

A Simulation Analysis of Transportation Policies on Health and Environment in Delhi, India

Authors:

Karolin Kokaz
Harvard University
PhD Candidate in Environmental Sciences and Engineering

Nagaraja Rao Harshadeep
South Asia Region Environment Unit, The World Bank
Environmental Specialist

Peter Rogers
Harvard University
Professor of Environmental Engineering and Professor of City and Regional Planning

Sumeeta Srinivasan
Harvard University
Post-doctoral Associate in Urban Systems

Abstract

For many countries like India the transport sector is the most rapidly growing energy end-use category. Choices made now will have impacts lasting well into the middle of the 21st century. The desire for personal mobility in urban areas, typically by means of personal-use vehicles, will comprise much of growing transportation energy demand. Automobile emissions are the fastest increasing source of urban air pollution in most developing cities. In India most urban areas including Delhi already have major air pollution problems that could be greatly exacerbated if growth of the transport sector is managed unwisely. Delhi's spatial growth over the last 25 years has been rapid and urban sprawl is contributing to increasing travel demand. We propose the development of decision support tools for understanding the different ways to manage this sprawl and plan for a better Delhi in years to come. This paper focuses on a vehicular air pollution information system, to provide some insight about the key parameters of the transport system of Delhi now and in the future.

Keywords: air quality, transportation planning, decision support systems, GIS, land use planning

Urban Transportation Planning for Air Quality Management

The number of vehicles in India has increased by 11.5 times from 1.9 millions in 1970 to 21 millions in 1990. The number of vehicles per 1000 people has increased from 3.4 to 25.31 in the same time, with estimates of 43 vehicles per 1000 people for year 2000 (Web-page sources 25 - adopted from MST 1993). The number of registered vehicles is maintaining its increasing trend with the growth from 25.2 millions in 1993 to 33.85 millions in 1996.

This accelerated growth of the transportation sector in India will have the greatest impact on large cities where development is occurring in a fast and imperfect form. The main reasons for the big cities to be most affected from this development will be the large population growth and the intensification of employment opportunities in such areas which will draw more people from the rural areas into the urban areas.

India's GDP has increased 2.5 times over the past two decades while vehicular pollution increased by 8 times. Every time GDP doubles in India, air pollution rises by 8 times, mostly as a result of increased emissions from the growing transportation sector. Auto emissions currently account for approximately 70% of air pollution (WWF, 1995; Indiainfoline, November 1999; and White Paper on Pollution in Delhi, 1997). Turnover period of vehicles is about 20 years compared to 6-8 years in developed countries which adds onto the air quality deterioration.

Delhi has 1% of the entire country's population but 10% of the total vehicles registered in India (largest vehicle population in the country). The number of vehicles increased by a factor of 9 from 1970 to 1990. Personal vehicles account for almost 90% of all vehicles in Delhi - largely with single occupancy, and are therefore not very efficient as a transport mode. The total number of vehicles per 1000 people in 1998 was 238.

Although Delhi has one of the highest per capita road lengths and lowest number of vehicles per unit road length when compared with large cities around the world, it is still the most congested city in India (TERI 1996). Delhi has the highest road length in India (26,379km of total length in 1998/1999), and its roads, if modern traffic management is applied, can accommodate 2-3 times the existing number of vehicles (Indian Institute of Technology, May 1997). Therefore, in order to reduce traffic congestion in Delhi, the use of well-designed traffic management control options are essential.

As a first step to study urban transport, we have developed a spreadsheet based vehicular air pollution information system for Delhi (Harshadeep 1998, Kokaz 2001). Our final goal is to create an optimization model, which will be used as a decision support system with a user-friendly graphic interface that will assess the optimal transportation mix to meet the turnover (passenger-km demand), environmental goals, and other constraints through a variety of policy options at a minimum cost. The results from these applications will also be linked to a GIS for Delhi for a visual representation and the evaluation of the effects of land use changes on air quality. Exposure and health impacts under each scenario will also be mapped in this GIS for Delhi.

The Spreadsheet Vehicular Air Pollution Information System

Introduction

This spreadsheet model which was developed for Delhi can also be applied to any other city provided with the necessary input data. We have represented the vehicle fleet in Delhi by 6 different vehicle types: cars/jeeps/station wagons (categorized as cars), two wheelers, three wheelers (autorickshaws), taxis, buses, and trucks. The model includes data and information from 1985 to 2020 and projects the number of vehicles, average vehicle fuel efficiencies (km/lt), average vehicle emission factors (g/km), age distribution of vehicles in each year, vehicle kilometers traveled per day, fuel consumption, and emissions for the 8 chosen pollutants (CO, NO_x, HC, Pb, TSP, PM10, SO₂, CO₂).

The spreadsheet model enables officials in Delhi to keep track of the vehicle population, including its age and model type; to monitor and calculate the average emission factors for different vehicle categories and pollutants; and to evaluate different emission control technologies including their effectiveness in emission reduction and cost. After the addition of the necessary input data, appropriate control options and/or policies for the future can be assessed by the model and the changes in the predictions of all the parameters could be observed. Also, health impacts estimation from vehicular emissions can be made by exposure assessment. Observing daily patterns of exposure of people can also provide information about which control options should be enforced and when.

The spreadsheet model for Delhi shows that the assumed growth of automobiles is from around 850,000 in 2000 to more than 5.8 millions in 2020 with the total number of vehicles surpassing 13.5 millions in 2020 (see table 1). It cannot be imagined where all these vehicles could be fit in the existing road network. Congestion becomes an increasingly important problem and average round trip commute times rise from slightly more than 60 minutes in 2000 to about 195 minutes in 2020. World Health Organization (WHO) names Delhi as the 4th most polluted city in the world in terms of suspended particulate matter (Pandey et. al. 1999). Particle levels in Delhi consistently remain 3 to 5 times the national standards and maximum levels have even reached 8 times the standards during the winter of 1998. Levels of PM10 in a residential area in Delhi (Ashok Vihar) have attained 10 times the limits in October 2000 (CSE 2001). Particulate pollution was reported to kill 1 person per hour in 1995 in Delhi (CSE 1997).

Approximately, 80% of CO, 70% of NO_x, and 95% of HC emissions have been estimated to come from mobile sources in Delhi (Workshop on Integrated Approach to Vehicular Pollution Control in Delhi, 1998). In our study, when congestion effects on emissions factors are considered through lowered speeds, concentrations resulting from motor vehicle emissions more than triples for CO and roughly doubles for TSP and PM10 from 2000 to 2020, further worsening air quality in Delhi (see table 2). SO₂ emissions decrease almost by 73%, even though the number of vehicles increase by more than 4 times from 2000 to 2020, due to the subsequent implementation of strict fuel quality standards for sulfur content in gasoline and diesel along with Euro emissions standards. Given these levels of emissions, our preliminary estimates are that the damages due to the health

impacts of air pollution from mobile sources alone would rise from \$520 million per year in 1995 to almost \$7 billion annually, in real terms, by the year 2020 (see table 3).

Transportation System Details - Delhi

The rapid growth of population and imbalance in the distribution of income among its people has created massive chaos in Delhi's transportation system. Delhi's large rail network (120km) is practically not used and all transport needs are being met by roads. Cars, taxis, buses, autorickshaws as well as bicycles, tricycles, handcarts, bullock carts, animals, and pedestrians share the same road space with no traffic segregation. Delhi has two ring roads and one ring railroad. Five railroads and nine roads, of which five are national highways, intersect in Delhi leading to high amounts of congestion in the city. Also, Delhi vehicles still lag behind European standards (Delhi just introduced Euro 2 norms in April 2000). As a result Delhi became one of the top ten most polluted cities in the world as announced by the WHO (Pandey et. al. 1999).

When compared with other big cities in the world, Delhi has less automobile usage, no subway or light rail passenger transport, and much more bus passenger transport and non-motorized vehicle usage (mainly walking and bicycling). Also, the share of air pollutant emissions from the mobile sector is lower in Delhi compared to more developed cities. The main reasons for this are that the transportation sector is rapidly growing now and that industries / stationary sources of air pollution are out in the suburb areas in more developed cities, whereas they are still scattered all over the whole area of Delhi. But this will change because of the Supreme Court's orders about relocating polluting stationary sources (114 polluting stone crushers forced outside the city boundaries – WWF, 1995) and the high growth rate of the transportation sector.

In 1995 the total number of vehicles in Delhi was slightly above 2 millions of which cars and two wheelers made up about 25% and 64% respectively (see table 1). Although, buses made up only 1.2% of the vehicle fleet in 1995, they contributed 7% and 60% to vehicle km traveled and passenger km traveled in the same year. The spreadsheet reports a great increase in the number of cars, from around 535,000 in 1995 to more than 5.8 millions in year 2020, accounting for 43% of the total number of vehicles in Delhi in that year. The other mode of transportation that continues to make up the greatest proportion of the vehicle fleet in Delhi (about 52% in 2020) is the two wheelers, reaching more than 7 million in 2020. The rest of the vehicle fleet composition in 2020 is made up of 98,282 taxis, 121,510 autorickshaws, 53,569 buses, and 406,557 trucks (see table 1).

Although the spreadsheet simulation has not included walking trips, this mode of travel met about 32% of the total trips in 1994 (Tiwari 1999). This accounted for about 7 million trips per day and totaled to approximately 4.4bpkm (about 5% of the total pkm traveled in 1994). As motorization continued over the years in Delhi, walking trips were somewhat reduced. In 2000, roughly 4.4 million people out of 13.8 million people met their travel needs by walking resulting in about 2.7bpkm travel (a little over 3% of total pkm traveled).

Figure 1 shows the number of vehicles of different ages in each year from 1995 to 2020. Based on Supreme Court orders (1997-2001), the retirement age for different vehicles in different years changes until 2001 and then is maintained at the same level into the future. The constant scrap rate that the model uses for each vehicle after year 2000 is 25 years for cars, 15 years for two wheelers, 10 years for autorickshaws, 15 years for taxis, 8 years for buses, and 12 years for trucks. The projections illustrate that the vehicle fleet becomes newer and cleaner because of the regulations enforced for the new vehicle emission standards.

Delhi has taken many actions so far to curb air pollution from motor vehicles and develop a sustainable transportation sector. Delhi has introduced Euro II standards for all new cars in April 2000 and Euro I for all new LDV and HDV. Leaded gasoline was phased out in September 1998 and catalysts were mandated on all new cars in October 1998. Sulfur content of diesel and gasoline were reduced to 0.05% by weight in April 2000. New retirement ages for vehicles as mentioned above were introduced. The use of alternative fuels and especially CNG buses are being pushed but the results of the implementation of such decisions are rather uncertain. Delhi Metro Rail Corporation is working on a large project for the implementation of Delhi MRTS which in its first phase plans to build an 11km of subway and 41km of surface and elevated rail system by 2005 in order to reduce congestion, air pollution, and accidents and save fuel and space (<http://www.delhimetrorail.com>). The full system is supposed to be finished by 2021 with 34.5km of subway, 35.5km elevated and 111km surface rail, and 17.5km dedicated busway with a total system length of 198.5km. On the traffic demand management side, the Supreme Court limited the monthly number of car registration to 1500 (previously 4000 vehicles per month were being sold). Finally, goods vehicles were restricted during the day within the city limits (December 1997).

Due to the uncertainties related to the implementation of alternative fuel vehicles and traffic demand management options, in this spreadsheet model we have focused on the technological improvements of vehicle engine designs to meet certain emissions standards and fuel quality improvements to investigate their impact on air pollution from mobile sources. In addition to Delhi being under Euro II standards for all new cars (2000), the model assumes that Euro III, US Tier II, and Euro IV standards will be enforced for all new vehicles by 2005, 2010, and 2015 respectively. The corresponding fuel qualities for sulfur content of gasoline and diesel are also required to comply with the Euro norms accordingly.

There are four cases considered for managing transportation in Delhi in this model:

- Case 1: Continuous technological advancement to meet fuel efficiency, emissions factors, and fuel quality improvements until 2020.
- Case 2: Stop technological advancement in year 2000 and keep 2000 technologies into the future.
- Case 3: Case 1 with the effects of reduced speeds and congestion on fuel efficiencies and emissions factors.
- Case 4: Case 3 with year 2000's speeds kept constant into the future.

The parameters used in the calculation of average emission factors in a year include speed, new vehicle emission factors and average vehicle emission factors from the previous year, number of old and new vehicles in that year. Average vehicle emission factors for 1995 are given and new vehicle emission factors are known for the future based on the spreadsheet's assumption about the implementation of strict European and US standards. Then, knowing the amount of new vehicles coming into the fleet, the number of vehicles being scrapped based on vehicle retirement ages, and their corresponding average and new vehicle emission standards, the average vehicle emission factors are calculated for each year.

However, many other factors will influence the emission factors such as the amount and quality of road infrastructure available, use of control options, age of vehicles, fuel quality, and speeds. Most of these options will be considered in the proposed optimization model introduced later on in this paper, but for the sake of keeping things simple enough for the production of a time constrained and manageable set of results, only the effects of speed on emission factors are taken into account in the spreadsheet model.

The first set of emission factors generated was based on the 1995 average speed level (31km/hr). Using our knowledge of the number of vehicles and average speeds in other years, estimates for the average speed levels for all the years are obtained using regression techniques. Also, using the polynomial relationships of speed with emission factors of different types of vehicles (as average speeds increase emissions factors decrease), emission factors are calculated for the speeds of each year and then they are used in scaling the emission factors obtained in the first step using 1995 as the base year, to get the final emissions factors trend from 1995 to 2020 for all types of vehicles and pollutants (CO, NO_x, and HC).

Since speed affects CO emission factors most among CO, HC, and NO_x, and at a much higher level than the other pollutants, the regulations on new vehicle emission standards are easily and quickly negated by the reduced speeds for this pollutant's emission factor trend over time. After around year 2006, average emission factors increase because the total number of vehicles becomes very high and therefore average speeds decrease a lot resulting in a large increase in the average vehicle emission factors that cannot be offset by the better new vehicle emission factors for the small amount of new vehicles that are added to the fleet (see figure 3 for an example of emission factor trend – CO).

The change of fuel efficiencies over time for different types of vehicles in Delhi were calculated based on 1995 average fuel efficiencies and improvements over the years in vehicle technologies, again finally being scaled up by using fuel efficiencies calculated from the speed versus fuel efficiency relationship (fuel efficiencies increase as speeds increase) using 1995 as the base year for scaling. The results show that improvements in vehicle technologies are not sufficient to overcome the adverse effects of reduced speeds. Finally, SO₂, TSP, PM10, and CO₂ emission factors are calculated as the weighted average of new vehicle and old vehicle emissions factors for these pollutants. Then these average emissions factors are scaled up based on fuel efficiencies, therefore, revealing the

effects of reduced overall fuel efficiencies from reduced speed levels on the trends of these pollutants emissions factors. Increasing CO₂ emissions factors can be observed from after around 2010 but a drastic increase in TSP and PM10 emission factors can be seen starting year 2015. This is because the last improvement on emissions factors for these pollutants occur in 2015 and then the huge increase in the number of vehicles results in a great drop in speeds and consequently in fuel efficiencies which result in these increasing trends of emission factors. SO₂ emission factors, on the other hand, continue to decrease due to the very strict fuel quality standards being enforced that lowers the sulfur content of gasoline and diesel to 0.005% by weight by 2015.

Using fuel efficiencies, emission factors, retirement ages, vehicle growth rates, number of vehicles, and vehicle kilometers traveled, the amount of fuel consumption and emissions from motor vehicles can be calculated. The amount of fuel consumption increases by 5.7 times from 1995 to 2020 (from 1,602 million liters/year to 9,123 million liters/year – see table 2). The energy supply deficit of India has been increasing since 1985. India already imports about twice as much as the amount of its domestic oil production. As a result of the discovery of most of India's easily recoverable oil, low recovery rates of Indian oil fields (30% on average), and the rapidly growing economy, India will have a very hard time keeping up with the demand for oil to feed its growing transportation sector.

On the other hand, CO, NO_x, HC, TSP, PM10, and CO₂ emissions are expected to rise to 19.50, 1.04, 6.36, 3.02, 3, 11.24 times their 1995 value in 2020 based on the model projections (see figure 2 and table 2). SO₂ emissions decrease almost by 90% in the same time period due to fuel quality improvements incorporated in the model. At the same time vehicle kilometers traveled is expected to increase by 5.8 times from 1995 to 2020, reaching about 120 billion-km traveled per year in year 2020. This will produce a much more unfavorable environment in the future with very high amounts of emissions from the transportation sector which will result in unbearable air pollution levels in the city (see table 2). Although buses and trucks together made up about 7 % of the total vehicle fleet (but 28% of vehicle km traveled) in 1995, they produced more than 80% of particulates and NO_x emissions and 65% of CO₂ emissions (see tables 1 and 2, and figure 4). Most of CO and HC emissions came from cars, two wheelers and autorickshaws (75-87%) and almost all SO₂ emissions came from buses and trucks (93%). A large increase in the number of cars changes this situation in 2020. Buses and trucks produce about 45% and 35% of particulates and CO₂ emissions in 2020. Cleaner diesel and gasoline fuels in terms of sulfur content results in much less SO₂ emissions from buses (9%). Most of CO and HC emissions come from cars and two wheelers (more than 80%).

A very simple rollback method is used to calculate air quality concentrations resulting from these emissions, based on relationships obtained for emissions versus concentration where data was available for both in previous years. The results for concentrations resulting only from vehicular emissions show that CO concentration more than triples, and NO_x and PM10 concentrations increase by about 8% and 91%, respectively, in 2020 compared to 2000. Finally, SO₂ concentration is reduced by more than 70%. (See table 2)

The emissions predicted by the spreadsheet model assume that all necessary technological advances (such as better engine designs, use of clean fuels, and additional control technologies) will be incorporated in the new vehicles that should have the new vehicle emissions standards demanded by the regulations. The discussions above focused on Case 3 results as mentioned earlier. If we were able to keep year 2000 average speed (21.2km/hr) constant into the future with the same number of vehicle growth rates, assuming that some traffic management options will be used to attain this goal, the fuel consumption in 2020 would be 6,385 million liters (2,738 million liters/year less than the previous case – see table 2). Case 4 CO₂ emissions would be about 30% less, PM10 emissions almost 80% less, and CO emissions more than 90% less compared to Case 3. CO, NO_x, PM10, and SO₂ concentrations would go down by 62%, 68%, 60%, and 22% respectively (see table 2 and figure 2).

Similar calculations for Case 1 where the effects of reduced speeds are not included in the model and continuous technological improvement takes place to achieve cleaner fuels and better engine designs to attain lower emissions standards and more fuel efficient vehicles, the results are more attractive in terms of their environmental and health implications. The fuel consumption in 2020 becomes 5,726 million liters (3.58 times the amount in 1995 and 3,397 million liter/year less than the fuel consumption in Case 3 – see table 2). CO₂, PM10, CO, and SO₂ emissions are 33%, 79%, 93%, and 57% lower respectively than in Case 3 (see table 2 and figure 2). CO, NO_x, PM10, and SO₂ concentrations would be 71%, 75%, 61%, and 22% less respectively compared to Case 3 (see table 2).

Furthermore, instead of assuming technological enhancement and applying new vehicle emissions standards, if we kept year 2000 control levels without any improvements into the future, i.e. Case 2, then the comparison between the emissions levels of the CO₂, PM10, CO, and SO₂ pollutants with Case 1 in year 2020 would yield 27%, 76%, 28%, and 400% higher levels for each one (see table 2 and figure 2). Similarly, the concentrations of CO, NO_x, PM10, and SO₂ under Case 2 would be 22%, 136%, 43%, and 89% higher than Case 1 in year 2020 (see table 2). And, total fuel consumption in 2020 becomes 7,410 million liters, 1,684 million liters/year more than in Case 1 (see table 2).

Value of Time, Fuel Costs, and Health Costs of Mobile Sources Air Pollution in Delhi

In order to evaluate the economic consequences of transportation we need to calculate the value of externalities from the transportation sector in Delhi to assess the relative magnitudes of the different components. Two main externalities are considered in this section: production loss due to time spent in traffic and health damages due to air pollution resulting from vehicular emissions. Furthermore, transportation sector fuel costs are calculated.

Parameters required for the calculation of annual production loss due to time spent in traffic are average wage levels, economic growth rate, workdays in a year, work hours per day, valuation of an hour of time in traffic, average speed, round trip commute time per day per commuter, and number of people commuting. Time spent in traffic for

commuting increases a lot over time due to the increased number of vehicles on roads and reduced speeds. Every hour spent in traffic is valued at half the average hourly wage (Small 1992). The value of time increases from \$142.34 million in 1995 to \$314.88 million in 2000, and to almost \$12.5 billion in 2020 (see table 3). It starts off as the lowest component of the damages and becomes very high in 2020 due to high levels of congestion attributable to the expected rapid increase in motorization despite Delhi's high road density.

Parameters required for fuel cost calculations are average speed, fuel efficiencies, number of vehicles, vehicle kilometers traveled, economic growth rate, and fuel prices. The amounts of fuel used can then be calculated. Total gasoline and diesel use in 2020 becomes 3.6, 4.6, 5.7, and 4 times its value in 1995 for Cases 1, 2, 3, and 4 respectively (see table 2). The corresponding cost of fuel consumption was \$586.70 million in 1995 and it increases to \$8,134.81 million, \$10,676.61 million, \$13,123.32 million, and \$9,216.71 million in 2020 for Cases 1, 2, 3, and 4 individually (see table 3). Stopping technology improvements in year 2000 results in \$2,541.80 million increase in fuel costs (Case 2 – Case 1), while the effects of congestion results in a larger increase, almost double, of \$4,987.87 million (Case 3 – Case 1). If some traffic management options, land use planning and/or infrastructure building are used to keep year 2000's speed constant into the future, then \$3,906.61 million per year in fuel costs could be saved in 2020 (Case 4 – Case 3). This shows that technology improvements alone will not solve the problems and other traffic control options to reduce congestion should also be implemented to attain a sustainable transportation system in the future for Delhi.

Parameters required for the calculation of the health impacts of mobile sources emissions are dose-response coefficients, concentrations resulting from vehicular emissions, population and its composition, cost per case of health impacts, economic growth rate, disability adjusted life years (DALYs) for each health impact, life years lost on average for a premature death due to air pollution, and total annual crude death rate. In estimating the health damages due to air pollution, dose-response coefficients developed by Ostro (1994) are used for each health impact case except the premature mortality case. This is because premature deaths due to air pollution mostly affect people after the age of 65 in the U.S. whereas in Delhi more than 70% of all deaths occur before the age of 65. Cropper (1997) reports that peak effects of air pollution are observed in the 15-44 age group. Therefore, we have used her estimate of 2.3% of change in total non-trauma mortality for a $100\mu\text{g}/\text{m}^3$ change in TSP to calculate the change in premature mortality for a unit change in PM10 concentration using also the fact stated in Cropper's (1997) report that on average 53% of TSP is PM10 in Delhi. We then converted this short-term dose-response coefficient calculated using Ostro's methodology (Ostro, 1994) into the long term one using Pope and Dockery's estimate for this dose-response coefficient (World Bank, 1997) to include both the acute and chronic effects of air pollution on premature mortality in Delhi. The results of these calculations show that health costs are \$520.65 million in 1995, and they rise to \$2,721.48 million, \$3,900.81 million, \$6,901.12 million, and \$2,753.33 million in 2020 for Cases 1, 2, 3, and 4 separately (see table 3). The technology improvements yield a reduction of \$1179.33 million (Case 2 – Case 1) while congestion results in a \$4,179.64 million increase in health costs per year in 2020

(Case 3 – Case 1). If Delhi acts so that year 2000's speed can be maintained constant into the future then \$4,147.79 million per year (Case 3 – Case 4) in health costs could be saved in 2020. This shows that although technological improvements are necessary to reduce emissions from vehicles, measures directed at reducing congestion are even more crucial in lowering vehicular emissions and their health impacts.

Health impacts can be estimated through other parameters such as life years lost due to premature deaths from air pollution or DALYs. The results given in Table 3 for these parameters agree with our previous conclusion that although technological improvements to reduce vehicular emissions are necessary, reducing congestion levels are even more important in attaining lower health impacts such as the ones mentioned here.

An important outcome of these calculations is that while health costs and fuel costs are by far larger than the value of time in years 1995 and 2000, the value of time is the one increasing most from 2000 to 2020 and it becomes the largest component of these costs by year 2020. The reasons for this are that increased number of vehicles and reduced speeds on roads due to the rapid growth of the transportation sector increases the time spent in traffic and increased valuation of time due to higher incomes resulting from the fast economic growth in India increases congestion costs.

Finally, costs of congestion resulting from delay time in traffic, the amount of fuel wasted, and increased health impacts are calculated to show the possible reductions in these costs that can be attained by increasing speeds and reducing congestion levels (see table 3). Case 3 results which include the reduced speed effects due to increased number of vehicles on Delhi's roads are compared to the outcome of another case where a free flow speed of 40 km/hr is assumed constant for all vehicles from 1995 to 2020. The calculations demonstrate that in 2020 more than \$5 billion per year for each of the \$6.9 billion of health costs and \$13.1 billion of fuel costs can be saved from wasted fuel and health impacts and similarly more than \$10 billion per year of the \$12.5 billion of value of time spent in traffic can be avoided by cutting of the delay time in traffic due to lower speeds. The daily travel times could go down from about 3 hours to less than 40 minutes, a total of almost 4,000 million tons of gasoline and diesel fuel could be saved, and more than 11,500 premature deaths due to air pollution could be avoided in 2020 if average speeds could kept at 40 km/hr.

Conclusions from the Spreadsheet Model

The spreadsheet model results show that the transportation sector in Delhi is developing very fast and if uncontrolled the results could be disastrous. The number of vehicles is expected to grow by more than 4.6 times from 2000 to 2020 and total vehicular emissions will approximately become 9 times as much in the same period of time. As a result the air quality will be profoundly worsened. Therefore, technological improvements alone to make each vehicle cleaner will not be enough to solve Delhi's air pollution problems resulting from vehicular emissions. Also, although currently value of time spent in traffic is low compared to the health damages and fuel costs of Delhi's transportation system, if careful land use planning and traffic management are not implemented these costs will become very significant and the highest among the three damages mentioned. The costs

of congestion (from delay time in traffic, fuel wasted, and health costs) are very high and increasing speeds will achieve great savings.

The aim of transportation planning should be directed at efficient passenger transport rather than vehicle transport because that is the only way the city will be able to meet the growing transportation demand in a sustainable manner. For this purpose, energy use per passenger-km and emissions per passenger-km will be good parameters to consider in order to frame the action plan that will enable the city's future transportation system meet the demand. Mass rapid transit systems such as buses, subway and light rail systems are the most efficient modes of transport that have low levels for these parameters. Maintaining a friendly and safe environment for pedestrians and non-motorized vehicles is also very important. These parameters are included in the optimization model being developed as part of the proposed integrated decision support system.

An Optimization Model

Motivation for the Optimization Model

In most developed countries, total energy demand is distributed in roughly equal proportions to three categories - transportation, industrial, and household and commercial sectors. Most developing countries are transportation-poor, with about ten percent of total energy demand from this sector (20% for India in 1995). As this distribution approaches that of the developed world the transport sector will become the most rapidly growing energy end-use category. The desire for personal mobility in urban areas - typically by means of personal-use vehicles - will comprise much of growing transportation energy demand. Motor vehicles were responsible for 22% of global anthropogenic CO₂ emissions in 1990 of which 70% came from high-income countries. Projections made based on assumptions on GNP and income elasticities of motor vehicles taken from previous studies show that high income countries will have more than half of the motor vehicles in the world and therefore the corresponding CO₂ emissions until at least 2050 (Ingram & Zhi, 1999). Western nations like the U.S., with growing concern for possible climate changes associated in large part with global fossil energy use, likewise have an interest in the technology, policy, and investment options in environmentally sound transportation development in emerging market countries as well as clean transportation systems and vehicle technologies for the growing number of vehicles in high-income countries.

Wegener (1998) notes that most land use/transport/environment models do not have the feedback from environmental conditions to the behavior of urban actors. US EPA's (2000) study of 22 models of land use change also indicates that most models do not carry through the process of modeling land use to effects on the environment in particular emissions and their dispersion. Also, most models carry out separate optimizations for different aspects of the problem, for example, traffic assignment models where the capacity of the network is constrained. Models that combine trip assignment and distribution also split the models into several distinct mathematical programming components with each component being solved sequentially (Hanley and Kim, 1998). Thus, the complexity of issues involved in understanding the linkages between transportation, land use and the environment indicate that several optimization models

need to be linked with other tools such as GIS based spatial models and simulation models.

The Model

The transportation sector is the most rapidly growing category of energy end-use in developing countries. The air quality standards already cannot be met in most regions and with the rapid growth in motorization the situation will become much more severe in the future. Therefore, the mix of vehicles and other modes of travel in the transportation sector need to change. Hence, we will develop an optimization model to assess what the best (cost effective and environmentally friendly) mix shall be under all the existing and potential constraints.

Given the turnover (passenger-km demand) projections and all other necessary input parameters, such as fuel efficiencies, occupancies, emission factors, VKT per year for each type of vehicle, etc., we can calculate an emissions inventory for the transportation sector. From emissions we can estimate concentrations, calculate material damages, and then using dose response coefficients we can estimate the health damages, and finally we can calculate the total cost of the system including the direct costs (such as fuel costs, vehicle costs, infrastructure investments, etc.) and social costs (health and materials damages). The mathematical model that will be developed will give the optimal transportation mix to meet the turnover, environmental goals and other constraints through a variety of policy options at the minimum cost.

The model will include all the modes of transportation (motor vehicles – cars/jeeps/station wagons, two wheelers, autorickshaws, taxis, buses, trucks – light rail, subway, bicycle, tricycle, walking) with all the different types of fuels and technologies available for each mode (gasoline, diesel, ethanol, methanol, natural gas, LPG, electric, hybrid, hydrogen fuel cells). The many different control options that the model can choose from include pricing measures (taxes and subsidies), technical policy options (engine designs, fuel quality improvement, catalytic converters, alternative fuels, fuel switching, reduced scrappage rate, infrastructure investments), traffic demand management measures (traffic management, HOV and bus lanes, parking management, inspection and maintenance programs), and incentive related and educational policy options (education and driver behavior, ride sharing, telecommuting). Accordingly, the model structure is given schematically in Figure 5.

GIS Model

Geographical Information systems (GIS) can be an important element in carrying out research which involves spatial data. GIS can be used for input, storage, analysis and visualization of spatial data. Most factors that are used to predict air quality such as terrain, traffic, concentrations of pollutants, land use, meteorological data etc can be obtained as geo-referenced data. These factors can be combined to study various aspects of air quality management in Delhi:

- The interpolation of point data for various pollutants like CO₂, PM₁₀, NO_x and SO₂

- The exposure of the population to pollutant concentrations in various locations of the city
- The generation of trips by location in the city based on land use, population, and employment
- Modeling the concentration of pollutants based on traffic generated due to various land use scenarios in the future
- Modeling the location of land uses based on current plans for Delhi

As indicated in Figure 6, GIS is used as a tool to generate data for the optimization, land use / transport and simulation models. Also, GIS is then linked to the visualization of data generated from the models. The data generated for visualization is assumed to have the same weights as those that were input into the model. GIS are also used for data exploration itself (see figures 7 and 8). Figure 7 indicates the extrapolation of air quality results from the monitoring stations and Figure 8 shows the expected mortality based on these extrapolations. Clearly, a location based mapping of mortality indicates that northern locations in the city are affected more by the air quality in terms of mortality and that these trends do not necessarily follow the population density.

Ideally, the use of GIS could be extended to real time predictions of air quality in the region through web-based tools. However, in its current form, given the paucity of data in Delhi, even building such a decision support tool that merely indicates the spatial aspects of the problem would be on the “cutting edge” of research.

Summary

Clearly the results from the spreadsheet model indicates that Delhi, as well as other similar cities and surrounding regions of India and other emerging markets, need a broad, systematic but practical assessment of the conventional concepts of personal-use transportation. Even though these models are preliminary, we believe that strong conclusions can be drawn from them, namely; technical advancement to improve vehicle technologies and fuel quality alone will not be enough to solve Delhi’s air pollution and congestion problems resulting from the rapidly growing transportation sector, and that travel demand management and land use planning are essential to attain a sustainable transportation system in Delhi.

To address these problems more directly we plan to develop models that will take the predicted demand for person-kilometers traveled as the primary input, and seek the most cost-effective mix of transportation options to meet this demand, subject to a variety of adjustable policy, technology, and environmental parameters. To do this we need to go beyond the spreadsheet model to include the optimization model, which in turn needs to be linked to the spatial database through GIS and land use/transport models. The resulting spatial decision support system could be a useful tool for the various agencies that are responsible for planning for the Delhi region of 2025.

Acknowledgements

This research was supported by the Ford Motor Company and the Harvard University Committee on Environment.

List of Abbreviations

bpkm/yr: billion passenger km per year
CNG: compressed natural gas
CO: carbon monoxide
CO₂: carbon dioxide
DALYs: disability adjusted life years
g/km: grams per kilometer
GDP: Gross Domestic Product
GIS: Geographic Information Systems
GNP: Gross Natural Product
HC: hydrocarbons
HDV: heavy duty vehicles
HOV: high occupancy vehicles
LDV: light duty vehicles
LPG: liquified petroleum gas
MRTS: Mass Rapid Transit System
MST: Ministry of Surface Transport
NO_x: nitrogen dioxide
NV: number of vehicles
Pb: lead
PM10: particulate matter less than 10 micron in diameter
PKM: passenger kilometers
SO₂: sulphur dioxide
TERI: Tata Energy Research Institute
TSP: total suspended particulates
US EPA: United States Environmental Protection Agency
VKT: vehicle kilometers traveled
WHO: World Health Organization
WWF: World Wide Fund for Nature

Appendix A: Tables and Figures

Table 1: Vehicle Fleet Composition in Delhi from 1995 to 2020

		1995	2000	2020
# of vehicles	Total	2,076,120	2,936,505	13,556,004
% of vehicles	Cars	25.77	29.05	43.02
	two wheelers	64.02	62.24	51.97
	Autorickshaws	2.95	2.36	0.90
	Taxis	0.46	0.40	0.73
	Buses	1.18	0.65	0.40
	trucks	5.62	5.30	3.00
PKM traveled	Total (bpkm/yr)	95	97	354
% of PKM by vehicle	cars	12.5	18.56	35.59
	two wheelers	9.37	12.37	12.71
	autorickshaws	5.21	5.15	2.54
	taxis	1.04	1.03	1.98
	buses	59.38	46.39	35.32
	trucks	12.50	16.50	11.86

Figure 1: The Age Distribution of Vehicles in Delhi from 1995 to 2020

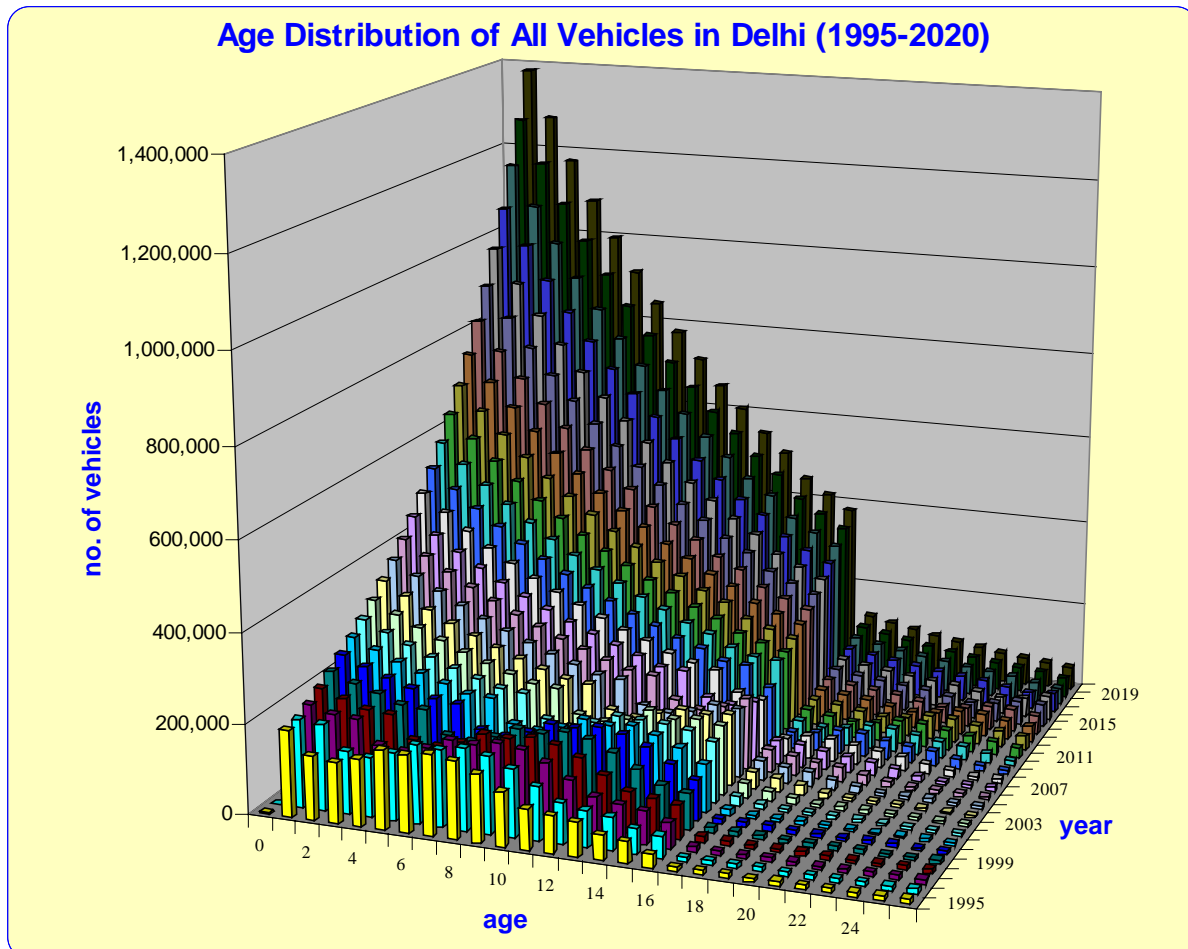


Table 2: Fuel Consumption, Emissions, and Concentrations from Transportation in Delhi in the 4 Cases

	1995*	2000				2020			
	Base Case	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
Emissions (tons/day)									
CO	697	729	729	1,033	1,033	894	1,144	13,594	1,268
HC	222	228	228	298	298	176	310	1,418	229
NO _x	268	217	217	267	267	119	200	279	139
SO ₂	19	10	10	11	11	1	5	23	1
TSP	41	38	38	42	42	26	46	124	26.8
PM10	33	30	30	33	33	21	37	99	21.5
CO ₂	22,778	28,619	28,619	28,883	28,883	87,807	111,316	130,682	92,393
<i>Total</i>	<i>24,059</i>	<i>29,872</i>	<i>29,872</i>	<i>30,563</i>	<i>30,563</i>	<i>89,044</i>	<i>113,058</i>	<i>205,415</i>	<i>94,078</i>
Concentrations (µg/m³)									
CO	3,123	3,286	3,286	4,550	4,550	4,027	4,918	13,880	5,293
NO _x	23.67	16.69	16.69	23.50	23.50	6.20	14.64	25.27	8.00
PM10	38.36	36.25	36.25	38.53	38.53	29.04	41.63	73.66	29.38
SO ₂	2.5	0.74	0.74	0.84	0.84	0.18	0.34	0.23	0.18
Fuel Consumption (million liters/year)									
Gasoline	682	958	958	989	989	3,657	4,949	6,062	4,289
Diesel	920	991	991	1,019	1,019	2,069	2,461	3,061	2,096
<i>Total</i>	<i>1,602</i>	<i>1,949</i>	<i>1,949</i>	<i>2,008</i>	<i>2,008</i>	<i>5,726</i>	<i>7,410</i>	<i>9,123</i>	<i>6,385</i>

Case 1: Technological advancement to meet fuel efficiency, emissions factors, and fuel quality standards enforced in the model until 2020. Case 2: Stop technological advancement in year 2000 and keep 2000 technologies into the future. Case 3: Case 1 with the effects of reduced speeds and congestion on fuel efficiencies and emissions factors. Case 4: Case 3 with year 2000's speeds kept constant into the future.

*Base year emissions are calculated using average emission factors put together from Workshop on Integrated Approach to Vehicular Pollution Control in Delhi (1998), Bose (1999), as well as other CSE and TERI reports. US Tier 2 and stricter Euro standards are assumed for new vehicles in the future. Concentrations for the base year come from CPCB air quality data on their webpage and the White Paper on Pollution in Delhi with an Action Plan (1997), together with data from Workshop on Integrated Approach to Vehicular Pollution Control in Delhi (1998). Future concentrations from vehicular emissions are calculated based on the relation obtained between emissions and concentrations. Base year fuel efficiencies come from the same sources as the base year average emissions factors.

Table 3: Value of Time, Fuel Costs, and Health Impacts of Vehicular Air Pollution

	1995	2000			2020		
	<i>Base Case</i>	<i>Case 1</i>	<i>Case 2</i>	<i>Case 3</i>	<i>Case 1</i>	<i>Case 2</i>	<i>Case 3</i>
Health Costs (million \$)	520.65	815.87	815.87	867.11	2,721.48	3,900.81	6,901.12
DALYs	423,391	496,288	496,288	527,470	624,130	894,629	1,582,802
life years lost	156,332	181,655	181,655	193,022	227,810	326,422	577,300
# of premature deaths due to air pollution	4,225	4,910	4,910	5,217	6,157	8,822	15,603
% of total annual deaths	4.18	3.91	3.91	4.15	NA		
accidents / deaths	10,178 / 2,074	NA / 1,956			NA		
million tons of carbon	2.38	2.96	2.96	3.00	8.88	11.26	27.6
Fuel Costs (million \$)	586.70	970.21	970.21	1,000.10	8,134.81	10,676.61	13,123.32
Value of Time (million \$)	142.34	314.88			12,471.76		

The effect of Speed Case 3 vs Case 4	2020	2020	2020
	<i>Case 3</i>	<i>Case 4</i>	<i>Difference</i>
Health Costs (million \$)	6,901.12	2,753.33	4,147.79
Fuel Costs (million \$)	13,123.32	9,216.71	3,906.61
Value of Time (million \$)	12,471.76	5749.40	6,722.36
<i>Total Costs</i>	<i>32,496.20</i>	<i>17,719.44</i>	<i>14,776.76</i>
DALYs	1,582,802	631,435	951,367
Life years lost	577,300	230,473	346,827
# of premature deaths due to air pollution	15,603	6,229	9,374
million tons of carbon	27.6	9.4	18.2

Costs of Congestion¹		Gasoline	Diesel	Total Fuel	Fuel Costs	Health Costs	Time Costs
Million \$/yr or Million lt/yr	1995	4	5	9	3.35	23.64	24.75
	2000	59	53	112	56.78	279.95	126.49
	2020	2,440	1,296	3,736	5,344.88	5,170.83	10,041.37

¹ Comparing free flow traffic at 40 km/hr with Case 3 which includes the reduced speed effect on all parameters.

Figure 2: Growth of Vehicles and Vehicle Km Traveled, and Trend of Emissions from Motor Vehicles in Delhi from 1995 to 2020

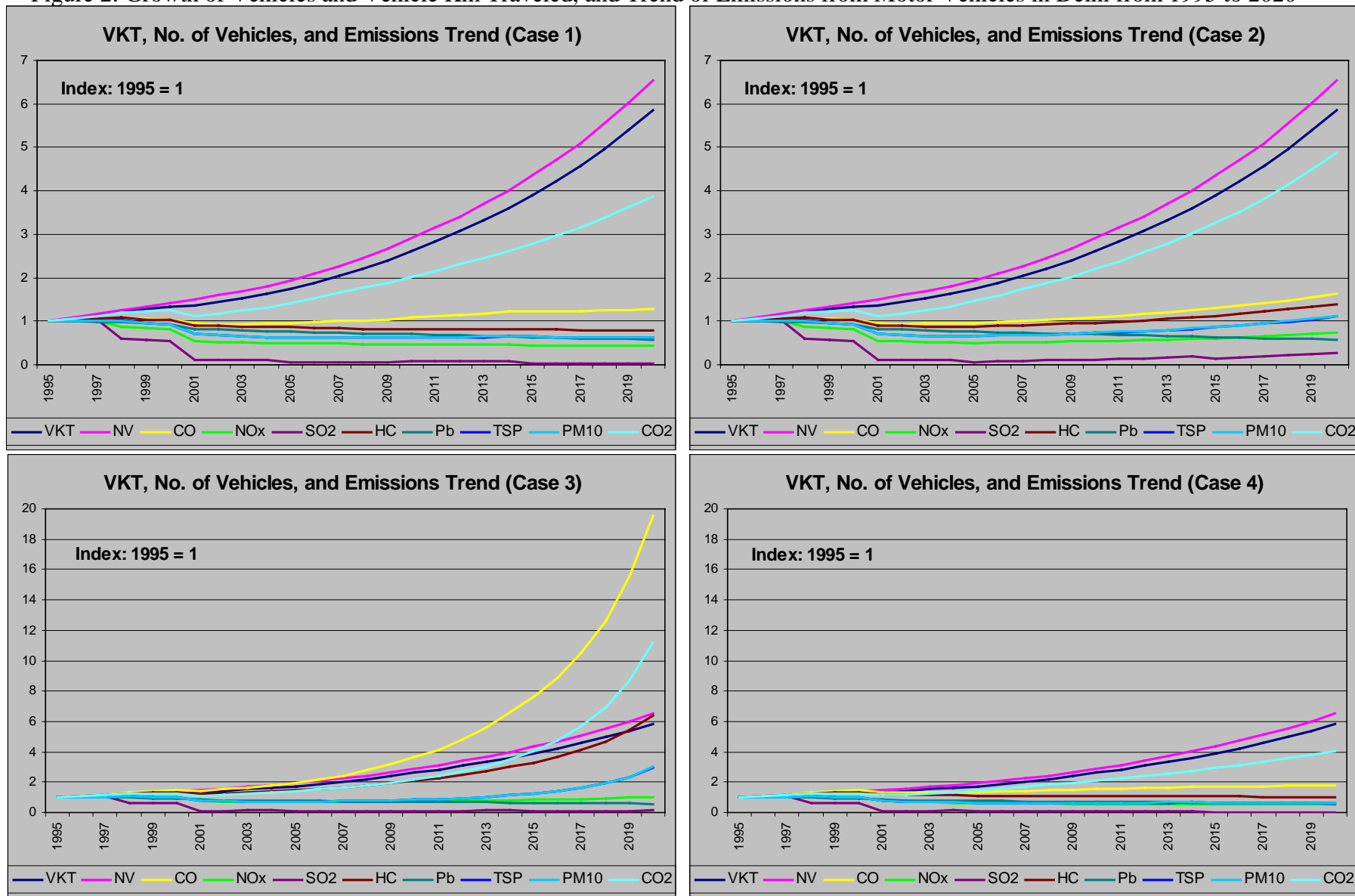


Figure 3: Average CO Emission Factors Trends for Each Vehicle Type from 1995 to 2020 in Delhi for All Cases

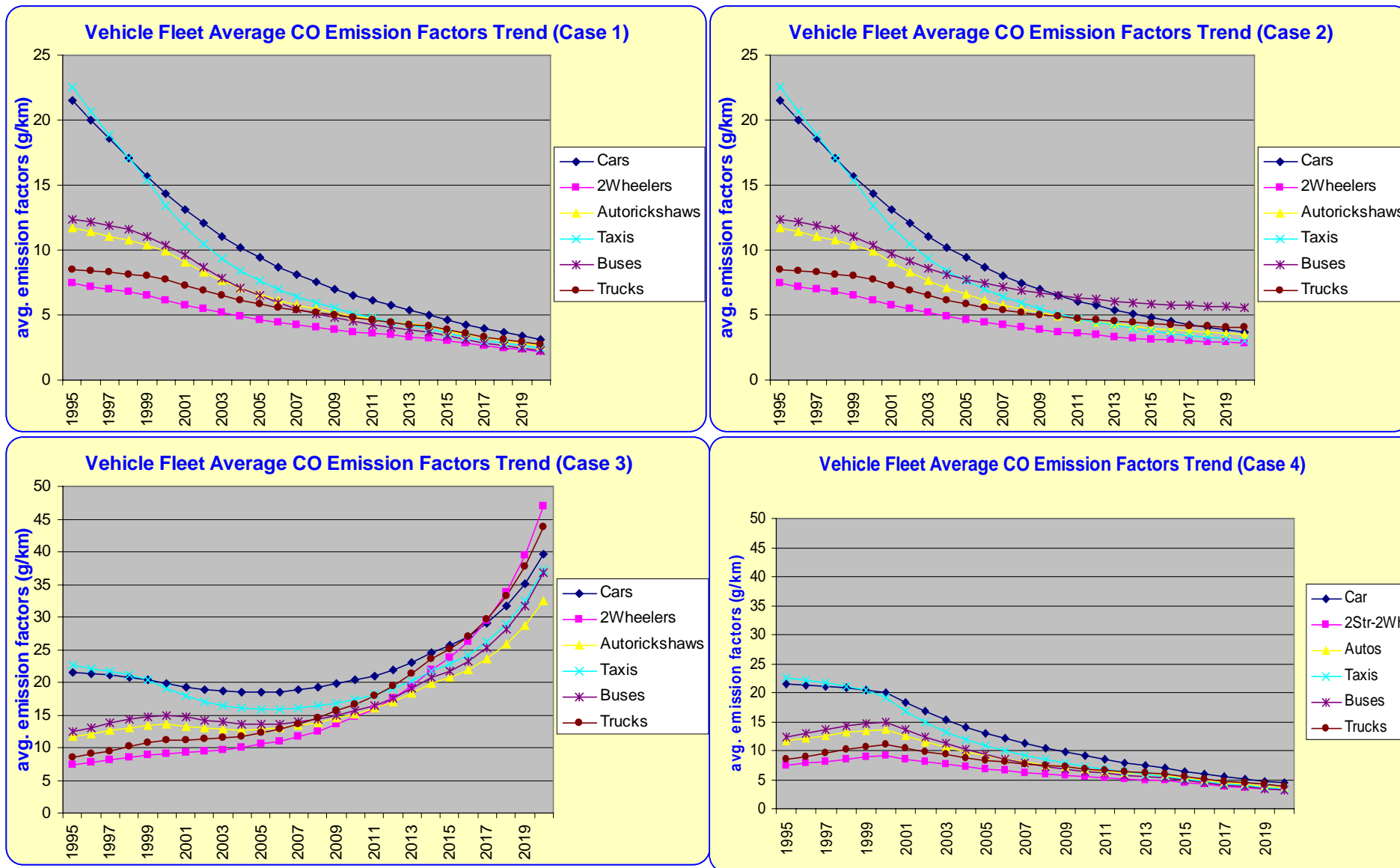


Figure 4: PM10 Emissions from Vehicles in Delhi from 1995 to 2020 for All Cases

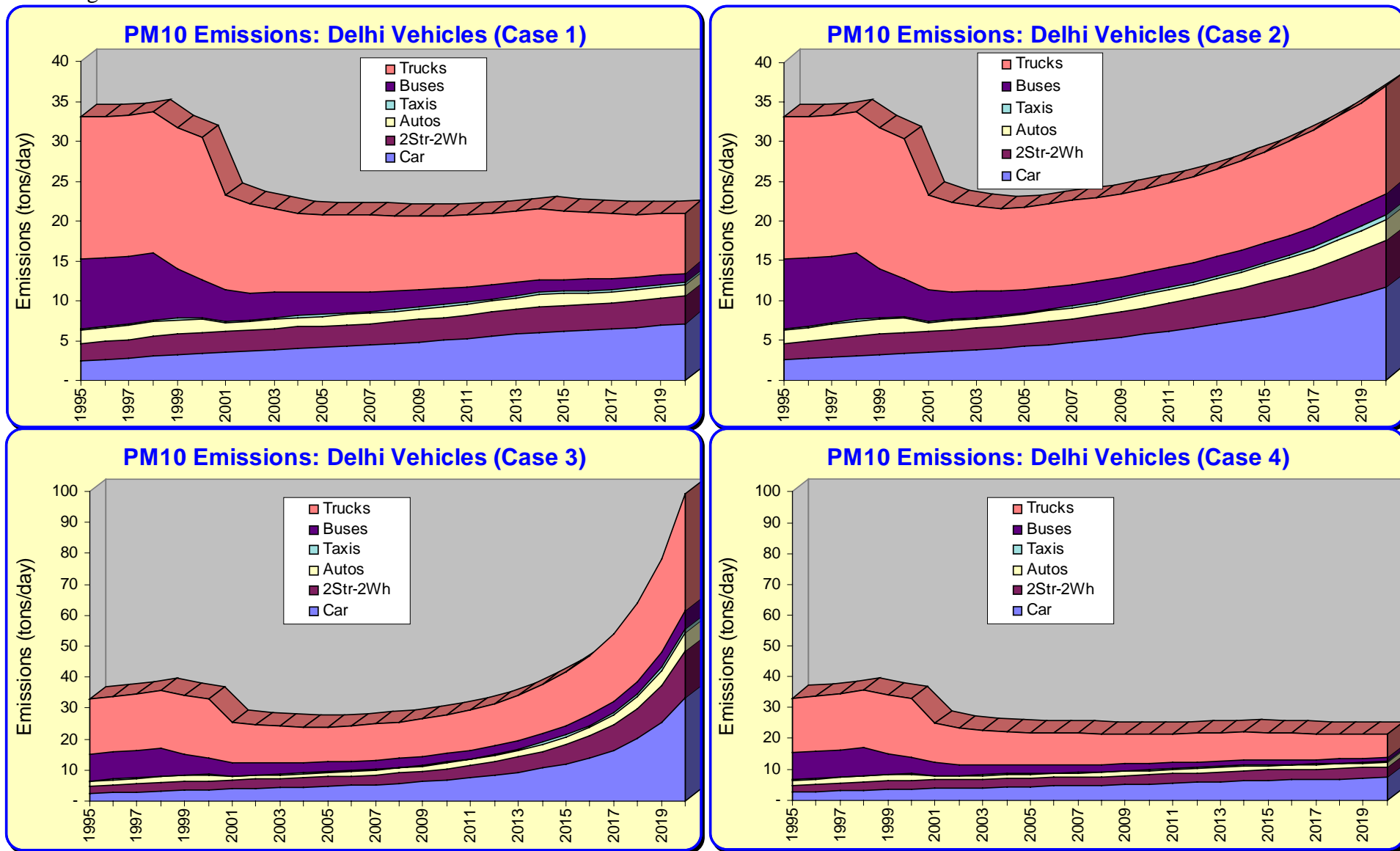


Figure 5: The Model Structure

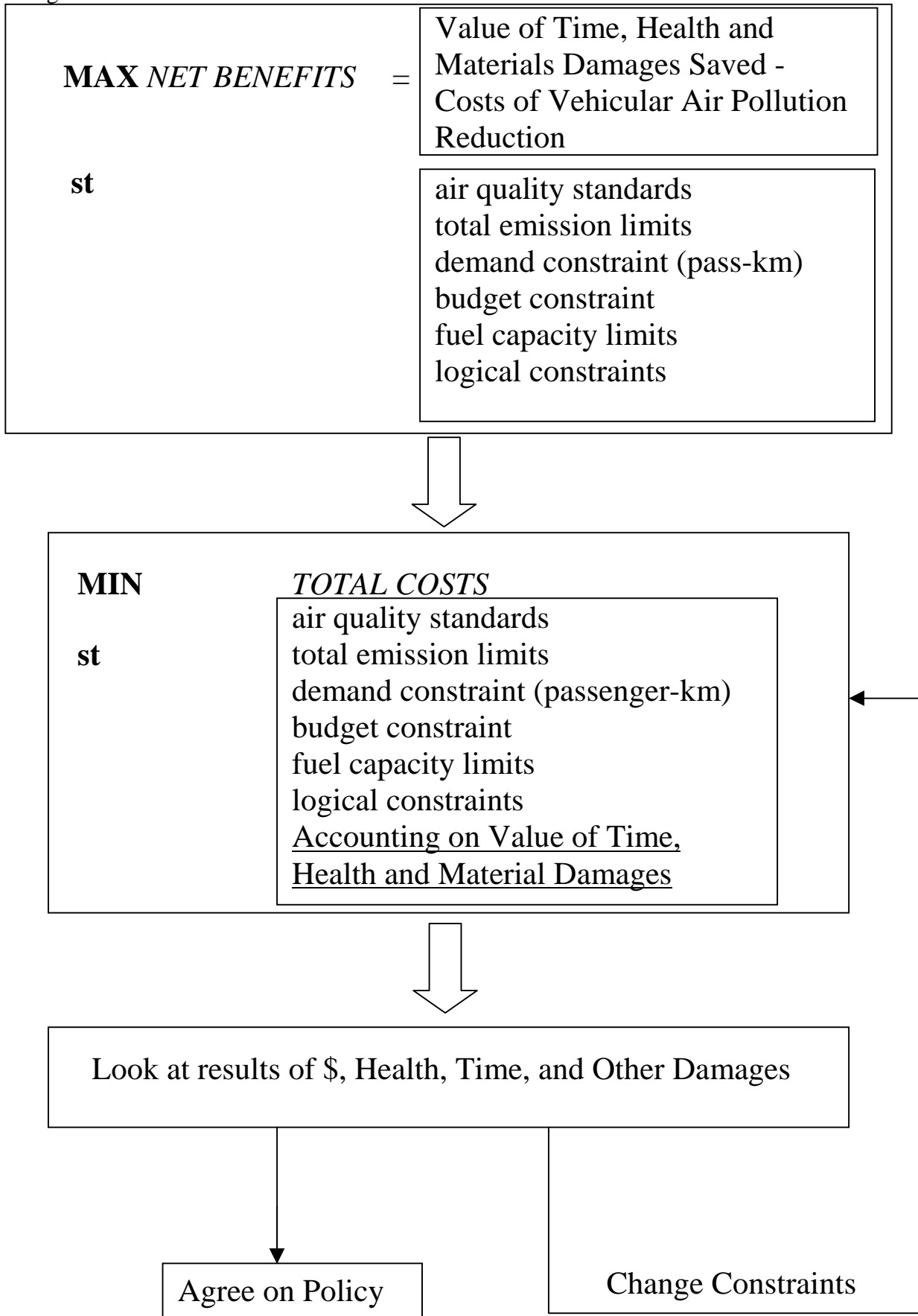


Figure 6: Interrelationships between models and GIS in the Decision Support System

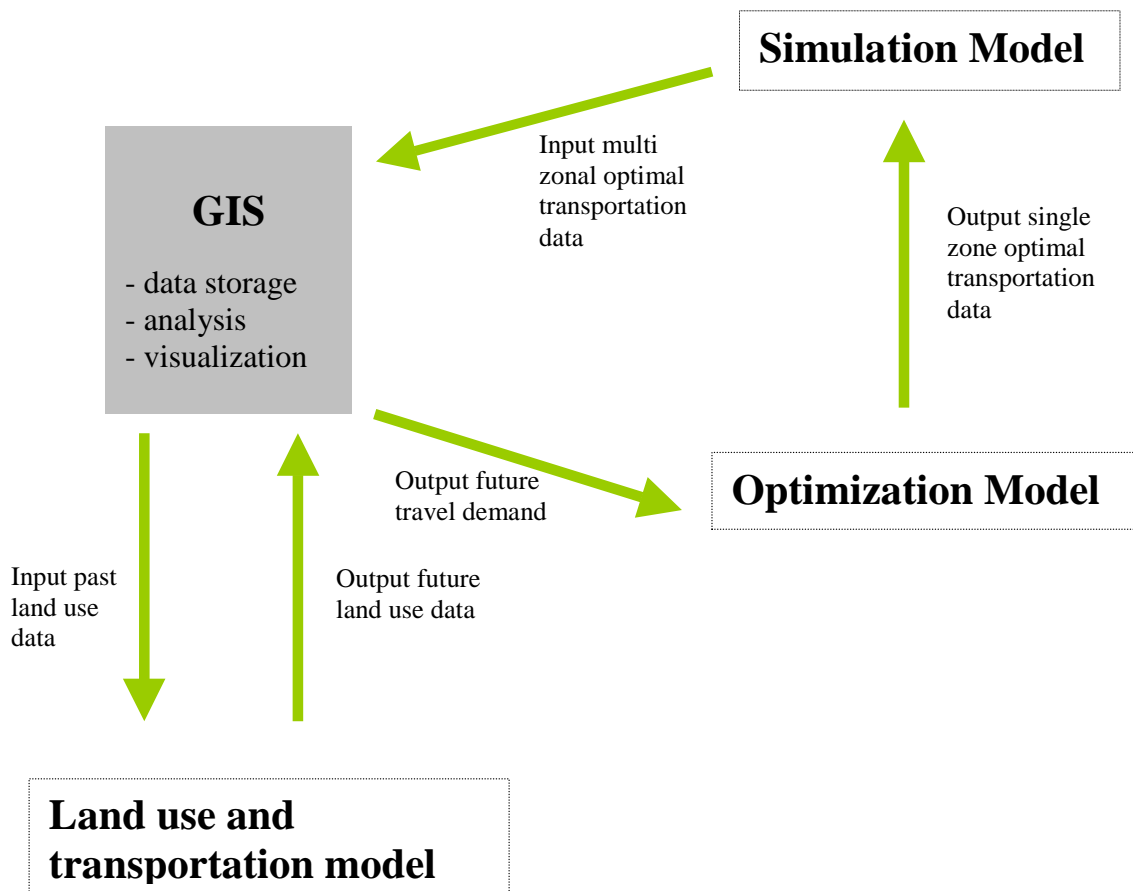


Figure 7: Interpolation of TSP over Delhi using October 2000 monthly average

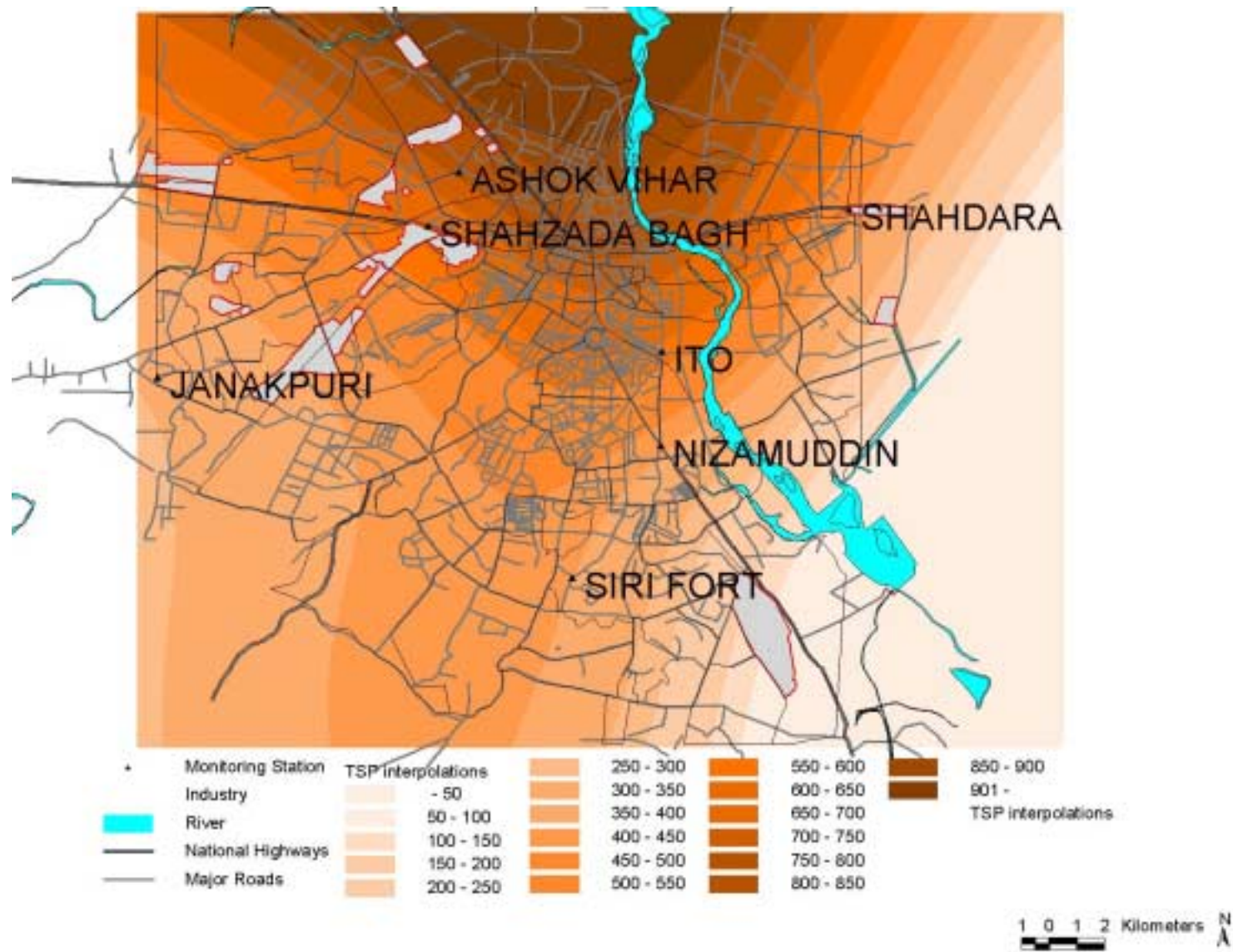
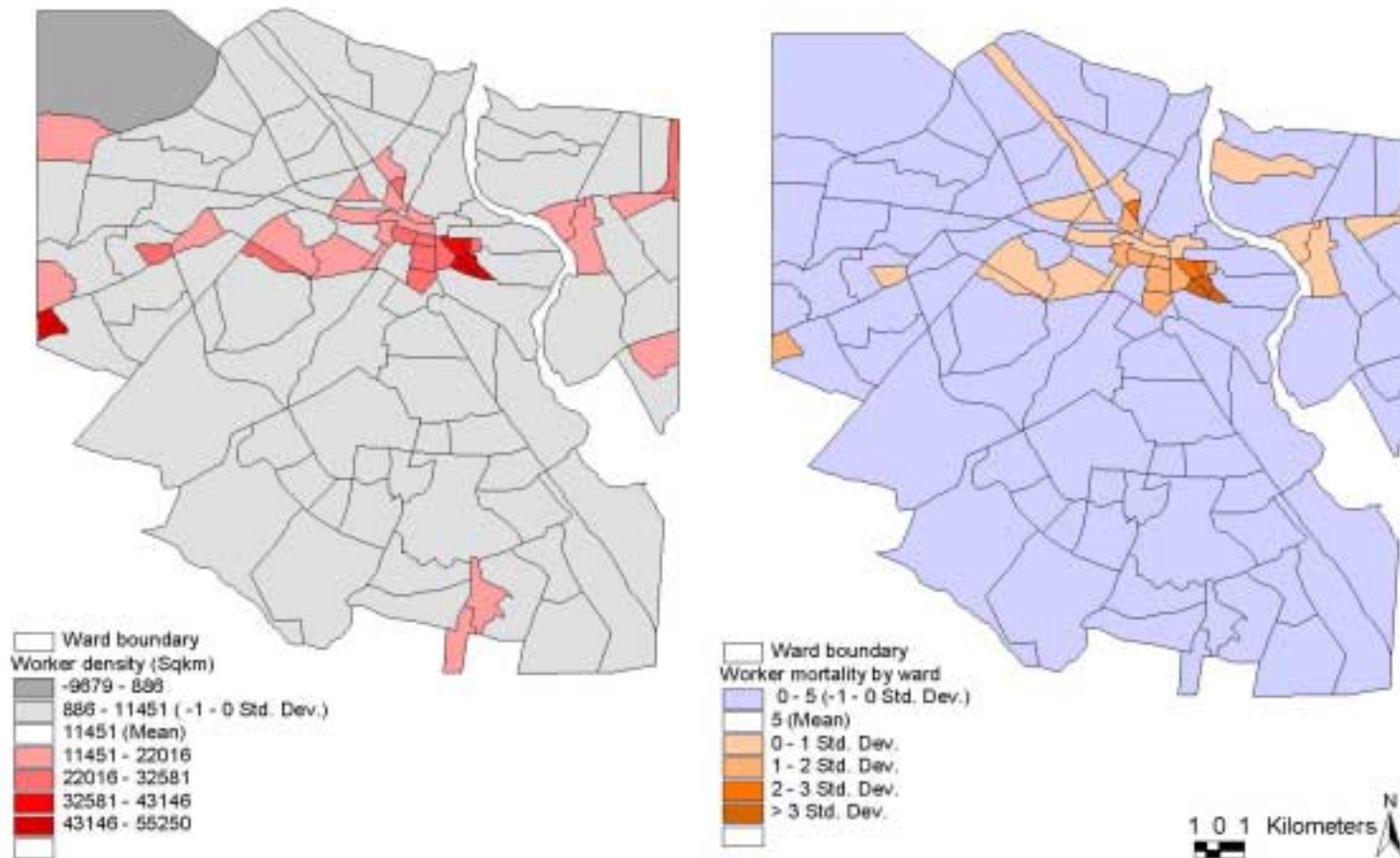


Figure 8: Worker density and mortality for October 2000 data on TSP and standard dose response coefficient



References

1. Agarwal, M K. (December 1996). Urban Transportation in India New Delhi, India: Indian National Academy of Engineering, Allied Publishers Limited.
2. Bose, Ranjan K. Sundar, S. Nesamani, K S. (2000). Clearing the air: better vehicles better fuels. New Delhi, India: TERI.
3. Bose, Ranjan Kumar. (September 1999). Towards Better Urban Transport Planning – Problems and Policies: case of Delhi. Tata Energy Research Institute (TERI). New Delhi, India.
4. Chatterjee, Arun. Miller, Terry L. et. al. (1997). Improving Transportation Data for Mobile Source Emission Estimates. National Cooperative Highway Research Program, Report 394. Washington, D.C.: National Academy Press.
5. Cropper, Maureen L. Simon, Nathalie B. Alberini, Anna. & Sharma P.K. (December 1997). The Health Effects of Air Pollution in Delhi, India. Policy Research Working Paper #1860. World Bank. Washington DC.
(http://www.worldbank.org/nipr/work_paper/1860/delhipap.pdf)
6. Department of Environment, Government of NCT, Delhi. (1995). Delhi Environmental Status Report: An Information Handbook for Citizen Action. Pollution Monitoring and Technology Co-operation Division, World Wide Fund for Nature (Eds). New Delhi, India.
7. Focas, Caralampo. (1998). The Four World Cities Transport Study. London Research Center.
8. Gomez-Ibanez, Jose A. Tye, William B. Winston, Clifford. (1999). Essays in Transportation Economics and Policy: A Handbook in Honor of John R. Meyer. Washington, DC: Brookings Institution Press.
9. Government of India. Ministry of Environment of India. (August 1997). White Paper on Pollution in Delhi with an Action Plan. New Delhi, India.
10. Hanley, P. F. and T. J. Kim. (1998). A combined economic activity and transportation model: a solution procedure and application to multi-regional planning. In Network Infrastructure and the Environment. L. Lundquist, L-G. Mattson and T. J. Kim (Eds). (pp 381-394).
11. Harshadeep, N R. (1998). Vehicular Air Pollution Information System for Delhi Software. South Asia Region Environment Unit, The World Bank. Modified by Kokaz Karolin. (2001). Division of Engineering and Applied Sciences, Harvard University.
12. Ingram, Gregory K. Liu, Zhi. (January 1999). Determinants of Motorization and Road Provision. Policy Research Working Paper 2042. The World Bank. Washington DC.
13. Ksenyia, L., et al. (October 2000). Environmental Costs of Fossil Fuels: A Rapid Assessment Method with Application to Six Cities. Environment Department Papers, No. 78. Washington DC: World Bank.
14. McCubbin, Donald R. Delucchi, Mark A. (September 1999). The Health Costs of Motor-Vehicle-Related Air Pollution. Journal of Transport Economics and Policy. Volume 33, Part 3.
15. National Capital Region Planning Board. (1999). Delhi 1999: A Fact Sheet. New Delhi, India.
16. Ostro, Bart. (May 1994). Estimating the Health Effects of Air Pollution: A Method with an Application to Jakarta. World Bank.

17. Pandey, Mihir. Gupta, Shreekant. Banerjee, Shankari. Hazra, Arnab Kumar. Kumar, Ashish. Bahari, Anjali. et. al. (October 1999). Capacity building for Integrating Environmental Considerations in Development Planning and Decision Making. National Council of Applied Academic Research. New Delhi, India.
18. Pickrel, Don. (December 1998). Cars and Clean Air: A Repraisal. U.S. Department of Transportation. Cambridge, Massachusetts: Volpe Center.
19. Saksena, Sumeet. Dayal, Vikram. (January 1997). Total exposure as a basis for the economic valuation of air pollution in India.
20. Simon, Nathalie B. Cropper, Maureen L. Alberini, Anna. & Arora, Seema. (March 1999). Valuing Mortality Reductions in India: A Study of Compensating-Wage Differentials. World Bank Working Paper Series #2078. Washington, DC. (<http://www.worldbank.org/html/dec/Publications/Workpapers/wps2000series/wps2078/wps2078.pdf>)
21. Small, Kenneth A. (1992). Urban Transportation Economics. Switzerland: Harwood Academic Publishers.
22. The Economist. (September 5, 1998). A Survey of Commuting.
23. Tiwari, Geetham. (May 1999). Planning for Non-Motorized Traffic: A Prerequisite for Sustainable Transport System. Transportation Research and Injury Prevention Programme. Indian Institute of Technology. Delhi, India. IATSS Research, Vol. 23, No. 2.
24. Tiwari, Geetham. Raje, N. R. Sengupta, B. & Goyal, Pramila. (April 1998). Workshop on Integrated Approach to Vehicular Pollution Control in Delhi. 5 Volumes. New Delhi, India.
25. U.S. EPA. (2000). Projecting land use change: A summary of models for assessing the effects of community growth and change on land-use patterns. EPA/600/R-00/098. U.S. Environmental Protection Agency, Office of Research and Development. Cincinnati, OH.
26. Vikas, Sadan. (1996). Master Plan for Delhi 2001. Delhi Development Authority. New Delhi, India.
27. Wegener, M. (1998). Applied models of urban land use, transport and environment: state of the art and future developments. In Network Infrastructure and the Environment. L. Lundquist, L-G. Mattson and T. J. Kim (Eds). (pp 245-267).
28. World Bank. (May 23, 1997). Kingdom of Morocco Environment Review.
29. World Bank. (1997). Vehicular Air Pollution: Experience from Seven Latin American Urban Cities.
30. Wormley, David. (1997). Critical Issues In Transportation. Pennsylvania State University. US Transportation Research Board.

Web-page Sources:

1. <http://www.arij.org/profile/vol8/chapter10.htm>
2. <http://auto.indiamart.com/going-green/euro-norms.html>
3. <http://auto.indiamart.com/going-green/emission-standards.html>
4. <http://auto.indiamart.com/going-green/india-in-euro-norms2.html>
5. <http://www.eia.doe.gov/emeu/cabs/india.html>
6. <http://ens.lycos.com/ens/sep2000/2000L-09-25-03.html>

7. <http://envfor.nic.in/cpcb/> (Ambient concentrations as measured by 7 stations in Delhi from CPCB webpage)
8. <http://law.indiainfo.com/environment/euro1.html>
9. <http://solstice.crest.org/efficiency/nrdc/mobility/airpollu.html>
10. <http://www.bts.gov/NTL/DOCS/taq2.html>
11. <http://www.bts.gov/NTL/DOCS/images/LBDAP/TAQ2T1.GIF>
12. <http://www.bts.gov/NTL/DOCS/images/LBDAP/TAQ2T1B.GIF>
13. http://www.cseindia.org/html/dte/dte20010315/dte_analy.htm
14. <http://www.delhimetrorail.com>
15. <http://www.dieselnet.com/news/9904in.html>
16. <http://www.dieselnet.com/standards/eu/ld.html>
17. <http://www.epa.gov/OMSWWW/ld-hwy.htm>
18. <http://www.hindubusinessline.com/1999/11/24/stories/042467mu.htm>
19. <http://www.iglindia.com/press/clip7.htm>
20. <http://www.india-today.com/itoday/17051999/biz.html>
21. <http://www.odci.gov/cia/publications/factbook/geos/in.html>
22. <http://www.oneworld.org/cse/html/cmp/cmp53.htm#ca> (Down to Earth Publications)
23. http://www.oneworld.org/cse/html/dte/dte990531/dte_news.htm
24. http://www.oneworld.org/cse/html/dte/dte991031/dte_analy.htm
25. <http://www.teriin.org/reports/rep02/rep0205.htm>
26. <http://www.teriin.org/urban/accident.htm>
27. <http://www.teriin.org/urban/gasoline.htm>
28. <http://www.teriin.org/urban/stats.htm#per>
29. <http://www.teriin.org/urban/urban.htm>
30. <http://www.unfoundation.org/unwire/archives/UNWIRE990519.cfm#12>