not only a one time addition of older cars but an ongoing of the fleet, since older, lower technology cars are being added to it. In 1990, the Mexican authorities determined that every new car purchased had to had a catalytic convertor control system. The day without a car regulation makes the fleet older on average and, even worse, keeps it that way for as long as the regulation lasts.

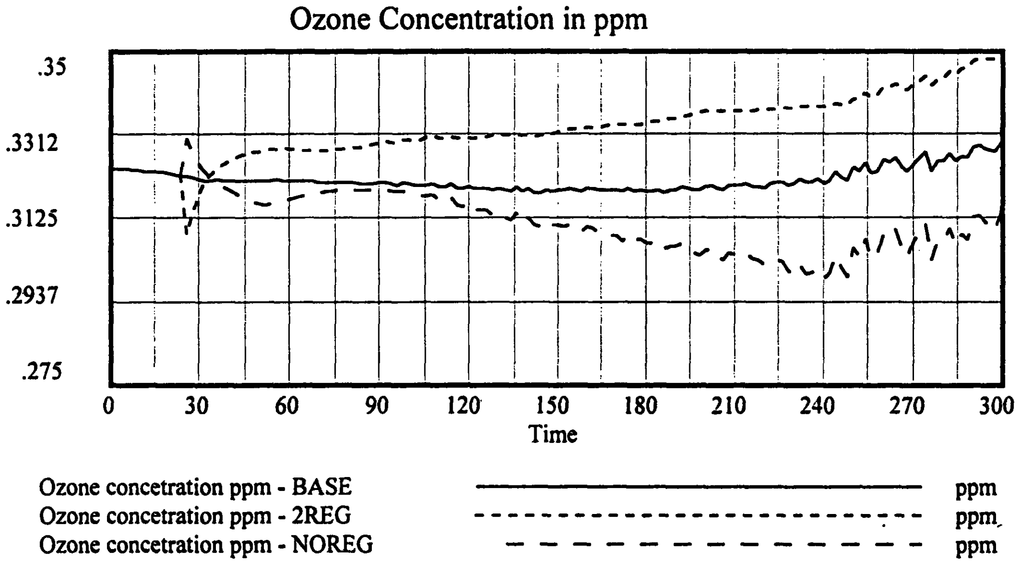
Termination Of The "Day Without A Car" Program

At present, Mexican authorities are not only aware that the "No Circula" regulation did not achieve a positive environmental effect but even that it backfired. However, one of the fears of lifting the regulation is that the increased vehicle fleet, now free from any circulation restrictions, would instantaneously augment the ozone precursors emissions as well as generate severe congestion problems. Studies are being carried out in order to determine what the best phase-out strategies are.

Here we present a simulation that takes out the "No Circula" Program without any phase-out strategy and evaluate the dynamic implications of it. The parameters of the simulation are the following.

Switch	BASE Value	RAIL Value
Model structure switches		
Convertor equilibrium switch	0	0
Random multiplier switch	1	1
Demand equilibrium switch	1	1
Symmetric cascade switch	0	0
Speed pollution switch	1	1
Infrastructure Policy switches		
Road capacity	1,515,940	1,515,940
Willingness to build and use rail capacity	0	0
Road tax to PC at full capacity	0	0
Transit Policy switches		
Regulation switch	0.8	1 in 1997
Subsidized car retirement	0	0
Energy Policy switches		
Magna Vs Premium Proportion	50% by 2007	50% by 2007
Pemex Magna substitution fraction	0	0
Gasoline tax per km to private cars	0	0

The behavior of the system predicted intuitively would be to see an instantaneous increase in emissions and thus in Ozone levels and then a progressive return to the BASE case levels. Ozone levels are compared for the three “No Circula” scenarios: current regulation (BSE), double “No Circula” (2REG) and no regulation (NOREG).



Let us divide the Ozone concentration level into four segments. The concentration increase (t=25), decrease with an undershoot relative to the base case (t=50), a new increase in ozone levels (t=90), and a last decrease until infrastructure saturation (t=240)

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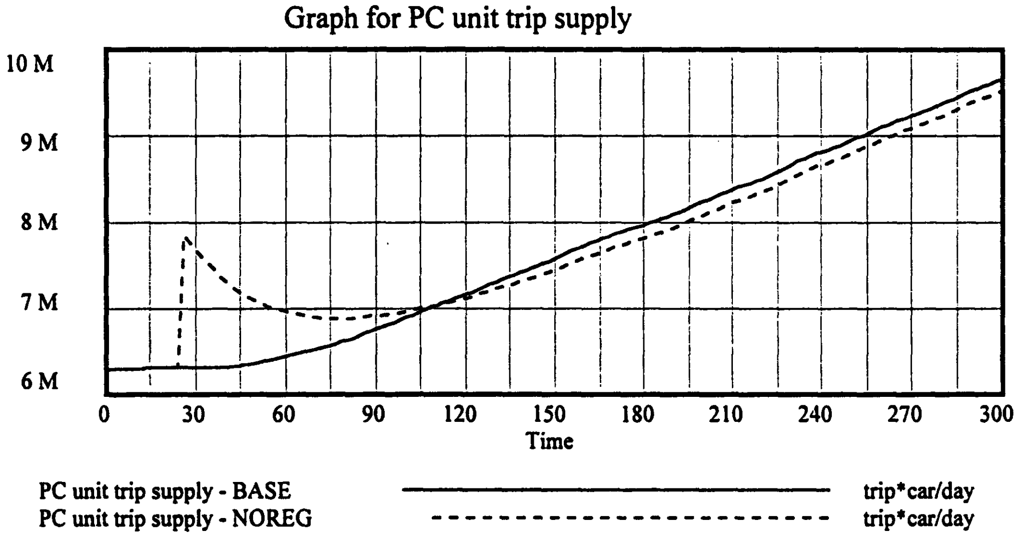
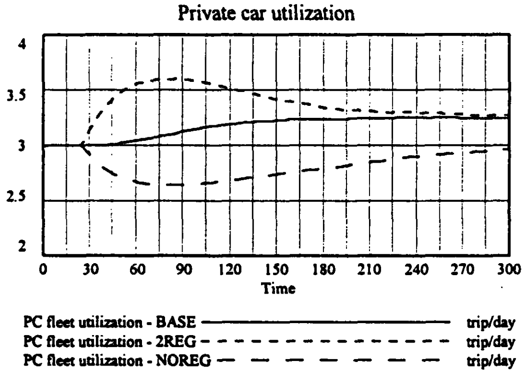
1st Segment increase (t=25)

The first segment behavior is very intuitive, as the regulation disappears, the supply of trips by private cars is instantaneously increased by 20%.



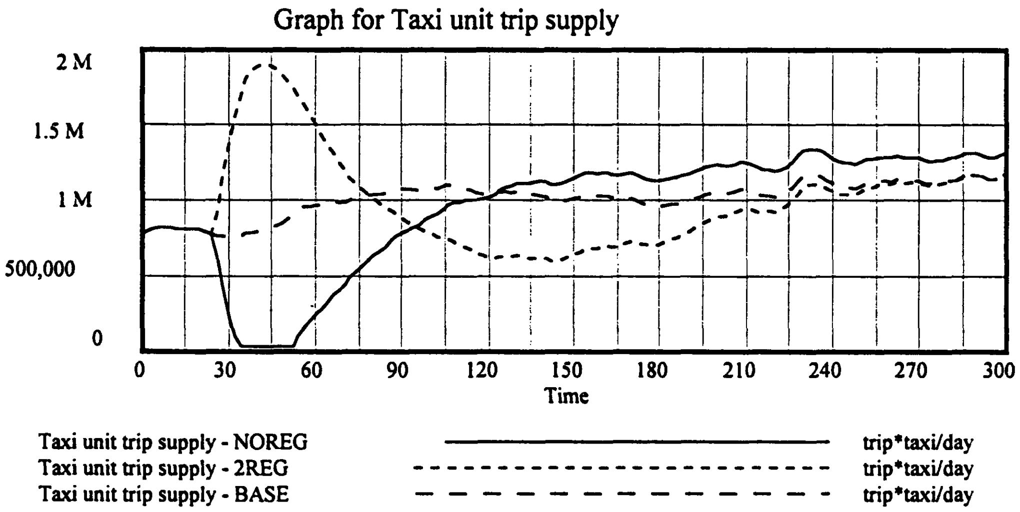
Private car utilization decreases following the same logic as in the last case and increases as the equilibrium is approached. Up to this point, the logic is similar than to the regulation case.



2^{nd} segment: decrease and undershoot (t=50)

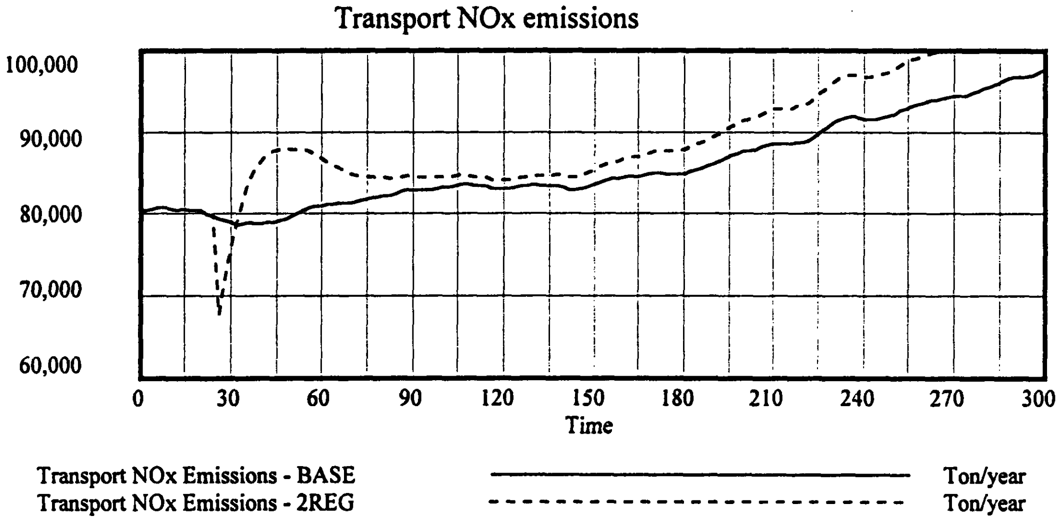
As utilization decreases, private trip supply decreases also and public transport and taxi trips start to increase again. When the private car demand and supply equilibrium point is reached, utilization rates react with a delay, and thus generate an undershoot with the equilibrium demand level. It's worth noting that the equilibrium demand level in this case is not the base case level, since it is a regulation case and thus it will have a different private car utilization level.

During the period when private car utilization is going down, public transport and taxi modes are gaining trips.



3^{rd} Segment: a new increase in ozone levels (t=90)

This increase in surface public transport and particularly in taxi trips accounts for higher NOx emissions.



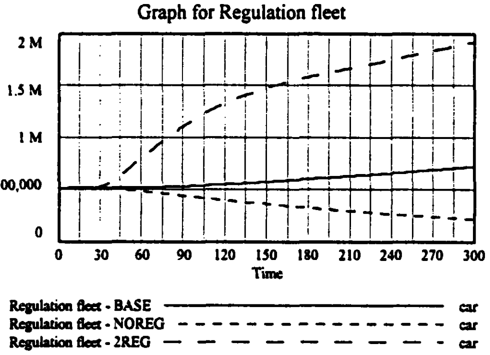
Here it is worth to stop and analyze the very large effects of taxi trips on emissions. Two factors explain this. First is that the variations in taxi trip demand are greatly amplified in relative terms to the small taxi fleet. This means that when there are demand gaps from unmet PC demand, the part of this demand that is satisfied by the taxi transport mode is going to be large relative to the fleet. Because of the significant size of this demand shocks relative to the taxi fleet, utilization levels react abruptly.

The second is that taxis are extremely pollutant per trip. This is due to the fact that for every trip satisfied the taxi vehicle drove without a passenger. If these emissions are assigned for emission accounting purposes to the actual trip made, then in environmental terms, taxis are the most inefficient transport mode.

4^{th} segment: last decrease until infrastructure saturation(t=90)

Once the public transport and the taxi transportation modes start losing trips, NOx emissions decrease. The following decrease is steeper while Premium gasoline is being introduced and then flattens out.

One of the stronger effects of the deregulation is that it rejuvenates the fleet. As there is no need to fulfill private trip incremental demands (caused by the deregulation) the system ceases to purchase regulation fleet. The result is a more efficient combustion and emission control technology on the average and thus reduced emissions.



The regulation fleet represents the cars purchased to satisfy a private trip demand need given a capacity restriction. As the restriction disappear, so does the need for such cars.

We can conclude that terminating the "No Circula" Program has a great potential to decrease emissions and thus ozone levels in Mexico City. It is an easy to implement, no cost policy that promises a significant upgrade in the average combustion and control technologies of the private fleet, and thus in the metropolitan area air quality. The ozone concentration reduction levels attained are as high as 6%.

However, there is an important negative short term effect in terms of both pollution and congestion that has to be dealt with. The effect can be mitigated by an economic instrument policy such as the congestion or the gasoline tax.

Renewal of the private car fleet

The private car fleet in Mexico City is roughly 13 years old in average. Among other things, emissons are a function of car conditions and they differ substantially between cars equipped with catalytic convertors and with overall good maintenanceand cars without them. Thus, most of the private car trips that the city is demanding are being provided by old private cars, which are relatively inefficient in terms of pollution.

The average age of the car fleet in Mexico City is in part due to the day without a car program, which caused a massive inflow of junk vehicles into the city. We shall not dwell on the inadequacy of this policy since we have discussed it at great length. However, another reason for this aging of the car fleet are the barriers that citizens face in order to enter the new car market. Specifically, securing a downpayment for a new car constitutes a substantial effort for some households, even for those who could afford the subsequent costs associated with the new vehicle.

The high entry barriers to the new auto market deter people from renewing their cars at any environmentally convenient time. In this situation cars that should be museum relics are kept in use in order to avoid a new car purchase.

This policy seeks to improve the conditions in which the private car demand is satisfied, rather than alter the decision mechanisms that create it. If the private car fleet is rejuvenated to an average age of approximately 9.5 years, we should observe a consequent ozone reduction just by virtue of burning the same fuel with more efficent cars.

One way to renew the private car fleet is to purchase the oldest vehicles and to retire them from circulation. Yet, a vehicle repurchase program faces two in addition to the obvious budget constraints. On one hand, since this policy does not change the underlying demand for private car travel, it is necessary to substitute the old purchased cars with new ones. Otherwise owners of old cars have no incentive to sell their vehicles. Additionally, this policy assumes that the people from whom the old cars are bought are able to meet the operational costs of the new vehicles and only deterred from the new car market by the entry barriers. Hence, the effectiveness of this measure is both limited by the number of owners willing to sell and the fact that cars are being replaced, rather than retired.

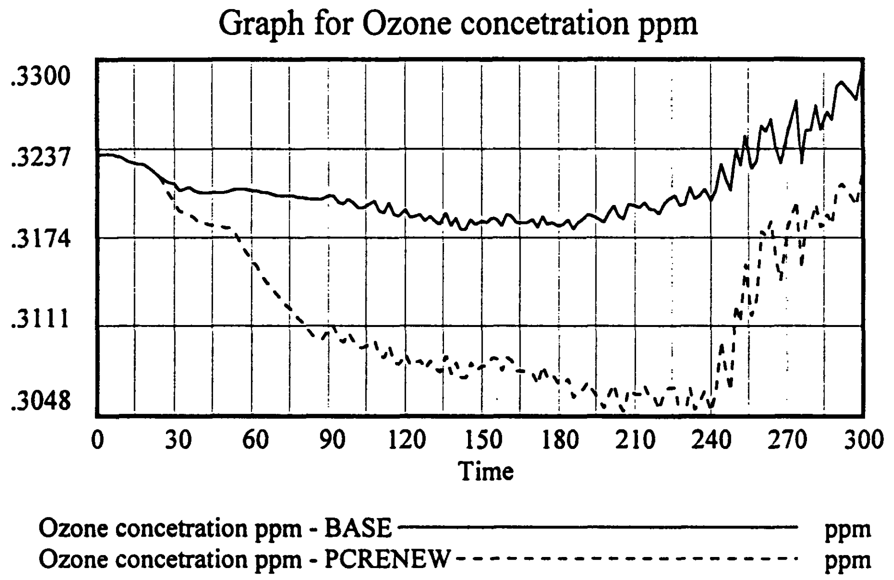
We have included a *subsidized car retirement* control switch in the model in order to simulate this dynamic. The policy proposes a substitution of 100,000 cars per year during a period of 5 years starting in 1997. Thus, the net effect of this policy on the private car fleet is to decrease the old car fleet by 500,000 cars over these five years while increasing the number of new cars on order in the same period. Note that because of the delivery chain involving new cars, the replacements for the retired cars will be delayed in time. This will create an initial decrease in the total car fleet which will be only temporary, since every car that is retired is assumed to have generated a new order for a replacement. Again, the purpose of the policy is not shrink the car fleet, it is to rejuvenate it.

The table below summarizes the values for the different model switches during this simulation and compares them to the BASE case. We have named this scenario PCRENEW.

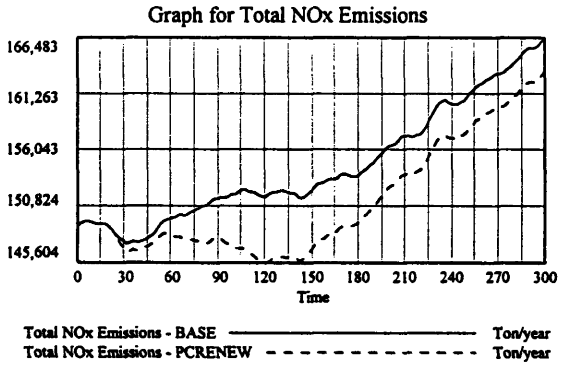
Switch	BASE Value	RAIL Value
Model structure switches		
Convertor equilibrium switch	0	0
Random multiplier switch	1	1
Demand equilibrium switch	1	1
Symmetric cascade switch	0	0
Speed pollution switch	1	1
Infrastructure Policy switches		
Road capacity	1,515,940	1,515,940
Willingness to build and use rail capacity	0	0
Road tax to PC at full capacity	0	0
Transit Policy switches		
Regulation switch	0.8	0.8
Subsidized car retirement*	0	100,000 car/yr.
Energy Policy switches		
Magna Vs Premium Proportion	50% by 2007	50% by 2007
Pemex Magna substitution fraction	0	0
Gasoline tax per km to private cars	0	0

* Lasts only five years

Ozone levels are initially reduced from their 1996 BASE level until approximately 1998. In 1999 the simulated ozone concentration starts falling at a much faster rate and begins to slow down when it reaches a value of roughly 0.31 ppm in 2002 (month 85). This is when the repurchase program reaches its goal of 500,000 vehicles.



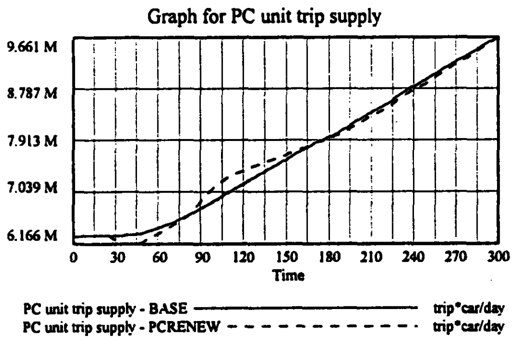
Between 2002 and 2014, Ozone levels continue to drop, albeit at a slower rate, and reach a low point of 0.304 ppm. From this point on, Ozone levels rise dramatically to finish the 25 year simulation period approximately at the level in which they started. This behavior is strongly driven by nitrogen oxide emissions from the transport sector.



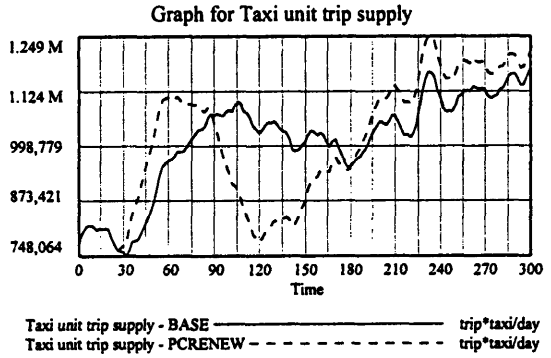
The initial reduction in Ozone levels can be easily explained by the old cars which are being purchased. Since it will take some time for these cars to be replaced, the first few months enjoy some reduction in hydrocarbon and nitrogen oxide emissions.

However, during the time between the sale of the old car and the delivery of the new car, the owners face a shortage in their transport supply. As a first substitute they turn to taxis and thus we see a surge in taxi demand and a subsequent rise in taxi utilization rates and trips.

Taxi trips start increasing in mid 1997 (month 30) and grow in number to meet the rising trip demand from owners selling their old cars until the end of month 60. At this time the first cars that were ordered by the owners of the old cars start being delivered and private car trip supply starts increasing.



At month 90 the car fleet is actually above its BASE level because cars are not being repurchased any more and there is still a large backlog of new cars on order to replace those that were sold in the previous months.



However, ozone levels maintain their downward trend because the taxi trips, which had been slowly declining since the car fleet started to grow, suffer a dramatic drop in their supply level. From a high trip supply level of over 1.1 million trips taxi per day in month 60 and slightly over 1 million in month 90, they drop to roughly 750,000 trips taxi per day in 30 months.

This sharp decline in taxi supply account for ozone levels dropping during this period.

As the additional trips provided by the new cars start approaching their BASE levels, taxi demand starts rising again and for the first time since the beginning of the program, all surface transport trips are growing simultaneously.

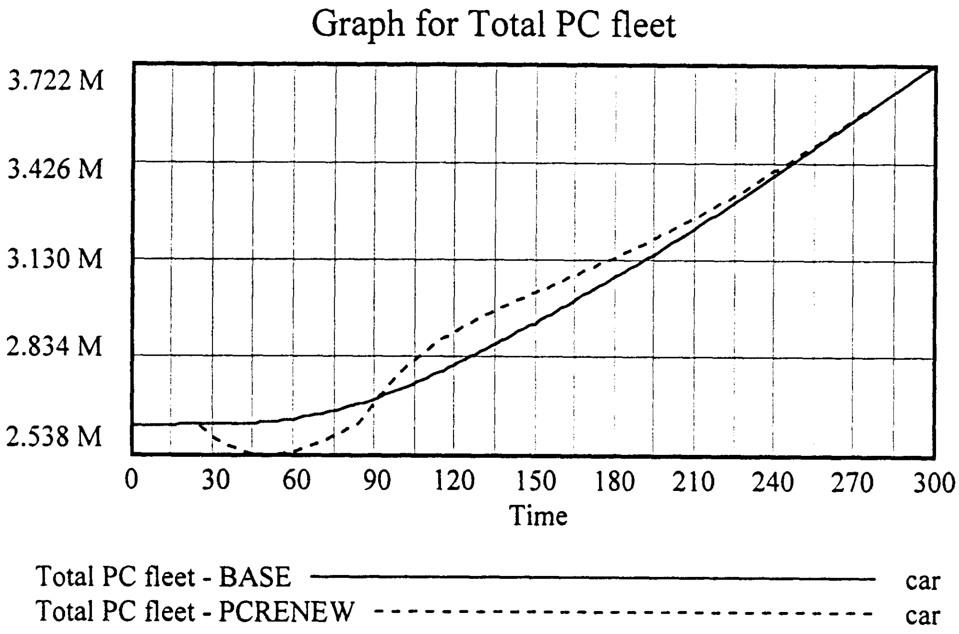
Defying intuition, Ozone levels do not rise between the months 120 and 240, even in the face of growing transport supply. Part of this further reduction is due to the Premium gasoline which is curtailing combustion emissions and another part is due to a favorable region in the ozone isopleth curves.

Hydrocarbon levels are still dropping as a consequence of introducing the new Premium gasoline. Hydrocarbon concentration reaches its minimum point when the penetration of the Premium gasoline has leveled off at 50% of the unleaded market. At this point hydrocarbon emissions start to rise driven by the city's growth because there is no futher technological improvement curtailing them.

Regarding the favorable isopleth region, it is a product of the non-linear relationship between ozone concentrations and levels of hydrocarbons and nitrogen oxides. Because both pollutants are initially reduced but regain their prior levels at different times, the trajectory upon the ozone isopleths is not the same one going down than going up.

It is relevant to point out that the total car fleet is not reduced in the long term by this policy but rather temporarily. The policy assumes a substitution rather than a retirement of old cars. Moreover, the rejuvenation effect itself is also temporary and in the long term the car fleet will regain its current average age, along with its pollution consequences.

Thus, there are two ways to understand a private car fleet renewal program. One is to complement another program as a means of accelerating the retirement of the regulation fleet. For instance, the abolishment of the day without a car program reduces the desired regulation fleet but the physical reduction of this fleet is only achieved as the cars age beyond their useful liVes and are not repaired nor replaced. A private car renewal program would probably entice old cars that were bought as a product of the regulation to be destroyed at a faster pace. The second way to think about this policy is simply to buy time because the fundamental dynamics of the system are not altered and the present fleet will again eventually become old. In other words, the effect of this policy is only temporary because the system structure that makes people want to hold on to their cars as long as possible has not been changed.


Graph for Total PC fleet
3.722 M
3.426 M
3.130 M
2.834 M
2.538 M
0
30
60
90
120
150
180
210
240
270
300
Time
Total PC fleet - BASE ——— car
Total PC fleet - PCRENEW - - - - car

ENERGY POLICIES

Gasoline Quality Improvements

One of the most immediate policies that come to mind to deal with air pollution is to impose the use of the best available technologies both in terms of combustion and emission control equipment and fuel formulation. In chapter 2 we examined the effects that the introduction of mandatory catalytic convertors in new vehicles have had in the ozone concentration increase trend. Since growth is the main driver of transport demand, effects issued from incremental technological improvements are temporary by nature as they do not affect the underlying structure of the system. However this strategies can be rapidly implemented and offer a relief for a few years.

This approach has also been taken in relation to fuel quality. In October 1996 the Mexican government started the introduction of Pemex-Magna gasoline which is a high quality, unleaded upgrade. Magna Sin will replace Nova and Magna Gasolines.

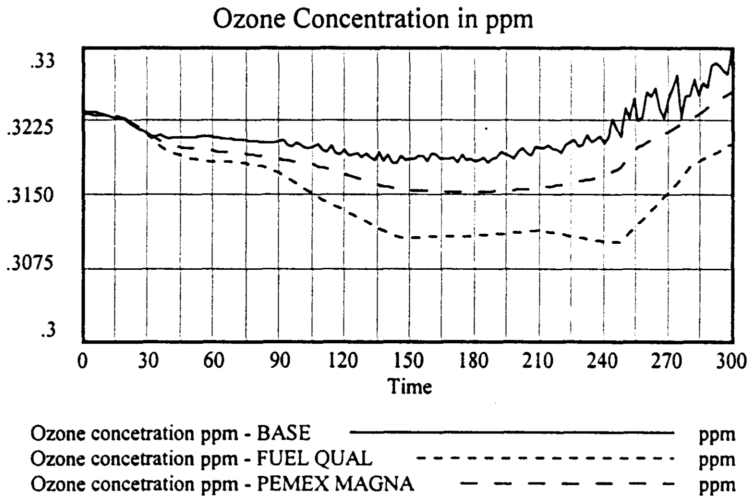
Following are some of the fuel specifications. In terms of emissions performance Magna sin is superior to Nova gasoline.

	% Reduction Vs Magna Sin In vehicles with cat conv	% Reduction Vs Nova In vehicles w/o cat conv
Combustion emissions HC	3%	6%
Evaporative emissions HC	24.4%	NA
Total Emissions NOx	4.2%	0%

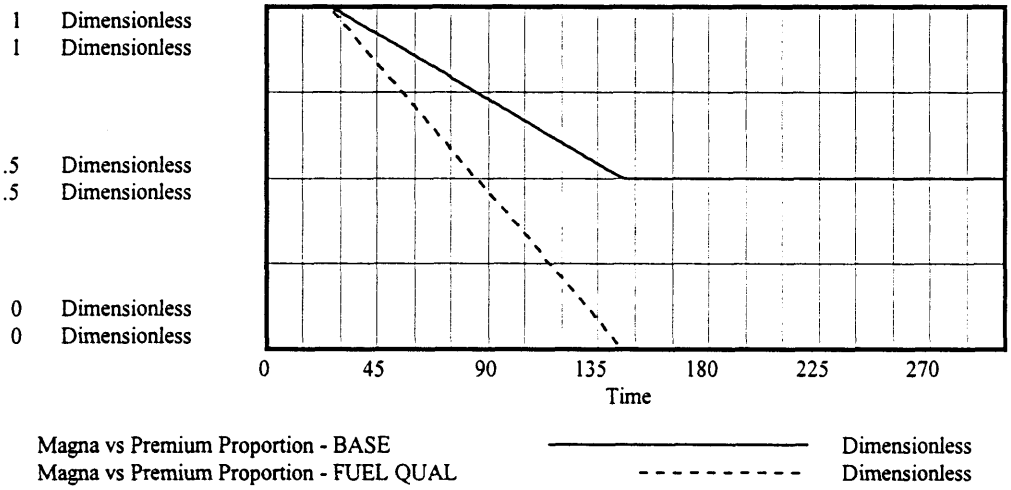
Pemex magna is a lower sulfur gasoline that has that decreases emissions of ozone precursors. The Pemex Magna scenario considers 100% replacement of Nova and Magna Sin gasolines in the course of three years. The Fuel Qual scenario also simulates this policy plus the complete replacement of Magna Sin by Premium gasoline. As mentioned in chapter 2, for the purposes of this study, premium gasoline is considered to meet CARB emissions standards

Following are the parameters of the simulation:

Switch	BASE Value	Pemex Magna Value	Fuel Qual Value
Model structure switches			
Convertor equilibrium switch	0	0	0
Random multiplier switch	1	1	1
Demand equilibrium switch	1	1	1
Symmetric cascade switch	0	0	0
Speed pollution switch	1	1	1
Infrastructure Policy switches			
Road capacity	1,515,940	1,515,940	1,515,940
Willingness to build and use rail capacity	0	0	0
Road tax to PC at full capacity	0	0	0
Transit Policy switches			
Regulation switch	0.8	0.8	0.8
Subsidized car retirement	0	0	0
Energy Policy switches			
Magna Vs Premium Proportion	50% by 2007	50% by 2007	100% by 2007
Pemex Magna substitution fraction	0	100% by 2000	100% by 2000
Gasoline tax per km to private cars	0	0	0

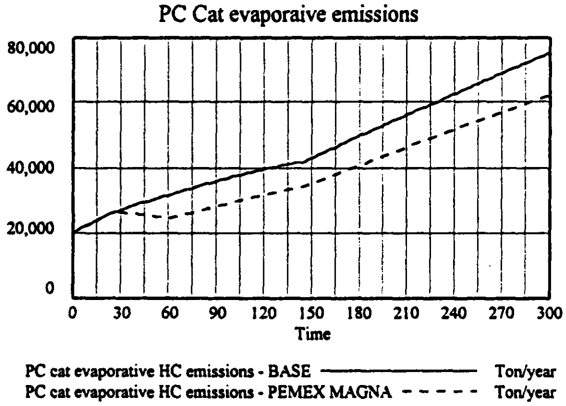


The introduction of the gasoline is completed after 36 months. In the Fuel Qual scenario Premium gasoline totally replaces Magna at time 145

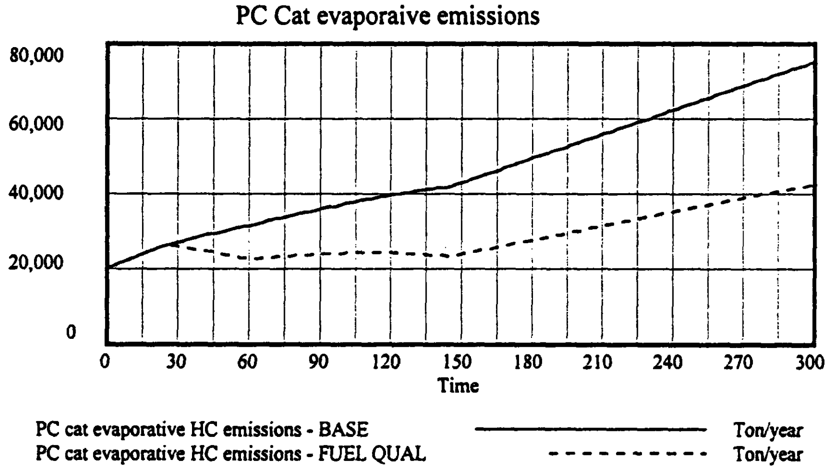


This gasoline brings a decrease in emissions until time 145. At that point, the premium completely replaces Pemex Magna, and Pemex Magna has replaced Nova.

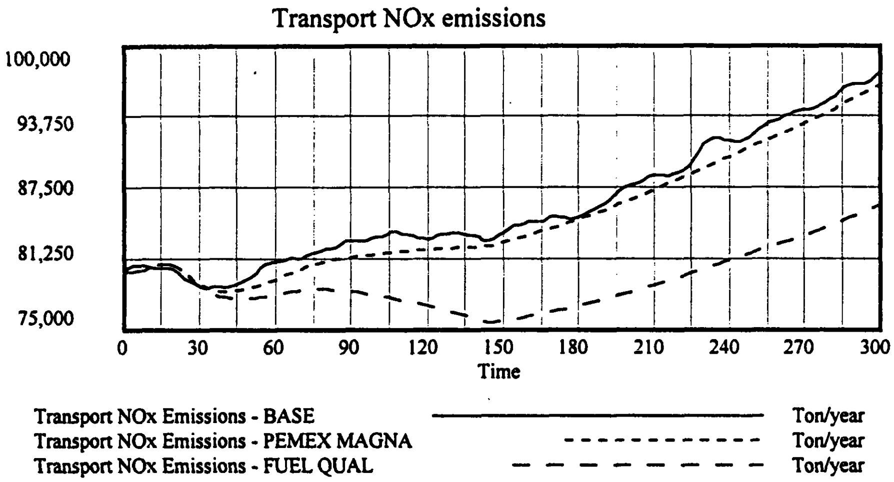
One of the effects of Pemex Magna gasoline is not the same for different technologies. In particular, for cars without a catalytic convertor HC emissions reductions are considered to be 0. Consequently as the cars with catalytic convertors represent a more significant part of the fleet the effect on evaporative emissions will be higher. We can illustrate this point by simulating the introduction of Pemex Magna but with the same Premium penetration than the base case.

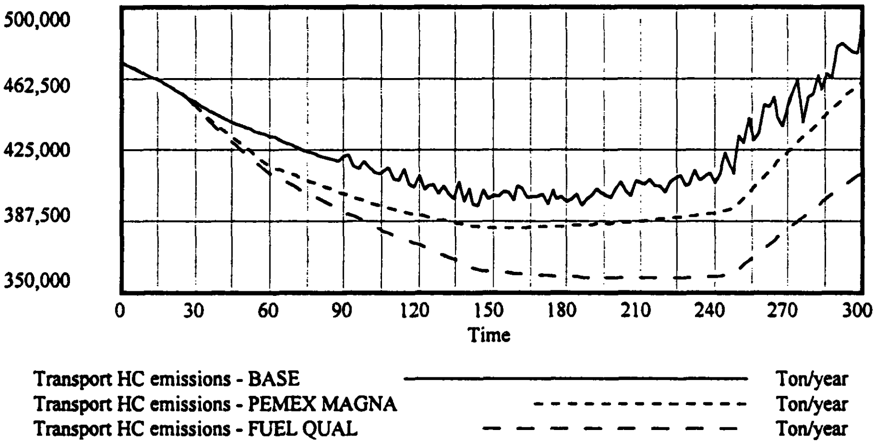


When Premium is introduced at a higher rate the result is the following reduction. As we see this effects accounts for the increased difference due to Pemex magna introduction.



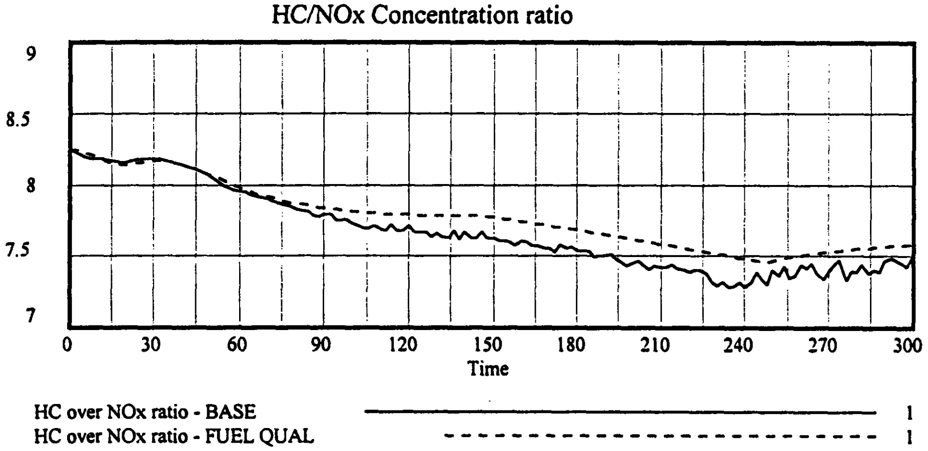
Following are the resulting NOx and HC transport emissions





It can be seen in the previous graphs that until premium gasoline is completely introduced, HC emissions are decreasing while NOx emissions slightly increases at first and then decreases. This behavior accounts for the ozone concentration pattern behavior seen above. The rates at which HC and NOx concentration levels are increased at different rates dependent on the emissions of each transport mode, which in turn are a function of the control technology and fuel used.

This results in different HC/NOx concentration ratios than in the base case.



The introduction of Pemex Magna and the aggressive introduction of Premium, result in a higher HC concentration relative to NOx. This means that the emissions are now richer in HC than in the base case, and thus relatively lower in NOx. As was mentioned in chapter 1, in Mexico City has a high HC/NOx concentration ratio, and thus the most efficient strategy would be a reduction in NOx.

It is clear that the introduction of reformulated , high quality fuels has a positive impact in the air quality of the city. However, in absolute terms the reductions are not very significant even with an efficient trajectory in emission reductions.

The maximum reduction obtained with the introduction of the Pemex Magna alone gasoline are in the order of 0.8%. This is consistent with values from the IMP (Mexican institute of Petroleum) from a study that estimates the impact of Pemex Magna introduction results in reductions of less than 1%. If this policy is enhanced by the aggressive penetration of Premium gasoline, the maximum ozone reduction levels are in the order of 3%.

Reduction levels by fuel quality upgrades, are have a limited impact, even in aggressive and "trajectory efficient" scenarios. Even if they represent an improvement in air quality, fuel quality improvements have to be weighted against the high costs involved in refining investments. For example the net present value of the costs in refining investments to meet the 086 Ecological Norms natonally is estimated by Pemex to be in the order of US

$ 2,300 million. To strive for higher environmental standards would impose important costs for the country. According to Pemex, the NPV cost to achieve California standards (CARB 96) would be US $ 9,300 million, which is clearly unaffordable for the country at the present moment.

Additionally, if the standards would have to be applied immediately, the investment would have to be even higher. This strategy has to weight the very significant costs implied against the resulting impact in environmental quality.

Finally, even if a technological solution is chosen. The impact that a new fuel upgrade specification is a function of the combustion quality and control technology available in the vehicular fleet. In other words; a technological strategy has at least two dimensions that have to be considered: fuel qualities and engine technology (i.e. Fuel injection, combustion efficiency, control technology etc.). Consequently, one policy can be implemented and its impact be offset by a deficient quality in the other.

Gasoline Tax

Given the poor performance that traditional instruments have had in combating high ozone levels in Mexico City. Economic instruments are often proposed as an alternative policy mechanism. They would seem to offer a way to harmonize growth with environmental protection by means of internalizing environmental impacts directly into the prices of goods and services. This would lead to a more rational use of environmental resources.

Green taxation is one of such instruments. A gasoline tax in particular would seem to lead consumers to limit their gasoline consumption. A study by Belausteguigoitia et al (1996) estimates demand of unleaded gasoline to have negative positive income elasticity (0.1) and a negative price elasticity (-0.5). These values tell us that raising gasoline prices relative to the rest of the economy will produce a reduction in consumption.

Environmental impacts for different scenarios of gasoline demand consumption reductions.

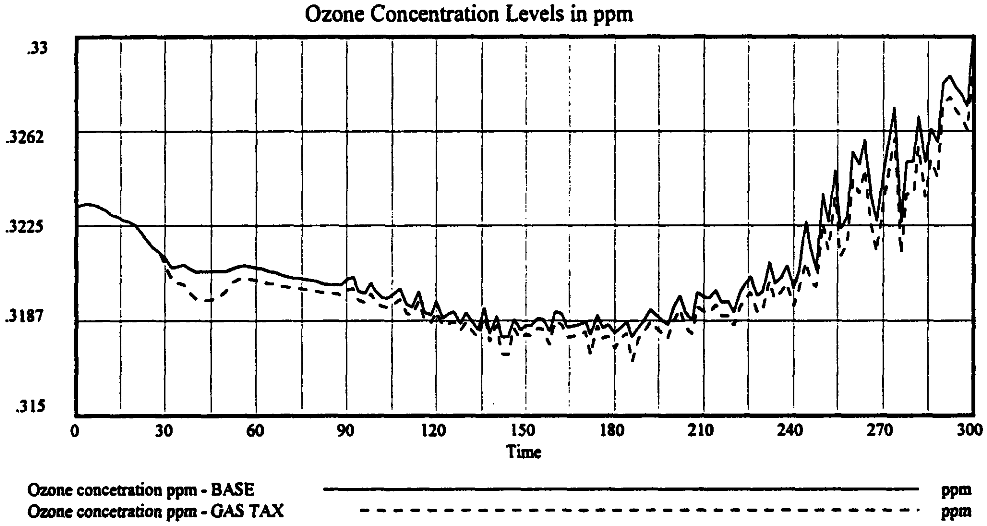
Case	% Price Variation	% Gas Sales Variation	% in HC Emissions Variation	% in NOx Emissions Variation	% in Peak O_3 Variation
1	+33.73	-9.0	-6.8	-5.0	-1.6
2	+34.92	-14.0	-9.6	-7.0	-2.4
3	+37.71	-27.0	-18.5	-13.6	-5.1

We can see that the medium case estimates a 14% reduction in gasoline consumption and a 2.4% reduction in the ozone peak level. Ozone levels were calculated by changing the emission data that feeds the IMP/Los Alamos model with the meteorological and initial concentration levels of the February 1991 simulation (the same that that is used in this study). The 1995 Emission Inventory (same that is used in this study) is modified by the gasoline reduction levels. However, it is not specified how is this gasoline consumption reduction distributed along the day. Ozone level reduction in the medium case is 2.4% which is not a very significant decrease.

We arrive to even smaller O_3 reductions, by implementing a 40% increase in the gasoline cost per km of each trip with the following simulation:

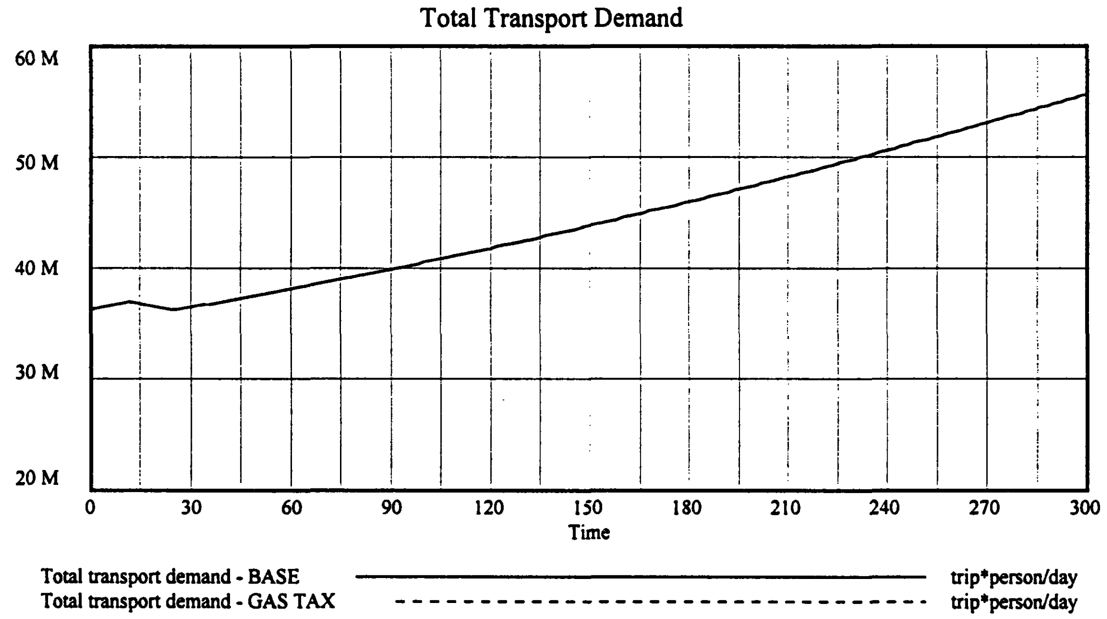
Switch	BASE Value	Gas Tax Value
Model structure switches		
Convertor equilibrium switch	0	0
Random multiplier switch	1	1
Demand equilibrium switch	1	1
Symmetric cascade switch	0	0
Speed pollution switch	1	1
Infrastructure Policy switches		
Road capacity	1,515,940	1,515,940
Willingness to build and use rail capacity	0	0
Road tax to PC at full capacity	0	0
Transit Policy switches		
Regulation switch	0.8	0.8
Subsidized car retirement	0	0
Energy Policy switches		
Magna Vs Premium Proportion	50% by 2007	50% by 2007
Pemex Magna substitution fraction	0	0
Gasoline tax per km to private cars	0	0.24

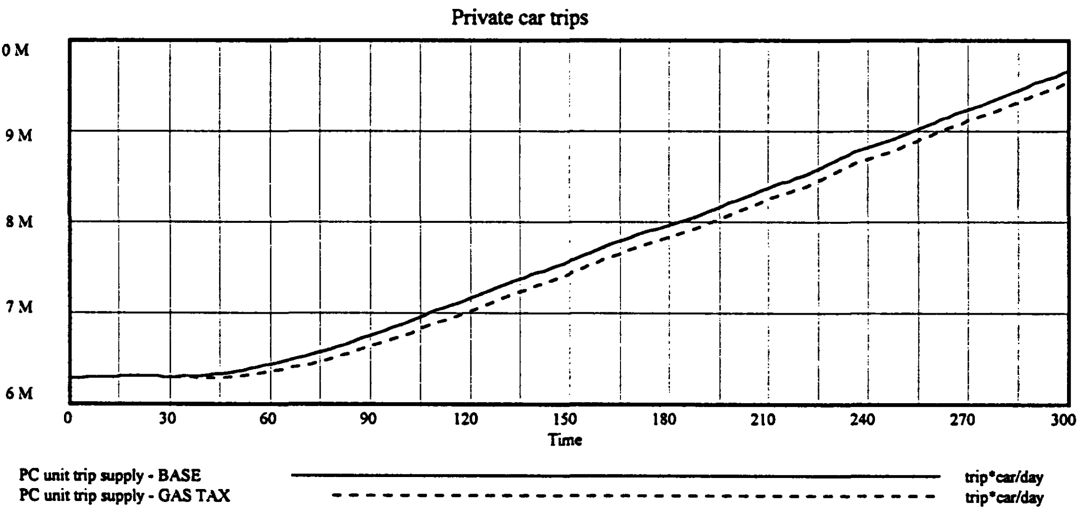
The Ozone concentration variations obtained are the following.



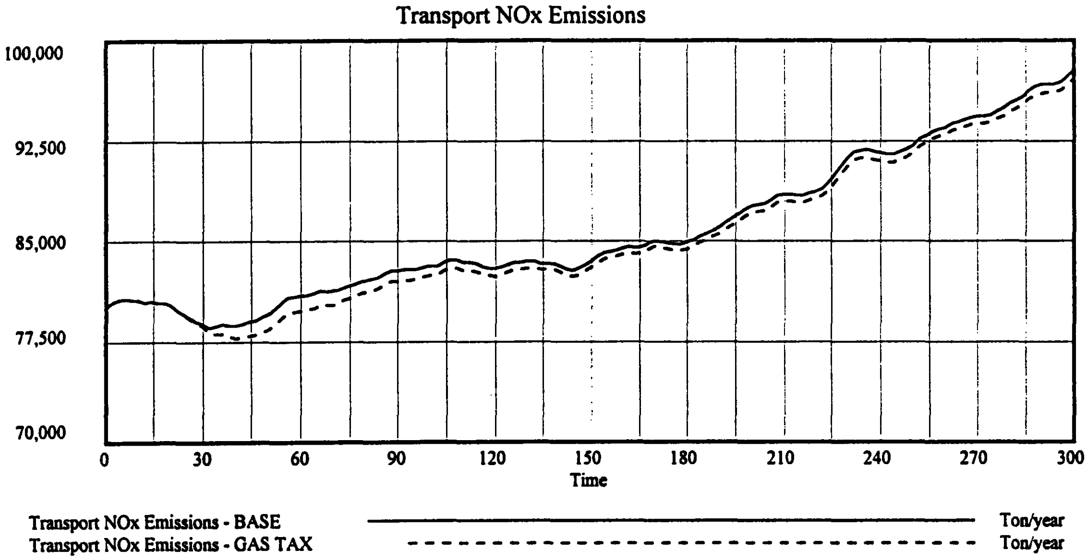
We can see that even though there is an ozone concentration reduction, this reduction is in the range of 0.4% (6 times lower than the Belausteguigoitia et al study) at its maximum level of reduction. Before contrasting both values, two points have to be mentioned. First is that this model does not pretend to be predictive. As it has been mentioned before, some of the values contained in this study come from gross approximations since many times relevant was not available and had to be estimated. Even though a model that englobes such a diversity of phenomena is illustrative by nature, some insights can be gained by contrasting the results of both studies.

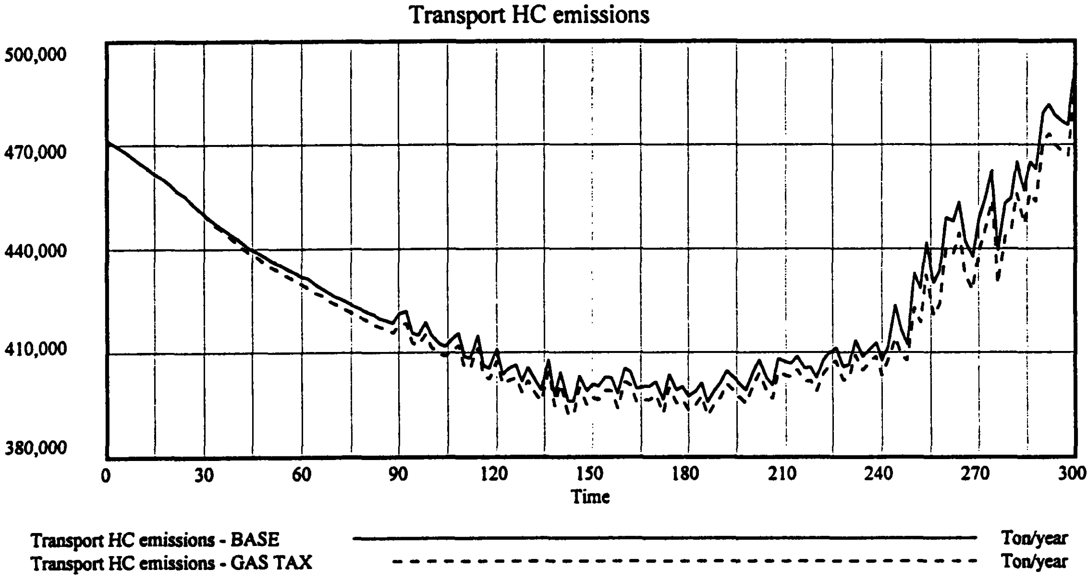
In the APDM, emissions are quantified by estimating actual trips for every trip mode choice. Increases in costs per Km affect the private car mode of transportation, and the attractiveness the car mode decreases. As we can see Total trip demand remains constant but Private car trips decrease.





However the demand for trips has to be fulfilled by other transport means. The surface transport emissions are the following:

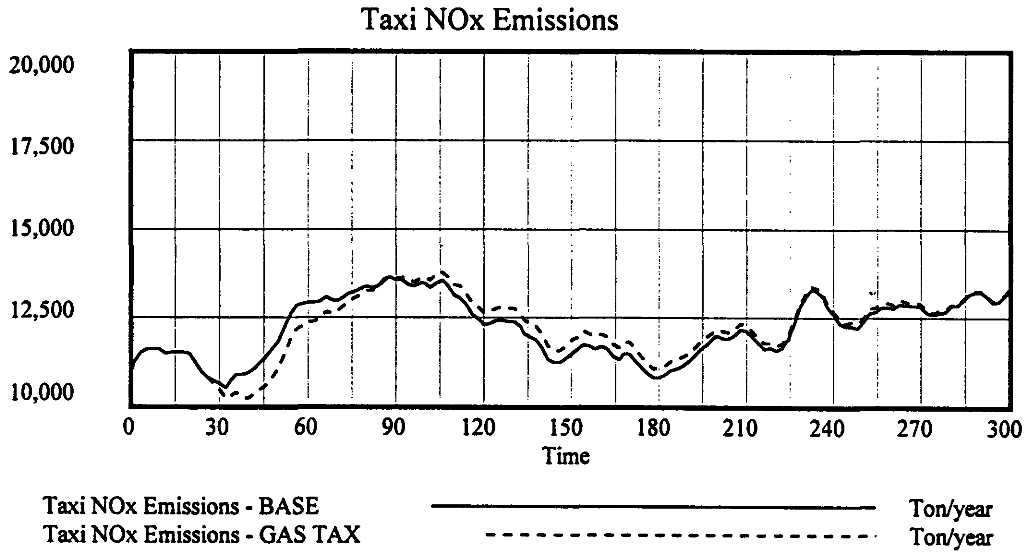




As we can see emissions are mainly affected mostly at the NOx level. This can be explained because NOx emissions come from combustion. On the other hand HC emissions have an important evaporative component. This evaporative emissions would not be affected by a decrease in private car trips.

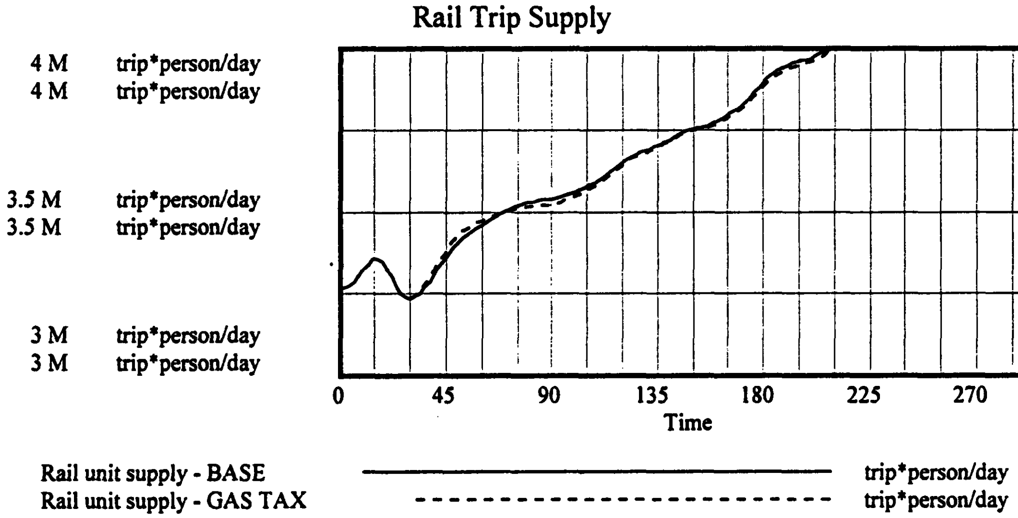
Private car trip choice mode is very unresponsive to cost in this model, so the reduction in private car trips is not very significant; 2% at its highest. This would imply much smaller reductions in NOx and HC emissions than the ones considered in the Belausteguigoitia study.

An interesting feature of the simulation is that the ozone reduction is high during the first months after the simulation. This is a result of the reduced NOx emissions during this same period of time. As seen above, part of this reduction comes from the reduction in private trip demand. However a significant portion of the NOx emissions reduction comes from a decrease in the taxi trip mode choice, and thus in the resulting combustion emissions. Taxi trip decrease does not arise as a direct response to higher gasoline prices, it is a result of the trip mode choices and time delays inherent in the system.


Taxi NOx Emissions

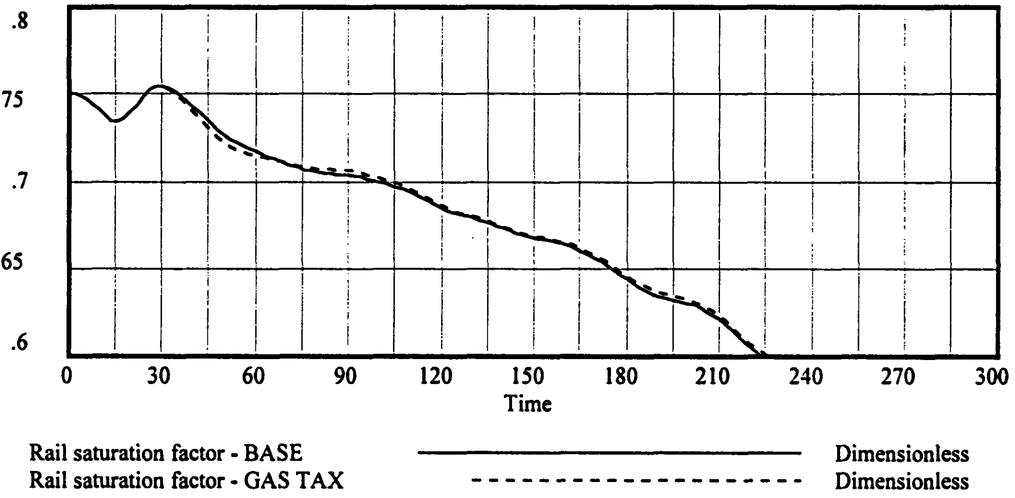
Here, the Taxi NOx emissions decrease after the tax is implemented, but after time 90 emissions are increased relative to the base case. This dynamic effect has as a consequence that the difference in NOx emissions between the Base scenario and the Gas Tax scenario reaches a maximum point in the month 45 (20 months after implementation). However, at the end of the simulation horizon NOx differences are much lower, and thus most of the (small) benefits in terms of air quality are lost or at least diminished.

This effect illustrates the amplification effect mentioned in the previous section. Between times 25 and 90 the private car unmet trip demand decreases as the private car fleet is more capable of satisfying demand. This illustrates that part of the taxi trips in the base case were private car trips that were not able to be satisfied by the supply and chose to be fulfilled by the alternative transport modes between surface public transport, rail and taxi. Public transportation remains above the base case for all the simulation horizon. However, rail transport presents the following behavior.



As private car trips decrease, rail trips become more attractive and capture a higher market share. However as the capacity limit is approached rail trips lose market share in the gas Tax scenario relative to the base case. This behavior is due to the saturation or effect in the subway. In time 70 the rail saturation factor becomes higher given that it has absorbed some of the unmet private trip demand. Logically, capacity limits are reached earlier and thus the attractiveness of the rail trip decreases. We can see that from this point rail trips in the Gas Tax scenario represent a lower market share than in the Base scenario.

RAIL SATURATION FACTOR



Some of these exceeding trips are captured by the taxi trip mode. Taxi trips are extremely inefficient in terms of emissions per trip*person/km since for every taxi trip each person does, the taxi has driven without a passenger. In the final accounting, these is equivalent to a higher level of pollution per trip*person/km for the taxi mode.

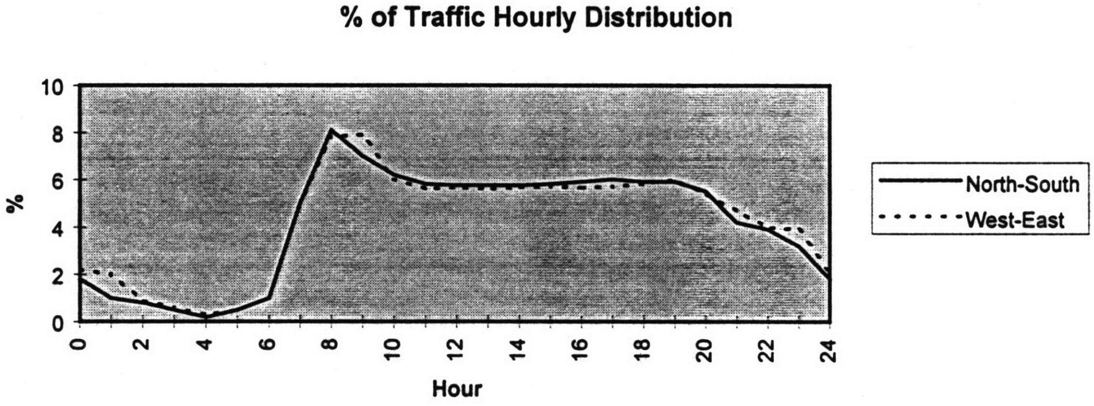
So far, we have identified two effects of the tax on the model. First a reduction in private trip demand and in the taxi trip mode, second an increase in rail transport. There is also a third effect that makes the gasoline impact less noticeable in the longer term, and can be explained by the penetration of the catalytic convertor cars in the fleet. As more cars have convertors the emissions per trip will be lower. This means that every additional trip avoided will be contribute less in relative terms. At the end of our simulation horizon we end up with even smaller reductions on ozone levels. This three effects combine themselves to give rise to the dynamic behavior observed; a transitory (and small) reduction on ozone levels and (as rail infrastructure saturates) a relative increase of ozone slightly beneath the levels of the base case.

For illustration purposes, here are values that represent the maximum reduction attained by the model. It is worth saying that not all of these occur at the same time. Once again our values do not pretend to accurate but rather gross estimations. However, when followed across the time horizon of the simulation, they are illustrative of the boundaries of the dynamics of the system.

Maximum Reductions Attained with Gasoline Tax

Case	% Price Variation	% Private Car Trip Variation	% in HC Emissions Variation Max	% in NOx Emissions Variation Max	% in Peak O_3 Variation Max
1	+40.0	-2.0	-0.33	-1	-0.4

An additional consideration that might account for the differences in values is how was the gasoline consumption reduction distributed along the day. The authors of the cited study recognize that a gasoline tax would probably not have a significant effect on peak hour travel. However Mexico City private vehicle transit distribution is quite flat during working hours.



Additionally, work trip mode choices are specially unresponsive to cost perturbation. This would suggest that reductions in gasoline combustion would rather occur during the non working hours. The model of this study has weighted coefficients of responsiveness to time and cost variations for work and non work trips. This would explain part of the lack of responsiveness of the private car trip choice mode to a cost increase.

Another fact that should be considered is that Ozone peaks occur during working time (since ozone formation is a photochemical reaction) and thus if reductions are mainly carried out in non working hours, reductions in the predicted environmental effects of the gasoline tax could be lower.

As a conclusion, even if the ozone concentration levels predicted by the two models are different (0.4% Vs 2.4%), neither is very significant. The relevant insight from our simulation is that a standalone gasoline tax or any other Pigovian tax that could be incorporated as a higher expense per Km (i.e. automobile ownership taxes) can present a policy resistance dynamic if they are not implemented considering the alternatives to meet the displaced demand.

Additional points to be evaluated if a gasoline tax policy is being considered are the following among others:

- Work related trip mode choice cost elasticity reduction given an increase in gasoline prices
- Distribution of this reduction along the hourly trip demand.
- Surface public transport and taxi resulting emissions be
- Effects in terms of peak ozone concentrations

And the resulting impact on air quality has to be weighted against negative effects of the policy such as:

- Inflationary pressures given that gasoline prices have an effect on the general price index
- Equity and political considerations, since the low income population will have a relatively higher burden.

FURTHER AREAS OF STUDY

This research has uncovered several of the structural links between public policies and air pollution in Mexico City. The insight that these links bring regarding transportation, energy and infrastructure as a dynamic and complex system is essential to understand the potential consequences of current policies. However, there are still several areas of work that could enhance the usefulness of this research significantly.

The research opportunities around this topic include working with the model presented in this thesis, applying the system dynamics methodology to other aspects of this problem and enhancing not only our understanding but also our definition of the air pollution problem and the regulatory options surrounding it.

Working with the Air Pollution Dynamic Model may include studies regarding the various parameters used or adjusting it to serve as a local policy tool, instead of an aggregate one. The system dynamics methodology might provide valuable insights regarding the growth dynamics of Mexico City and may also help policy makers understand the underlying dynamics of their policy making process itself, thus allowing them to redesign it. Finally, broadening not only our understanding, but our definition of the pollution problem will help to leverage the confluence of many different fields, from physics to economics, around the pollution problem.

Further work with the APDM

Over the course of this research there were several assumptions that had to be made in the absence of relevant Mexican data. The parameters thus derived were selected from sources as similar as possible to Mexico City and therefore we hold the structural relationships found in this thesis acceptable. However, obtaining these parameters for the case of Mexico will not only validate our assumptions but additionally increase the precision of the model. Eventually, the model could also be used as a predictive tool for transport flows and capacity planning.

The main parameters that would be needed to validate and enhance the predictive power of the APDM are the econometrics of mode choice, the saturation factor of the subway, the automobile scrappage rates and the city's road capacity.

An econometric study in transport mode choice for Mexico City would feed into the calculation of each mode's attractiveness and thus of its market share and trip demand. The transport modes defined in the econometric study would necessarily be identical to the ones used in the APDM, either as they stand today or changing them to meet some other established categories.

In the case of rail, econometric studies obtaining price elasticities can be misleading because it is a subsidized form of transport in Mexico City. It is important to complement price elasticities with saturation elasticities. As the subway utilization approaches full capacity, its trip demand drops due to a crowding effect. In fact, it would be useful to compare the results of such a study when using nominal subway capacity vs. "real" subway capacity. This could be done for daily or hourly intervals, depending on the later use for the model.

Automobile scrappage rates are taken from a study done in the United States and are further assumed to be constant over time. Obtaining these car scrap rates for the Mexican economy would again validate our assumptions and elevate the predictive power of the model. Furthermore, investigating the relationship between these scrap rates and other variables such as the economy, total car fleet, transport surplus/deficit, etc. would incorporate some interesting dynamics that have been neglected at this stage.

Road capacity is a key driver of the long term behavior of the system. It is estimated in a gross approximation based on the assumption that current utilization levels are 50%, which minimizes the potential error to an unknown utilization. Other factors affecting flow capacity of surface transport such as signalization, parking, etc. have been simplified for the purposes of this thesis. Estimating them in separately would not only aid in improving the model but also in estimating the costs associated with the road capacity policies.

Also regarding road capacity, it would yield increased accuracy for the model to calculate both the relationship it bears to expected travel time and to the uncertainty around it. Of particular concern is the assumption that maximum uncertainty is observed at 11% utilization, according to the study cited in this thesis.

In terms of enhancing the application range of the model, it is possible to adapt it to capture the dynamics for a specific region of the city, or even a specific transport corridor. Additionally, the time horizon of the model could also be changed to simulated shorter term policies such as peak pricing, although this is presently unlikely.

In order to adapt the model to a specific region or transport corridor, it would be necessary to separate the transport supply along that corridor into its different modes and estimate the elasticities for each mode. Additionally, the vehicle fleets and overall transportation capacities, along with their current utilization levels would need to be obtained.

A model built or adjusted in this way would capture local differences in transportation dynamics, maybe changing the implementation of certain public policies by region of the city. For instance, in a region where the demand for rail is highly elastic, or its utilization is relatively low compared to the rest of the system, expanding the rail capacity might prove to be an unwise policy.

In the case of Mexico City, the trip demand curve is relatively flat, which implies a saturated system. We have assumed that the observed demand pattern has flattened in response to natural pressures from the system. Under this scenario, enacting a peak congestion tax as a means of demand-side management is practically futile, since the demand curve is already flat. However, it may prove worthwhile to study the hourly flows of transport in the city by region or transport corridor.

A model that captured this dynamic would need the relevant short (really short) term elasticities of every transport mode per route. This would in fact mean customizing the model not only spatially, but chronologically as well, i.e., a different model would be built to understand the dynamics of a given transport corridor at 9 in the morning and at 6 in the evening.

Further work in System Dynamics

As a complement to the APDM, understanding the dynamics of the city as a growing entity, both physically and economically would be useful. A city's growth is very complex, as it can happen along many dimensions. For instance, a city might grow spatially, expanding its physical frontiers to unused areas of land located in its outskirts. Additionally, it might grow demographically, increasing the number of people that go about their daily activities there, even those who do no necessarily *live* there. Further, a city might grow economically, generating more wealth that can be attributed to it. Finally, a city can grow in its transportation needs, requiring additions to its transport infrastructure in order to satisfy them. A city's growth is generally a combination of several of these variables.

The construction of an Urban Dynamics model for Mexico City would help policy makers identify the relationships and drivers behind the city's growth along its many dimensions. The interaction of a model such as the APDM with an Urban Dynamics model would allow policy makers to search public policies whose effects would be enhanced by the city's growth in conjunction with its transportation dynamics.

For example, an Urban Dynamics model could capture the underlying dynamics linking land usage and zoning with transport demand. Understanding the structural consequences of locating, for instance, all residential areas adjacent to their respective working centers would be crucial in the design of coherent public policies.

At a more conceptual level, system dynamics could be helpful in identifying the causal loops involved in the policy making process in countries such as Mexico. By identifying the underlying structure behind the policy decisions, it may be possible to improve the environment in which they are made and thus their quality.

One example of such problems is the trade off that policy makers must face between short and long term consequences of their policies. It is often the case that the highest yielding policy in the long term requires some sort of sacrifice in the short term, either economic, political or social. However, because a policy maker's professional time horizon is almost always much smaller than the horizon of the problem at hand, there is an incentive to choose the policy with the highest short term payoff, instead of the policy with the long run best results.

To make matters worse, society's political memory seems to be extremely good in the very short and long terms, but mangled in the medium time horizons, which are usually the most sensitive to poor policy decisions.

Recognizing this sort of problem in a formal way and searching for ways to realign the incentive structure of policy makers with the long term results of their policies is one of the least explored fields in system dynamics and perhaps one of the most promising.

Further work in air pollution regulation

On a larger scale, further research regarding air pollution as a more general problem is also needed. Areas with a high impact potential in this regard are valuation and technological solutions.

It is difficult to assign a monetary value to environmental problems and even more so to internalize this cost into the population's decision process. However, it is important to recognize that not all environmental problems pose the same risks or cause the same costs to society. Further, the translation to economic terms of different problems allows policy makers to evaluate public policies in the context of scarce economic resources. At the end of the day, it would be ideal to optimize the return on environmental investments in terms of their real economic costs and benefits, including factors such as resource depletion, health effects, etc., not on achievements that are abstract by any economic standards.

In the case of Mexico it would be necessary to evaluate the true costs of ozone pollution as compared, for instance, with suspended particles, or even illiteracy rates. We feel that further studies in this regard would enrich the public debate that leads to public policy decisions.

Finally, it is also important to stress the role of technological R&D in the control of air pollution. If we define growth, even in a global scale, as the primary driver of increasing air pollution, we'll see that R&D of new motors, new fuels and even new transport modes will continue to be a key factor in the containment of air pollution.

Conclusions

There are several conclusions arising from the discussion and analysis set forth in this thesis. These conclusions, like the thesis itself, do not pretend to identify the optimal course of action regarding air pollution in Mexico City. They seek to enhance the understanding of the problem in a way which improves the position of policy makers to identify successful policies.

Current tools for evaluating policy decisions face some limitations. By having an analysis structure which is implicitly static and isolated, they fail to recognize Mexico City as a complex, dynamic system whose feedback loops and interactions must be understood before they can be shaped successfully in the form of an environmental policy.

Regarding the discussion around command and control vs. economic incentives strategies, it is unclear whether one type of strategy is *a priori* better suited to address the problem than the other. Simulated policies of both types (e.g. gasoline tax and second day without a car) generated counter-intuitive policy resistance behavior and therefore it would seem more reasonable to evaluate the different options on a case by case basis.

Moreover, policies of either type that seek to override the behavior of the system without taking into account the structure which generates that behavior face, at best, a small chance of temporary success. Such was the case of the "No Circula Program" for which our findings show that a complete removal would improve the long term pollution conditions of the city without imposing dramatic short term pollution levels.

Finally, even considering the use of the tools introduced in this thesis, it is improbable that any policy will reduce ozone concentrations in Mexico City by more than 10% over the next 20 to 25 years. Energy policies such as improving gasoline quality or imposing a fuel tax as well as infrastructure alternatives like rail expansion fail to provide ozone concentration reductions above 8 to 10% of current levels. Further, they exhibit relatively short lived effects and would represent substantial financial burdens. Still, understanding the nature of the problem and using the correct tools to analyze it is important because incorrect policy decisions can have much larger negative effects on ozone levels in the future.

Appendix 1

Air Pollution Dynamic Model
****
.demand
****

(004) Average income per capita = GDP/Population
Units: (pesos/year)/person
:GROUP .demand
Annual income per capita in Mexico City measured in pesos

(005) Average income per capita high = Average income per capita*Avg income multiplier for high income
Units: pesos/(year*person)
:GROUP .demand
Annual income of the population traveling in private car and taxi expressed in annual terms.

(006) Average income per capita low = Average income per capita*Avg income multiplier for low income
Units: pesos/(year*person)
:GROUP .demand
Annual income of the population traveling in public vehicle and rail system expressed in annual terms.

(008) Avg income multiplier for high income = 2.5
Units: Dimensionless
:GROUP .demand
Average income of the population traveling by private car and taxi divided by the city's income per capita.

(009) Avg income multiplier for low income = 0.9
Units: Dimensionless
:GROUP .demand
Average income of the population traveling by public vehicles and rail system divided by the city's income per capita.

(014) Base mobility per person = 1
Units: trip/day
:GROUP .demand
Number of trips-person per day per person generated in the city regardless of income.

(015) Base PC trip cost = 1.3
Units: (pesos*car)/Km
:GROUP .demand
Base cost per km traveled in private cars.

(038) Change in PC mkt share = PC market share gap/Time to correct PC mkt share
Units: 1/Month
:GROUP .demand
Monthly correction of the real market share of private car travel in the city.

(040) Change in PubV mkt share = PubV mkt share gap/Time to change PubV mkt share
Units: 1/Month
:GROUP .demand
Monthly correction of the real market share of public vehicle travel in the city.

(042) Change in RV mkt share = RV market share gap/Time to change RV mkt share
Units: 1/Month
:GROUP .demand
Monthly correction of the real market share of rail travel in the city.

(044) Change in TX mkt share = TX mkt share gap/Time to adjust TX mkt share
Units: 1/Month
:GROUP .demand
Monthly correction of the real market share of taxi travel in the city.

(053) Daily income high = Average income per capita high/Days per year
Units: pesos/(day*person)
:GROUP .demand
Annual income of the population traveling in private car and taxi expressed in daily terms.

(054) Daily income low = Average income per capita low/Days per year
Units: pesos/(person*day)
:GROUP .demand
Annual income of the population traveling in public vehicles and rail system expressed in daily terms.

(055) Days per year = 365
Units: day/year
:GROUP .demand
Days per year

(056) Demand equilibrium switch = 1
Units: Dimensionless
:GROUP .demand

Changes values of GDP and population growth between zero and estimates from relevant sources.

(064) Elasticity of mobility to income = 3.25e-005
Units: (trip*person*year)/(day*pesos)
:GROUP .demand
Number of trips-person per day per person generated for every peso of extra income.

(068) Exchange rate = 8
Units: pesos/USD
:GROUP .demand
Estimated exchange rate for the simulation.

(070) Gasoline tax per km to PC = 0
Units: person*pesos/Km
:GROUP .demand
Value in pesos to be charged to gasoline consumption per private cars expressed in pesos per trip per km, i.e., adjusting for gasoline consumption per trip

(071) GDP = INTEG(GDP growth,4.4e+011)
Units: pesos/year
:GROUP .demand
Gross domestic product measured in pesos

(072) GDP growth = IF THEN ELSE(Demand equilibrium switch=1,GDP*GDP growth fraction/Percentage adjustment,0)
Units: pesos/year/Month
:GROUP .demand

(073) Table function "Lookup month to GDP change" has argument with dimension
Month
GDP growth fraction = Lookup month to GDP change(Time)
Units: 1/Month
:GROUP .demand
Monthly GDP growth in percentage terms. Assumed zero in equilibrium or taken from Lookup graph where month zero is January 1994.

(078) High income to minimum wage = Daily income high/Exchange rate/Minimum wage in USD
Units: Dimensionless
:GROUP .demand
Daily income for the population traveling in private cars and taxis divided by the minimum wage in Mexico City. Both quantities expressed in US dollars. Ratio is constant regardless of currency.

(079) Income mobility per person = Elasticity of mobility to income*Average income per capita
Units: trip/day
:GROUP .demand
Number of trips-person per day per person generated in the city due to income effects.

(088) Low income to minimum wage = Daily income low/Exchange rate/Minimum wage in USD
Units: Dimensionless
:GROUP .demand
Daily income for the population traveling in public vehicles and the rail system divided by the minimum wage in Mexico City. Both quantities expressed in US dollars. Ratio is constant regardless of currency.

(108) Minimum wage in USD = 5
Units: USD/(person*day)
:GROUP .demand
Minimum daily wage in Mexico City expressed in US dollars.

(110) Net population change rate = IF THEN ELSE(Demand equilibrium switch=1,Population*Population growth fraction/Percentage adjustment,0)
Units: person/Month
:GROUP .demand
Rate at which the population of the city grows in persons per month.

(132) PC attractiveness = EXP(PC attributes)
Units: Dimensionless
:GROUP .demand
Exponential function of the total attributes for private car travel. It is taken as the best proxy of the attractiveness of private car travel relative to other modes of transport.

(133) PC attributes = PC trips specific constant+PC trip cost elasticity*PC trip cost to income in min wage+PC trip time elasticity*PC average net trip time
Units: Dimensionless
:GROUP .demand
Measure of the attractiveness of private car travel compared to other modes of transport. See discussion about multi-attribute demand models ch. 2.

(135) PC average net trip time = PC trip time*(1+(RANDOM 0 1()-0.5)*Random trip time multiplier)
Units: minute/trip
:GROUP .demand
Estimated travel time taking a random component into account due to congestion levels.

(157) PC market share = INTEG(Change in PC mkt share,Underlying PC market share)
Units: Dimensionless
:GROUP .demand
Real market share of private car travel in the city.

(158) PC market share gap = Underlying PC market share-PC market share
Units: Dimensionless
:GROUP .demand
Difference between the calculated and the real market shares of private car travel in the city.

(167) PC trip cost = PC average Km per Trip*PC trip cost per km
Units: pesos/trip
:GROUP .demand
Estimated cost of the average trip in a private car. Cost per km=1.30 pesos while average trip length is 17.5 km.

(168) PC trip cost elasticity = -0.166355
Units: trip/USD
:GROUP .demand
Elasticity of private car trips (see discussion about multi-attribute travel demand models, ch. 2) to cost per trip. Source: Swait et al, study of travel mode substitution in Sao Paulo.

(169) PC trip cost in USD = PC trip cost/Exchange rate
Units: USD/trip
:GROUP .demand
Estimated cost of the average private car trip expressed in US dollars.

(170) PC trip cost per km = Base PC trip cost+Tax impact per person
Units: (pesos*car)/Km
:GROUP .demand
Net cost per km traveled in private cars including the effect of gasoline and road taxes.

(171) PC trip cost to income in min wage = PC trip cost in USD/High income to minimum wage
Units: USD/trip
:GROUP .demand
Estimated cost of the average trip in private cars divided by the income of the relevant population expressed in times the minimum wage.

(175) PC trip time elasticity = -0.020903
Units: trip/minute
:GROUP .demand
Elasticity of private car trips to average travel time measured in minutes.

(176) PC trips specific constant = 3.8475
Units: Dimensionless
:GROUP .demand
Base attributes of private car travel.

(184) Percentage adjustment = 100
Units: Dimensionless
:GROUP .demand
Division by 100

(204) Population = INTEG(Net population change rate,2.2e+007)
Units: person
:GROUP .demand
Population of the Mexico City area

(205) Table function "Lookup time to population growth" has argument with dimension Month
Population growth fraction = Lookup time to population growth(Time)
Units: 1/Month
:GROUP .demand
Monthly population growth in percentage terms.

(210) Pub trip time elasticity = -0.02096
Units: trip/minute
:GROUP .demand
Elasticity of public vehicle trips to average travel time measured in minutes.

(211) PubV attractiveness = EXP(PubV attributes)
Units: Dimensionless
:GROUP .demand
Exponential function of the total attributes for public vehicle travel. It is taken as the best proxy of the attractiveness of public vehicle travel relative to other modes of transport.

(212) PubV attributes = PubV trips specific constant+Pub trip time elasticity*PubV net trip time+PubV trip cost elasticity*PubV trip cost to low income in min wage

Units: Dimensionless
:GROUP .demand
Measure of the attractiveness of public vehicle travel compared to other modes of transport. See discussion about multi-attribute demand models ch. 2.

(213) PubV cost in USD = PV trip cost/Exchange rate
Units: USD/trip
:GROUP .demand
Estimated cost of the average public vehicle trip expressed in US dollars.

(216) PubV mkt share = INTEG(Change in PubV mkt share,Underlying PubV market share)
Units: Dimensionless
:GROUP .demand
Real market share of public vehicle travel in the city.

(217) PubV mkt share gap = Underlying PubV market share-PubV mkt share
Units: Dimensionless
:GROUP .demand
Difference between the calculated and the real market shares of public vehicle travel in the city.

(218) PubV net trip time = PubV trip time*(1+(RANDOM 0 1()-0.5)*Random trip time multiplier)
Units: minute/trip
:GROUP .demand
Trip time for average trip in a public vehicle at street level

(220) PubV trip cost elasticity = -0.22641
Units: trip/USD
:GROUP .demand
Elasticity of public vehicle trips (see discussion about multi-attribute travel demand models, ch. 2) to cost per trip. Source: Swait et al, study of travel mode substitution in Sao Paulo.

(221) PubV trip cost to low income in min wage = PubV cost in USD/Low income to minimum wage
Units: USD/trip
:GROUP .demand
Estimated cost of the average trip inpublic vehicle divided by the income of the relevant population expressed in times the minimum wage.

(225) PubV trips specific constant = 5.6855
Units: Dimensionless
:GROUP .demand
Base attributes of public vehicle travel.

(230) PV trip cost = 5
Units: pesos/trip
:GROUP .demand
Average cost of trip in public vehicle

(237) Rail saturation factor = Lookup rail utilization to saturation factor(Utilization of rail)
Units: Dimensionless
:GROUP .demand
Multiplier which enhances of reduces the attractiveness of rail transport due to saturation. It exhibits a highly non-linear behavior approaching zero at 100% saturation and 1 as utilization approaches 0%.

(252) Road tax impact on PC trips = Road tax to PC per km at full capacity*Road utilization factor
Units: person*pesos/Km
:GROUP .demand
Tax to be levied because of observed congestion levels.

(253) Road tax to PC per km at full capacity = 0
Units: person*pesos/Km
:GROUP .demand
Congestion tax at full road infrastructure utilization. Tax is interpolated between 0 and 100% utilization according to present utilization levels.

(255) RV attractiveness = EXP(RV attributes)
Units: Dimensionless
:GROUP .demand
Exponential function of the total attributes for rail travel. It is taken as the best proxy of the attractiveness of rail travel relative to other modes of transport.

(256) RV attributes = (RV trips specific constant+RV trip cost to low income in min wage*RV trips cost elasticity+RV trip time* RV trips time elasticity)*Rail saturation factor
Units: Dimensionless
:GROUP .demand
Measure of the attractiveness of rail travel compared to other modes of transport. See discussion about multi-attribute demand models ch. 2.

(257) RV market share gap = Underlying RV market share-RV mkt share
Units: Dimensionless
:GROUP .demand
Difference between the calculated and the real market shares of rail travel in the city.

(258) RV mkt share = INTEG(Change in RV mkt share,Underlying RV market share)
Units: Dimensionless
:GROUP .demand
Real market share of rail travel in the city.

(259) RV trip cost = 0.4
Units: pesos/trip
:GROUP .demand
Average cost of trip in rail

(260) RV trip cost in USD = RV trip cost/Exchange rate
Units: USD/trip
:GROUP .demand
Estimated cost of the average rail trip expressed in US dollars.

(261) RV trip cost to low income in min wage = RV trip cost in USD/Low income to minimum wage
Units: USD/trip
:GROUP .demand
Estimated cost of the average trip inrail system divided by the income of the relevant population expressed in times the minimum wage.

(262) RV trip time = 50
Units: minute/trip
:GROUP .demand
Trip time for average trip in the rail system

(263) RV trips cost elasticity = -3.96706
Units: trip/USD
:GROUP .demand
Elasticity of rail trips (see discussion about multi-attribute travel demand models, ch. 2) to cost per trip. Source: Swait et al, study of travel mode substitution in Sao Paulo.

(264) RV trips specific constant = 4.0134
Units: Dimensionless
:GROUP .demand

(265) RV trips time elasticity = -0.01826
Units: trip/minute
:GROUP .demand
Elasticity of rail trips to average travel time measured in minutes.

(287) Tax impact per person = Tax impact per vehicle trip per km/Persons per PC
Units: car*pesos/Km
:GROUP .demand
Cost per km traveled of gasoline and road congestion taxes for private cars

(288) Tax impact per vehicle trip per km = Gasoline tax per km to PC+Road tax impact on PC trips
Units: pesos*person/Km
:GROUP .demand

(313) Time to adjust TX mkt share = 6
Units: Month
:GROUP .demand
Average time to correct differences between the real and the calculated market share of taxi travel.

(315) Time to change PubV mkt share = 6
Units: Month
:GROUP .demand
Average time to correct differences between the real and the calculated market share of public vehicle travel.

(318) Time to change RV mkt share = 6
Units: Month
:GROUP .demand
Average time to correct differences between the real and the calculated market share of rail travel.

(319) Time to correct PC mkt share = 6
Units: Month
:GROUP .demand
Average time to correct differences between the real and the calculated market share of private car travel.

(330) Total transport attractiveness = PC attractiveness+PubV attractiveness+RV attractiveness+TX attractiveness
Units: Dimensionless
:GROUP .demand
Summation of the attractiveness of all four modes of transport: private cars, taxis, public vehicles and rail (metro).

(331) Total transport demand = (Base mobility per person+Income mobility per person)*Population

Units: trip*person/day
:GROUP .demand
Total demand for person-trips per day generated in the city.

(336) TX attractiveness = EXP(TX attributes)
Units: Dimensionless
:GROUP .demand
Exponential function of the total attributes for taxi travel. It is taken as the best proxy of the attractiveness of taxi travel relative to other modes of transport.

(337) TX attributes = TX trips specific constant+TX net trip time*TX trip time elasticity+TX trip cost to income in min wage*TX trip cost elasticity
Units: Dimensionless
:GROUP .demand
Measure of the attractiveness of taxi travel compared to other modes of transport. See discussion about multi-attribute demand models ch. 2.

(338) TX mkt share = INTEG(Change in TX mkt share,Underlying TX market share)
Units: Dimensionless
:GROUP .demand
Real market share of taxi travel in the city.

(339) TX mkt share gap = Underlying TX market share-TX mkt share
Units: Dimensionless
:GROUP .demand
Difference between the calculated and the real market shares of taxi travel in the city.

(340) TX net trip time = TX trip time*(1+(RANDOM 0 1()-0.5)*Random trip time multiplier)
Units: minute/trip
:GROUP .demand
Average total time for a taxi trip. May include the randomness component of traffic congestion.

(343) TX trip cost = 17.5
Units: pesos/trip
:GROUP .demand
Estimated cost of the average trip in a taxi.

(344) TX trip cost elasticity = -0.47996
Units: trip/USD
:GROUP .demand
Elasticity of taxi trips (see discussion about multi-attribute travel demand models, ch. 2) to cost per trip. Source: Swait et al, study of travel mode substitution in Sao Paulo.

(345) TX trip cost in USD = TX trip cost/Exchange rate
Units: USD/trip
:GROUP .demand
Estimated cost of the average taxi trip expressed in US dollars.

(346) TX trip cost to income in min wage = TX trip cost in USD/High income to minimum wage
Units: USD/trip
:GROUP .demand
Estimated cost of the average trip in taxi divided by the income of the relevant population expressed in times the minimum wage.

(349) TX trip time elasticity = -0.02115
Units: trip/minute
:GROUP .demand
Elasticity of taxi trips to average travel time measured in minutes.

(350) TX trips specific constant = 1.7102
Units: Dimensionless
:GROUP .demand
Base attributes of taxi travel.

(352) Underlying PC market share = PC attractiveness/Total transport attractiveness
Units: Dimensionless
:GROUP .demand
Calculated market share of private car travel from total travel demand. Percentage of total travel demand.

(353) Underlying PubV market share = PubV attractiveness/Total transport attractiveness
Units: Dimensionless
:GROUP .demand
Calculated market share of public vehicle travel from total travel demand. Percentage of total travel demand.

(354) Underlying RV market share = RV attractiveness/Total transport attractiveness
Units: Dimensionless
:GROUP .demand
Calculated market share of rail travel from total travel demand. Percentage of total travel demand.

(355) Underlying TX market share = TX attractiveness/Total transport attractiveness
Units: Dimensionless
:GROUP .demand
Calculated market share of taxi travel from total travel demand. Percentage of total travel demand.

****
.supply
****

(007) Average persons per PubV = (Persons per bus*Bus fleet+Persons per microbus*Microbus fleet+Persons per pesero*Pesero fleet)/(Bus fleet+Microbus fleet +Pesero fleet)
Units: person/pubv
:GROUP .supply
Number of people involved in the average public vehicle trip.

(037) Change in PC fleet utilization = PC fleet utilization change fraction/Time to adjust PC fleet utilization
Units: (trip/day)/Month
:GROUP .supply
Rate at which the utilization of the private car fleet changes per month.

(039) Change in PubV fleet utilization = PubV utilization change fraction/Time to change PubV utilization
Units: (trip/day)/Month
:GROUP .supply
Rate at which the utilization of the public vehicle fleet changes per month.

(041) Change in rail utilization = Rail utilization gap fraction/Time to change rail utilization
Units: 1/Month
:GROUP .supply
Rate at which the utilization of the rail system changes per month.

(043) Change in taxi fleet utilization = Taxi utilization gap fraction/Time to adjust utilization of taxis
Units: (trip/day)/Month
:GROUP .supply
Rate at which the utilization of the taxi fleet changes per month.

(057) Demanded PC Fleet utilization = (PC unit trip demand/Total PC fleet)/Regulation switch
Units: trip/day
:GROUP .supply
Implied utilization of the current private car fleet that would produce equilibrium of private car trip supply and demand.

(058) Demanded PubV utilization = PubV unit demand/PubV fleet
Units: trip/day
:GROUP .supply
Implied utilization of the current public vehicle fleet that would produce equilibrium of public vehicle trip supply and demand.

(059) Demanded rail utilization = Net rail trip demand/Rail capacity
Units: Dimensionless
:GROUP .supply
Implied peak hourly utilization of the current rail system that would produce equilibrium of rail trip supply and demand.

(060) Demanded taxi fleet utilization = Taxi unit demand/Taxi fleet
Units: trip/day
:GROUP .supply
Implied utilization of the current taxi fleet that would produce equilibrium of taxi trip supply and demand.

(111) Net rail trip demand = Rail trip demand+Unmet PubV trip demand
Units: trip*person/day
:GROUP .supply
Total demand for rail transport measured in person trips per day.

(126) Optimal rail capacity gap = Target rail capacity-Rail capacity
Units: trip*person/day
:GROUP .supply
Difference between the calculated rail capacity at target utilization and the current rail capacity.

(127) Optimal taxi fleet gap = Target taxi fleet-Taxi fleet
Units: taxi
:GROUP .supply
Difference between the calculated taxi fleet at target utilization and current taxi fleet.

(155) PC fleet utilization = INTEG(Change in PC fleet utilization,2.9929)
Units: trip/day
:GROUP .supply
Aveage number of trips per day made by private cars.

(156) PC fleet utilization change fraction = Demanded PC Fleet utilization-PC fleet utilization
Units: trip/day
:GROUP .supply
Difference between the actual utilization of the private car fleet and the demanded utilization by transport needs.

(172) PC trip demand = PC market share*Total transport demand
Units: trip*person/day
:GROUP .supply
Number of trips-person per day demanded from private cars.

(173) PC trip supply = PC unit trip supply*Persons per PC
Units: trip*person/day
:GROUP .supply
Total trips provided by private cars measured in person trips per day

(178) PC unit trip supply = Total PC fleet*PC fleet utilization*Regulation switch
Units: trip*car/day
:GROUP .supply
Number of private cars trips made per day in the city.

(185) Persons per bus = 50
Units: person/pubv
:GROUP .supply

(186) Persons per microbus = 20
Units: person/pubv
:GROUP .supply

(187) Persons per PC = 1.25
Units: person/car
:GROUP .supply
Number of persons involved in the average private car tirp.

(188) Persons per pesero = 8
Units: person/pubv
:GROUP .supply
Average number of people traveling in one pesero.

(189) Persons per TX = 1.25
Units: person/taxi
:GROUP .supply
Number of persons involved in an average taxi trip.

(214) PubV fleet = Bus fleet+Microbus fleet+Pesero fleet
Units: pubv
:GROUP .supply

(215) PubV fleet utilization = INTEG(Change in PubV fleet utilization
,Target PubV utilization)
Units: trip/day
:GROUP .supply
Aveage number of trips per day made by public vehicles.

(222) PubV trip demand = Total transport demand*PubV mkt share
Units: trip*person/day
:GROUP .supply
Number of trips-person per day demanded from the public vehicle system.

(223) PubV trip supply = Average persons per PubV*PubV unit supply
Units: trip*person/day
:GROUP .supply
Total number of trips provided by public vehicles measured in person trips per day

(226) PubV unit demand = (PubV trip demand+Unmet taxi trip demand)/Average persons per PubV
Units: (trip*pubv)/day
:GROUP .supply
Number of public vehicle trips per day demanded in the metropolitan area.

(227) PubV unit supply = PubV fleet*PubV fleet utilization
Units: trip*pubv/day
:GROUP .supply
Number of public vehicle trips, not including taxis or the metro, made per day.

(228) PubV utilization change fraction = Demanded PubV utilization-PubV fleet utilization
Units: trip/day

:GROUP .supply

(235) Rail capacity = INTEG(Rail capacity addition rate,6.53e+006)
Units: trip*person/day
:GROUP .supply
Total hourly capacity measured in trips-person in the rail system.

(236) Rail capacity addition rate = MAX(Optimal rail capacity gap/Time to adjust rail capacity*Willingness to build and use rail capacity,0)
Units: (trip*person/day)/Month
:GROUP .supply
Number of hourly trip capacity added to the rail system per month.

(238) Rail trip demand =RV mkt share*Total transport demand
Units: trip*person/day
:GROUP .supply
Number of trips-person per day demanded in the rail system.

(239) Rail unit supply = Rail capacity*Utilization of rail
Units: trip*person/day
:GROUP .supply
Total trips provided by the rail system at peak hour.

(240) Rail utilization gap fraction = Demanded rail utilization-Utilization of rail
Units: Dimensionless
:GROUP .supply
Difference between the actual utilization of the rail system and the demanded utilization by trnasport needs.

(280) Target PubV utilization = 6.1529
Units: trip/day
:GROUP .supply
Long-run equilibrium level of average daily trips by public vehicles. Serves as the inital value of the observed utilization in equilibrium.

(281) Target rail capacity = Net rail trip demand/Target rail utilization
Units: trip*person/day
:GROUP .supply
Calculated hourly rail capacity if current demand for rail trips was met with target utilization.

(282) Target rail utilization = 0.5
Units: Dimensionless
:GROUP .supply
Long-run equilibrium level of average peak percentage utilization of rail. Serves as the inital value of the observed utilization in equilibrium.

(285) Target taxi fleet = Taxi unit demand/Target taxi fleet utiliztation
Units: taxi
:GROUP .supply
Calculated taxi fleet if current demand for taxi trips was met with target utilization.

(286) Target taxi fleet utiliztation = 5.6291
Units: trip/day
:GROUP .supply
Long-run equilibrium level of average daily trips by taxis. Serves as the inital value of the observed utilization in equilibrium.

(291) Taxi fleet = INTEG(Taxi purchases-TX scrappage,136500)
Units: taxi
:GROUP .supply
Total number of taxis in the metropolitan area.

(299) Taxi purchases = MAX(Optimal taxi fleet gap/Time to adjust taxi purchases+TX scrappage,0)
Units: taxi/Month
:GROUP .supply
Number of taxis additioned to the taxi fleet per month.

(300) Taxi trip supply = Persons per TX*Taxi unit trip supply
Units: trip*person/day
:GROUP .supply
Total number of trips person per day provided by taxis

(303) Taxi unit demand = (TX trip demand+Umet PC trip demand)/Persons per TX
Units: (trip*taxi)/day
:GROUP .supply
Number of taxi trips demanded in the metropolitan area.

(304) Taxi unit trip supply = MAX(Taxi fleet*Utilization of taxi fleet,33400)
Units: trip*taxi/day
:GROUP .supply
Number of taxi trips made per day in the city.

(305) Taxi utilization gap fraction = Demanded taxi fleet utilization-Utilization of taxi fleet
Units: trip/day
:GROUP .supply
Difference between the actual utilization of the taxi fleet and the demanded utilization by trnasport needs.

(309) Time to adjust PC fleet utilization = 36
Units: Month
:GROUP .supply
Average time for the population to change its utilization of private cars measured in months.

(311) Time to adjust rail capacity = 60
Units: Month
:GROUP .supply
Average time to effect the design, construction and operation of new capacity in the city's rail system.

(312) Time to adjust taxi purchases = 66
Units: Month
:GROUP .supply
Average time to correct shortfalls in the taxi fleet.

(314) Time to adjust utiliz of taxis = 12
Units: Month
:GROUP .supply
Average time for the population to change its utilization of taxis measured in months.

(316) Time to change PubV utilization = 12
Units: Month
:GROUP .supply
Average time for the population to change its utilization of private vehicles measured in months.

(317) Time to change rail utilization = 24
Units: Month
:GROUP .supply
Average time for the population to change its utilization of rail measured in months.

(327) Total PC fleet = PC cars 0 to 6+PC cars old+Regulation fleet
Units: car
:GROUP .supply
Total number of private cars in the metropolitan area.

(332) Total transport surplus or deficit = Total trip supply-Total transport demand
Units: trip*person/day
:GROUP .supply
Total transport supply by all modes minus total transport demand for the citymesured in trips person per day

(333) Total trip supply = PC trip supply+PubV trip supply+Rail unit supply+Taxi trip supply
Units: trip*person/day
:GROUP .supply
Total number of trips person per day satisfied by all modes of transport

(341) TX scrap fraction = 0.003
Units: 1/Month
:GROUP .supply
Observed percentage of taxi fleet retired monthly. Corresponds with 3.6% annual scrappage.

(342) TX scrappage = Taxi fleet*TX scrap fraction
Units: taxi/Month
:GROUP .supply
Number of taxis retired from the taxi fleet per month.

(347) TX trip demand = Total transport demand*TX mkt share
Units: trip*person/day
:GROUP .supply
Number of trips-person per day demanded from taxis.

(351) Umet PC trip demand = Unmet PC unit demand*Persons per PC
Units: trip*person/day
:GROUP .supply
Number of person trips per day that were demanded from private cars but were not met because of under utilization of shortfall of the fleet.

(357) Unmet PC unit demand = IF THEN ELSE(Symmetric cascade switch=0,PC unit trip demand-PC unit trip supply,MAX(0,PC unit trip demand-PC unit trip supply
))
Units: trip*car/day
:GROUP .supply
Number of private car trips per day that were demanded but could not be provided by current private car fleet.

(359) Unmet PubV trip demand = Average persons per PubV*Unmet PubV unit demand
Units: trip*person/day
:GROUP .supply
Number of person trips per day that were demanded from public vehicles but were not met because of under utilization of shortfall of the fleet.

(360) Unmet PubV unit demand = IF THEN ELSE(Symmetric cascade switch=0,PubV unit demand-PubV unit supply,MAX(0,PubV unit demand-PubV unit supply))
Units: trip*pubv/day
:GROUP .supply
Number of puclic vehicle trips per day that were demanded from public vehicles but were not met because of under utilization of shortfall of the fleet.

(361) Unmet taxi trip demand = Unmet taxi unit demand*Persons per TX
Units: trip*person/day
:GROUP .supply
Number of public vehicle trips per day that were demanded but could not be provided by current public vehicle fleet.

(362) Unmet taxi unit demand = IF THEN ELSE(Symmetric cascade switch=0,Taxi unit demand-Taxi unit trip supply,MAX(Taxi unit demand-Taxi unit trip supply
,0))
Units: trip*taxi/day
:GROUP .supply
Number of person trips per day that were demanded from taxis but were not met because of under utilization of shortfall of the taxi fleet.

(363) Utilization of rail = INTEG(Change in rail utilization,Target rail utilization)
Units: Dimensionless
:GROUP .supply
Percentage of maximum hour rail capacity used at peak traffic.

(364) Utilization of taxi fleet = INTEG(Change in taxi fleet utlization
,Target taxi fleet utiliztation)
Units: trip/day
:GROUP .supply
Aveage number of trips per day made by taxis.

(377) Willingness to build and use rail capacity = 0
Units: Dimensionless
:GROUP .supply
Fraction of the rail capacity deficit for which construction is actually planned due to political, economic and technical limitations.

****
.fleets
****

(001) Aging convertors = Aging new cars*New cars with convertor
Units: convertor/Month
:GROUP .fleets
Number of catalytic convertors per month which having reached the age of six are not retired from circulation.

(002) Aging new cars = (1-Scrap fraction 0 to 6)*Out of 0 to 6
Units: car/Month
:GROUP .fleets
Number of private cars per month which having reached the age of six are not retired from circulation.

(003) Average car life = 360
Units: Month
:GROUP .fleets
Average life of a private car measured in months.

(021) Bus fleet = INTEG(Bus purchases-Bus scrappage,53396)
Units: pubv
:GROUP .fleets

(022) Bus fleet gap = Target bus fleet-Bus fleet
Units: pubv
:GROUP .fleets

(026) Bus purchases = MAX(Bus fleet gap/Time to adjust PubV fleet+Bus scrappage,0)
Units: pubv/Month
:GROUP .fleets

(027) Bus scrappage = Bus fleet*PV scrap fraction
Units: pubv/Month
:GROUP .fleets

(028) Bus trip demand = Total PubV trip demand*Bus trip percentage+Unmet microbus demand
Units: trip*person/day
:GROUP .fleets
Number of trips demanded per day from buses

(029) Bus trip percentage = 0.6783
Units: Dimensionless
:GROUP .fleets

(030) Bus trip supply = Bus fleet*Persons per bus*PubV fleet utilization
Units: trip*person/day
:GROUP .fleets

(031) Bus unit supply = Bus trip supply/Persons per bus
Units: trip*pubv/day
:GROUP .fleets

(034) Cars on order with convertor = Convertors on order/PC new cars on order
Units: convertor/car
:GROUP .fleets
Fraction of cars on order which have catalytic convertors installed. Under current regulation, all new cars must be equipped with such convertors, therefore this number is always equal to one.

(036) Cars with convertor = Convertor fleet/Total PC fleet
Units: convertor/car
:GROUP .fleets
Fraction of PC car fleet (not including regulation fleet) that is equiped with a catalytic convertor

(045) Convertor deliveries = New car deliveries*Cars on order with convertor
Units: convertor/Month
:GROUP .fleets
Number of catalytic convertors that are actually delivered per month.

(046) Convertor equilibrium switch = 0
Units: Dimensionless
:GROUP .fleets
Value of 1 means equilibrium

(047) Convertor fleet = Convertors 0 to 6+Convertors old
Units: convertor
:GROUP .fleets
Total number of catalytic convertors including old and new

(048) Convertor purchases = New car purchases*Convertors per car
Units: convertor/Month
:GROUP .fleets
Number of catalytic convertors purchased per month.

(049) Convertors 0 to 6 = INTEG(-Aging convertors+Convertor deliveries
-New convertor scrappage,IF THEN ELSE(Convertor equilibrium switch=0,436673,109736))
Units: convertor
:GROUP .fleets
Number of catalytic convertors which are between zero and six years old.

(050) Convertors old = INTEG(Aging convertors-Old convertor scrappage
,IF THEN ELSE(Convertor equilibrium switch=0,10000,421259))
Units: convertor
:GROUP .fleets
Number of catalytic convertors older than 6 years.

(051) Convertors on order = INTEG(-Convertor deliveries+Convertor purchases
,IF THEN ELSE(Convertor equilibrium switch=0,109168,27307.6))
Units: convertor
:GROUP .fleets
Number of catalytic convertors on order. Under current regulations all new cars must have catalytic convertors. This started in 1991

(052) Convertors per car = IF THEN ELSE(Convertor equilibrium switch=0,1,0.2513)
Units: convertor/car
:GROUP .fleets
Number of catalytic convertors per car. The primary use of this variable is to convert a count of cars to a count of convertors.

(094) Micro purchases = MAX(Microbus fleet gap/Time to adjust PubV fleet+Micro scrappage,0)
Units: pubv/Month
:GROUP .fleets

(095) Micro scrappage = Microbus fleet*PV scrap fraction

Units: pubv/Month
:GROUP .fleets

(096) Micro unit supply = Microbus trip supply/Persons per microbus
Units: trip*pubv/day
:GROUP .fleets
Number of microbus trips supplied per day

(099) Microbus fleet = INTEG(Micro purchases-Micro scrappage,36155)
Units: pubv
:GROUP .fleets

(100) Microbus fleet gap = Target Microbus fleet-Microbus fleet
Units: pubv
:GROUP .fleets

(104) Microbus trip demand = Total PubV trip demand*Microbus trip percentage+Unmet pesero demand
Units: trip*person/day
:GROUP .fleets

(105) Microbus trip percentage = 0.1837
Units: Dimensionless
:GROUP .fleets

(106) Microbus trip supply = Microbus fleet*Persons per microbus*PubV fleet utilization
Units: trip*person/day
:GROUP .fleets

(112) New car deliveries = PC new cars on order/Time to deliver cars
Units: car/Month
:GROUP .fleets
Number of private cars that are actually delivered per month.

(113) New car purchases = MAX(0,(Optimal PC car fleet gap/Time to order cars+Subsidized car retirement))
Units: car/Month
:GROUP .fleets
Number of private cars purchased per month.

(114) New car scrappage = Out of 0 to 6*Scrap fraction 0 to 6
Units: car/Month
:GROUP .fleets
Number of private cars which are retired from circulation monthly.

(115) New cars with convertor = Convertors 0 to 6/PC cars 0 to 6
Units: convertor/car
:GROUP .fleets
Fraction of cars between zero and six years old which have catalytic convertors installed.

(116) New convertor scrappage = New car scrappage*New cars with convertor
Units: convertor/Month
:GROUP .fleets
Number of catalytic convertors which are retired from circulation monthly.

(122) Old car discardment = PC cars old/Time to discard old cars+Subsidized car retirement
Units: car/Month
:GROUP .fleets
Number of private cars older than six years old that are retired from circulation per month. Because the distribution within this age cohort is assumed to be uniform the number of retiring cars is equal to one twentyfourth (given an average life of 30 years and a starting age of six) of the stock.

(123) Old cars with convertor = Convertors old/PC cars old
Units: convertor/car
:GROUP .fleets
Fraction of cars older than six years old which have catalytic convertors installed.

(124) Old convertor scrappage = Old car discardment*Old cars with convertor
Units: convertor/Month
:GROUP .fleets
Number of catalytic convertors older than six years old that are retired from circulation per month. Because the distribution within this age cohort is assumed to be uniform the number of retiring convertors is equal to one twentyfourth (given an average life of 30 years and a starting age of six) of the stock.

(125) Optimal PC car fleet gap = Real target PC car fleet-PC car fleet
Units: car
:GROUP .fleets
Difference between the calculated private car fleet at target utilization and current private car fleet.

(130) Out of 0 to 6 = PC cars 0 to 6/Time in 0 to 6
Units: car/Month
:GROUP .fleets
Number of private cars between zero and six years old that reach the age of six. Becuase the distribution is assumed to be uniform within this age cohort, the number of cars reaching age six is precisely one sixth.

(137) PC car fleet = PC cars 0 to 6+PC cars old
Units: car
:GROUP .fleets

(138) PC cars 0 to 6 = INTEG(-Aging new cars+New car deliveries-New car scrappage ,436673)
Units: car
:GROUP .fleets
Number of private cars which are between zero and six years old.

(139) PC cars old = INTEG(Aging new cars-Old car discardment ,1.67632e+006)
Units: car
:GROUP .fleets
Number of private cars which are older than six years.

(159) PC new cars on order = INTEG(-New car deliveries+New car purchases ,109168)
Units: car
:GROUP .fleets
Number of private cars on order.

(177) PC unit trip demand = PC trip demand/Persons per PC
Units: (trip*car)/day
:GROUP .fleets
Number of private car trips per day demanded in the metropolitan area.

(192) Pesero fleet = INTEG(Pesero purchases-Pesero scrappage,67890)
Units: pubv
:GROUP .fleets
Total number of peseros registered with the Mexican department of motor vehicles

(193) Pesero fleet gap = Target pesero fleet-Pesero fleet
Units: pubv
:GROUP .fleets
Difference between the calculated pesero fleet at target utilization and current pesero fleet.

(197) Pesero purchases = MAX(Pesero fleet gap/Time to adjust PubV fleet+Pesero scrappage,0)
Units: pubv/Month
:GROUP .fleets
Number of peseros bought per month in Mexico City

(198) Pesero scrappage = Pesero fleet*PV scrap fraction
Units: pubv/Month
:GROUP .fleets

(199) Pesero trip demand = Total PubV trip demand*Pesero trip percentage
Units: trip*person/day
:GROUP .fleets
Number of trips demanded per day from peseros

(200) Pesero trip percentage = 0.138
Units: Dimensionless
:GROUP .fleets
Percentage of public vehicle trips that are provided by peseros. Measured in percentage of person trips per day.

(201) Pesero trip supply = Pesero fleet*Persons per pesero*PubV fleet utilization
Units: trip*person/day
:GROUP .fleets

(202) Pesero unit supply = Pesero trip supply/Persons per pesero
Units: trip*pubv/day
:GROUP .fleets
Number of pesero trips supplied per day

(229) PV scrap fraction = 0.003
Units: 1/Month
:GROUP .fleets
Observed percentage of taxi fleet retired monthly. Corresponds with 3.6% annual scrappage.

(243) Real target PC car fleet = PC unit trip demand/Target PC fleet utilization
Units: car
:GROUP .fleets
Calculated private car fleet if current demand for private car trips was met with target utilization.

(244) Reg cars on order = INTEG(-Regulation car deliveries+Regulation car purchases ,31954.8)
Units: car
:GROUP .fleets
Number of private cars on order due to regulation.

(245) Regulation car deliveries = MAX(0,Reg cars on order/Time to deliver cars)
Units: car/Month
:GROUP .fleets
Number of cars due to regulation that are actually delivered per month.

(246) Regulation car discardment = Regulation fleet/Time to discard old cars
Units: car/Month
:GROUP .fleets
Number of regulation cars retired from circulation per month.

(247) Regulation car purchases = MAX(0,Regulation fleet gap/Time to order cars)
Units: car/Month
:GROUP .fleets
Number of cars purchased per month due to regulation effects.

(248) Regulation fleet = INTEG(Regulation car deliveries-Regulation car discardment ,511277)
Units: car
:GROUP .fleets
Number of cars in fleet due to regulation restricting car usage.

(249) Regulation fleet gap = Target regulation fleet-Regulation fleet
Units: car
:GROUP .fleets
Difference between the calculated private car fleet at target regulated utilization and current regulation private car fleet.

(250) Regulation switch = 0.8
Units: Dimensionless
:GROUP .fleets
Effective cars per car (no circula=0.8), considering a work week of 5 days.

(267) Scrap fraction 0 to 6 = 0.04
Units: Dimensionless
:GROUP .fleets
Fraction of cars between zero and six years old which are retired from circulation per month. Source: "Economics of automovile recycling", Zamudio, P., 1996.

(272) Subsidized car retirement = 0
Units: car/Month
:GROUP .fleets
Number of old cars to purchased every month by the government. Underlying assumption that for every car retired there must be a new car ordered as an incentive for old car owners to enter the program.

(276) Target bus fleet = Bus trip demand/Persons per bus/Target PubV utilization
Units: pubv
:GROUP .fleets
Calculated bus fleet if current demand for bus trips was met with target utilization.

(277) Target Microbus fleet = Microbus trip demand/Persons per microbus/Target PubV utilization
Units: pubv
:GROUP .fleets
Calculatedmicrobus fleet if current demand for microbus trips was met with target utilization.

(278) Target PC fleet utilization = 2.5
Units: trip/day
:GROUP .fleets
Long-run equilibrium level of average daily trips by private cars.

(279) Target pesero fleet = Pesero trip demand/Persons per pesero/Target PubV utilization
Units: pubv
:GROUP .fleets
Calculated pesero fleet if current demand for pesero trips was met with target utilization.

(283) Target regulated utilization = Target PC fleet utilization*Regulation switch
Units: trip/day
:GROUP .fleets
Long-run equilibrium level of average daily trips by private cars corrected by the effect of car usage restrictions.

(284) Target regulation fleet = Total demanded fleet-Real target PC car fleet
Units: car
:GROUP .fleets

Difference between the target fleet with and without regulation.

(307) Time in 0 to 6 = 72
Units: Month
:GROUP .fleets
Average time for cars to age between 0 and 6 years of age. (72 months)

(310) Time to adjust PubV fleet = 66
Units: Month
:GROUP .fleets
Average time to correct shortfalls in the public vehicle fleet.

(320) Time to deliver cars = 18
Units: Month
:GROUP .fleets

(321) Time to discard old cars = Average car life-Time in 0 to 6
Units: Month
:GROUP .fleets
Average time to retire a car which is older than six years. Twentyfour (given an average life of 30 years and a starting age of six) years, expressed in months.

(322) Time to order cars = 66
Units: Month
:GROUP .fleets
Average time to purchase the cars needed to close a gap between the desired car fleet and the actual one.

(323) Total demanded fleet = PC unit trip demand/Target regulated utilization
Units: car
:GROUP .fleets
Calculated private car fleet if current demand for private car trips was met with target regulated utilization.

(328) Total PubV trip demand = PubV trip demand+Unmet taxi trip demand
Units: trip*person/day
:GROUP .fleets
Number of person trips demanded daily from public vehicles in general

(356) Unmet microbus demand = Microbus trip demand-Microbus trip supply
Units: trip*person/day
:GROUP .fleets

(358) Unmet pesero demand = Pesero trip demand-Pesero trip supply
Units: trip*person/day
:GROUP .fleets

****

.emission

****

(012) Base Magna evap emissions per engine = 0.04468
Units: Ton/(year*engine)
:GROUP .emission
Estimation of the yearly evaporative emissions per engine using Magna gasoline.

(013) Base Magna NOx per km = 1.04
Units: g/Km
:GROUP .emission
Base Magna emissions of NOx per km

(019) Bus burn HC emission = Bus unit supply*Days per year*Diesel HC grams per Km*Surface Public transport Km per Trip/Grams per ton
Units: Ton/year
:GROUP .emission
Total HC combustion emissions from buses

(020) Bus evaporative HC emissions = Bus vehicles*Diesel HC evaporative emissions per car*Engine per pubv
Units: Ton/year
:GROUP .emission
Estimation of the yearly HC evaporative emissions from buses.

(024) Bus HC emissions = Bus burn HC emission+Bus evaporative HC emissions
Units: Ton/year
:GROUP .emission
Total yearly HC emissions from buses.

(025) Bus NOx Emissions =Bus unit supply*Diesel g NOx per Km*Surface Public transport Km per Trip*Days per year/Grams per ton
Units: Ton/year
:GROUP .emission
Total nitrogen oxides emissions by buses in Mexico City. Measured in tons per year.

(033) Carga HC emissions = 46159.2
Units: Ton/year
:GROUP .emission

Total yearly HC emissions from freight and cargo handling in Mexico City. Source Pro-Aire, 1995.

(061) Diesel g NOx per Km = 1.43
Units: g/Km
:GROUP .emission
Average emissions of public vehicles consuming Diesel per km traveled. Measured in grams of nitrogen oxide per km.

(062) Diesel HC evaporative emissions per car = 0.00219
Units: Ton/(year*engine)
:GROUP .emission
Estimation of the yearly evaporative emissions per engine using Diesel.

(063) Diesel HC grams per Km = 0.5
Units: g/Km
:GROUP .emission
Average emissions per kilometer from burning Diesel.

(075) HC Concentration per day = Total HC emissions/HC ppm per ton per year
Units: ppm
:GROUP .emission

(076) HC evap reduction for Magna = 0.244*Pemex Magna substitution fraction
Units: Dimensionless
:GROUP .emission
Reduction in evaporative emissions per year of Hydrocarbons from Magna gasoline resulting from substitution for new gasoline called "Pemex Magna"

(077) HC ppm per ton per year = 675215
Units: (Ton/year)/ppm
:GROUP .emission

(080) Industry NOx = 14151
Units: Ton/year
:GROUP .emission

(089) LP Gas Distribution HC emissions = 484158
Units: Ton/year
:GROUP .emission
Total yearly HC emissions from Liquid Petroleum Gas handling leaks.

(092) Magna NOx per km reduction equivalent = 0.042*Pemex Magna substitution fraction
Units: Dimensionless
:GROUP .emission
Reduction of NOx emissions per km resulting from the substitution of Magna Sin gasoline for a new gasoline "Pemex Magna"

(093) Magna Vs Premium Proportion = 1+ramp(-0.01/12,25,145)
Units: Dimensionless
:GROUP .emission
Share of the unleaded gasoline market that the Magna gasoline holds against the new Premium gasoline at any time.

(097) Microbus burn HC emissions =Days per year* Magna grams HC per Km*Micro unit supply*Surface Public transport Km per Trip /Grams per ton
Units: Ton/year
:GROUP .emission
Total HC combustion emissions from microbuses

(098) Microbus evaporative HC emissions = Qty adj Magna HC evap emissions per engine*Microbus vehicles*Engine per pubv
Units: Ton/year
:GROUP .emission
Estimation of the yearly HC evaporative emissions from micro-buses.

(102) Microbus HC emissions = Microbus burn HC emissions+Microbus evaporative HC emissions
Units: Ton/year
:GROUP .emission
Total yearly HC emissions from microbuses.

(103) Microbus NOx Emissions = Micro unit supply*Quality adjusted Magna g NOx per Km*Surface Public transport Km per Trip*Days per year/Grams per ton
Units: Ton/year
:GROUP .emission
Total nitrogen dioxide emissions by microbuses in Mexico City. Measured in tons per year.

(119) Nova HC evaporative emissions per engine = 0.141036
Units: Ton/(year*engine)
:GROUP .emission
Estimation of the yearly evaporative emissions per engine using Nova gasoline.

(120) NOx Concentration per day = Total NOx Emissions/NOx ppm per ton per year
Units: ppm
:GROUP .emission

(121) NOx ppm per ton per year = 641925
Units: (Ton/year)/ppm
:GROUP .emission

(128) Other HC emissions = 209255
Units: Ton/year
:GROUP .emission
Total yearly HC emissions from sources classified as "other". Source Pro-Aire, 1995.

(129) Other Transport NOx = 31434.3
Units: Ton/year
:GROUP .emission

(131) Ozone concetration ppm = Sum z by xi weighted
Units: ppm
:GROUP .emission

(134) PC average Km per Trip = 17.5
Units: Km/(trip*car)
:GROUP .emission
Average distance per trip for a private car

(140) PC cat burn HC emissions = PC cat burn Magna emissions+PC cat burn Premium emissions
Units: Ton/year
:GROUP .emission
Total combustion emissions from private cars equipped with catalytic convertors.

(141) PC cat burn Magna emissions =Days per year* Magna grams HC per Km*PC cat Trips Magna*PC average Km per Trip/Grams per ton
Units: Ton/year
:GROUP .emission
Total combustion emissions from private cars equipped with catalytic convertors burning Magna gasoline.

(142) PC cat burn Premium emissions = Days per year*PC cat Trips Premium*PC average Km per Trip*Premium grams HC per Km/Grams per ton
Units: Ton/year
:GROUP .emission
Total combustion emissions from private cars equipped with catalytic convertors burning Premium gasoline.

(143) PC cat evaporative HC emissions = Qty adj Magna HC evap emissions per engine*PC cat Magna vehicles*Engine per car+PC cat Premium Vehicles*Premium HC evap emissions per engine
*Engine per car
Units: Ton/year
:GROUP .emission
Estimation of the yearly HC evaporative emissions from cars equipped with catalytic convertors.

(144) PC cat HC Emissions = PC cat burn HC emissions+PC cat evaporative HC emissions
Units: Ton/year
:GROUP .emission
Total yearly HC emissions from cars equipped with catalytic convertors.

(145) PC cat Magna NOx Emissions = PC cat Trips Magna*PC average Km per Trip*Quality adjusted Magna g NOx per Km*Days per year/Grams per ton
Units: Ton/year
:GROUP .emission
Total nitrogen dioxide emissions from private cars equipped with catalytic convertors

(146) PC cat Magna vehicles = PC cat vehicles*Magna Vs Premium Proportion
Units: car
:GROUP .emission
Number of private cars which use Magna gasoline.

(147) PC cat NOx Emissions = PC cat Magna NOx Emissions+PC cat Premium NOx Emissions
Units: Ton/year
:GROUP .emission
Total NOx emissions for private cars with catalytic converter

(148) PC cat Premium NOx Emissions = PC cat Trips Premium*PC average Km per Trip*Premium g NOx per Km*Days per year/Grams per ton
Units: Ton/year
:GROUP .emission

(149) PC cat Premium Vehicles = PC cat vehicles*(1-Magna Vs Premium Proportion)
Units: car
:GROUP .emission
Number of private cars which use Premium gasoline.

(150) PC cat Trips Magna = PC convertor trips per day*Magna Vs Premium Proportion
Units: trip*car/day
:GROUP .emission

(151) PC cat Trips Premium = PC convertor trips per day*(1-Magna Vs Premium Proportion)
Units: trip*car/day
:GROUP .emission

(152) PC cat vehicles = Convertor fleet/Convertors per car
Units: car
:GROUP .emission
Number of private cars equipped with catalytic convertors.

(160) PC no cat burn HC emissions = Nova grams HC per Km*PC average Km per Trip*PC no conv trips per day*Days per year/Grams per ton
Units: Ton/year
:GROUP .emission
Total HC combustion emissions from private cars not equipped with catalytic convertors.

(161) PC no cat evaporative HC emissions = Nova HC evaporative emissions per engine*PC no cat vehicles*Engine per car
Units: Ton/year
:GROUP .emission

(162) PC no cat HC emissions = PC no cat burn HC emissions+PC no cat evaporative HC emissions
Units: Ton/year
:GROUP .emission

(163) PC no cat NOx Emissions = PC average Km per Trip*PC no conv trips per day*PC Nova g NOx per Km*Days per year/Grams per ton
Units: Ton/year
:GROUP .emission
Total NOx emissions for private cars without catalytic converter

(164) PC no cat vehicles = Total PC fleet-PC cat vehicles
Units: car
:GROUP .emission
Number of private cars not equipped with catalytic convertors

(166) PC Nova g NOx per Km = 1.5
Units: g/Km
:GROUP .emission
Average emissions of vehicles consuming Nova gasoline per km traveled. Measured in grams of nitrogen oxide per km.

(190) Pesero burn HC emissions =Days per year* Nova grams HC per Km*Pesero unit supply*Surface Public transport Km per Trip/Grams per ton
Units: Ton/year
:GROUP .emission
Total HC combustion emissions from peseros

(191) Pesero evaporative HC emissions = Nova HC evaporative emissions per engine*Pesero vehicles*Engine per pubv
Units: Ton/year
:GROUP .emission
Estimation of the yearly HC evaporative emissions from peseros.

(195) Pesero HC emissions = Pesero burn HC emissions+Pesero evaporative HC emissions
Units: Ton/year
:GROUP .emission
Total yearly HC emissions from peseros.

(196) Pesero NOx Emissions = PC Nova g NOx per Km*Pesero unit supply*Surface Public transport Km per Trip*Days per year/Grams per ton
Units: Ton/year
:GROUP .emission
Total nitrogen oxides emissions by peseros in Mexico City. Measured in tons per year.

(207) Premium g NOx per Km = 0.62
Units: g/Km
:GROUP .emission
Average emissions of vehicles consuming Premium gasoline per km traveled. Measured in grams of nitrogen oxide per km.

(209) Premium HC evap emissions per engine = 0.01752
Units: Ton/(year*engine)
:GROUP .emission

Estimation of the yearly evaporative emissions per engine using Premium gasoline.

(231) Qty adj Magna HC evap emissions per engine = Base Magna evap emissions per engine*(1-HC evap reduction for Magna)
Units: Ton/(year*engine)
:GROUP .emission
Estimation of the yearly evaporative emissions per engine using Magna gasoline.

(232) Quality adjusted Magna g NOx per Km = Base Magna NOx per km*(1-Magna NOx per km reduction equivalent)
Units: g/Km
:GROUP .emission
Average emissions of vehicles consuming Magna gasoline per km traveled. Measured in grams of nitrogen oxide per km and considering potential quality improvements from substituting Magna for a new gasoline called "Pemex Magna"

(268) Services NOx = 5145.8
Units: Ton/year
:GROUP .emission

(269) Solvents HC emissions = 42056.1
Units: Ton/year
:GROUP .emission
Total yearly HC emissions from the use of solvents in Mexico City. Source Pro-Aire, 1995.

(273) Sum z by xi weighted = Z indexed by x in p 1*Weight of z by x in p 1+Z indexed by x in p 2*Weight of z by x in p 2+Z indexed by x in p 3*Weight of z by x in p 3
+Z indexed by x in p 4*Weight of z by x in p 4+Z indexed by x in p 5
*Weight of z by x in p 5+Z indexed by x in p 6*Weight of z by x in p 6+Z indexed by x in p 7*Weight of z by x in p 7+Z indexed by x in p 8*Weight of z by x in p 8
+Z indexed by x in p 9*Weight of z by x in p 9+Z indexed by x in p 10
*Weight of z by x in p 10+Z indexed by x in p 11*Weight of z by x in p 11
Units: ppm
:GROUP .emission
Weighted average of the interpolated values of ozone at the different P interval projections upon the xz plane.

(274) Surface Public transport Km per Trip = 25
Units: Km/(trip*pubv)
:GROUP .emission
Average distance per trip for a public vehicle

(289) Taxi burn HC emnissions =Days per year* Taxi Km per Trip*(Magna grams HC per Km*Taxi Trips Magna+Premium grams HC per Km*Taxi Trips Premium)/Grams per ton
Units: Ton/year
:GROUP .emission
Total HC combustion emissions from taxis

(290) Taxi evaporative HC emissions = Qty adj Magna HC evap emissions per engine*Taxi magna vehicles*Engine per taxi+Premium HC evap emissions per engine
*Taxi premium vehicles*Engine per taxi
Units: Ton/year
:GROUP .emission
Estimation of the yearly HC evaporative emissions from taxis.

(292) Taxi HC emissions = Taxi burn HC emnissions+Taxi evaporative HC emissions
Units: Ton/year
:GROUP .emission
Total yearly HC emissions from taxis.

(293) Taxi Km per Trip = 37.5
Units: Km/(trip*taxi)
:GROUP .emission
Average distance per trip for a taxi

(294) Taxi Magna NOx Emissions = Quality adjusted Magna g NOx per Km*Taxi Km per Trip*Taxi Trips Magna*Days per year/Grams per ton
Units: Ton/year
:GROUP .emission
Total nitrogen dioxide emissions from taxis mesured in tons per year

(295) Taxi magna vehicles = Magna Vs Premium Proportion*Taxi fleet
Units: taxi
:GROUP .emission

(296) Taxi NOx Emissions = Taxi Magna NOx Emissions+Taxi Premium NOx Emissions
Units: Ton/year
:GROUP .emission

(297) Taxi Premium NOx Emissions = Premium g NOx per Km*Taxi Km per Trip*Taxi Trips Premium*Days per year/Grams per ton
Units: Ton/year

:GROUP .emission
Total yearly emissions of nitrogen dioxide by taxis consuming Premium gasoline. Mesured in tons per year.

(298) Taxi premium vehicles =Taxi fleet*(1-Magna Vs Premium Proportion)
Units: taxi
:GROUP .emission

(301) Taxi Trips Magna = Taxi unit trip supply*Magna Vs Premium Proportion
Units: trip*taxi/day
:GROUP .emission
Number of trips-taxi/day that are supplied using Magna gasoline

(302) Taxi Trips Premium = Taxi unit trip supply*(1-Magna Vs Premium Proportion)
Units: trip*taxi/day
:GROUP .emission
Number of trips-taxi/day that are supplied using Premium gasoline

(306) Thermoelectrical Generation NOx = 18010.4
Units: Ton/year
:GROUP .emission
Total nitrogen dioxide emissions from thermo electrical generation in Mexico City measured in tons per year

(324) Total HC emissions = Carga HC emissions+LP Gas Distribution HC emissions+Other HC emissions+Solvents HC emissions+Transport HC emissions+Vegetation HC emissions
Units: Ton/year
:GROUP .emission
Total yearly emissions of HC in Mexico City including all sources.

(325) Total NOx Emissions = Industry NOx+Services NOx+Thermoelectrical Generation NOx+Transport NOx Emissions+Other Transport NOx
Units: Ton/year
:GROUP .emission
Total Tons of NOx Emissions per year

(334) Transport HC emissions = Bus HC emissions+Microbus HC emissions+PC cat HC Emissions+PC no cat HC emissions+Pesero HC emissions+Taxi HC emissions
Units: Ton/year
:GROUP .emission
Total yearly HC emissions from transport in Mexico City. Source Pro-Aire, 1995.

(335) Transport NOx Emissions = Bus NOx Emissions+Microbus NOx Emissions+PC cat NOx Emissions+PC no cat NOx Emissions+Pesero NOx Emissions+Taxi NOx Emissions
Units: Ton/year
:GROUP .emission
Total Passenger transport NOx emissions in Tons per year

(365) Vegetation HC emissions = 38978.9
Units: Ton/year
:GROUP .emission
Total yearly HC emissions coming from vegetation in Mexico City. Source Pro-Aire, 1995.

(366) Weight of z by x in p 1 = IF THEN ELSE(NOx Concentration per day>Y value p 0:AND:NOx Concentration per day<=Y value p 1,(NOx Concentration per day -Y value p 0)/(Y value p 1-Y value p 0),IF THEN ELSE(NOx Concentration per day >Y value p 1:AND:NOx Concentration per day<Y value p 2,(Y value p 2-NOx Concentration per day)/(Y value p 2-Y value p 1),0))
Units: Dimensionless
:GROUP .emission
Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(367) Weight of z by x in p 10 = IF THEN ELSE(NOx Concentration per day>Y value p 9:AND:NOx Concentration per day<=Y value p 10,(NOx Concentration per day -Y value p 9)/(Y value p 10-Y value p 9),IF THEN ELSE(NOx Concentration per day >Y value p 10:AND:NOx Concentration per day<Y value p 11,(Y value p 11-NOx Concentration per day)/(Y value p 11-Y value p 10),0))
Units: Dimensionless
:GROUP .emission
Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(368) Weight of z by x in p 11 = IF THEN ELSE(NOx Concentration per day>Y value p 10:AND:NOx Concentration per day<=Y value p 11,(NOx Concentration per day
-Y value p 10)/(Y value p 11-Y value p 10),IF THEN ELSE(NOx Concentration per day
>Y value p 11:AND:NOx Concentration per day<Y value p 12,(Y value p 12-NOx Concentration per day)/(Y value p 12-Y value p 11),0))
Units: Dimensionless
:GROUP .emission
Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(369) Weight of z by x in p 2 = IF THEN ELSE(NOx Concentration per day>Y value p 1:AND:NOx Concentration per day<=Y value p 2,(NOx Concentration per day
-Y value p 1)/(Y value p 2-Y value p 1),IF THEN ELSE(NOx Concentration per day
>Y value p 2:AND:NOx Concentration per day<Y value p 3,(Y value p 3-NOx Concentration per day)/(Y value p 3-Y value p 2),0))
Units: Dimensionless
:GROUP .emission
Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(370) Weight of z by x in p 3 = IF THEN ELSE(NOx Concentration per day>Y value p 2:AND:NOx Concentration per day<=Y value p 3,(NOx Concentration per day
-Y value p 2)/(Y value p 3-Y value p 2),IF THEN ELSE(NOx Concentration per day
>Y value p 3:AND:NOx Concentration per day<Y value p 4,(Y value p 4-NOx Concentration per day)/(Y value p 4-Y value p 3),0))
Units: Dimensionless
:GROUP .emission
Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(371) Weight of z by x in p 4 = IF THEN ELSE(NOx Concentration per day>Y value p 3:AND:NOx Concentration per day<=Y value p 4,(NOx Concentration per day
-Y value p 3)/(Y value p 4-Y value p 3),IF THEN ELSE(NOx Concentration per day
>Y value p 4:AND:NOx Concentration per day<Y value p 5,(Y value p 5-NOx Concentration per day)/(Y value p 5-Y value p 4),0))
Units: Dimensionless
:GROUP .emission
Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(372) Weight of z by x in p 5 = IF THEN ELSE(NOx Concentration per day>Y value p 4:AND:NOx Concentration per day<=Y value p 5,(NOx Concentration per day
-Y value p 4)/(Y value p 5-Y value p 4),IF THEN ELSE(NOx Concentration per day
>Y value p 5:AND:NOx Concentration per day<Y value p 6,(Y value p 6-NOx Concentration per day)/(Y value p 6-Y value p 5),0))
Units: Dimensionless
:GROUP .emission
Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(373) Weight of z by x in p 6 = IF THEN ELSE(NOx Concentration per day>Y value p 5:AND:NOx Concentration per day<=Y value p 6,(NOx Concentration per day
-Y value p 5)/(Y value p 6-Y value p 5),IF THEN ELSE(NOx Concentration per day
>Y value p 6:AND:NOx Concentration per day<Y value p 7,(Y value p 7-NOx Concentration per day)/(Y value p 7-Y value p 6),0))
Units: Dimensionless
:GROUP .emission
Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(374) Weight of z by x in p 7 = IF THEN ELSE(NOx Concentration per day>Y value p 6:AND:NOx Concentration per day<=Y value p 7,(NOx Concentration per day
-Y value p 6)/(Y value p 7-Y value p 6),IF THEN ELSE(NOx Concentration per day
>Y value p 7:AND:NOx Concentration per day<Y value p 8,(Y value p 8-NOx Concentration per day)/(Y value p 8-Y value p 7),0))
Units: Dimensionless
:GROUP .emission

Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(375) Weight of z by x in p 8 = IF THEN ELSE(NOx Concentration per day>Y value p 7:AND:NOx Concentration per day<=Y value p 8,(NOx Concentration per day -Y value p 7)/(Y value p 8-Y value p 7),IF THEN ELSE(NOx Concentration per day >Y value p 8:AND:NOx Concentration per day<Y value p 9,(Y value p 9-NOx Concentration per day)/(Y value p 9-Y value p 8),0))
Units: Dimensionless
:GROUP .emission
Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(376) Weight of z by x in p 9 = IF THEN ELSE(NOx Concentration per day>Y value p 8:AND:NOx Concentration per day<=Y value p 9,(NOx Concentration per day -Y value p 8)/(Y value p 9-Y value p 8),IF THEN ELSE(NOx Concentration per day >Y value p 9:AND:NOx Concentration per day<Y value p 10,(Y value p 10-NOx Concentration per day)/(Y value p 10-Y value p 9),0))
Units: Dimensionless
:GROUP .emission
Specific weight associated with the projection of the ozone function on the zy plane at a given HC interval named Pi

(378) Y value p 0 = -10
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(379) Y value p 1 = 0
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(380) Y value p 10 = 0.3
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(381) Y value p 11 = 0.35
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(382) Y value p 12 = 100
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(383) Y value p 2 = 0.05
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(384) Y value p 3 = 0.1
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(385) Y value p 4 = 0.15
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(386) Y value p 5 = 0.17
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(387) Y value p 6 = 0.19
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(388) Y value p 7 = 0.21
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(389) Y value p 8 = 0.23
Units: ppm
:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(390) Y value p 9 = 0.25
Units: ppm

:GROUP .emission
Boundary value for NOx used in the bi-dimensional interpolation routine.

(402) Table function "z by x in p1" has argument with dimension
ppm
Z indexed by x in p 1 = z by x in p1(HC Concentration per day)
Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

(403) Table function "z by x in p10" has argument with dimension
ppm
Z indexed by x in p 10 = z by x in p10(HC Concentration per day)
Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

(404) Table function "z by x in p11" has argument with dimension
ppm
Z indexed by x in p 11 = z by x in p11(HC Concentration per day)
Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

(405) Table function "z by x in p2" has argument with dimension
ppm
Z indexed by x in p 2 = z by x in p2(HC Concentration per day)
Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

(406) Table function "z by x in p3" has argument with dimension
ppm
Z indexed by x in p 3 = z by x in p3(HC Concentration per day)
Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

(407) Table function "z by x in p4" has argument with dimension
ppm
Z indexed by x in p 4 = z by x in p4(HC Concentration per day)
Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

(408) Table function "z by x in p5" has argument with dimension
ppm
Z indexed by x in p 5 = z by x in p5(HC Concentration per day)
Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

(409) Table function "z by x in p6" has argument with dimension
ppm
Z indexed by x in p 6 = z by x in p6(HC Concentration per day)
Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

(410) Table function "z by x in p7" has argument with dimension
ppm
Z indexed by x in p 7 = z by x in p7(HC Concentration per day)
Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

(411) Table function "z by x in p8" has argument with dimension
ppm
Z indexed by x in p 8 = z by x in p8(HC Concentration per day)
Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

(412) Table function "z by x in p9" has argument with dimension
ppm
Z indexed by x in p 9 = z by x in p9(HC Concentration per day)

Units: ppm
:GROUP .emission
Projection of ozone concentrations on the xz plane at given HC value named Pi

****
.other
****

(010) Base difference PC to PubV trip time = Base PubV trip time-Base PC trip time
Units: minute/trip
:GROUP .other
Out-of-vehicle average travel time in public vehicles. It is the difference between the base private car trip time and the base public vehicle time.

(011) Base difference PC to TX trip time = Base TX trip time-Base PC trip time
Units: minute/trip
:GROUP .other
Out-of-vehicle average travel time in taxi. It is the difference between the base private car trip time and the base taxi time.

(016) Base PC trip time = 30
Units: minute/trip
:GROUP .other
Average total time per trip in priate cars measured in minutes at 50% capacity congestion of road capacity. This is assumed to be twice the time at zero congestion.

(017) Base PubV trip time = 65
Units: minute/trip
:GROUP .other
Average total time per trip in public vehicles measured in minutes at 50% capacity congestion of road capacity. This is assumed to be twice the time at zero congestion.

(018) Base TX trip time = 20
Units: minute/trip
:GROUP .other
Average total time per trip in taxi measured in minutes at 50% capacity congestion of road capacity. This is assumed to be twice the time at zero congestion.

(023) Bus fleet percentage = 0.3392
Units: Dimensionless
:GROUP .other
Percentage of the public vehicle fleet represented by buses

(032) Bus vehicles = Bus fleet percentage*PubV fleet
Units: pubv
:GROUP .other

(035) Cars per taxi = 1
Units: car/taxi
:GROUP .other

(065) Engine per car = 1
Units: engine/car
:GROUP .other
Number of engines per car or vehicle used for surface transportation

(066) Engine per pubv = 1
Units: engine/pubv
:GROUP .other
Number of engines per pubv used for surface transportation

(067) Engine per taxi = 1
Units: engine/taxi
:GROUP .other
Number of engines per taxi used for surface transportation

(074) Grams per ton = 1e+006
Units: g/Ton
:GROUP .other

(090) Magna base HC grams per km = 0.82
Units: g/Km
:GROUP .other
Magna gasoline base emissions of HC per km

(091) Magna grams HC per Km = Quality adjusted Magna HC grams per km*speed multiplier
Units: g/Km
:GROUP .other
Average emissions per kilometer from burning Magna gasoline.

(101) Microbus fleet percentage = 0.2296
Units: Dimensionless
:GROUP .other

(107) Microbus vehicles = Microbus fleet percentage*PubV fleet
Units: pubv
:GROUP .other
Number of Microbuses in Mexico City

(109) Minutes per hour = 60
Units: minute/hour
:GROUP .other

(117) Nova basic HC grams per km = 2.95
Units: g/Km
:GROUP .other
Nova emissions of hydrocarbons per km

(118) Nova grams HC per Km = Quality adjusted Nova HC grams per km*speed multiplier
Units: g/Km
:GROUP .other
Average emissions per kilometer from burning Nova gasoline.

(136) PC average speed = Minutes per hour*PC average Km per Trip/PC average net trip time
Units: Km/(hour*car)
:GROUP .other
Average trip distance divided by the expected trip time for private cars.

(153) PC convertor trips per day = PC unit trip supply*Cars with convertor/Convertors per car
Units: trip*car/day
:GROUP .other

(154) PC equivalent units = Pubv PC equivalence factor*PubV unit supply
Units: trip*car/day
:GROUP .other
Number of public vehicles circulating per day translated into private car equivalents for traffic estimation purposes.

(165) PC no conv trips per day = PC unit trip supply-PC convertor trips per day
Units: trip*car/day
:GROUP .other

(174) PC trip time = Lookup road utilization to PC trip time(Road utilization factor)*Base PC trip time
Units: minute/trip
:GROUP .other
Estimated average trip time measured in minutes in private car for the average trip.

(179) Peak hour PC equivalents = Peak traffic factor*Total PC equivalents per day
Units: trip*car/hour
:GROUP .other
Number of vehicles equivalent to private cars circulating at the peak hour of the day.

(180) Peak traffic factor = 0.08
Units: day/hour
:GROUP .other
Fraction of trips taken at the peak traffic hour of the day. Source: Survey of travel origin and destination 1994. (Unit analysis = trip*car/hr / trip*car/day = day/hr

(181) Pemex Magna reduction equivalent for Magna = 0.03*Pemex Magna substitution fraction
Units: Dimensionless
:GROUP .other
Reduction in HC burning emissions in cars that change from using Magna gasoline to Pemex Premium.

(182) Pemex Magna reduction equivalent for Nova = 0.06*Pemex Magna substitution fraction
Units: Dimensionless
:GROUP .other
Reduction in HC burning emissions in cars that change from using Nova gasoline to Pemex Premium.

(183) Pemex Magna substitution fraction = 0
Units: Dimensionless
:GROUP .other
Switch controlling the introduction of a new gasoline called "Pemex Magna" with stricter environmental standards.

(194) Pesero fleet percentage = 1-Bus fleet percentage-Microbus fleet percentage
Units: Dimensionless
:GROUP .other

(203) Pesero vehicles = Pesero fleet percentage*PubV fleet
Units: pubv
:GROUP .other
Number of peseros in Mexico City

(206) Premium base HC grams per km = 0.25
Units: g/Km
:GROUP .other

(208) Premium grams HC per Km = Premium base HC grams per km*speed multiplier
Units: g/Km
:GROUP .other

Average emissions per kilometer from burning Premium gasoline.

(219) Pubv PC equivalence factor = 2.5
Units: car/pubv
:GROUP .other
Traffic equivalent of public vehicles measured in private cars.

(224) PubV trip time = Lookup road utilization to PC trip time(Road utilization factor)*(Base PubV trip time-Base difference PC to PubV trip time
)+Base difference PC to PubV trip time
Units: minute/trip
:GROUP .other
Average total trip time in public vehicles measured in minutes. It is a function of the base time at 50% road capacity congestion and the traffic time multiplier. Includes out-of-vehicle travel time.

(233) Quality adjusted Magna HC grams per km = Magna base HC grams per km*(1-Pemex Magna reduction equivalent for Magna)
Units: g/Km
:GROUP .other
Magna emissions of hydrocarbons per km, taking into account the potential reductions from improving gasoline quality. Quality improvements require the substitution of Magna for an improved "Pemex Magna" gasoline.

(234) Quality adjusted Nova HC grams per km = Nova basic HC grams per km*(1-Pemex Magna reduction equivalent for Nova)
Units: g/Km
:GROUP .other
Nova emissions of hydrocarbons per km, taking into account the potential reductions from improving gasoline quality. Quality improvements require the substitution of Nova for an improved "Pemex Magna" gasoline.

(241) Random multiplier switch = 1
Units: Dimensionless
:GROUP .other
On/off switch to include the randomness effect of traffic on travel time in the simulation.

(242) Random trip time multiplier = Lookup road utilization to random time component(Road utilization factor)*Random multiplier switch
Units: Dimensionless
:GROUP .other
Random effect on travel times by car due to traffic.

(251) Road capacity = 1.51594e+006
Units: trip*car/hour
:GROUP .other
Estimation of the city's road capacity measured in vehicle throughput per hour. Vehicle refers to private cars (or equivalents)

(254) Road utilization factor = Peak hour PC equivalents/Road capacity
Units: Dimensionless
:GROUP .other
Percentage of the road capacity utilized at the peak traffic hour of the day.

(270) Table function "Lookup average speed to HC emissions multiplier" has argument with dimension
Km/(hour*car)
speed multiplier = MAX(Lookup average speed to HC emissions multiplier(PC average speed)*Speed pollution switch,1)
Units: Dimensionless
:GROUP .other
Factor of amplifications for hydrocarbon emissions per km for Nova, Magna and Premium gasolines. It is defined as the ratio of emissions at given speed and emissions at a benchmark speed of 36 km per hour.

(271) Speed pollution switch = 0
Units: Dimensionless
:GROUP .other
Switch controlling the effect of reduced speeds on hydrocarbon emissions per km traveled. A value of 0 means this effect is not included in the model.

(275) Symmetric cascade switch = 0
Units: Dimensionless
:GROUP .other
Switch to control the unmet demand from one mode to flow to the next mode and back or only to flow to the next mode but be zero if negative. When value is zero cascade is symmetrical.

(326) Total PC equivalents per day = PC equivalent units+PC unit trip supply+Taxi unit trip supply*Cars per taxi
Units: trip*car/day
:GROUP .other

Total taxis and public vehicles circulating every day in the city expressed in private car equivalents for traffic estimation purposes.

(329) Total street unit trips = PC unit trip supply*Engine per car+PubV unit supply*Engine per pubv+Taxi unit trip supply*Engine per taxi
Units: trip*engine/day
:GROUP .other
Addition of daily trips made by private cars, taxis and public vehicles.

(348) TX trip time = Lookup road utilization to PC trip time(Road utilization factor)*(Base TX trip time-Base difference PC to TX trip time)+Base difference PC to TX trip time
Units: minute/trip
:GROUP .other
Average total trip time in taxis measured in minutes. It is a function of the base time at 50% road capacity congestion and the traffic time multiplier. Includes out-of-vehicle travel time.

****
.apdm
****

(069) FINAL TIME = 300
Units: Month
:GROUP .apdm
The final time for the simulation.

(081) INITIAL TIME = 0
Units: Month
:GROUP .apdm
The initial time for the simulation.

(082) Lookup average speed to HC emissions multiplier ([(0,0)-(200,4)],
(0,4),(5,4),(10,2.5),(20,1.2),(30,1),(90,1),(100,4))
Units: Dimensionless
:GROUP .apdm

(083) Lookup month to GDP change ([(0,-0.8)-(400,0.8)],(0,0.15)
,(12,0.15),(13,-0.625),(24,-0.625),(25,0.15),(48,0.15),(49,0.208)
,(300,0.208))
Units: Dimensionless
:GROUP .apdm

(084) Lookup rail utilization to saturation factor ([(0,0)-(1,2)],
(0,1),(0.1,0.99),(0.2,0.96),(0.3,0.91),(0.4,0.84),(0.5,0.75)
,(0.6,0.64),(0.7,0.51),(0.8,0.36),(0.9,0.19),(1,0.01))
Units: Dimensionless
:GROUP .apdm

(085) Lookup road utilization to PC trip time ([(0,0)-(1,20)],
(0,0.5),(0.1,0.56),(0.2,0.63),(0.3,0.71),(0.4,0.83),(0.5,1),
(0.6,1.25),(0.7,1.67),(0.8,2.5),(0.9,5),(1,10))
Units: Dimensionless
:GROUP .apdm

(086) Lookup road utilization to random time component ([(0,0)-(1,0.8)],
(0,0.0131579),(0.0180412,0.0157895),(0.0335052,0.0184211),(0.0489691,0.0236842)
,(0.0592784,0.0421053),(0.064433,0.0657895),(0.0695876,0.101974)
,(0.0747423,0.155263),(0.0902062,0.473684),(0.0902062,0.539474)
,(0.0902062,0.586842),(0.0979381,0.626316),(0.108247,0.642105)
,(0.126289,0.654605),(0.139175,0.636842),(0.154639,0.608553)
,(0.190722,0.552632),(0.239691,0.473684),(0.275773,0.413158)
,(0.311856,0.368421),(0.347938,0.336842),(0.396907,0.307895)
,(0.448454,0.276316),(0.489691,0.255263),(0.53866,0.231579),
(0.582474,0.210526),(0.623711,0.192105),(0.675258,0.167763),
(0.713918,0.148026),(0.757732,0.128289),(0.814433,0.101974),
(0.868557,0.0789474),(0.935567,0.0559211),(1,0.0394737))
Units: Dimensionless
:GROUP .apdm

(087) Lookup time to population growth ([(0,0.1)-(400,0.2)],(0,0.125)
,(15.4639,0.127632),(26.8041,0.123026),(38.1443,0.126645),(58.7629,0.123684)
,(70.1031,0.126316),(78.3505,0.122368),(95.8763,0.125658),(109.278,0.122368)
,(122.68,0.127632),(136.082,0.125658),(146.392,0.122697),(158.763,0.125658)
,(168.041,0.123355),(183.505,0.126645),(189.691,0.124671),(197.938,0.124013)
,(197.938,0.126316),(214.433,0.124342),(214.433,0.126316),(221.649,0.124013)

,(231.959,0.125329),(235.052,0.124342),(253.6
08,0.126316),(258.763,0.123026)
,(269.072,0.126645),(274.227,0.126316),(282.4
74,0.126316),(289.691,0.124671)
,(293.814,0.124671),(300,0.125))
Units: 1/Month
:GROUP .apdm

(266) SAVEPER =
2
Units: Month
:GROUP .apdm
The frequency with which output is stored.

(308) TIME STEP = 0.25
Units: Month
:GROUP .apdm
The time step for the simulation.

(391) z by x in p1 ([(0,0)-(20,20)],(0,0),(5,0))
Units: ppm
:GROUP .apdm

(392) z by x in p10 ([(0,0)-
(6,0.4)],(0,0),(0.25,0.013),(0.5,0.024)
,(0.6,0.031),(0.7,0.038),(0.8,0.063),(0.9,0.074),(
1,0.087),(1.1,0.1)
,(1.2,0.123),(1.3,0.15),(1.4,0.175),(1.5,0.201),(1.
6,0.221),
(1.7,0.25),(1.8,0.277),(1.9,0.307),(2,0.328),(2.12
5,0.352),(2.25,0.362)
,(2.375,0.375),(2.5,0.379),(2.75,0.378),(3,0.371)
,(3.5,0.351)
,(4,0.345),(4.5,0.341),(5,0.337))
Units: ppm
:GROUP .apdm

(393) z by x in p11 ([(0,0)-
(6,0.6)],(0,0),(0.25,0.013),(0.5,0.022)
,(0.6,0.03),(0.7,0.03),(0.8,0.04),(0.9,0.058),(1,0.
068),(1.1,0.074)
,(1.2,0.092),(1.3,0.113),(1.4,0.137),(1.5,0.16),(1.
6,0.175),
(1.7,0.2),(1.8,0.225),(1.9,0.25),(2,0.275),(2.125,
0.312),(2.25,0.337)
,(2.375,0.37),(2.5,0.4),(2.75,0.408),(3,0.415),(3.
5,0.4),(4,0.381)
,(4.5,0.378),(5,0.37))
Units: ppm
:GROUP .apdm

(394) z by x in p2 ([(0,0)-
(6,0.2)],(0,0),(0.25,0.075),(0.5,0.148)
,(0.6,0.151),(0.7,0.151),(0.8,0.15),(0.9,0.148),(1,
0.144),(1.1,0.14)
,(1.2,0.133),(1.3,0.13),(1.4,0.129),(1.5,0.128),(1.
6,0.126),
(1.7,0.125),(1.8,0.123),(1.9,0.122),(2,0.121),(2.1
25,0.12),(2.25,0.119)
,(2.375,0.118),(2.5,0.117),(2.75,0.114),(3,0.112)
,(3.5,0.108)
,(4,0.103),(4.5,0.099),(5,0.094))
Units: ppm
:GROUP .apdm

(395) z by x in p3 ([(0,0)-
(6,0.4)],(0,0),(0.25,0.063),(0.5,0.125)
,(0.6,0.15),(0.7,0.157),(0.8,0.18),(0.9,0.198),(1,0
.209),(1.1,0.212)
,(1.2,0.213),(1.3,0.212),(1.4,0.208),(1.5,0.205),(
1.6,0.203)
,(1.7,0.2),(1.8,0.197),(1.9,0.196),(2,0.195),(2.12
5,0.193),(2.25,0.191)
,(2.375,0.189),(2.5,0.188),(2.75,0.184),(3,0.18),(
3.5,0.173)
,(4,0.165),(4.5,0.158),(5,0.15))
Units: ppm
:GROUP .apdm

(396) z by x in p4 ([(0,0)-
(6,0.4)],(0,0),(0.25,0.038),(0.5,0.075)
,(0.6,0.098),(0.7,0.125),(0.8,0.162),(0.9,0.202),(
1,0.225),(1.1,0.227)
,(1.2,0.238),(1.3,0.24),(1.4,0.252),(1.5,0.26),(1.6
,0.261),(1.7,0.261)
,(1.8,0.256),(1.9,0.252),(2,0.248),(2.125,0.246),(
2.25,0.244)
,(2.375,0.242),(2.5,0.24),(2.75,0.237),(3,0.233),(
3.5,0.225)
,(4,0.217),(4.5,0.21),(5,0.202))
Units: ppm
:GROUP .apdm

(397) z by x in p5 ([(0,0)-
(6,0.4)],(0,0),(0.25,0.033),(0.5,0.063)
,(0.6,0.077),(0.7,0.108),(0.8,0.15),(0.9,0.182),(1,
0.203),(1.1,0.217)
,(1.2,0.231),(1.3,0.244),(1.4,0.268),(1.5,0.278),(
1.6,0.28),
(1.7,0.279),(1.8,0.276),(1.9,0.273),(2,0.27),(2.12
5,0.268),(2.25,0.266)
,(2.375,0.264),(2.5,0.262),(2.75,0.258),(3,0.254)
,(3.5,0.246)
,(4,0.237),(4.5,0.229),(5,0.221))
Units: ppm
:GROUP .apdm

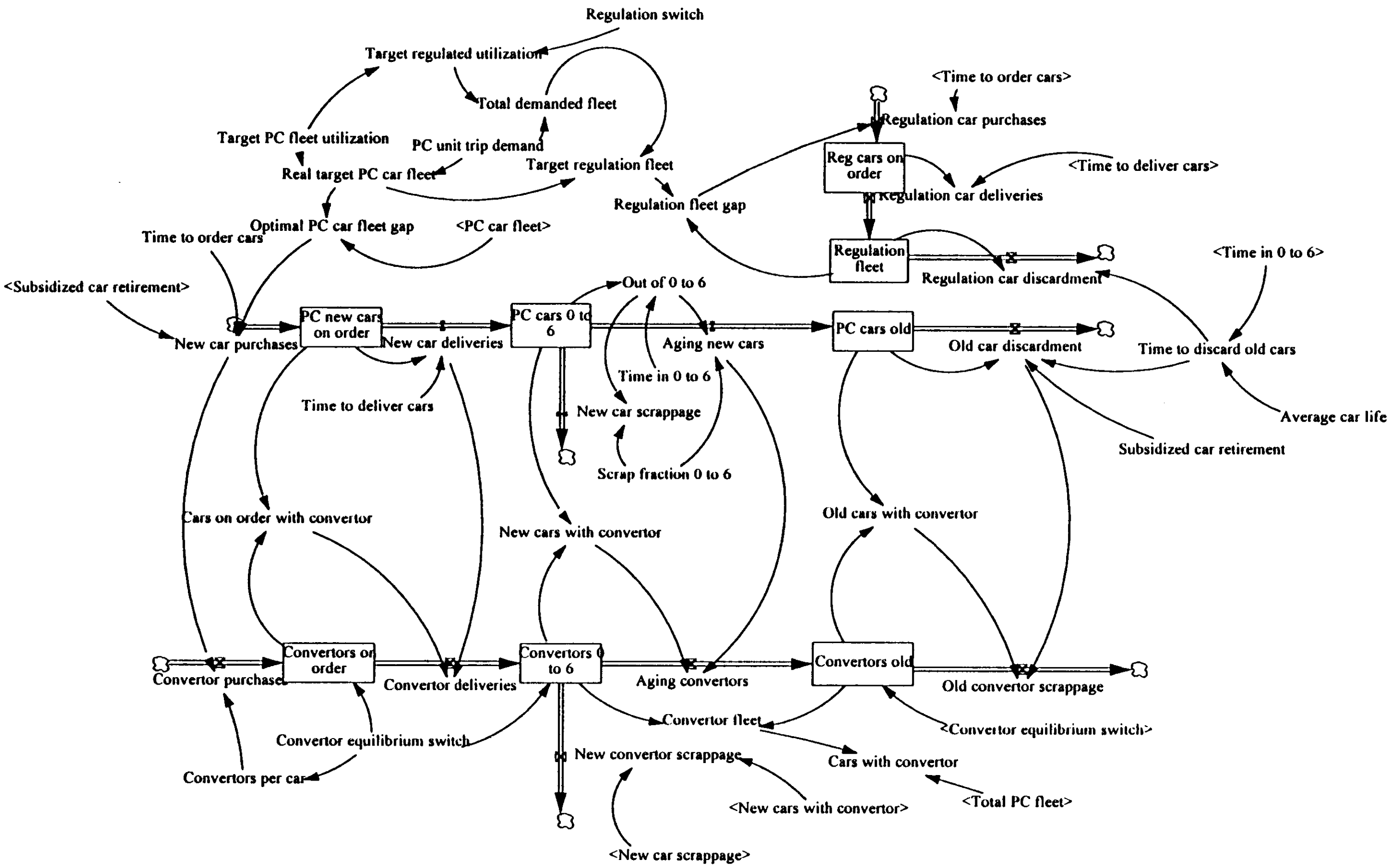
(398) z by x in p6 ([(0,0)-
(6,0.4)],(0,0),(0.25,0.027),(0.5,0.05),

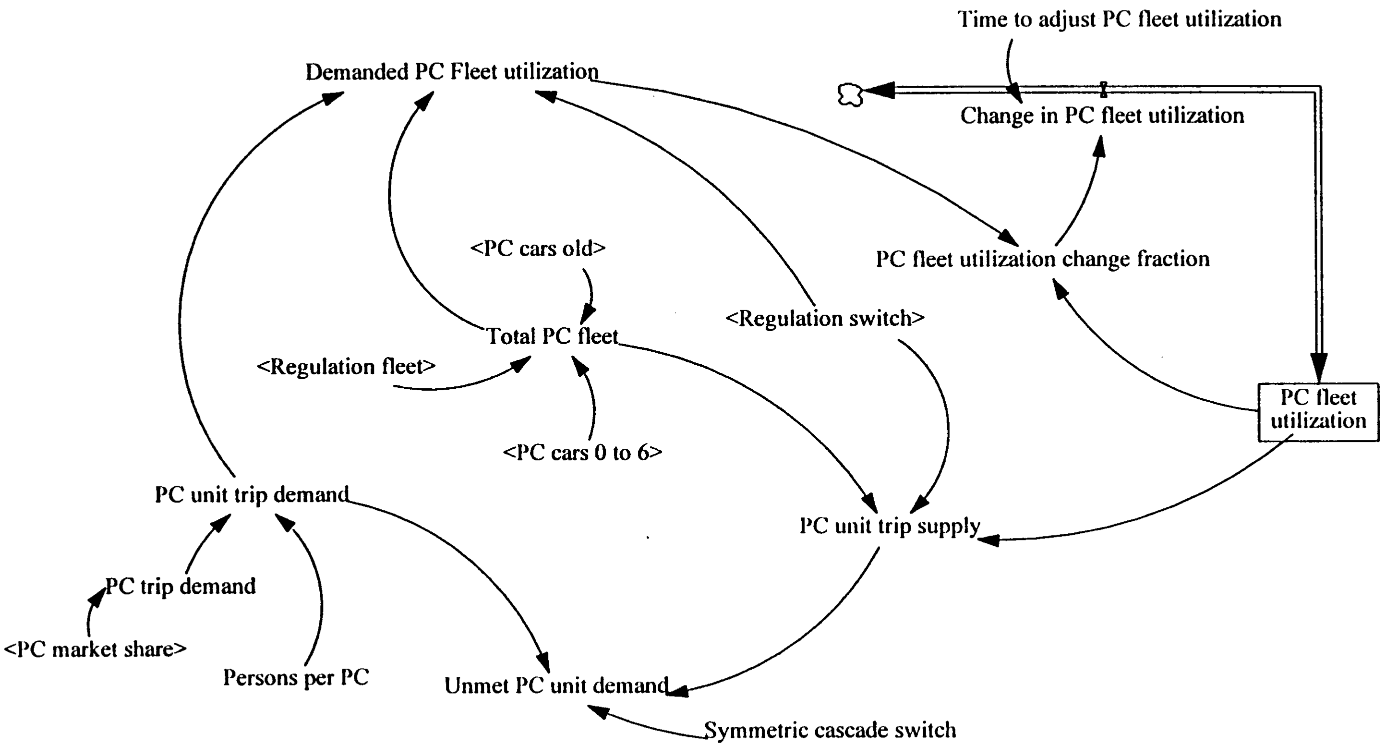
(0.6,0.071),(0.7,0.094),(0.8,0.133),(0.9,0.162),(1
,0.178),(1.1,0.2)
,(1.2,0.22),(1.3,0.247),(1.4,0.275),(1.5,0.28),(1.6
,0.284),(1.7,0.291)
,(1.8,0.292),(1.9,0.288),(2,0.286),(2.125,0.284),(
2.25,0.282)
,(2.375,0.28),(2.5,0.278),(2.75,0.275),(3,0.271),(
3.5,0.263)
,(4,0.255),(4.5,0.248),(5,0.24))
Units: ppm
:GROUP .apdm

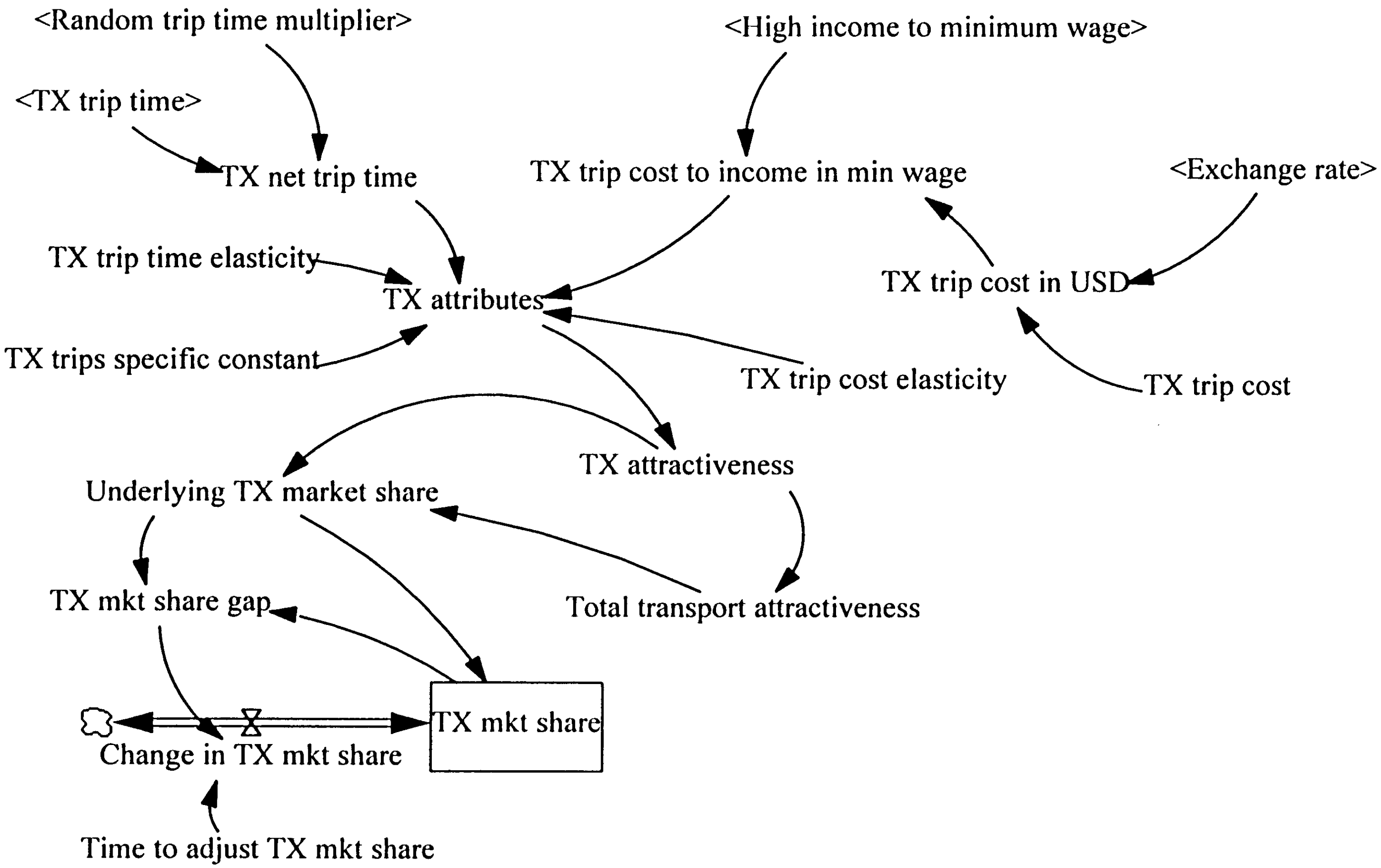
(399) z by x in p7 ([(0,0)-
(6,0.4)],(0,0),(0.25,0.023),(0.5,0.046)
,(0.6,0.06),(0.7,0.082),(0.8,0.116),(0.9,0.138),(1,
0.16),(1.1,0.18)
,(1.2,0.207),(1.3,0.234),(1.4,0.267),(1.5,0.283),(
1.6,0.3),(1.7,0.306)
,(1.8,0.307),(1.9,0.307),(2,0.306),(2.125,0.304),(
2.25,0.302)
,(2.375,0.3),(2.5,0.298),(2.75,0.294),(3,0.29),(3.
5,0.282),(4,0.274)
,(4.5,0.266),(5,0.258))
Units: ppm
:GROUP .apdm

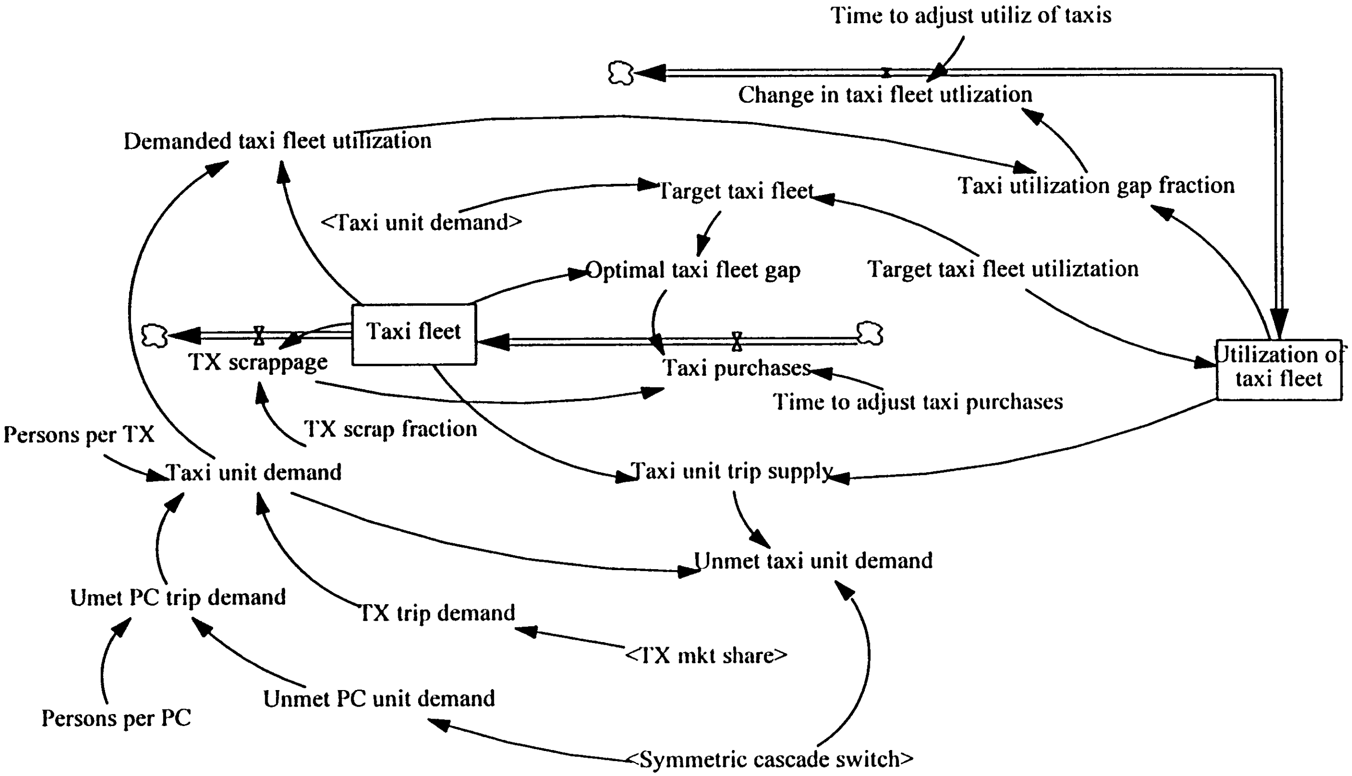
(400) z by x in p8 ([(0,0)-
(6,0.4)],(0,0),(0.25,0.019),(0.5,0.042)
,(0.6,0.05),(0.7,0.07),(0.8,0.1),(0.9,0.121),(1,0.1
3),(1.1,0.155)
,(1.2,0.187),(1.3,0.214),(1.4,0.25),(1.5,0.275),(1.
6,0.289),
(1.7,0.306),(1.8,0.318),(1.9,0.322),(2,0.326),(2.1
25,0.328),
(2.25,0.325),(2.375,0.323),(2.5,0.321),(2.75,0.31
6),(3,0.312)
,(3.5,0.304),(4,0.295),(4.5,0.287),(5,0.278))
Units: ppm
:GROUP .apdm

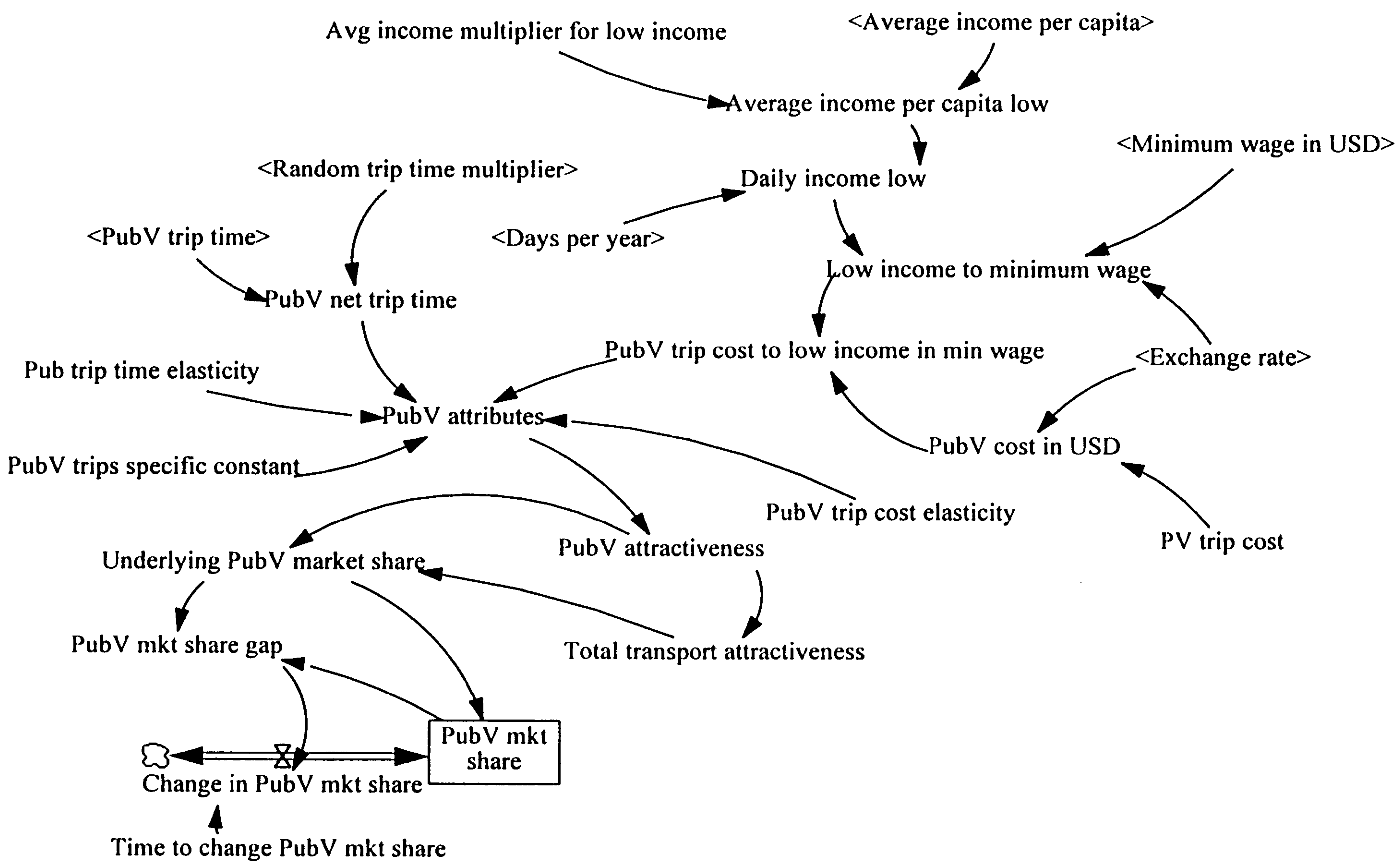
(401) z by x in p9 ([(0,0)-
(6,0.4)],(0,0),(0.25,0.015),(0.5,0.033)
,(0.6,0.044),(0.7,0.06),(0.8,0.088),(0.9,0.1),(1,0.
123),(1.1,0.14)
,(1.2,0.166),(1.3,0.192),(1.4,0.224),(1.5,0.252),(
1.6,0.273)
,(1.7,0.292),(1.8,0.318),(1.9,0.329),(2,0.337),(2.
125,0.336)
,(2.25,0.342),(2.375,0.34),(2.5,0.338),(2.75,0.33
4),(3,0.33)
,(3.5,0.322),(4,0.313),(4.5,0.305),(5,0.297))
Units: ppm GROUP .apdm

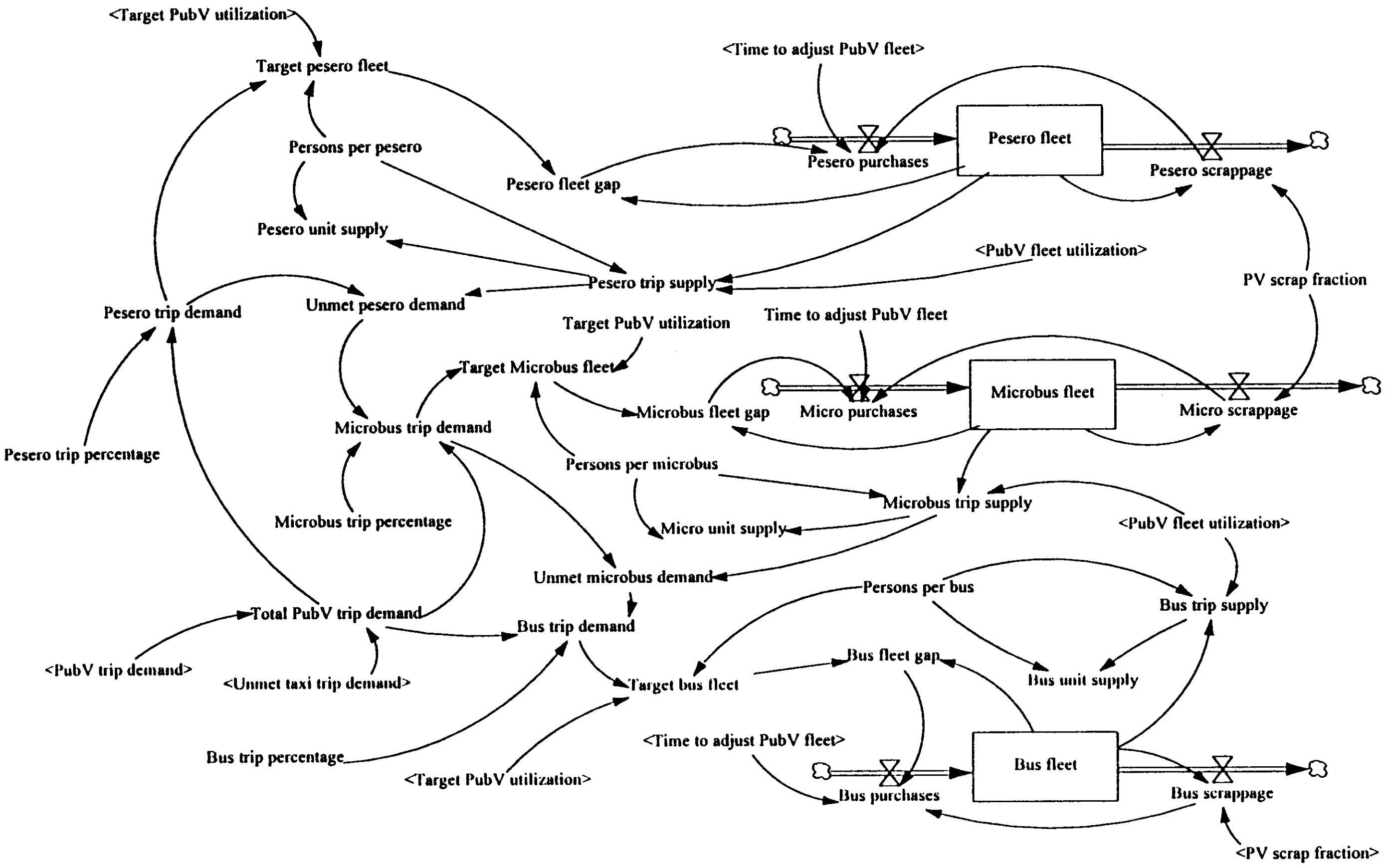

Regulation switch
Target regulated utilization
Total demanded fleet
Target PC fleet utilization
PC unit trip demand
Real target PC car fleet
Target regulation fleet
Regulation fleet gap
Optimal PC car fleet gap
<PC car fleet>
Time to order cars
<Subsidized car retirement>
<Time to order cars>
Regulation car purchases
Reg cars on order
Regulation car deliveries
<Time to deliver cars>
Regulation fleet
Regulation car discardment
<Time in 0 to 6>
New car purchases
PC new cars on order
New car deliveries
PC cars 0 to 6
Out of 0 to 6
Aging new cars
PC cars old
Old car discardment
Time to discard old cars
Time to deliver cars
Time in 0 to 6
New car scrappage
Scrap fraction 0 to 6
Average car life
Subsidized car retirement
Cars on order with convertor
New cars with convertor
Old cars with convertor
Convertor purchases
Convertors on order
Convertor deliveries
Convertors 0 to 6
Aging convertors
Convertors old
Old convertor scrappage
Convertor fleet
Convertor equilibrium switch
<Convertor equilibrium switch>
Convertors per car
New convertor scrappage
Cars with convertor
<New cars with convertor>
<Total PC fleet>
<New car scrappage>

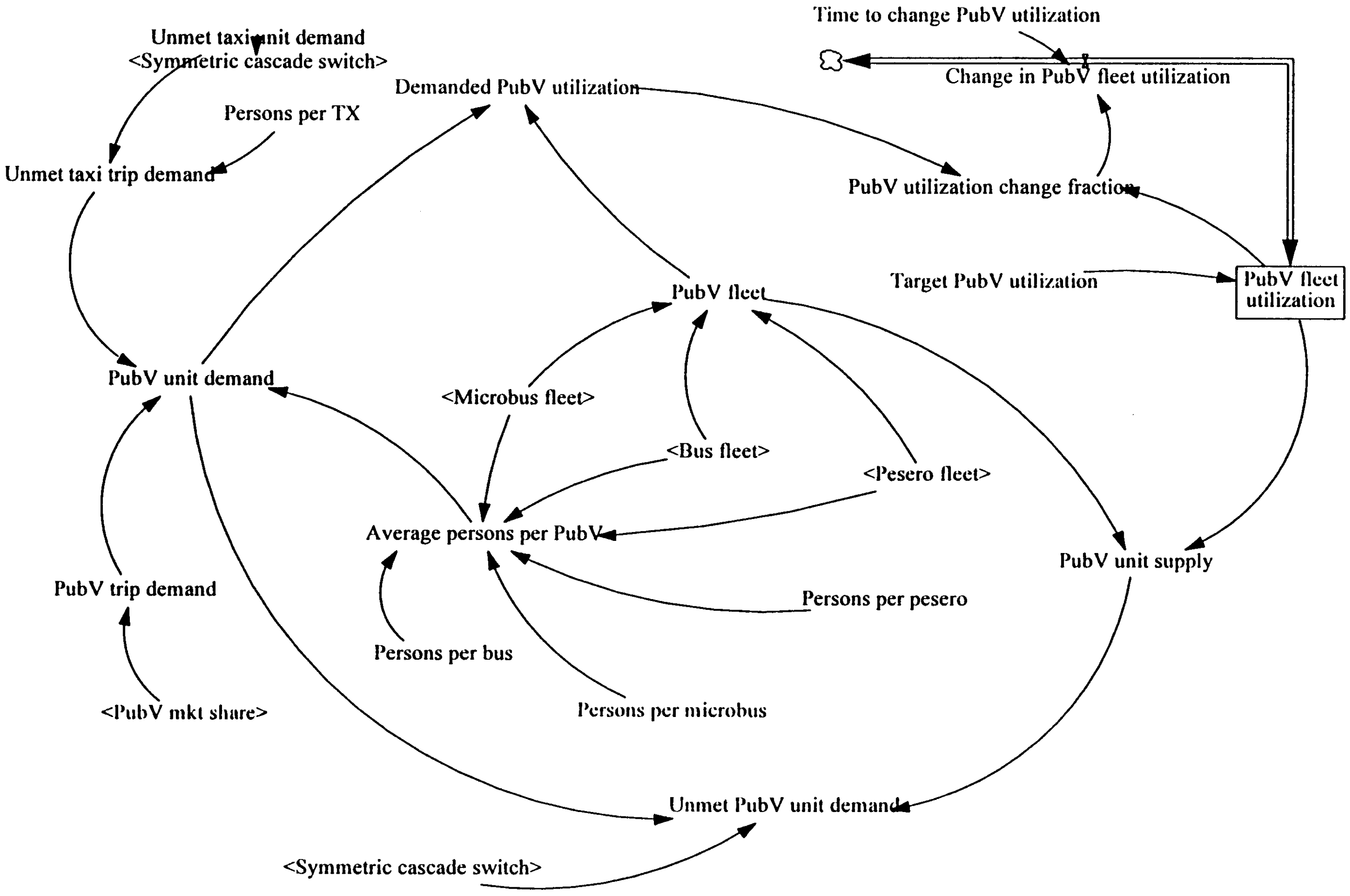

Time to adjust PC fleet utilization
Demanded PC Fleet utilization
Change in PC fleet utilization
PC fleet utilization change fraction
<PC cars old>
<Regulation switch>
Total PC fleet
<Regulation fleet>
PC fleet utilization
<PC cars 0 to 6>
PC unit trip demand
PC unit trip supply
PC trip demand
<PC market share>
Persons per PC
Unmet PC unit demand
Symmetric cascade switch

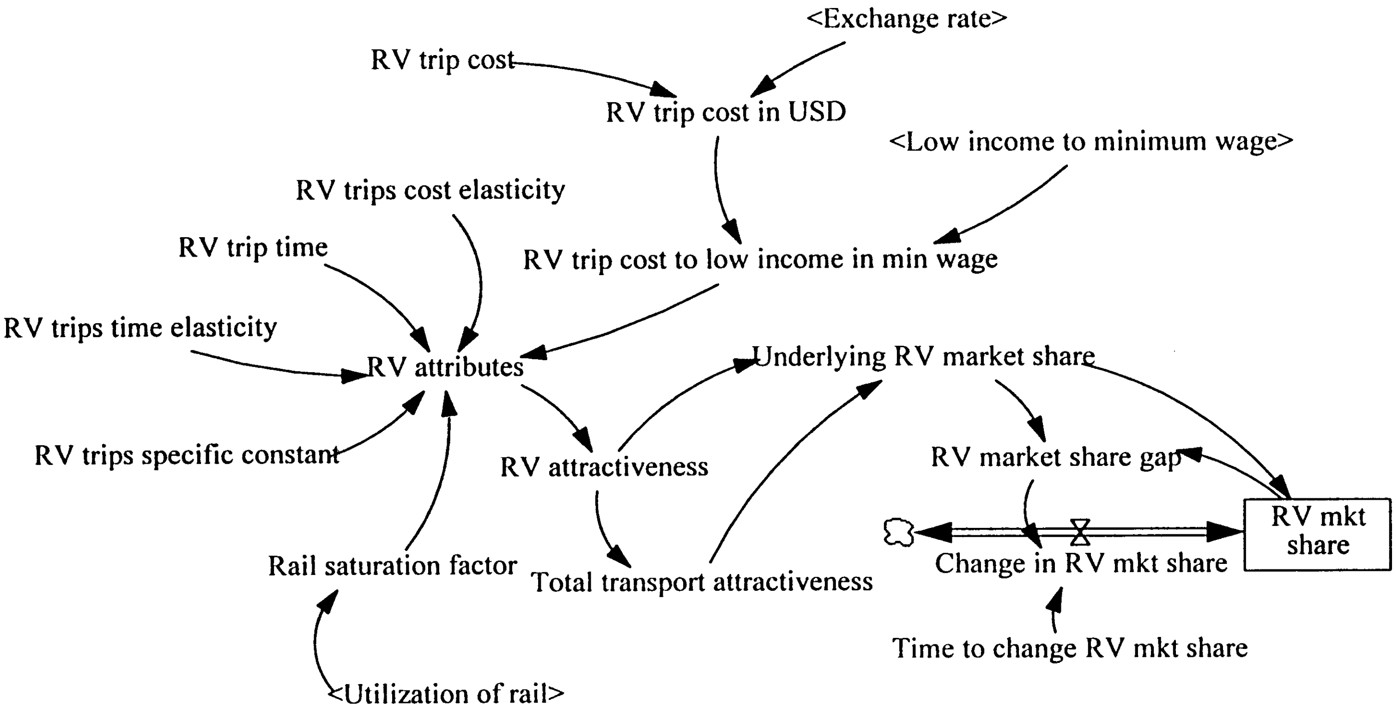

<Random trip time multiplier>
<High income to minimum wage>
<TX trip time>
TX net trip time
TX trip cost to income in min wage
<Exchange rate>
TX trip time elasticity
TX attributes
TX trip cost in USD
TX trips specific constant
TX trip cost elasticity
TX trip cost
TX attractiveness
Underlying TX market share
TX mkt share gap
Total transport attractiveness
TX mkt share
Change in TX mkt share
Time to adjust TX mkt share

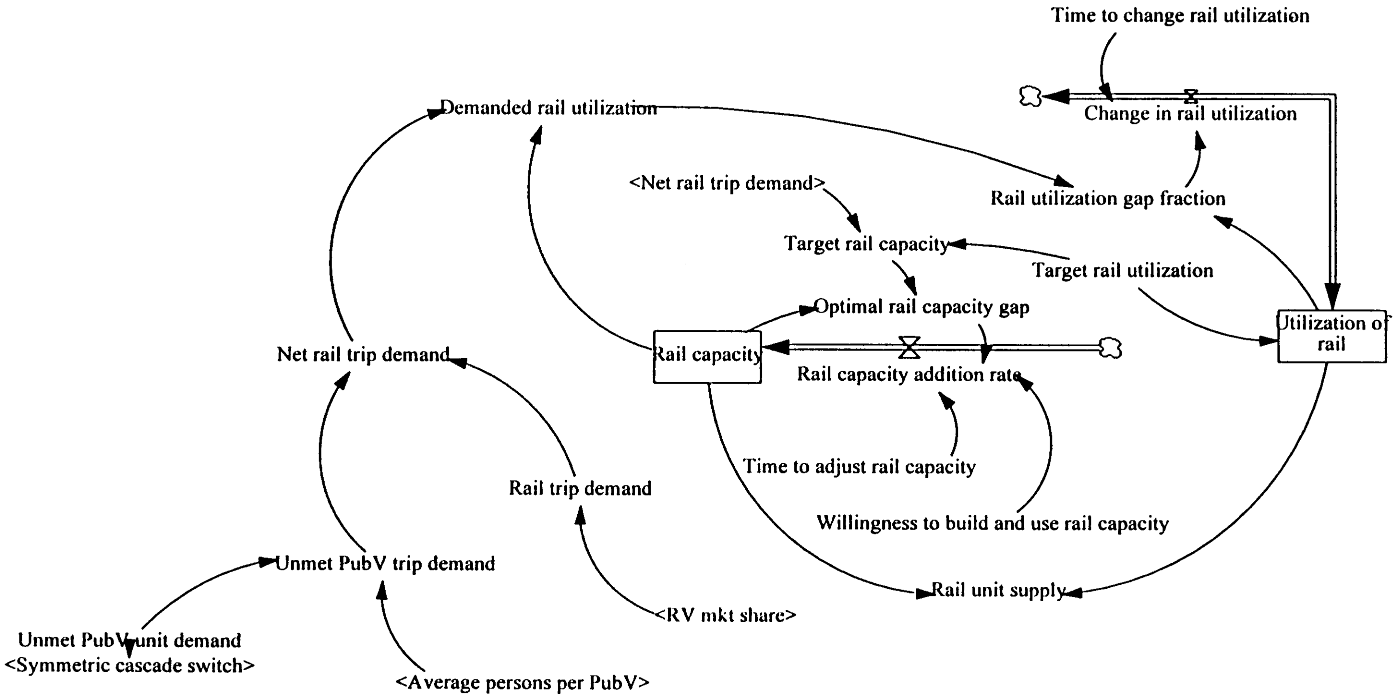

Time to adjust utiliz of taxis
Change in taxi fleet utlization
Demanded taxi fleet utilization
Taxi utilization gap fraction
<Taxi unit demand>
Target taxi fleet
Optimal taxi fleet gap
Target taxi fleet utiliztation
Taxi fleet
TX scrappage
Taxi purchases
Utilization of taxi fleet
Time to adjust taxi purchases
TX scrap fraction
Persons per TX
Taxi unit demand
Taxi unit trip supply
Unmet taxi unit demand
Umet PC trip demand
TX trip demand
<TX mkt share>
Unmet PC unit demand
Persons per PC
<Symmetric cascade switch>

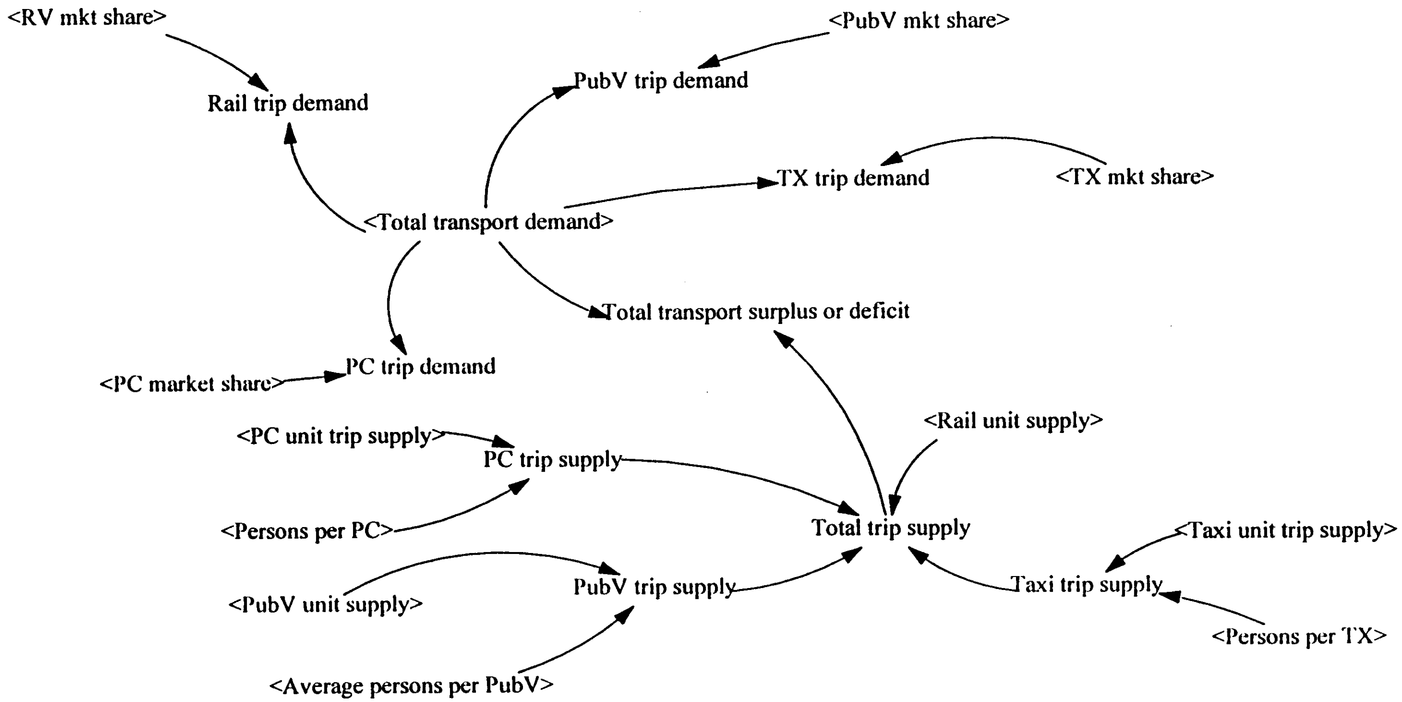

Avg income multiplier for low income
<Average income per capita>
Average income per capita low
<Minimum wage in USD>
<Random trip time multiplier>
Daily income low
<PubV trip time>
<Days per year>
Low income to minimum wage
PubV net trip time
PubV trip cost to low income in min wage
Pub trip time elasticity
<Exchange rate>
PubV attributes
PubV cost in USD
PubV trips specific constant
PubV trip cost elasticity
PV trip cost
Underlying PubV market share
PubV attractiveness
PubV mkt share gap
Total transport attractiveness
PubV mkt share
Change in PubV mkt share
Time to change PubV mkt share

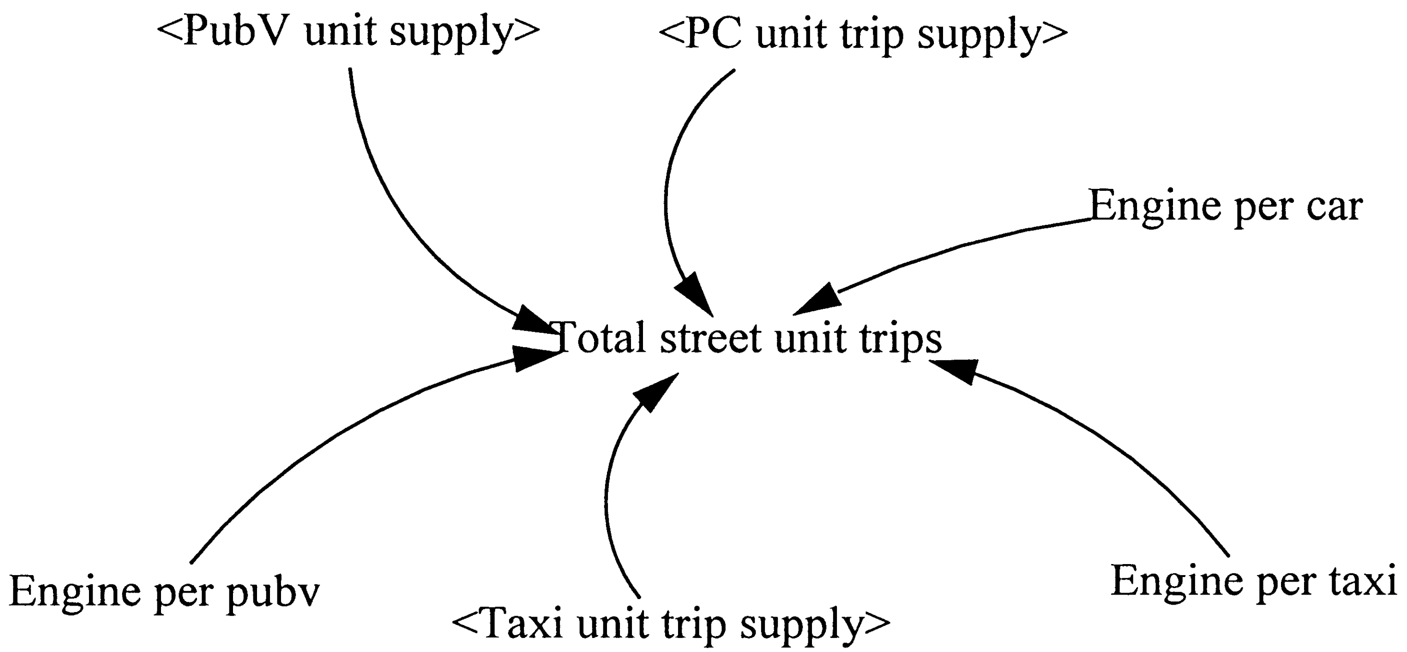

<Target PubV utilization>
Target pesero fleet
<Time to adjust PubV fleet>
Persons per pesero
Pesero fleet gap
Pesero purchases
Pesero fleet
Pesero scrappage
Pesero unit supply
<PubV fleet utilization>
Pesero trip supply
PV scrap fraction
Pesero trip demand
Unmet pesero demand
Target PubV utilization
Time to adjust PubV fleet
Target Microbus fleet
Microbus fleet gap
Micro purchases
Microbus fleet
Micro scrappage
Microbus trip demand
Pesero trip percentage
Persons per microbus
Microbus trip supply
Microbus trip percentage
Micro unit supply
<PubV fleet utilization>
Unmet microbus demand
Persons per bus
Bus trip supply
Total PubV trip demand
Bus trip demand
Bus fleet gap
Bus unit supply
<PubV trip demand>
<Unmet taxi trip demand>
Target bus fleet
<Time to adjust PubV fleet>
Bus fleet
Bus trip percentage
<Target PubV utilization>
Bus purchases
Bus scrappage
<PV scrap fraction>

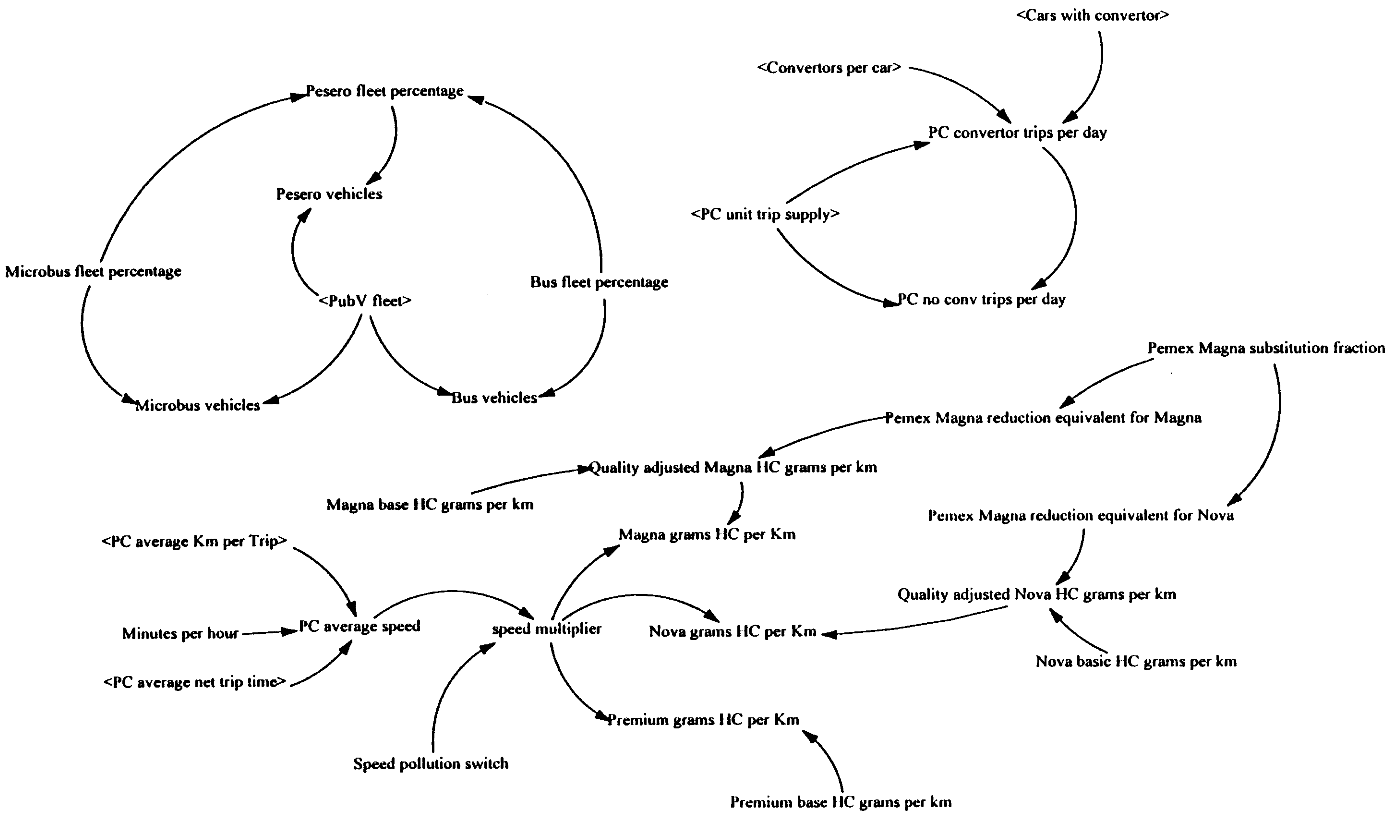

Time to change PubV utilization
Unmet taxi unit demand
<Symmetric cascade switch>
Change in PubV fleet utilization
Demanded PubV utilization
Persons per TX
Unmet taxi trip demand
PubV utilization change fraction
Target PubV utilization
PubV fleet utilization
PubV fleet
PubV unit demand
<Microbus fleet>
<Bus fleet>
<Pesero fleet>
Average persons per PubV
PubV unit supply
PubV trip demand
Persons per pesero
Persons per bus
<PubV mkt share>
Persons per microbus
Unmet PubV unit demand
<Symmetric cascade switch>


<Exchange rate>
RV trip cost
RV trip cost in USD
<Low income to minimum wage>
RV trips cost elasticity
RV trip time
RV trip cost to low income in min wage
RV trips time elasticity
RV attributes
Underlying RV market share
RV trips specific constant
RV attractiveness
RV market share gap
RV mkt share
Change in RV mkt share
Rail saturation factor
Total transport attractiveness
Time to change RV mkt share
<Utilization of rail>

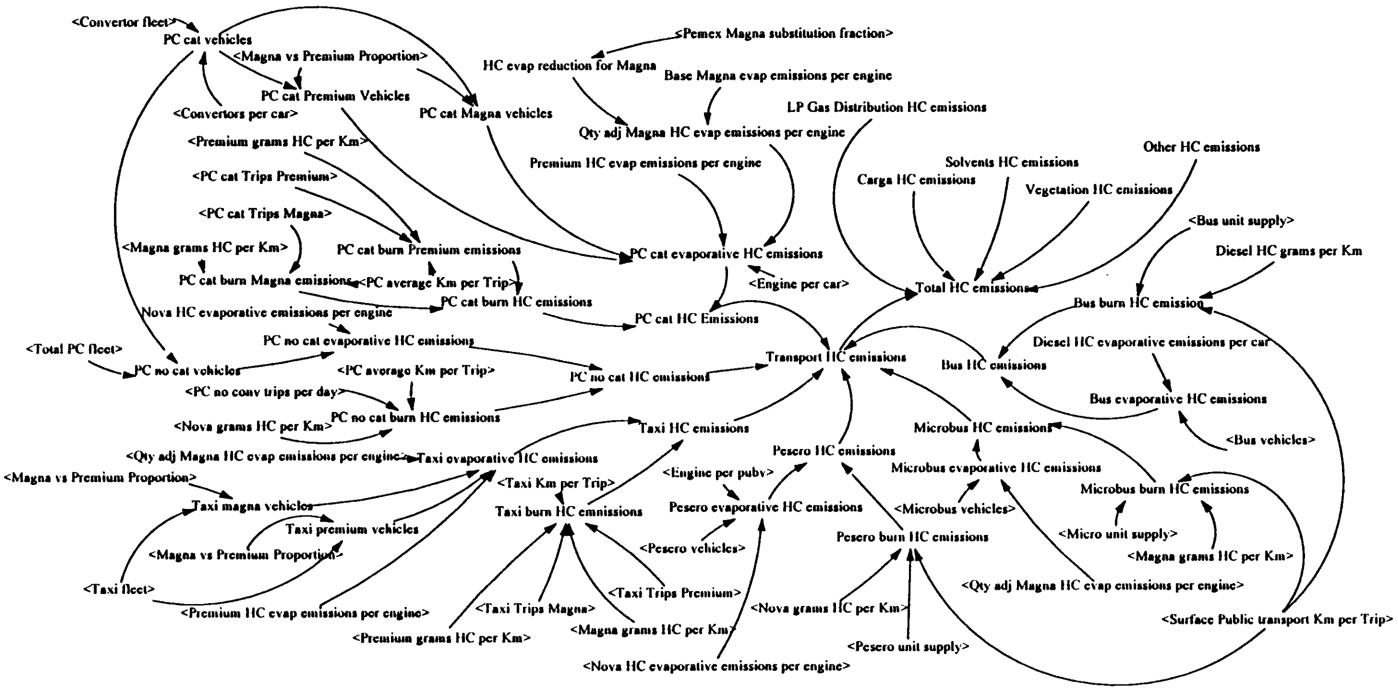

Time to change rail utilization
Change in rail utilization
Demanded rail utilization
<Net rail trip demand>
Rail utilization gap fraction
Target rail capacity
Target rail utilization
Optimal rail capacity gap
Utilization of rail
Net rail trip demand
Rail capacity
Rail capacity addition rate
Time to adjust rail capacity
Rail trip demand
Willingness to build and use rail capacity
Unmet PubV trip demand
Rail unit supply
<RV mkt share>
Unmet PubV unit demand
<Symmetric cascade switch>
<Average persons per PubV>


<RV mkt share>
Rail trip demand
PubV trip demand
<PubV mkt share>
TX trip demand
<TX mkt share>
<Total transport demand>
Total transport surplus or deficit
PC trip demand
<PC market share>
<PC unit trip supply>
PC trip supply
<Rail unit supply>
<Persons per PC>
Total trip supply
<Taxi unit trip supply>
<PubV unit supply>
PubV trip supply
Taxi trip supply
<Persons per TX>
<Average persons per PubV>


<PubV unit supply>
<PC unit trip supply>
Engine per car
Total street unit trips
Engine per pubv
<Taxi unit trip supply>
Engine per taxi



<Cars with convertor>
<Convertors per car>
PC convertor trips per day
<PC unit trip supply>
PC no conv trips per day
Pesero fleet percentage
Pesero vehicles
Microbus fleet percentage
<PubV fleet>
Bus fleet percentage
Microbus vehicles
Bus vehicles
Pemex Magna substitution fraction
Pemex Magna reduction equivalent for Magna
Quality adjusted Magna HC grams per km
Magna base HC grams per km
Pemex Magna reduction equivalent for Nova
Magna grams HC per Km
<PC average Km per Trip>
Quality adjusted Nova HC grams per km
Minutes per hour
PC average speed
speed multiplier
Nova grams HC per Km
Nova basic HC grams per km
<PC average net trip time>
Premium grams HC per Km
Speed pollution switch
Premium base HC grams per km


<Convertor fleet>
PC cat vehicles
<Magna vs Premium Proportion>
PC cat Premium Vehicles
<Convertors per car>
PC cat Magna vehicles
<Pemex Magna substitution fraction>
HC evap reduction for Magna
Base Magna evap emissions per engine
Qty adj Magna HC evap emissions per engine
LP Gas Distribution HC emissions
<Premium grams HC per Km>
<PC cat Trips Premium>
<PC cat Trips Magna>
<Magna grams HC per Km>
PC cat burn Premium emissions
PC cat burn Magna emissions
<PC average Km per Trip>
PC cat burn HC emissions
Premium HC evap emissions per engine
PC cat evaporative HC emissions
<Engine per car>
PC cat HC Emissions
Other HC emissions
Solvents HC emissions
Carga HC emissions
Vegetation HC emissions
Total HC emissions
<Bus unit supply>
Diesel HC grams per Km
Bus burn HC emission
Nova HC evaporative emissions per engine
PC no cat evaporative HC emissions
<Total PC fleet>
PC no cat vehicles
<PC average Km per Trip>
<PC no conv trips per day>
PC no cat HC emissions
Transport HC emissions
Bus HC emissions
Diesel HC evaporative emissions per car
Bus evaporative HC emissions
<Nova grams HC per Km>
PC no cat burn HC emissions
Taxi HC emissions
<Qty adj Magna HC evap emissions per engine>
Taxi evaporative HC emissions
<Magna vs Premium Proportion>
Taxi magna vehicles
Taxi premium vehicles
<Magna vs Premium Proportion>
<Taxi fleet>
<Premium HC evap emissions per engine>
<Taxi Km per Trip>
Taxi burn HC emnissions
<Taxi Trips Magna>
<Premium grams HC per Km>
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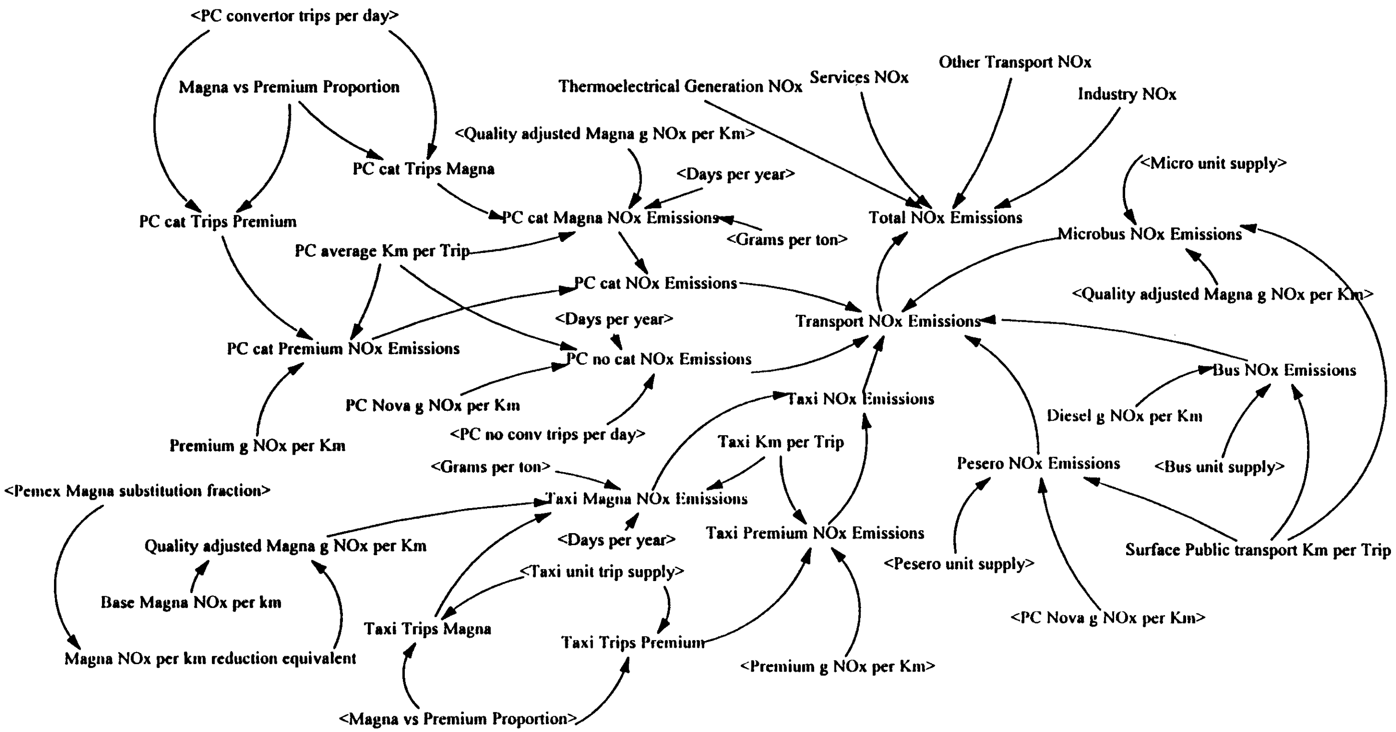
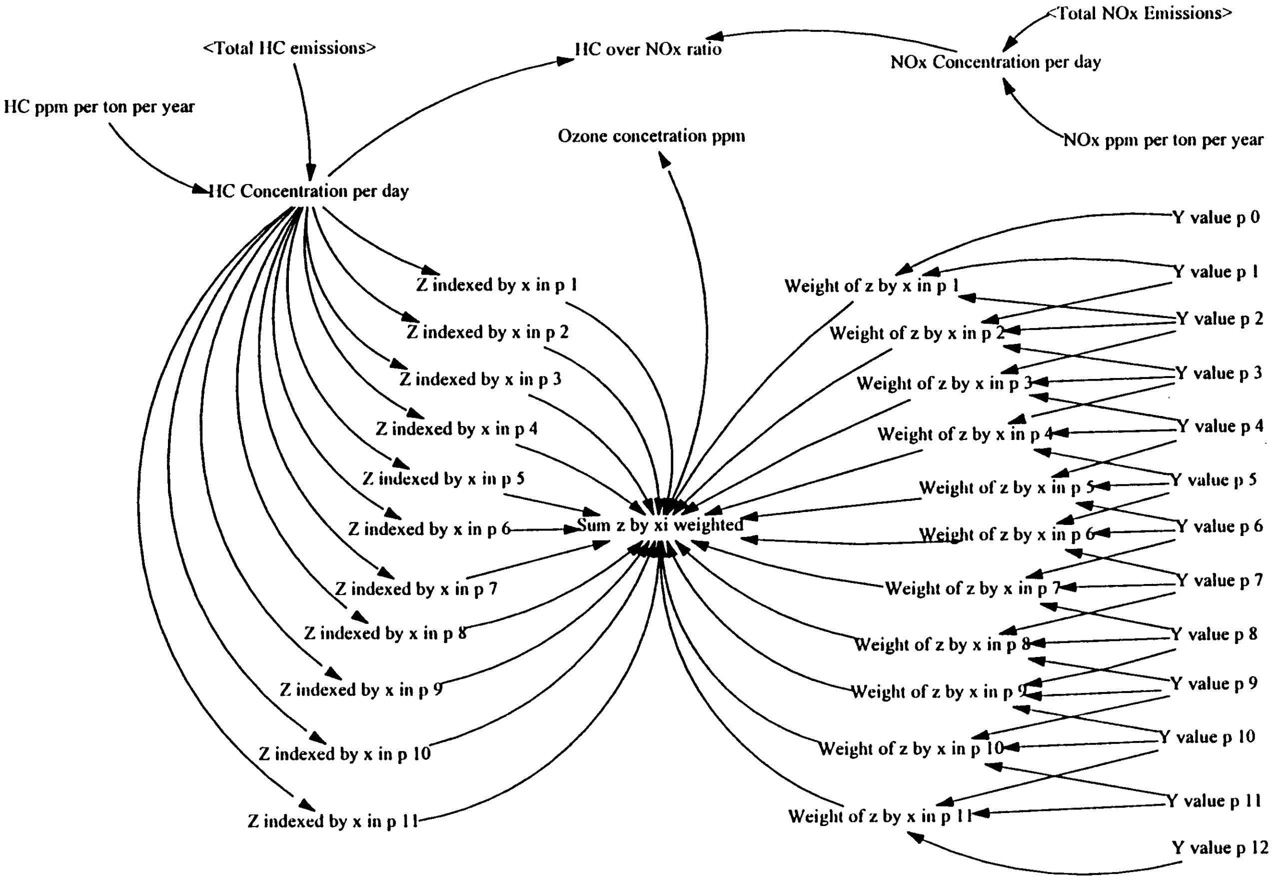
<Taxi Trips Premium>
<Engine per pubv>
Pesero evaporative HC emissions
<Pesero vehicles>
<Nova HC evaporative emissions per engine>
Pesero HC emissions
Pesero burn HC emissions
<Nova grams HC per Km>
<Pesero unit supply>
Microbus HC emissions
Microbus evaporative HC emissions
<Microbus vehicles>
<Bus vehicles>
Microbus burn HC emissions
<Micro unit supply>
<Magna grams HC per Km>
<Qty adj Magna HC evap emissions per engine>
<Surface Public transport Km per Trip>


<PC convertor trips per day>
Magna vs Premium Proportion
PC cat Trips Magna
PC cat Trips Premium
<Quality adjusted Magna g NOx per Km>
<Days per year>
PC cat Magna NOx Emissions
<Grams per ton>
PC average Km per Trip
PC cat NOx Emissions
<Days per year>
PC cat Premium NOx Emissions
PC no cat NOx Emissions
PC Nova g NOx per Km
<PC no conv trips per day>
Premium g NOx per Km
Thermoelectrical Generation NOx
Services NOx
Other Transport NOx
Industry NOx
Total NOx Emissions
<Micro unit supply>
Microbus NOx Emissions
<Quality adjusted Magna g NOx per Km>
Transport NOx Emissions
Bus NOx Emissions
Diesel g NOx per Km
<Bus unit supply>
Taxi NOx Emissions
Taxi Km per Trip
<Grams per ton>
Taxi Magna NOx Emissions
<Pemex Magna substitution fraction>
Quality adjusted Magna g NOx per Km
<Days per year>
Taxi Premium NOx Emissions
Pesero NOx Emissions
<Pesero unit supply>
Surface Public transport Km per Trip
Base Magna NOx per km
<Taxi unit trip supply>
Taxi Trips Magna
Taxi Trips Premium
Magna NOx per km reduction equivalent
<PC Nova g NOx per Km>
<Premium g NOx per Km>
<Magna vs Premium Proportion>


<Total NOx Emissions>
<Total HC emissions>
HC over NOx ratio
NOx Concentration per day
HC ppm per ton per year
Ozone concetration ppm
NOx ppm per ton per year
HC Concentration per day
Y value p 0
Y value p 1
Z indexed by x in p 1
Weight of z by x in p 1
Y value p 2
Z indexed by x in p 2
Weight of z by x in p 2
Y value p 3
Z indexed by x in p 3
Weight of z by x in p 3
Y value p 4
Z indexed by x in p 4
Weight of z by x in p 4
Y value p 5
Z indexed by x in p 5
Weight of z by x in p 5
Z indexed by x in p 6
Sum z by xi weighted
Weight of z by x in p 6
Y value p 6
Y value p 7
Z indexed by x in p 7
Weight of z by x in p 7
Y value p 8
Z indexed by x in p 8
Weight of z by x in p 8
Y value p 9
Z indexed by x in p 9
Weight of z by x in p 9
Y value p 10
Z indexed by x in p 10
Weight of z by x in p 10
Y value p 11
Z indexed by x in p 11
Weight of z by x in p 11
Y value p 12

Model structure

- <Convertor equilibrium switch>
- <Speed pollution switch>
- <Random multiplier switch>
- <Symmetric cascade switch>
- <Demand equilibrium switch>

Infrastructure policy

- <Willingness to build and use rail capacity>
- <Road capacity>
- <Road tax to PC per km at full capacity>

Transit policy

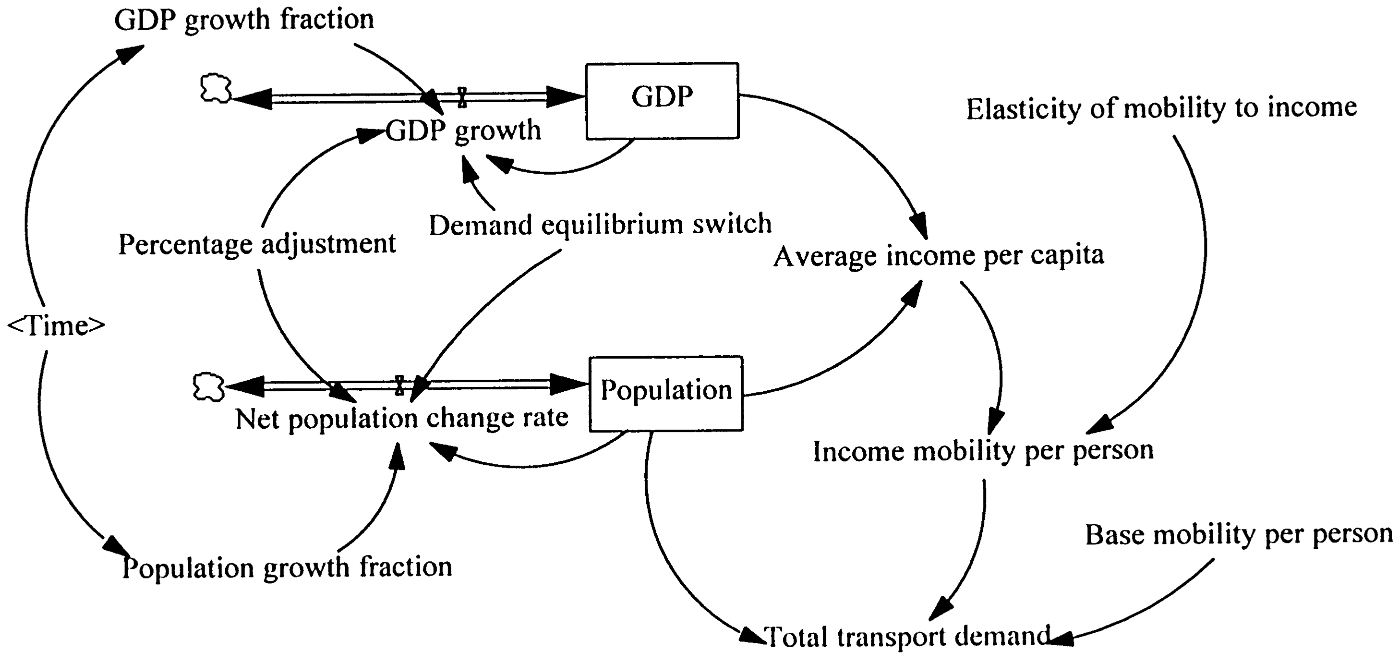
- <Regulation switch>
- <Subsidized car retirement>

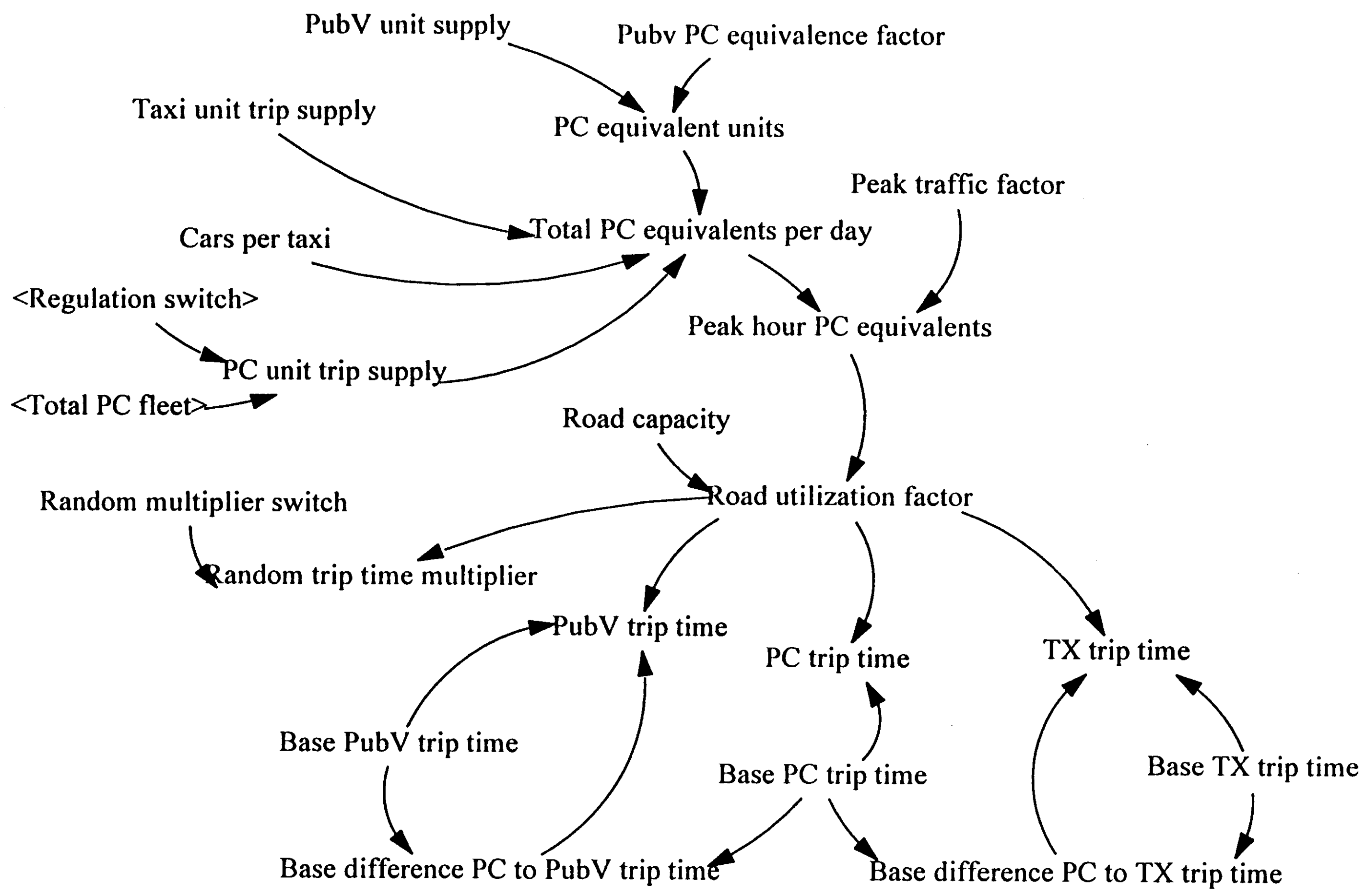
Energy policy

- <Magna vs Premium Proportion>
- <Pemex Magna substitution fraction>
- <Gasoline tax per km to PC>

Key monitor outputs

- <Total transport demand>
- <PC average speed>
- <Total trip supply>
- <Total PC fleet>
- <Total street unit trips>
- <PC unit trip supply>
- <Taxi unit trip supply>
- <PubV unit supply>
- <Rail unit supply>
- <Total transport surplus or deficit>
- <Total HC emissions>
- <HC over NOx ratio>
- <Total NOx Emissions>
- <Ozone concetration ppm>


GDP growth fraction
GDP
GDP growth
Elasticity of mobility to income
Percentage adjustment
Demand equilibrium switch
Average income per capita
<Time>
Population
Net population change rate
Income mobility per person
Base mobility per person
Population growth fraction
Total transport demand


PubV unit supply
Pubv PC equivalence factor
Taxi unit trip supply
PC equivalent units
Peak traffic factor
Cars per taxi
Total PC equivalents per day
<Regulation switch>
Peak hour PC equivalents
PC unit trip supply
<Total PC fleet>
Road capacity
Random multiplier switch
Road utilization factor
Random trip time multiplier
PubV trip time
PC trip time
TX trip time
Base PubV trip time
Base PC trip time
Base TX trip time
Base difference PC to PubV trip time
Base difference PC to TX trip time

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