

Systems Analysis of Personal Transportation Needs and Environmental Implications in India

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Presentation Outline

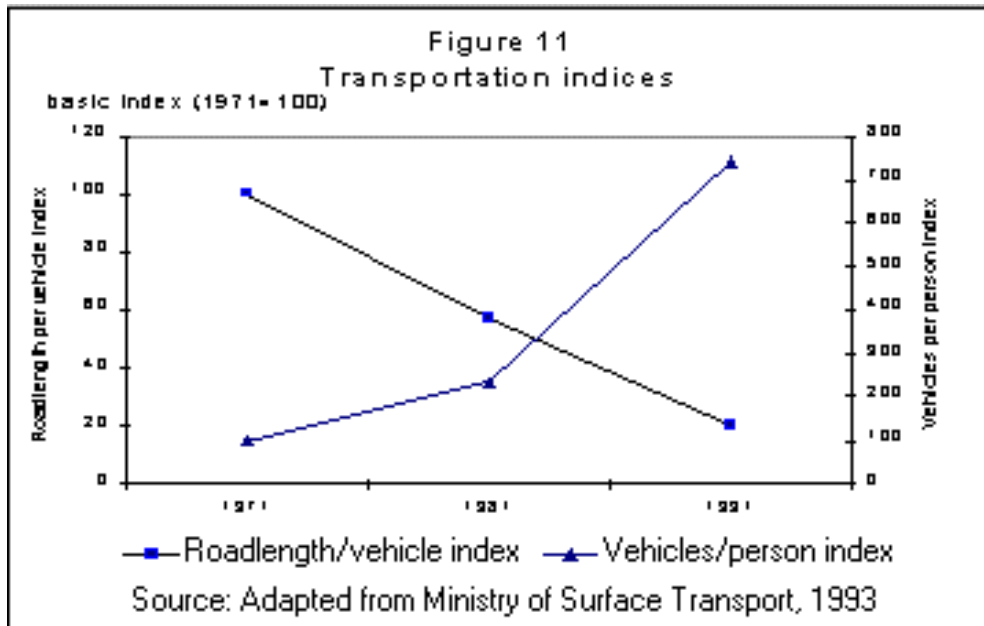
- Brief introduction to India
- Spreadsheet Vehicular Air Pollution Information System for Delhi
- Motivation for the Optimization Model
- The Optimization Model - Urban Transportation Planning for Air Quality Management

Purpose

- * *Automobile emissions are the most rapidly growing source of urban air pollution in most developing cities.*
- Evaluate strategies and policies for guiding the development of Delhi's transportation sector.
- Determine the impact of economic policies and environmental regulations on future technology choices.
- Analyze the technological and traffic demand and supply options available to India (Delhi) to reduce vehicular pollution.
- Develop a mathematical model that 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.

Facts about India

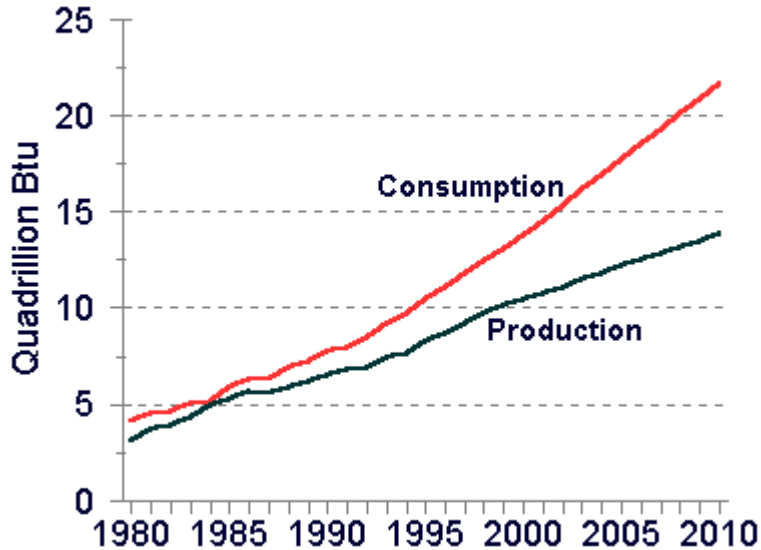
- World's seventh largest country (3,288,000 km² - 2.2% of global land)
- World's second most populous country (population: 989 million in 1998; projected 2020 population: 1330 millions)
- Urban population growing: 1981 - 160 million, 1994 - 234 million, and 2001 and 2020 expectations 350 and 472 millions, respectively (Urban population density in 1994 was 3462 persons/km².)
- Fifth largest carbon emitter in the world in 1997 (237mtce)
- Oil demand has increased by 72% from 1986 to 1996 and by 4.7% from 1996 to 1997
- Indian economy expands at 5.5% per year
- India's GDP has increased 2.5 times over the past two decades while vehicular pollution and pollution from industries have increased by 8 and 4 times, respectively.
- A report from MoEF estimates that the annual cost of environmental degradation in India in the past few years has been averaging about 4.5% of GDP.
- Auto emissions currently account for approximately 70% of air pollution.
- Turnover period of vehicles is about 20 years compared to 6-8 years in developed countries.
- Every time GDP doubles in India, air pollution rises by 8 times



- The figure on the left shows how road length per vehicle and vehicles per person has changed from 1971 to 1981 and to 1991 in India.
- Total length of roads grew from 917,000km in 1970/71 to 2,103,000km in 1990/91 and to 3,320,000km in 1995/96.
- 3 - 4 cars per 1000 inhabitants
- Projection of 16 million cars in 2015

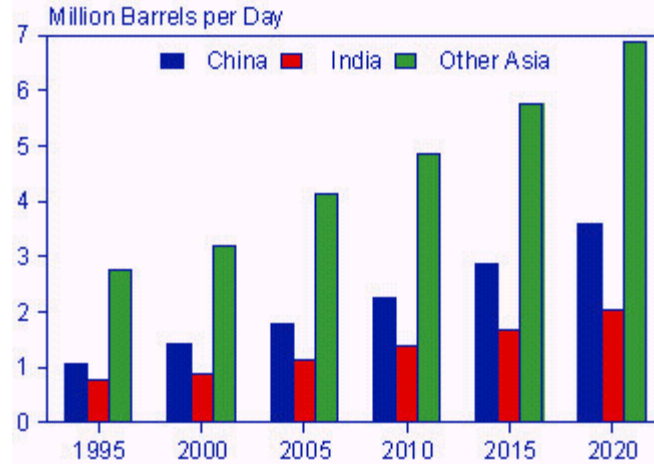
- The number of vehicles has increased by 11.5 times from 1.9 millions in 1970 to 21 millions in 1990 and number of vehicles per 1000 people has increased from 3.4 to 25.31 in the same time. There were 25.2 million vehicles registered in India in 1993 of which 12% was cars (33.85 million registered vehicles in 1996). Projections for year 2000's number of vehicles per 1000 people is 43 (MST 1993).
- High shares of NMV (walk trips, bicycles, rickshaws) and motorized two wheelers

India's Energy Balance



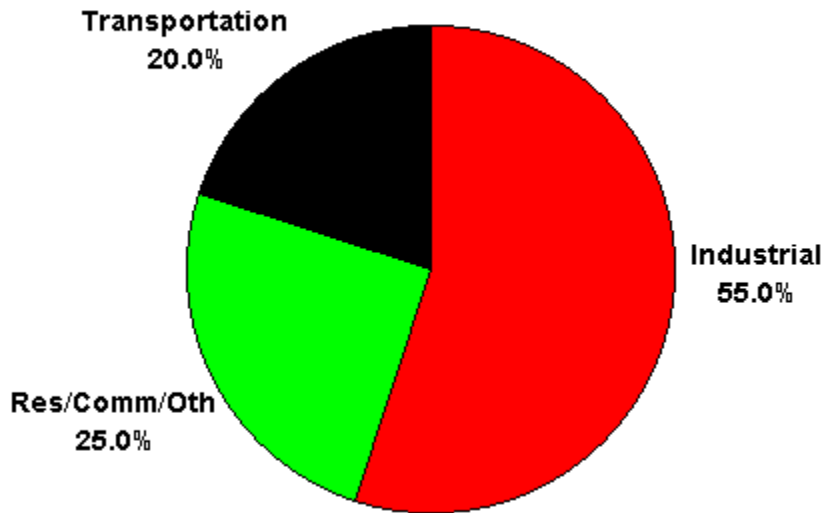
Source: U.S. Energy Information Administration

Oil Demand for Transportation in Developing Asia, 1995-2020



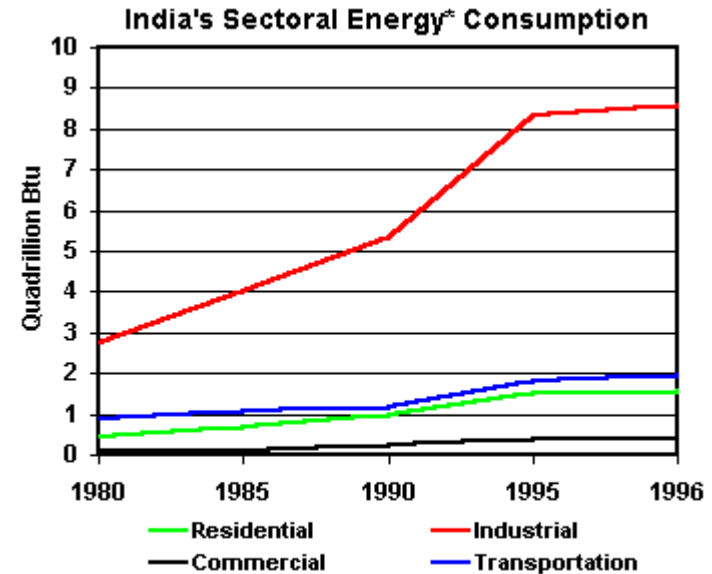
- Energy supply shortfall of India has been increasing since 1985. India's rapidly growing economy will drive energy demand growth at a projected annual rate of 4.6 percent through 2010. This is the highest incremental energy demand rate of any major country.
- India's average oil production level for 1999 was estimated at 659,000 bbl/d. India imported over 1.1 million bbl/d in 1998. Growth in oil demand on average was 3.6% per year from 1995 to 2000.

India's 1995 Energy Demand by Sector



(Total Consumption = 10.5 Quadrillion Btu)

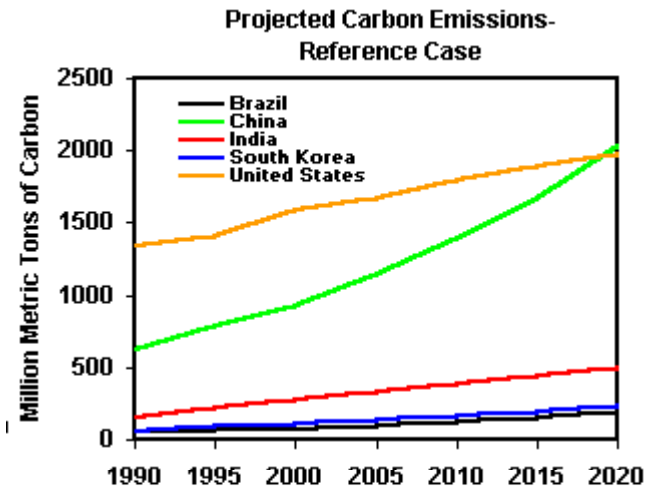
Source: U.S. Energy Information Administration



* Excludes solid biomass and animal products, biomass gas and liquids, and industrial and municipal wastes.

Energy consumption in 1995 was 10.5 Quadrillion BTU (2.9% of the world's energy consumption) and in 1996 it increased to 12 Quadrillion BTU.

Share of transport's energy use in 1996/1997 has increased to 22.94%. Transportation sector's energy consumption increased from 1.2 quads in 1990 to 1.95 quads in 1996.



Carbon Dioxide Emissions from the Consumption and Flaring of Fossil Fuels, 1989-1998 (Million Metric Tons of Carbon)

Country	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
India	144.43	153.79	159.55	173.58	185.73	195.15	225.69	235.33	244.61	252.55

Energy-related carbon emissions from India have grown nine-fold over the past four decades. With 237 million metric tons of carbon released from the consumption and flaring of fossil fuels in 1997, India ranked fifth in the world behind the United States, China, Russia and Japan. India's contribution to world carbon emissions is expected to increase in coming years.

14% of CO₂ emissions come from transportation with an upward trend. (Xie, Shah, Brandon)

Annual Incidence of Respiratory Health Effects due to PM10 in 1995 in India

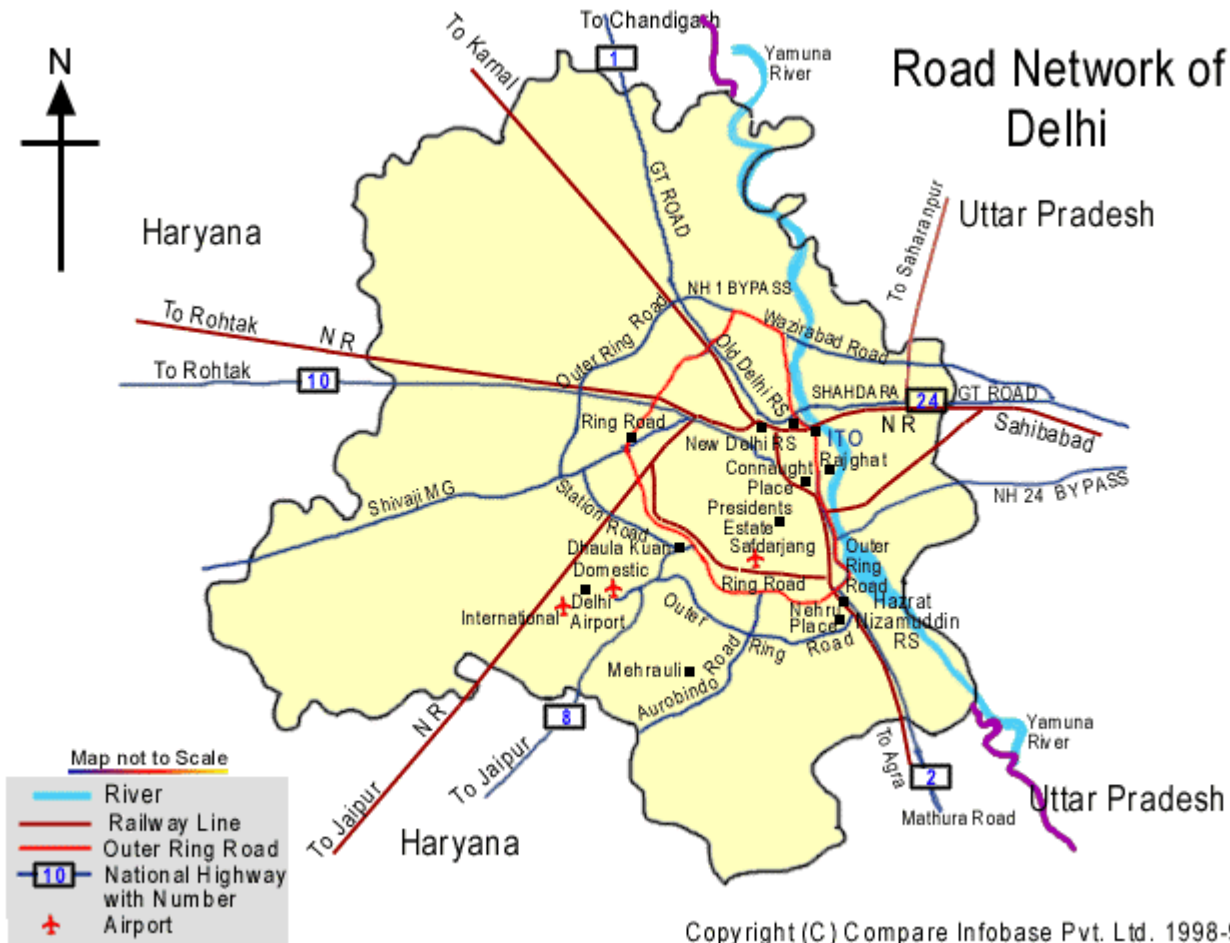
	Annual Incidence Rate (millions)
Premature Mortality	2.4
Respiratory Hospital Admissions	2.5
Emergency Room Visits	51
Restricted Activity Days	5,720
Lower Respiratory Illness	143
Asthma Attacks	484
Respiratory Symptoms	38,500
Chronic Bronchitis	13

Estimated per capita Health Costs (US\$/year)

Strata of Population	Low Estimate	High Estimate
By Location		
• Rural	1800	5600
• Slum	2000	7400
• Urban, non-slum	600	1500
By Gender		
• Female	2000	6000
• Male	1400	4400

Source: Saksena, Sumeet, Dayal, Vikram, “Total exposure as a basis for the economic valuation of air pollution in India”, January 1997.

Case 1: Delhi



WHO announces Delhi to be one of the top ten most polluted cities in the world!

- 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.
- Particulate pollution kills 1 person per hour in Delhi
- WHO: Delhi is the 4th most polluted city in the world in terms of SPM.
- 30% of the population suffers from respiratory disease in Delhi (12 times the national average) (India Today, August 31, 1991)
- One out of two policemen suffers from respiratory diseases and one in every four have been diagnosed positive for initial symptoms of tuberculosis (Times of India, October 1998).
- If air pollution is reduced to WHO annual average standards than 7500 premature deaths, 4 millions hospital admissions and sickness requiring medical treatment, and 242 millions of incidence of minor sicknesses (including RADs and RSDs) could be avoided in Delhi. (Source: Jian Xie, Jitendra J. Shah, Carter J. Brandon, “Fighting Urban Transport Air Pollution for Local and Global Good: The case of two-stroke engine three-wheelers in Delhi”, 1998.)

Air pollution kills in Delhi!

Main sources of pollution are:
vehicular emissions
untreated industrial smoke



Air Pollutant Emissions (1990s):

Domestic - 8%

Industrial - 12%

Power Plants - 16%

Motor Vehicles - 64% (67% in 1997)

Percentage Share of Air Pollution by Various Sources in Delhi

(%)	1970-1971	1980-1981	1990-1991	2000-2001
Industrial	56	40	29	20
Vehicular	23	42	63	72
Domestic	21	18	8	8

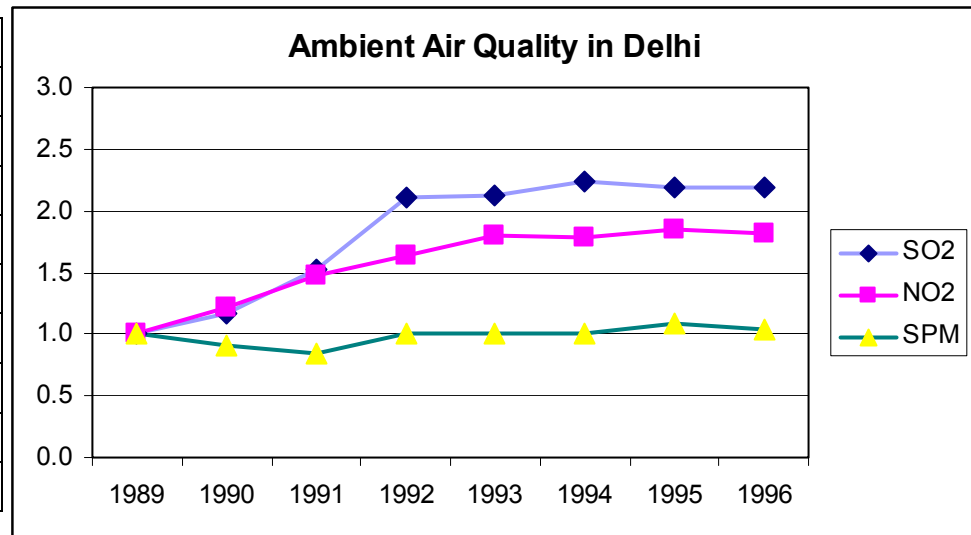
- With the Supreme Court directive of relocating polluting industries outside Delhi, share of vehicular pollution will go up significantly.
- TERI 1996: Delhi is the most congested city in India.
- Vehicle emissions account for 65% of the air pollution in Delhi and cause a similar proportion of the 9,900 deaths due to air pollution each year.

Annual Ambient Air Quality Standards in Delhi

Pollutant ($\mu\text{g}/\text{m}^3$)	Concentration in Ambient Air			WHO ($\mu\text{g}/\text{m}^3$)
	Industrial	Residential	Sensitive	
SO ₂	80	60	15	40-60
NO _x	80	60	15	
SPM	360	140	70	60-90
PM10	120	60	50	50
CO (mg/m^3)	5	2	1	

Ambient Air Quality in Delhi (annual average - $\mu\text{g}/\text{m}^3$)

	SO ₂	NO ₂	SPM
1989	8.7	18.5	373
1990	10.2	22.5	338
1991	13.3	27.2	317
1992	18.4	30.4	377
1993	18.5	33.2	372
1994	19.5	33.0	377
1995	19	34.1	407
1996	19	33.7	387
1997 (Jan-Aug)	16.2	33.0	370



Delhi's Vehicle Fleet (1)

Current and Projected Vehicle Population

year	1996	1997	1998	1999	2001	2011
# of vehicles	2,734,400	2,904,359	3,033,000	3,210,000	3,924,000	6,000,000

- Personal vehicles account for almost 90% of all vehicles in Delhi - largely single occupancy, therefore not very efficient as a transport mode.
- Average ownership of private vehicles: 178 vehicles/1000 people in 1995-1996. Total # of motor vehicles per 1000 people was 205 in 1993 (and 238 in 1998).
- Delhi has the highest road length in India: 1284km/100km² area (26,379km of total length in 1998/99)

• 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.

• Delhi's roads, if well traffic management is applied, can accommodate 2-3 times the existing number of vehicles.

• Source: Indian Institute of Technology, May 1997

Delhi's Vehicle Fleet (2)

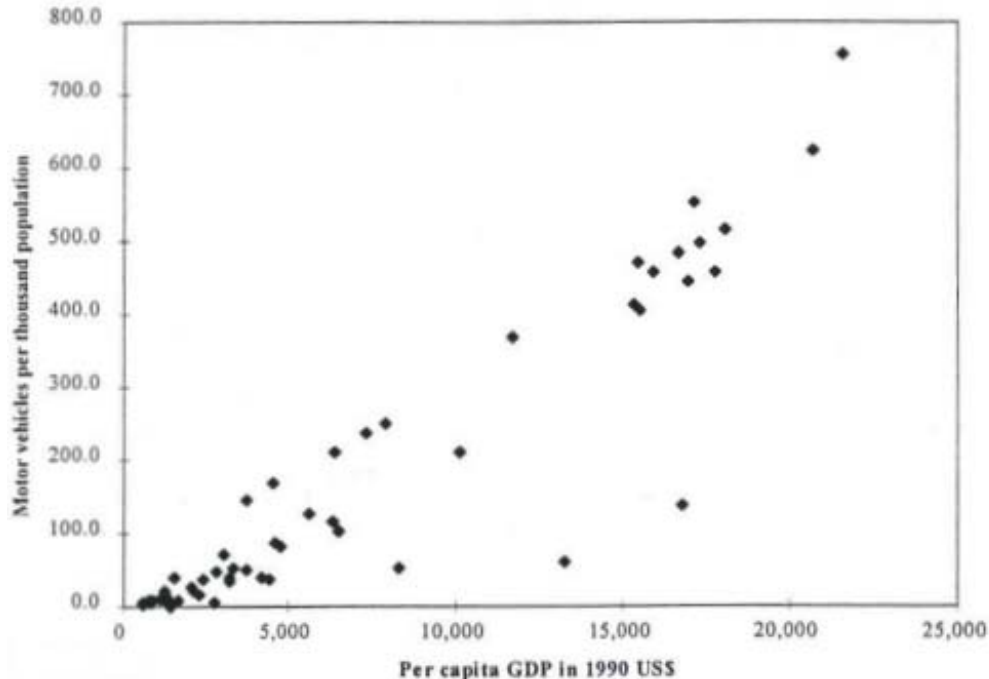
Growth of Population and Registered Motor Vehicles in Delhi				
	1970-1971	1980-1981	1990-1991	1995
population (millions)	3.65	6.22	9.42	
# of vehicles	204,078	557,000	1,813,000	2,432,320

- 1970 → 1990: population more than doubled while number of vehicles changed by 9 times
- 1980 → 1995: population increased by 67% while number of vehicles increased by 334% (TERI Statistics)
- Delhi has 1% of the entire country's population but 10% of the total vehicles registered in India (largest vehicle population in the country).

Current and Projected Population and registered Motor Vehicles

year	1996	1997	1998	1999	2001	2006	2011
# of vehicles	2,734,400	2,904,359	3,033,000	3,210,000	3,924,000		6,000,000
population (million)				13.42	14.36	17.16	19.51

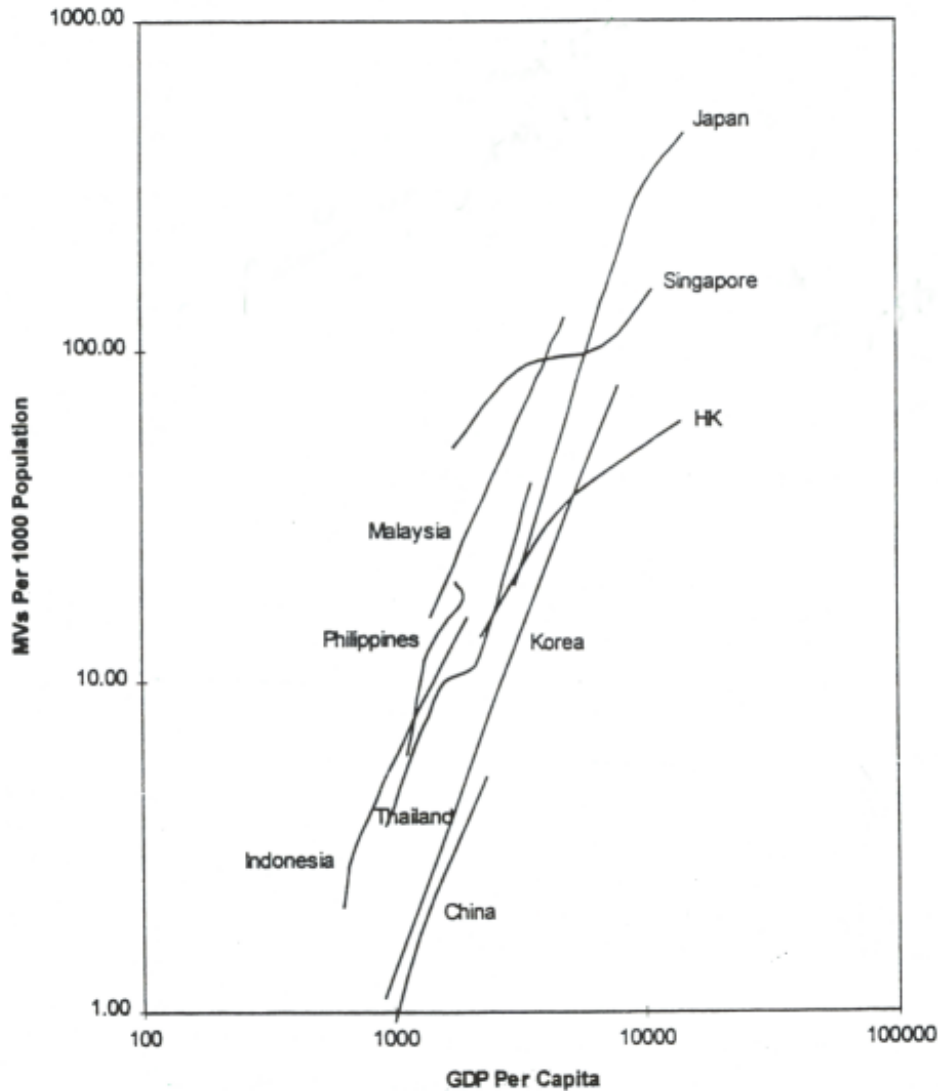
FIGURE 3: PER CAPITA INCOME AND MOTOR VEHICLE OWNERSHIP
IN 52 COUNTRIES OR REGIONS



- Clearly it can be seen from this graph from other countries experiences in the world that as per capita GDP increases motor vehicle ownership increases at a more than proportional rate.
- GDP-ppp/capita of India has been increasing: \$1240, \$1420, and \$1720 in 1993, 1995, and 1998 respectively. Number of vehicles per 1000 people was 25.31 in 1990 and is expected to grow to 43 by the year 2000 in India.
- Price elasticities are lower than income elasticities. Price elasticities (for fuel taxes) in India was found to be -0.52 (Imran and Quan, 1992).

Source for above figure: Stares and Zhi, "Theme Paper 1: Motorization in Chinese Cities: Issues and Actions

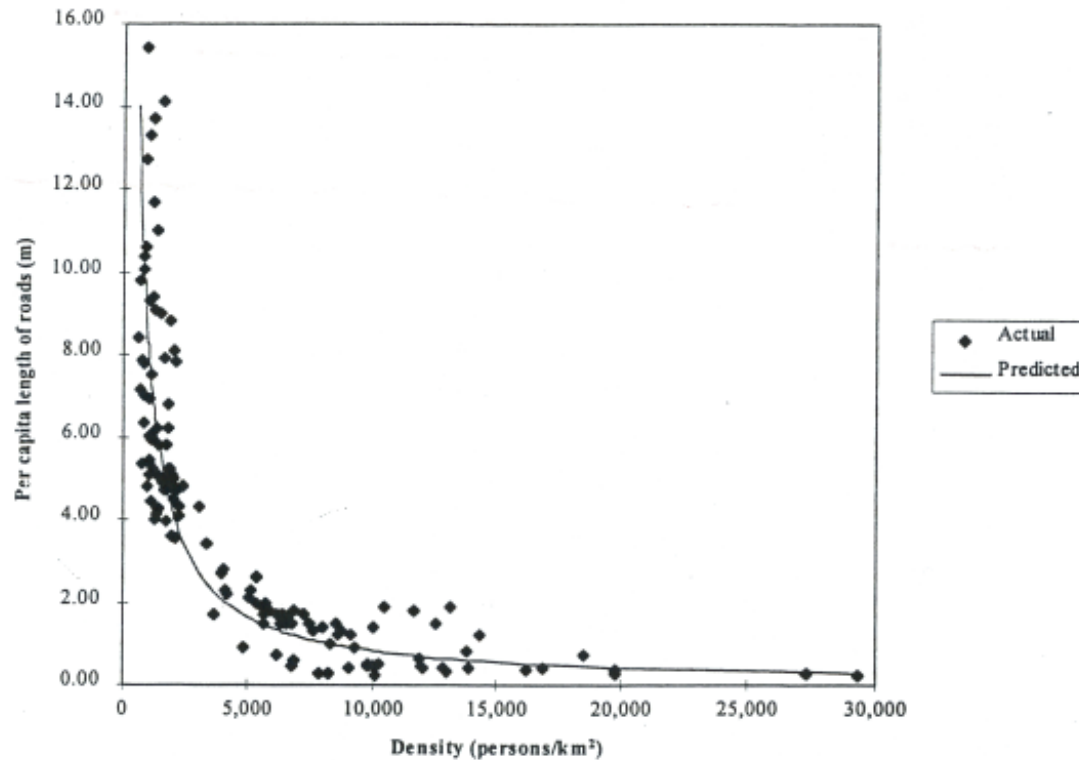
FIGURE 10: EAST ASIA MOTORIZATION, 1960-90



- This graph on the x-axis starts at 1960 on the left and goes until 1990 on the right.
- Examples of traffic management effects on the vehicle ownership can be seen for Singapore and Hong Kong.
- Still the same trend of increasing vehicle ownership with increasing GDP per capita is evident from this graph.

Source: Stares and Zhi, "Theme Paper 1: Motorization in Chinese Cities: Issues and Actions"

FIGURE 7: RELATIONSHIP BETWEEN URBAN POPULATION DENSITY AND PER CAPITA LENGTH OF URBAN ROADS
(137 observations for 65 world cities)



- 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.

- Delhi’s roads, if well traffic management is applied, can accommodate 2-3 times the existing number of vehicles.

- Source: Indian Institute of technology, May 1997

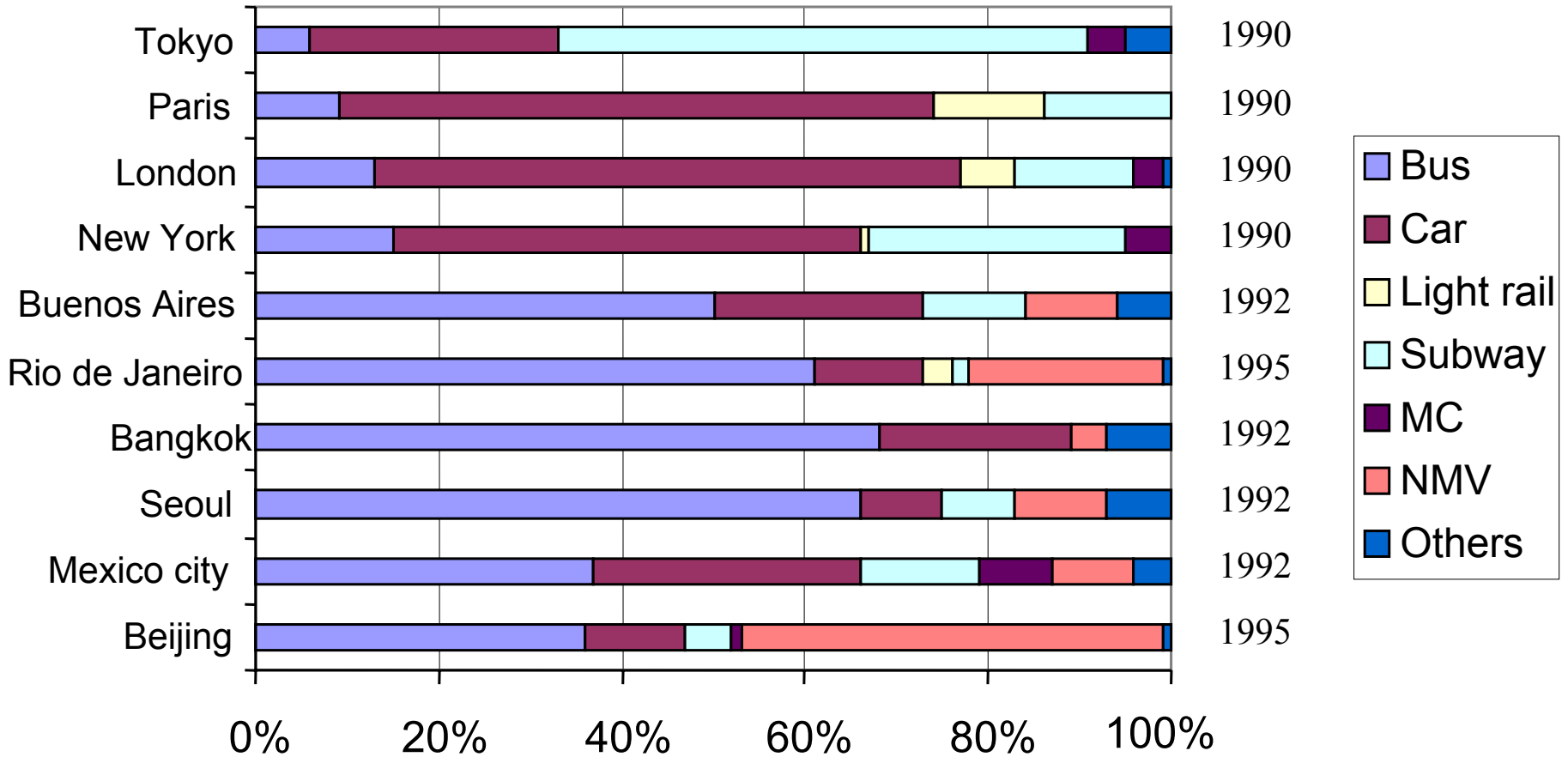
Delhi	Km of road / 1000 people	# of vehicles / 1000 people
1995	2.27	238

Delhi had 26,379km of road length in 1998/1999 and 90 vehicles/km of road in 1992.

Delhi urbanization: 57.5% of population living in urban area in 1911 → 90% in 1991. Population density in urban area in 1991 was 12,361 people/km² and in rural area 1,190 people/km².

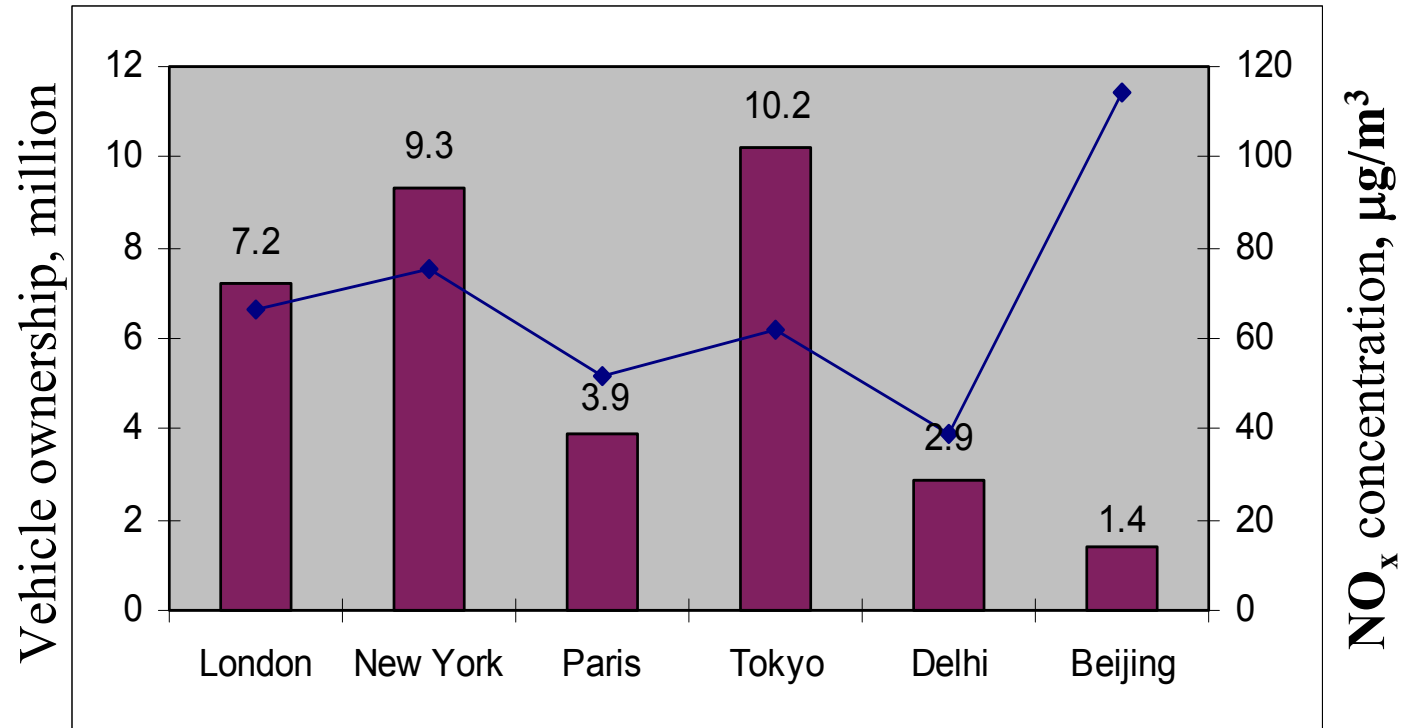
Source for above figure: Stares and Zhi, “Theme Paper 1: Motorization in Chinese Cities: Issues and Actions

Comparison of passenger trip mix among big cities in the world



Delhi, 1994	Buses	Cars	Light Rail/Subway	MC	NMV	Others
%	62.00%	6.94%	0.00%	17.59%	6.61%	6.86%
Others:	Autorickshaws	Taxis	Rail	Others		
%	2.80%	0.06%	0.38%	3.62%		

Comparison of Vehicle Ownership and Pollution in Big Cities in the World



Data for Delhi vehicle number is in 1997, NO_x pollution is monthly average in 1998. Data for Beijing is in 1998. Others are in 1990.

Air Pollution in Different Cities in the World in 1995 ($\mu\text{g}/\text{m}^3$)

City	TSP	SO ₂	NO ₂
Beijing	377	90	122
Delhi	415	24	41 (NO _x 47.2)
Tokyo	49	18	68
Mexico City	279	74	130
London		25	77
New York		26	79
Los Angeles		9	74

Share of Air Pollutant Emissions from the Mobile Sector

	CO	HC	NO _x	SO ₂	PM
Mexico, 1994	100%	53.3%	70%	26.5%	4.3%
Santiago, 1992	94.2%	82.7%	84.6%	24%	11.5%
São Paulo, 1995	96.4%	90.9%	97.3%	85.5%	42.7%
Rio de Janeiro, 1978	96.4%	73.2%	69.6%	9.5%	3.5%
Beijing, 1992	63.4%	73.5%	21.7%		
Beijing, 1995	86.2%		49.1%	10%	
Delhi, 1995	80.5%	95.2%	69.4%	4.6%	6.6%

Source: World Bank Report. Vehicular Air Pollution: Experience from Seven Latin American Urban Cities, 1997. Data in Beijing comes from the report titled China's Strategies for Controlling Motor Vehicle Emissions, 1997.

Comparison of Road Infrastructure & # of Vehicles in Big Cities in the World

	Road Supply (m/person)	Total Vehicles per km of Road
New York (1991)	4.70	99
Paris (1991)	0.90	410
London (1991)	1.90	186
Tokyo (1991)	1.90	140
Beijing (1995)	0.94	50
Delhi (1992)	2.17	90

Source: Newman and Kenworthy (1991). For Beijing; "China's Strategies for Controlling Motor Vehicle Emissions: Summary Report", China Environmental Technical Assistance Project: B-9-3, World Bank, May 1998.

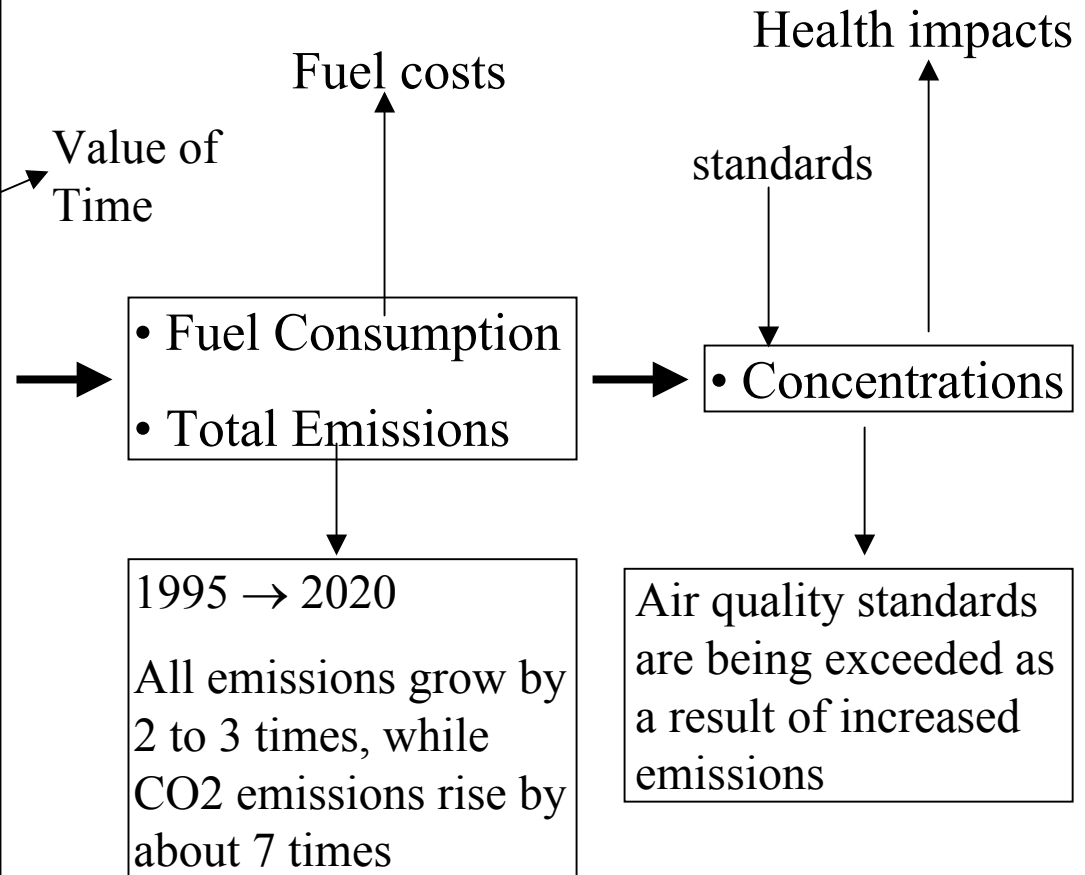
Delhi	1972	1981	1991	1997	1999	2001	2011
road length (km)	8,380	14,320	21,670	25,949	26,379		
# of vehicles (millions)	0.214			2.848	3.21	3.924	6
Speeds (km/hr)	23	19	18	15		10	5

Road length increased by 3 times from 1972 to 1997 in Delhi while # of vehicles increased by 13 times!

In 1997, road length in Delhi was 1749km of road per 100 km² while in India it was 73km/100km² in 1996.

Assumptions:

- Fuel Quality
- Average speed, vehicle growth rates, VKT, occupancy, fuel efficiency improvements, average trip distance
- Retirement age
- Base year emission factors and fuel efficiencies
- New vehicle emission factors
- # of vehicles vs speed
- Speed vs emission factors and fuel efficiencies
- Final scaled emission factors and fuel efficiencies



For testing only new vehicle emissions standards.

Speed Effect on Fuel Efficiencies and Emission Factors

$$RA(t) = RA95 + \text{SUM}(t, AM(\text{"ro"}, t) \times \text{width})$$

$$\text{Speed}(t) = [-10.635 \times \ln(NV(t)) + 168.3] \times [RA(t)/RA95] \times (1 + \Sigma \text{fri}^1) \times (1 \pm \text{fhb}^2)$$

$$FE_{\text{old}}(v, f, t) = FE95(v, f) \times [(1 + \text{imp}^3(v, f)/100)^{\text{ORD}(t)-1}]$$

$$FE_{\text{new}}(v, t) = A(v) \times \text{Speed}(t)^{0.2501}$$

$$FE(v, f, t) = FE_{\text{old}}(v, f, t) \times FE_{\text{new}}(t) / FE_{\text{new}}(\text{"1995"})$$

$$EFs(p, v, f, t) = A(v, p, f) \times \text{Speed}(t)^{B(v, p, f)}$$

$$EF(p, v, f, \text{"avg"}, t) = E = [(\text{SUM}(f, EF(p, v, f, \text{"0"}, t)) \times NV(v, \text{"0"}, f, t)) + \text{SUM}((a, f), EF(p, v, f, \text{"avg"}, t-1) \times NV(v, a, f, t))] / (\text{SUM}((f, a), NV(v, a, f, t))) \times EFs(p, v, f, t) / EFs(p, v, f, \text{"1995"});$$

$$EF(\text{"SO}_2", v, f, \text{"avg"}, t) = E = 2 \times \text{scontent}^4 \times \text{density}(f) \times 1000 / FE(v, f, t)$$

$$EF(\text{"TSP"}, v, f, \text{"avg"}, t) = E = \text{pcontent}^4 \times \text{density}(f) / FE(v, f, t)$$

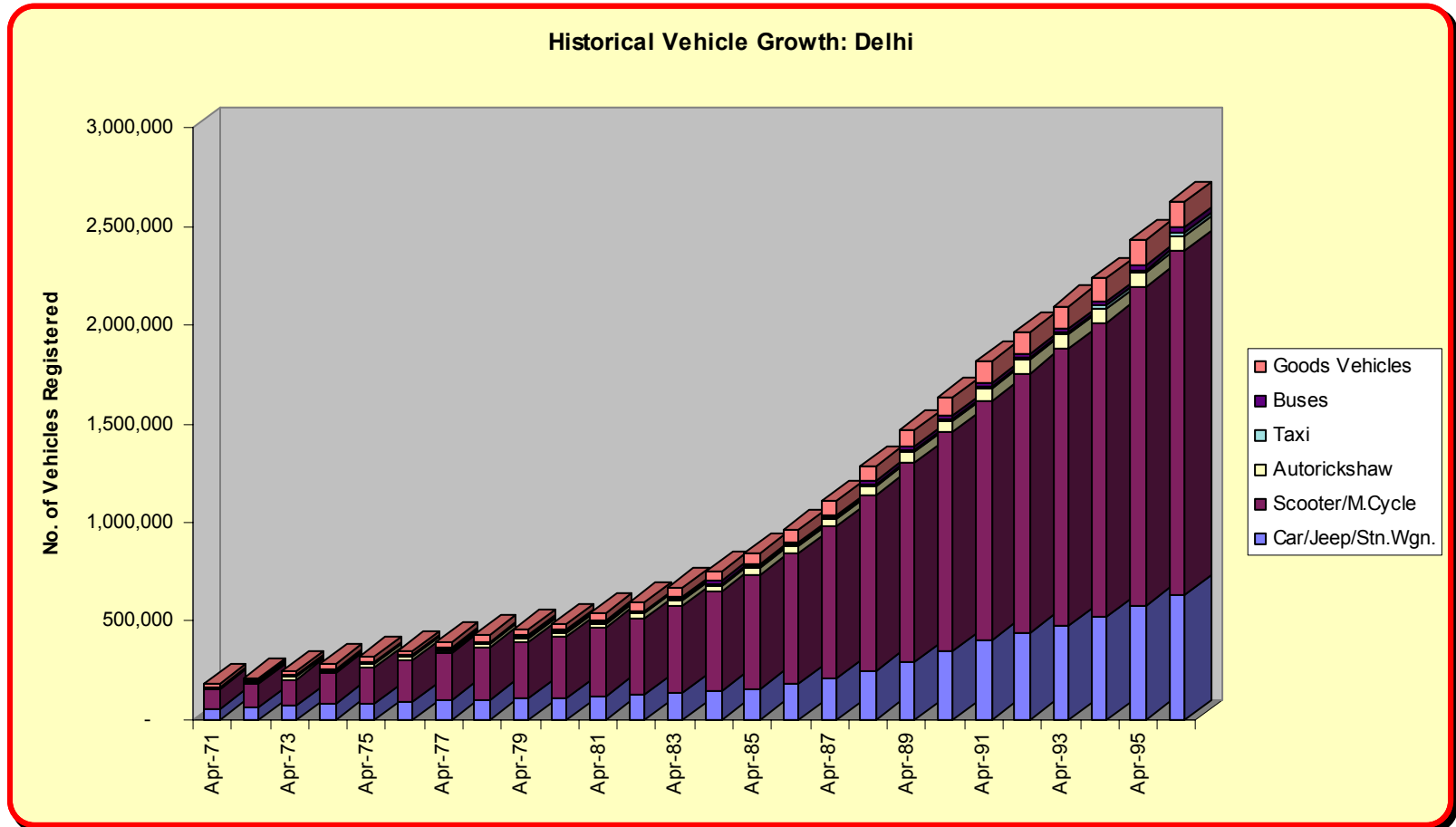
¹ fri: fractional increase in speed from the use of control options

² fhb: fractional increase/decrease in speed from the use of HOV and bus lanes

³ imp(v, f) annual fuel efficiency improvement rate

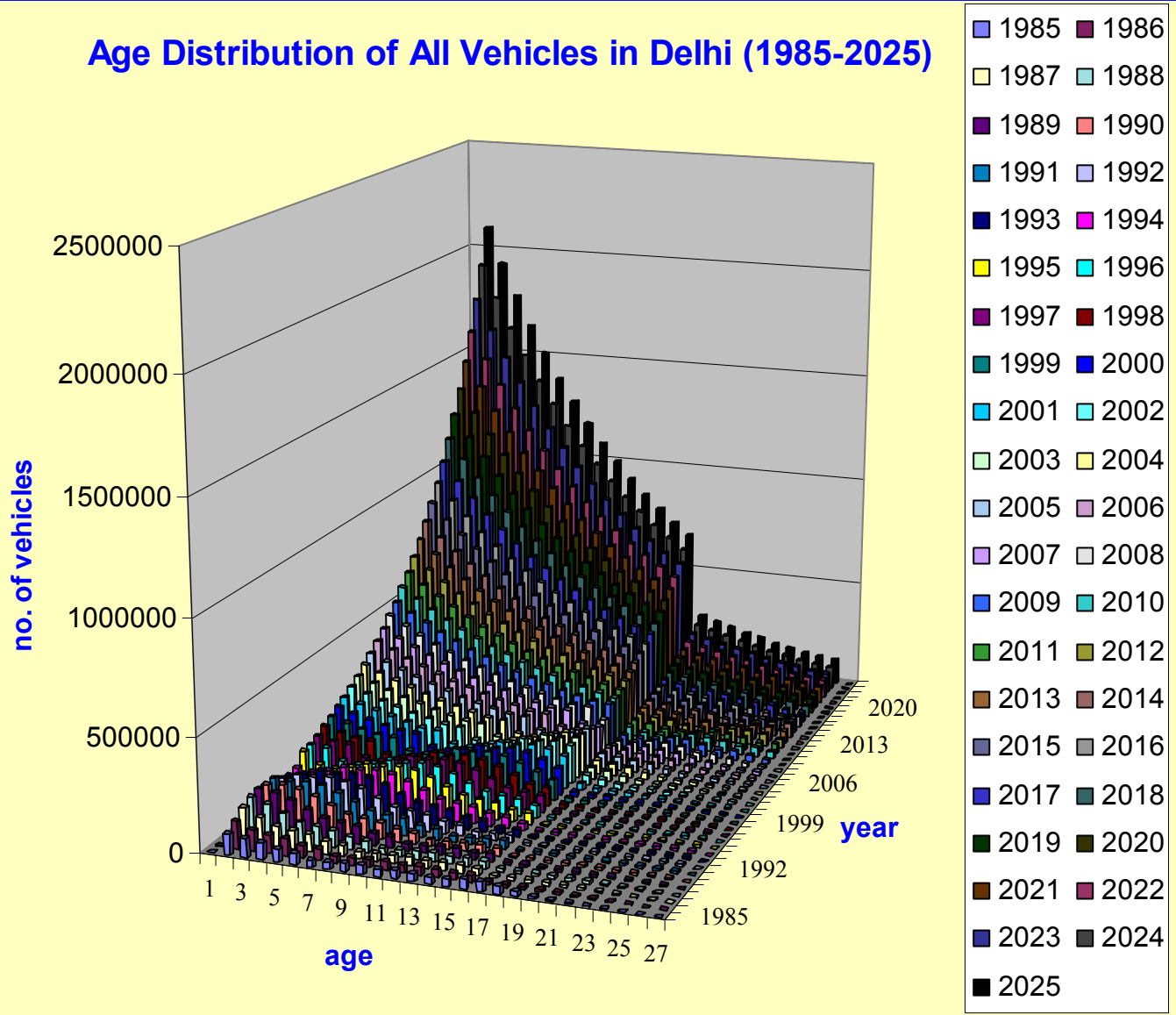
⁴ scontent is the % sulfur content of fuel f and pcontent is the g/kg particulates content of fuel f

Vehicular Air Pollution Information System, Delhi (1)



Vehicular Air Pollution Information System, Delhi (3)

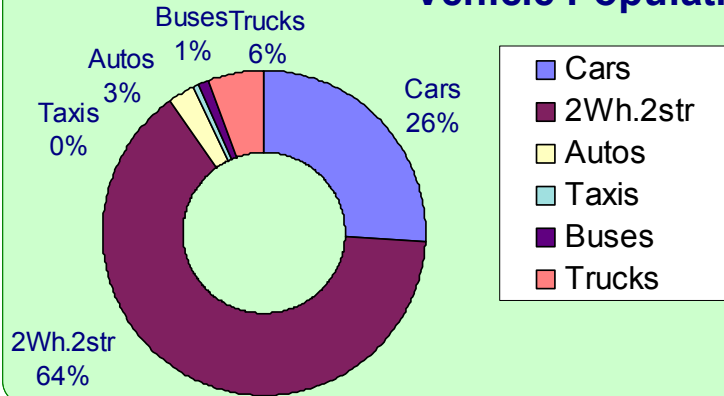
Age Distribution of All Vehicles in Delhi (1985-2025)



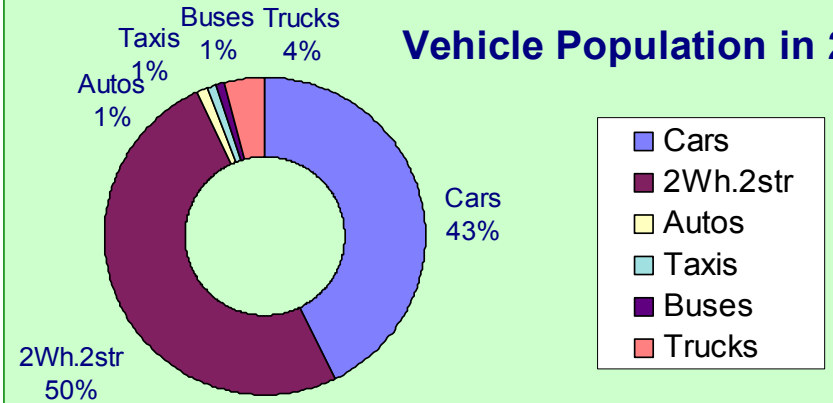
Vehicular Air Pollution Information System, Delhi (4)

Change in the Mix of the Vehicle Fleet from 1995 to 2020

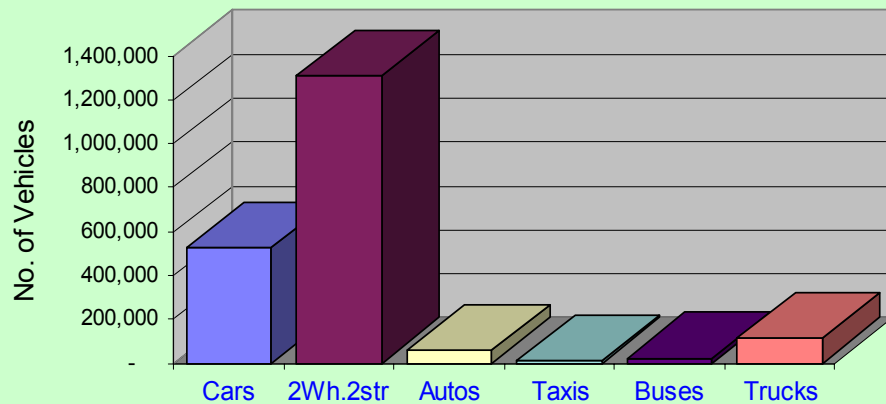
Vehicle Population in 1995



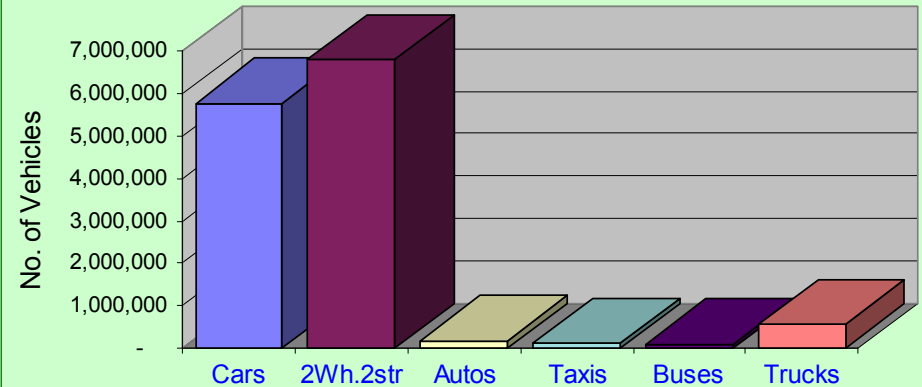
Vehicle Population in 2020



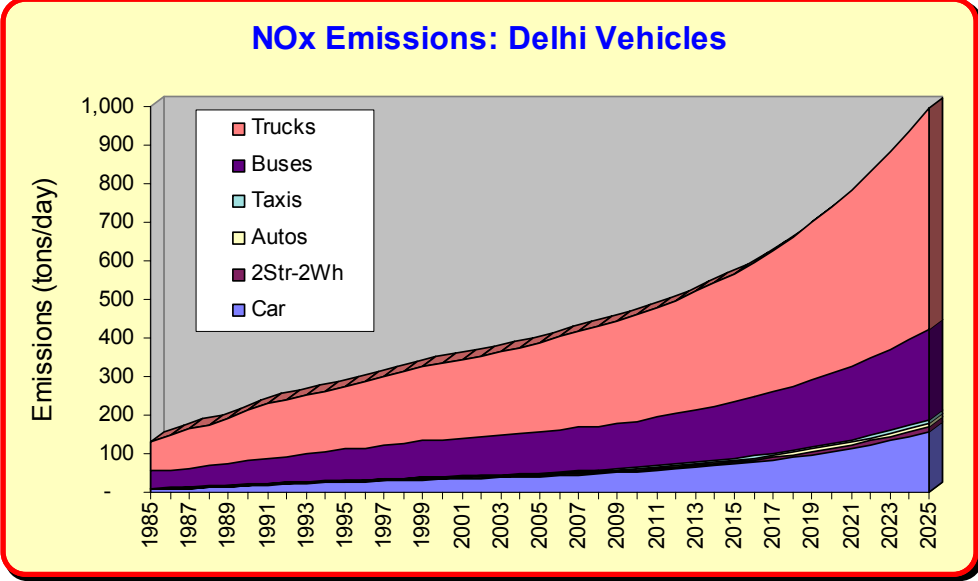
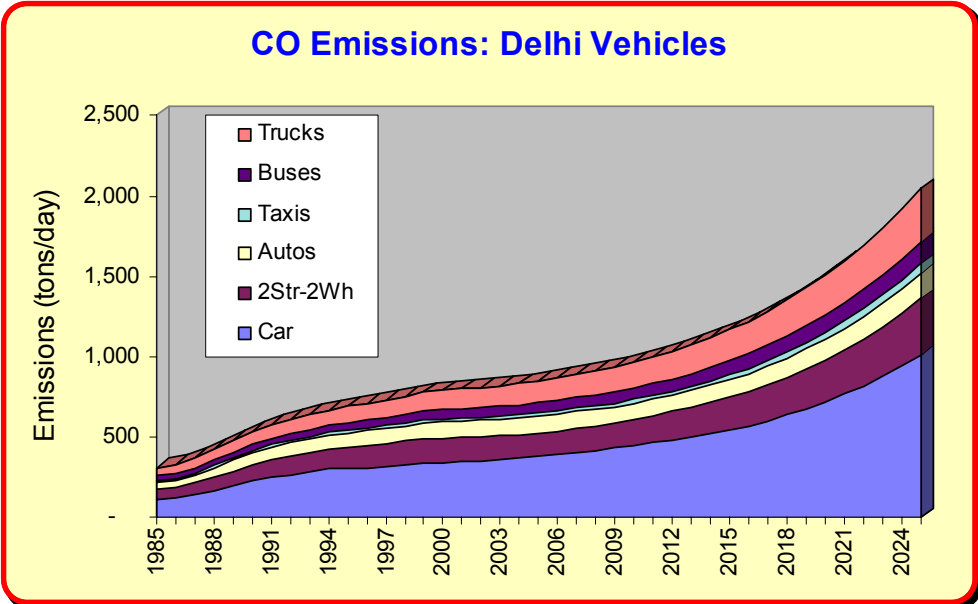
Vehicle Population in 1995



Vehicle Population in 2020

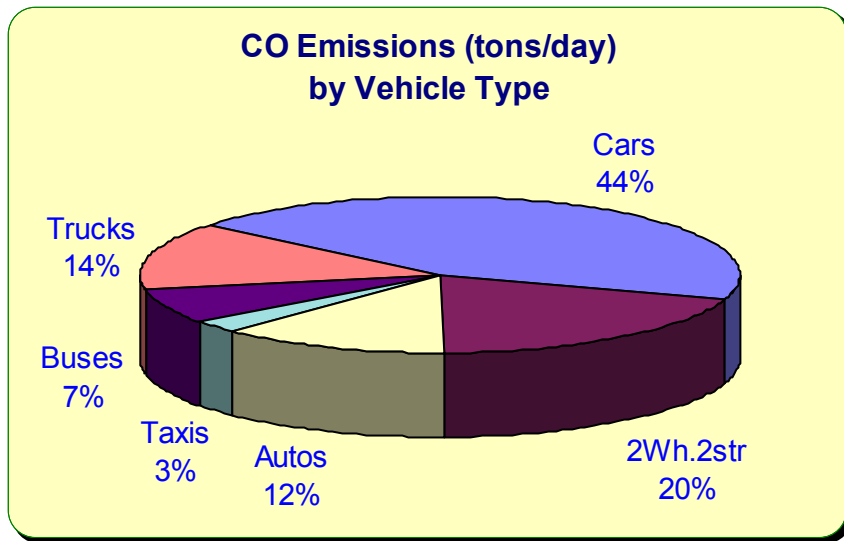


Vehicular Air Pollution Information System, Delhi (5)



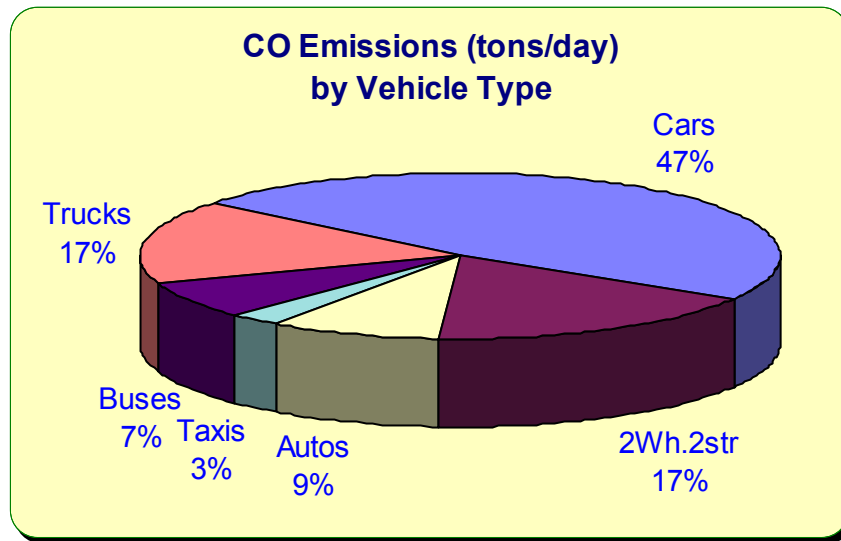
Vehicular Air Pollution Information System, Delhi (6)

Percentage of Emissions by Vehicles in 1995

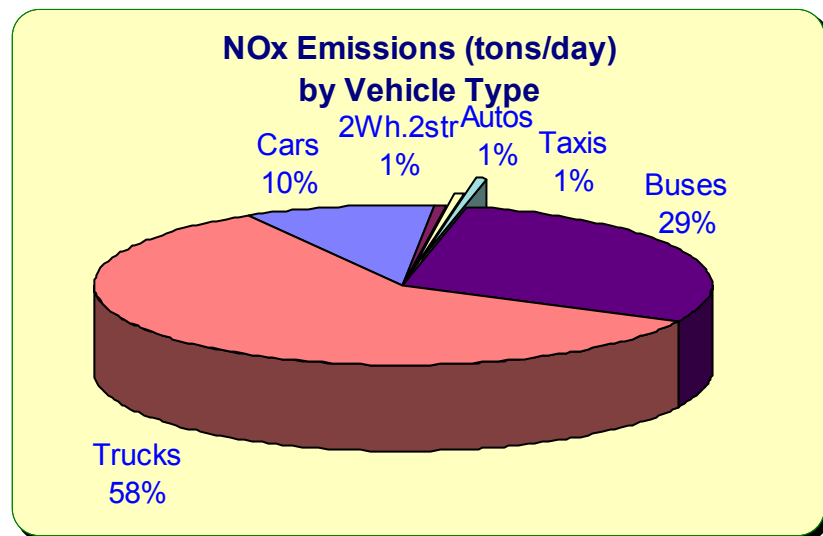


Total = 691 tons/day

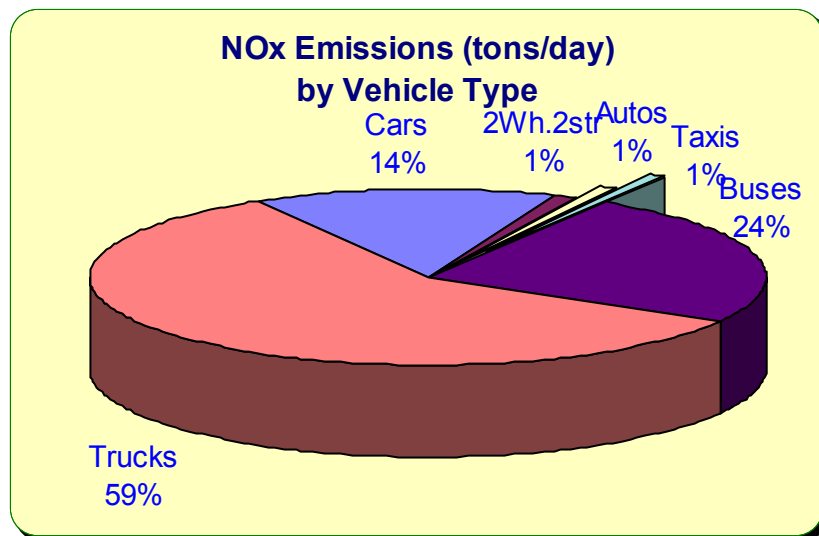
Percentage of Emissions by Vehicles in 2020



Total = 1,509 tons/day

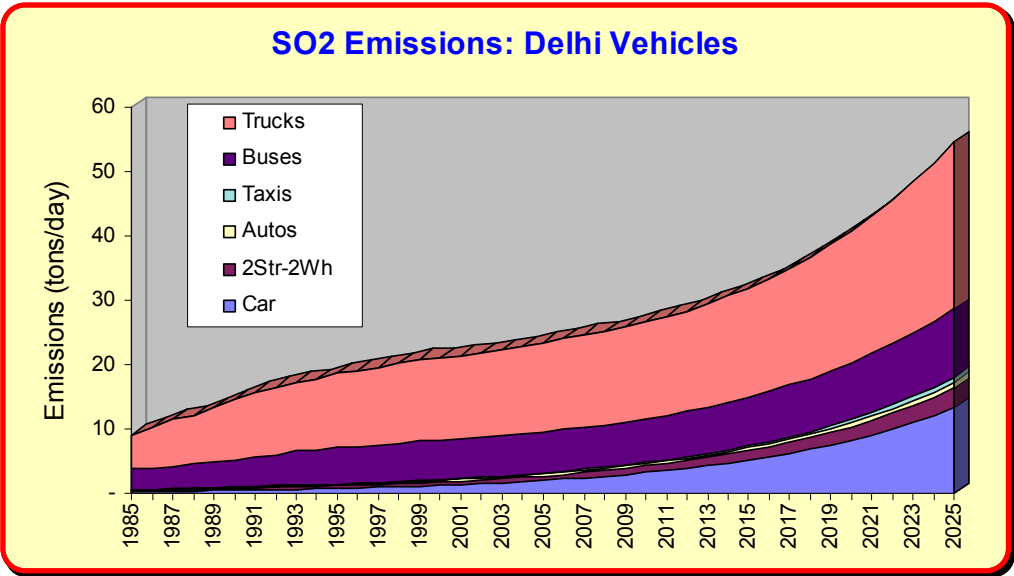
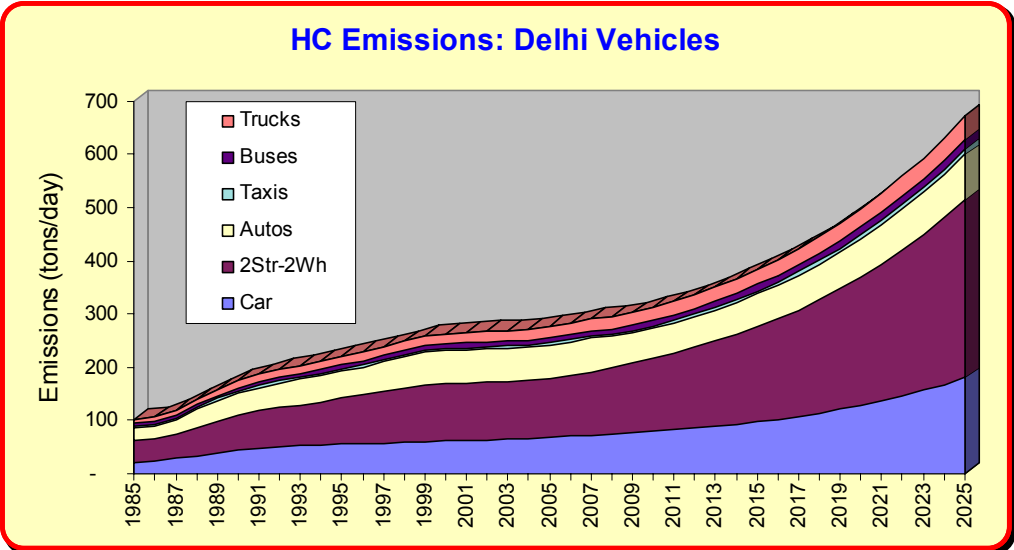


Total = 275 tons/day



Total = 740 tons/day

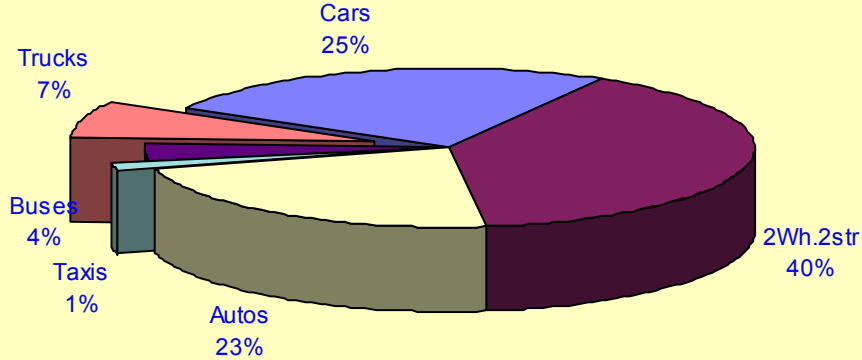
Vehicular Air Pollution Information System, Delhi (7)



Vehicular Air Pollution Information System, Delhi (8)

Percentage of Emissions by Vehicles in 1995

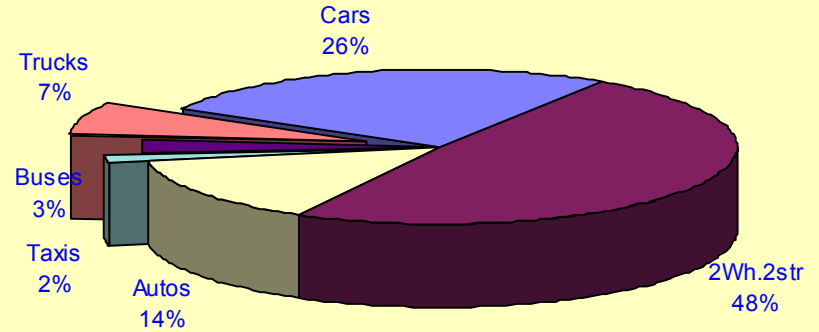
HC Emissions (tons/day) by Vehicle Type



Total = 220 tons/day

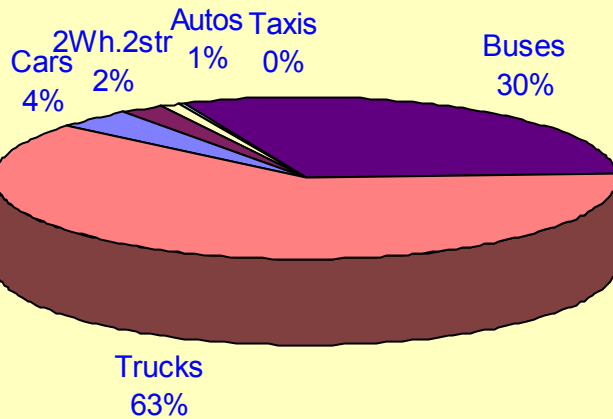
Percentage of Emissions by Vehicles in 2020

HC Emissions (tons/day) by Vehicle Type



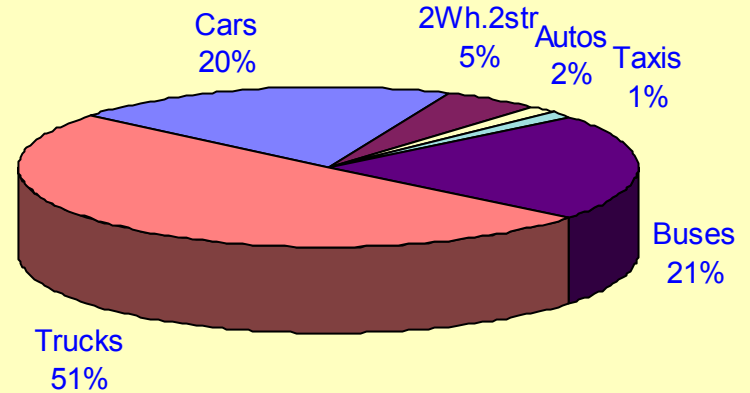
Total = 497 tons/day

SO2 Emissions (tons/day) by Vehicle Type



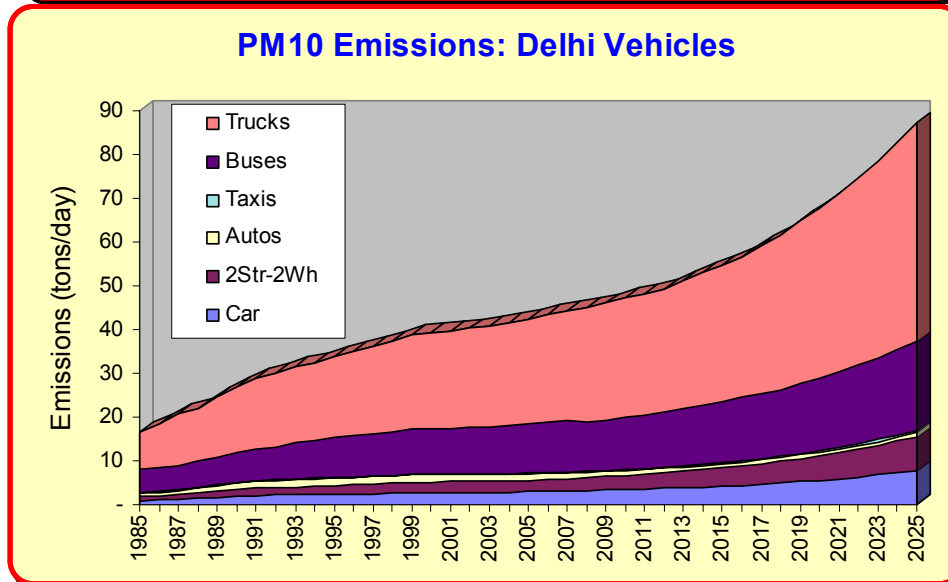
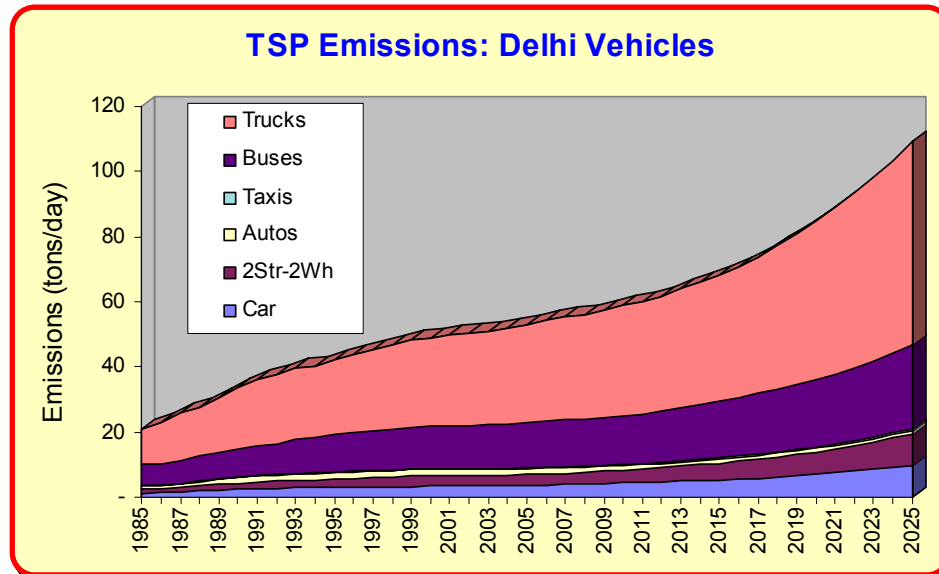
Total = 19 tons/day

SO2 Emissions (tons/day) by Vehicle Type



Total = 41 tons/day

Vehicular Air Pollution Information System, Delhi (9)

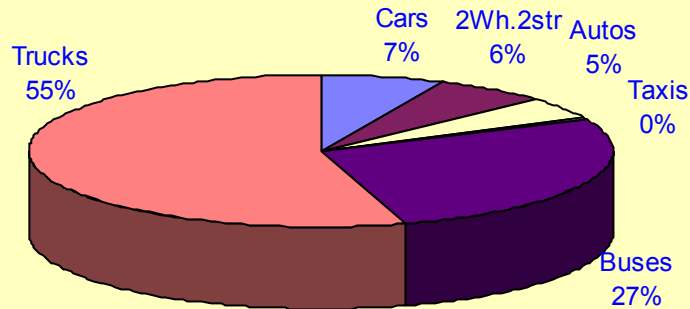


Vehicular Air Pollution Information System, Delhi (10)

Percentage of Emissions by Vehicles in 1995

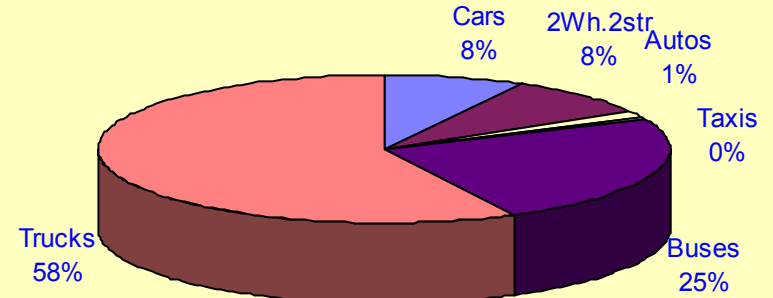
Percentage of Emissions by Vehicles in 2020

**TSP Emissions (tons/day)
by Vehicle Type**



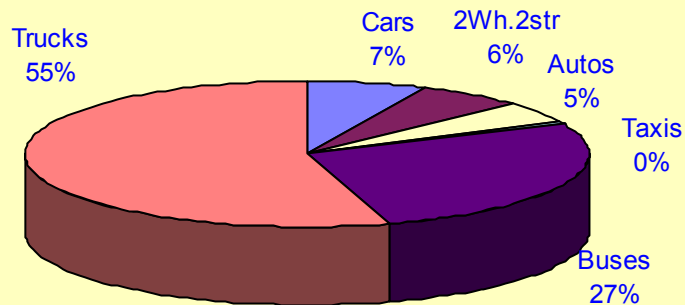
Total = 42.4 tons/day

**TSP Emissions (tons/day)
by Vehicle Type**



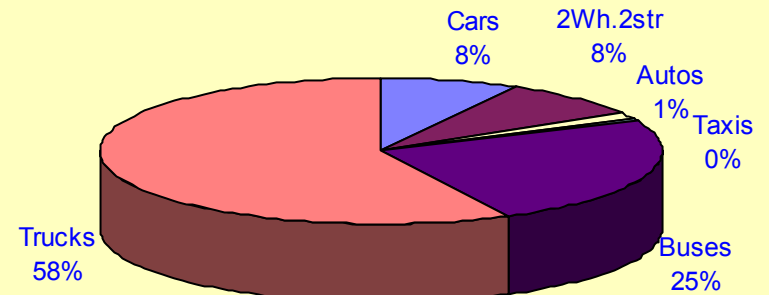
Total = 84.7 tons/day

**PM10 Emissions (tons/day)
by Vehicle Type**



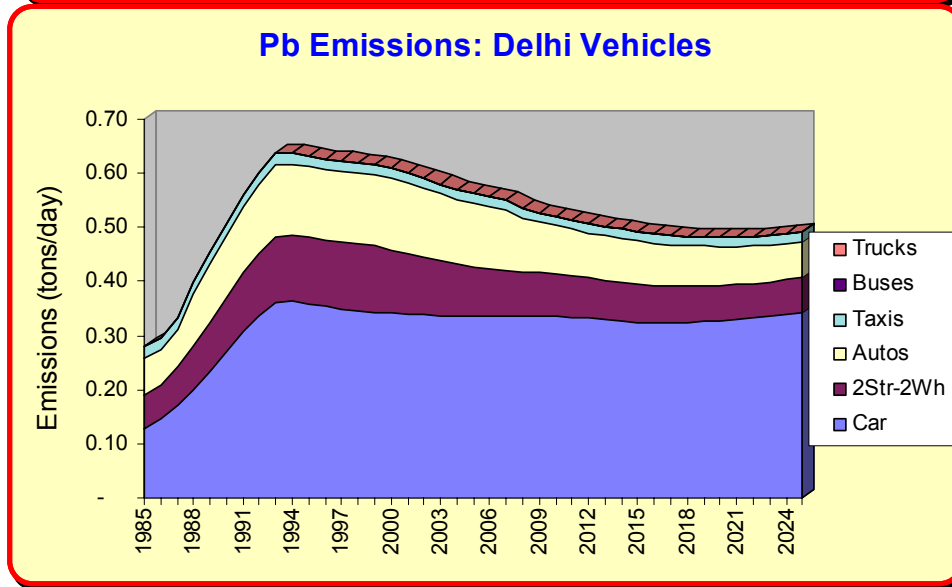
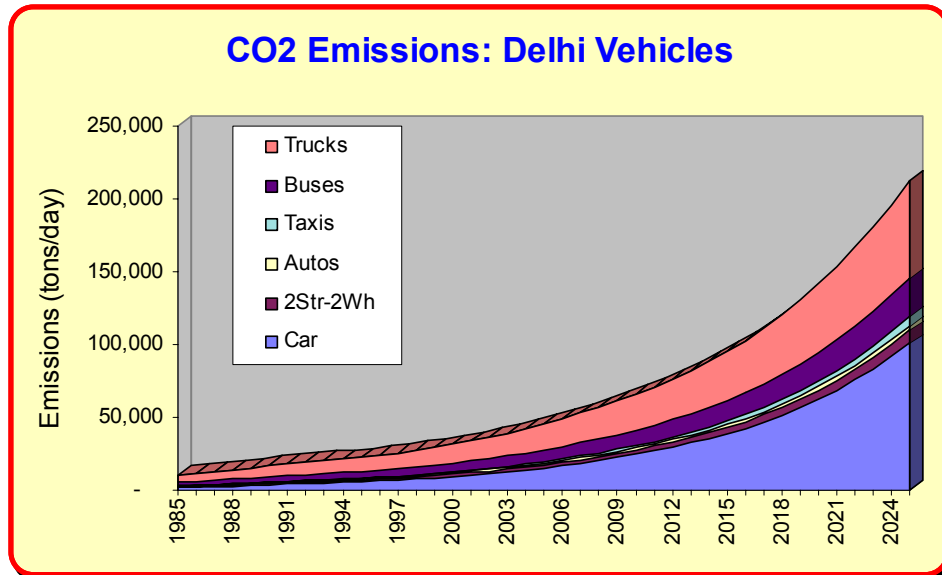
Total = 33.9 tons/day

**PM10 Emissions (tons/day)
by Vehicle Type**



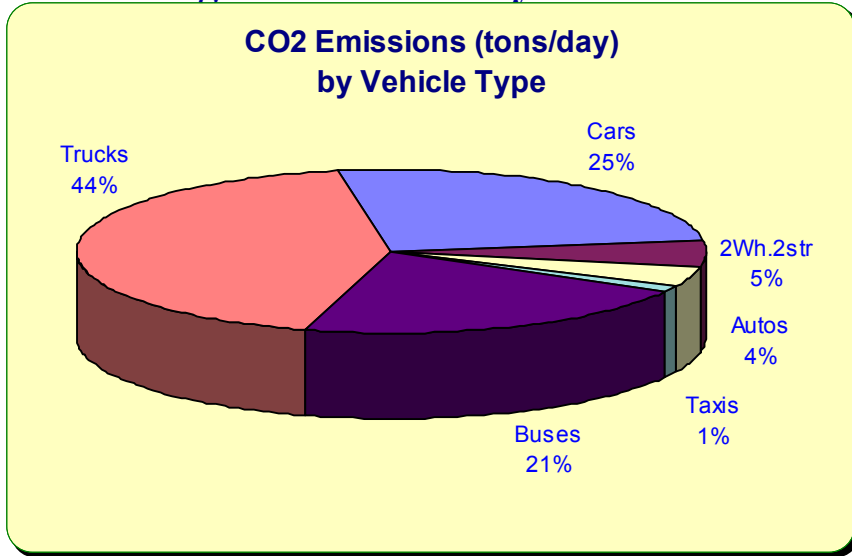
Total = 67.8 tons/day

Vehicular Air Pollution Information System, Delhi (11)



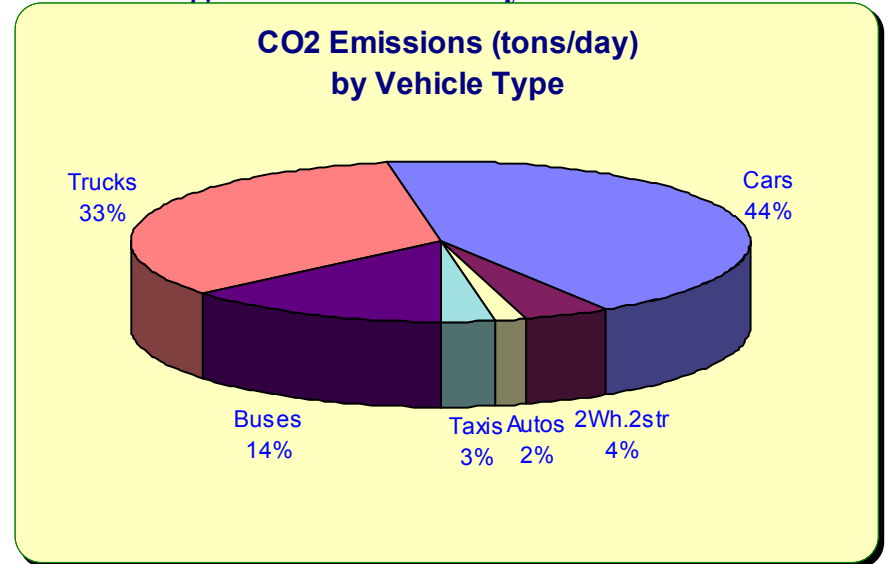
Vehicular Air Pollution Information System, Delhi (12)

Percentage of Emissions by Vehicles in 1995

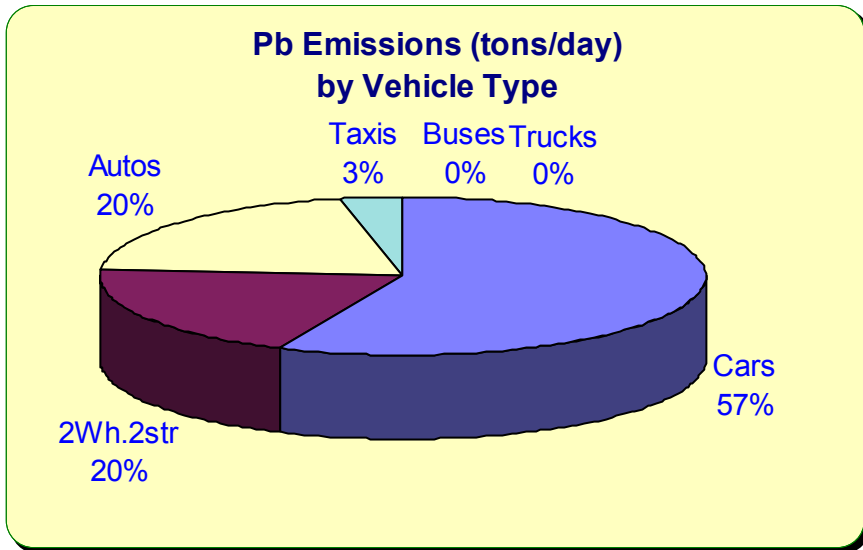


Total = 22,290 tons/day

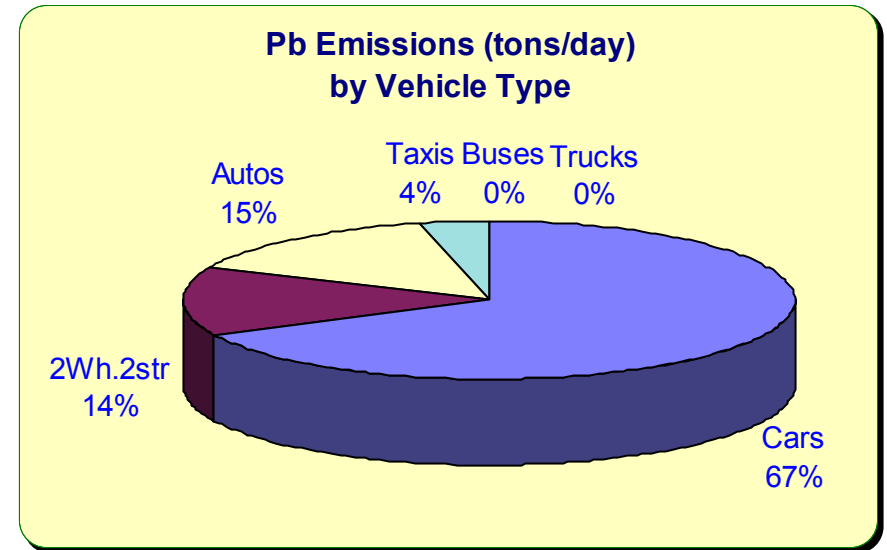
Percentage of Emissions by Vehicles in 2020



Total = 141,716 tons/day

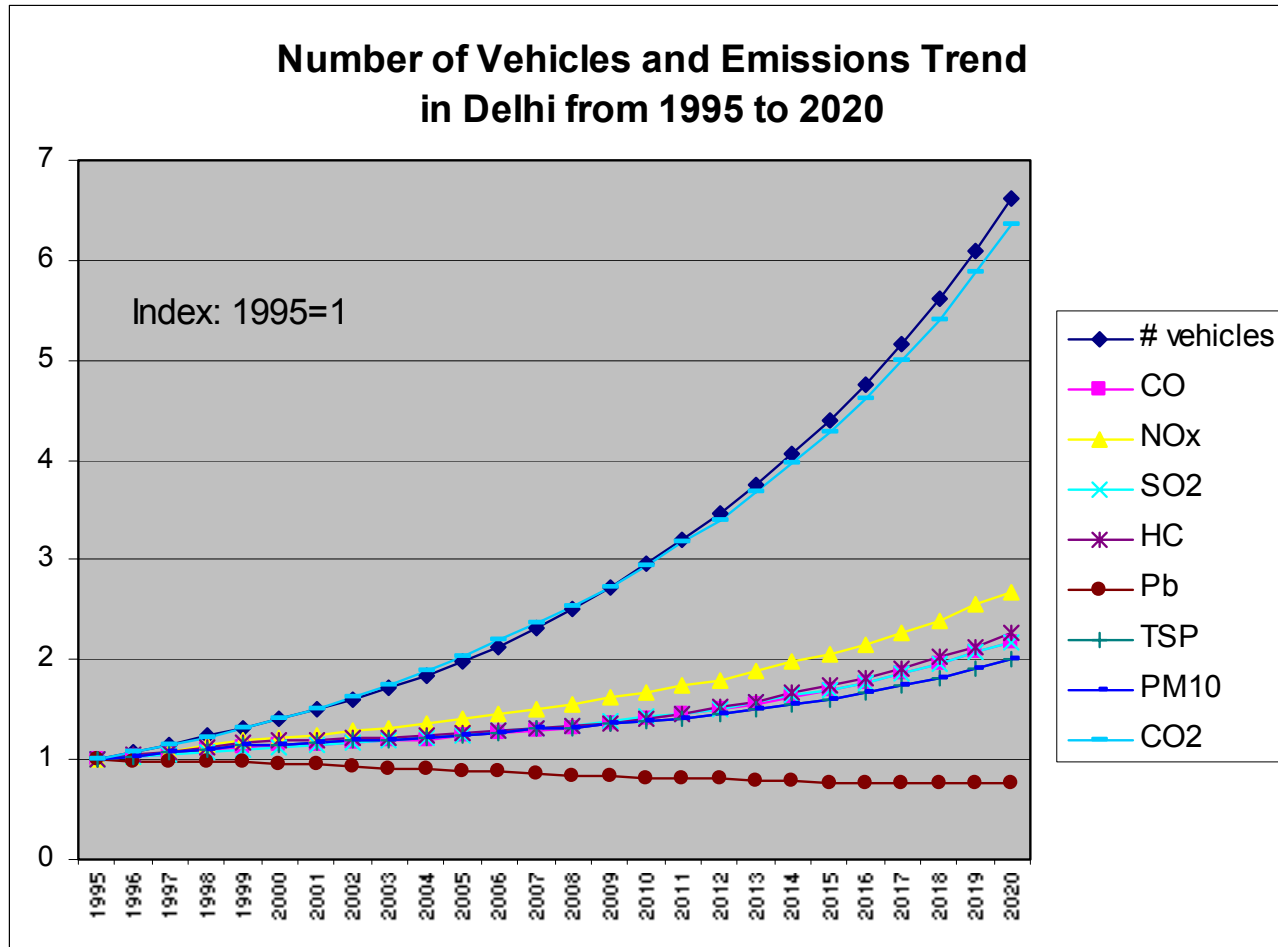


Total = 0.6 tons/day



Total = 0.5 tons/day

Vehicular Air Pollution Information System, Delhi (13)



Unit Values for Each Category of Health Impact

	Unit	Lower Estimate	Higher Estimate
Premature Mortality	Rs/death	147288	1400602
Respiratory Hospital Admissions	Rs/case	3147	7559
Emergency Room Visits	Rs/case	218	343
Restricted Activity Days	Rs/day	68	68
Lower Respiratory Illness	Rs/case	2	6
Asthma Attacks	Rs/case	14	35
Respiratory Symptoms	Rs/day	2	6
Chronic Bronchitis	Rs/case	264	356

Restricted activity days = daily wage

Source: Brandon and Hommann, 1995

Monetized Air Accounts for National Capital Territory – Delhi

Rs. In Millions	1992	1995
Damage Costs		
• Health Damage	867.6	1168.3
• Vegetation Damage	178.6	321.0
• Ecological Damage	15880	21390
Total	16926.2	22978.3
Avoidance Costs		
• Industrial Sector	107.8	143.2
• Power Sector	166.7	75.40
• Transportation Sector	577.50	804.00
• Domestic Sector	508.9	677.0
Total	1726.07	2182.3
Willingness-to-pay for Good Air Quality AQI = 50	3399.21	5089.81

1995: \$1=32.4Rs

AQI = Air Quality Index

AQI = 100 for levels of primary pollutants specified by the Central Pollution Control Board.

Since the contribution to exposure from vehicular emissions is high, targeting vehicular pollution control in NCT-Delhi is 12.58 folds more cost effective than the industrial sector.

Source: NEERI 1997, Natural Resource Accounting in Yamuna River Sub-basin

Costs of Controlling PM10 in Delhi

Measure	Abatement Costs (Rs/kg of emission)	Emissions Abatement Potential (tonnes/year)
All households in Delhi using fuelwood switch to kerosene	-72	260
All households in Delhi using traditional fuelwood stoves switch to improved cookstoves	-68	50
Coal washing for power plants in Delhi	0	1100
All households in Delhi using dung cake switch to kerosene	8	620
Trap oxidizers for 20% of buses in Delhi	32	810
All households in Delhi using dung cake switch to LPG	271	640
All households in Delhi using dung cake switch to LPG	471	280
CNG retrofits for 20% of buses in Delhi	566	670

Source: Saksena, Sumeet, Dayal, Vikram, "Total exposure as a basis for the economic valuation of air pollution in India", January 1997.

Injuries and Death from Traffic Accidents in Delhi

Year	No. of Accidents	Killed
1982	3,793	893

Source: Tokyo Metropolitan Government, 1985

Average speeds during peak hour range from 10 to 15 km/hr in central areas and from 25-40 km/hr in arterial streets. Delhi's traffic fatalities in 1993 were more than double those of all other major Indian cities combined.

Current Road Accidents in Delhi:

Average No. of Persons Killed / Day - 5

Average No. of persons injured - 13

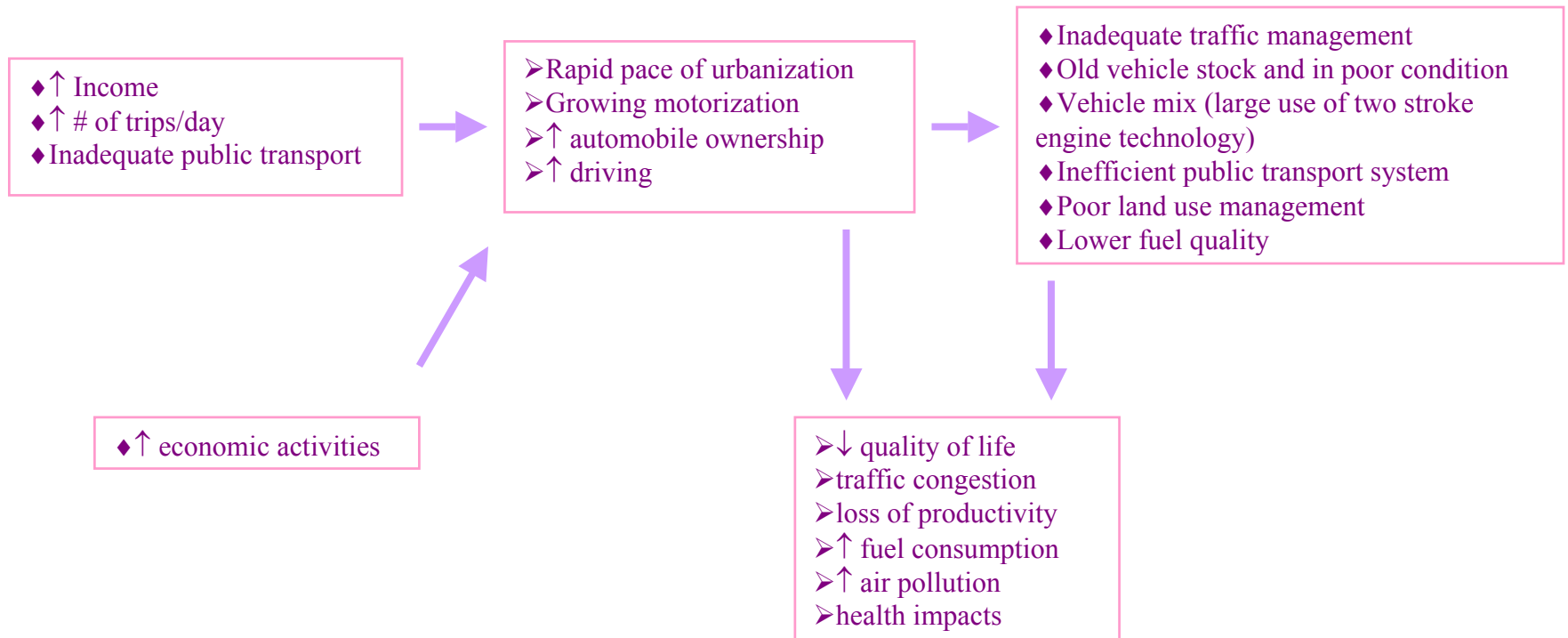
Buses contribute to the majority of the accidents

Source: <http://www.delhimetrorail.com>

Value of Time, Fuel Costs, & Health Costs from Passenger Transport in Delhi

(million \$)	1995	2000	2020
Value of Time	67.97	192.70	7,569.72
Fuel Costs	650.07	845.93	7,996.54
Health Costs	472.72	891.56	6,175.15

Transportation in Delhi



1. Clean fuels, clean vehicle technologies (electronic fuel injection, catalytic converters), new vehicle emission standards

2. Infrastructure investments
- build new roads to add more capacity

3. Traffic and demand management (manage existing street space to maximize available capacity and implement vehicle use controls)

4. I/M programs

5. Improve public transit

6. Land-use planning

Effect on:

- speeds
- emission factors
- fuel efficiencies
- traffic flow
- driver behavior

1. Reduction of emissions per vehicle kilometers traveled

2. Reduction of the total number of vehicle kilometers traveled

• New capacity attracts new demand and so traffic congestion will continue as long as incomes, population, and vehicle ownership continue to grow.

• So while managing road space, also implement vehicle use controls (rather than vehicle ownership controls) and develop public transit!

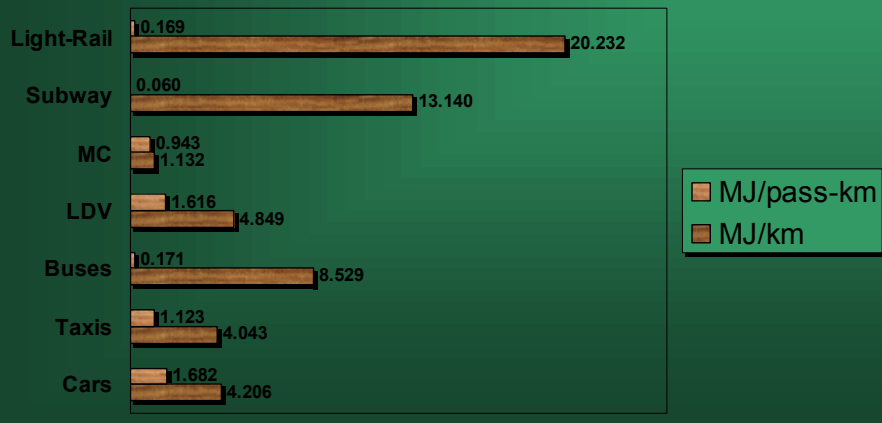
Move people not vehicles!

For a more efficient transportation system:

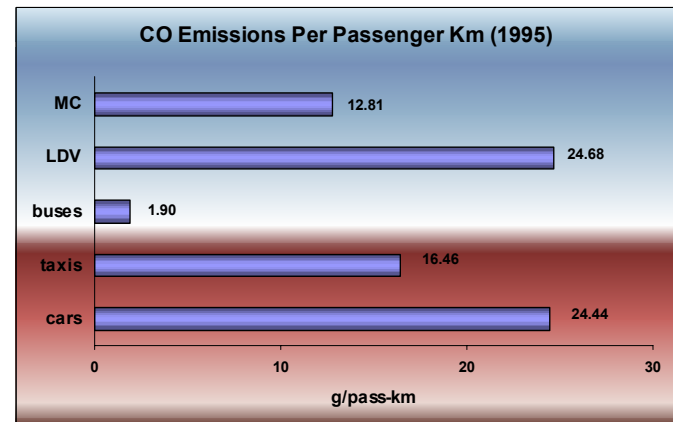
- * use low *energy use per passenger-km* modes
- * use low *emissions per passenger-km* modes
- * use modes with low *road space consumption per passenger*

Public transportation (buses, subway, light rail) achieves best values of above parameters. Therefore, their development is essential for attaining a sustainable transportation system in the future.

Energy Use per Km and per Passenger-Km for Different Transportation Modes in Beijing (1995)



	year	emissions/pass-km (g/pass-km)					
		CO	NOx	SO ₂	HC	TSP	CO ₂
cars	1995	24.44	0.7134	0.0509	2.528	0.0034	120.6
taxis	1995	16.46	0.5029	0.0349	1.664	0.0023	88.4
buses	1995	1.90	0.4692	0.0154	0.193	0.0037	13.9
LDV	1995	24.68	1.5786	0.0607	4.560	0.0041	145.4
MC	1995	12.81	0.0745	0.0299	4.434	0.0020	122.3
All	1995	15.04	1.3582	0.0629	2.405	0.0104	99.0



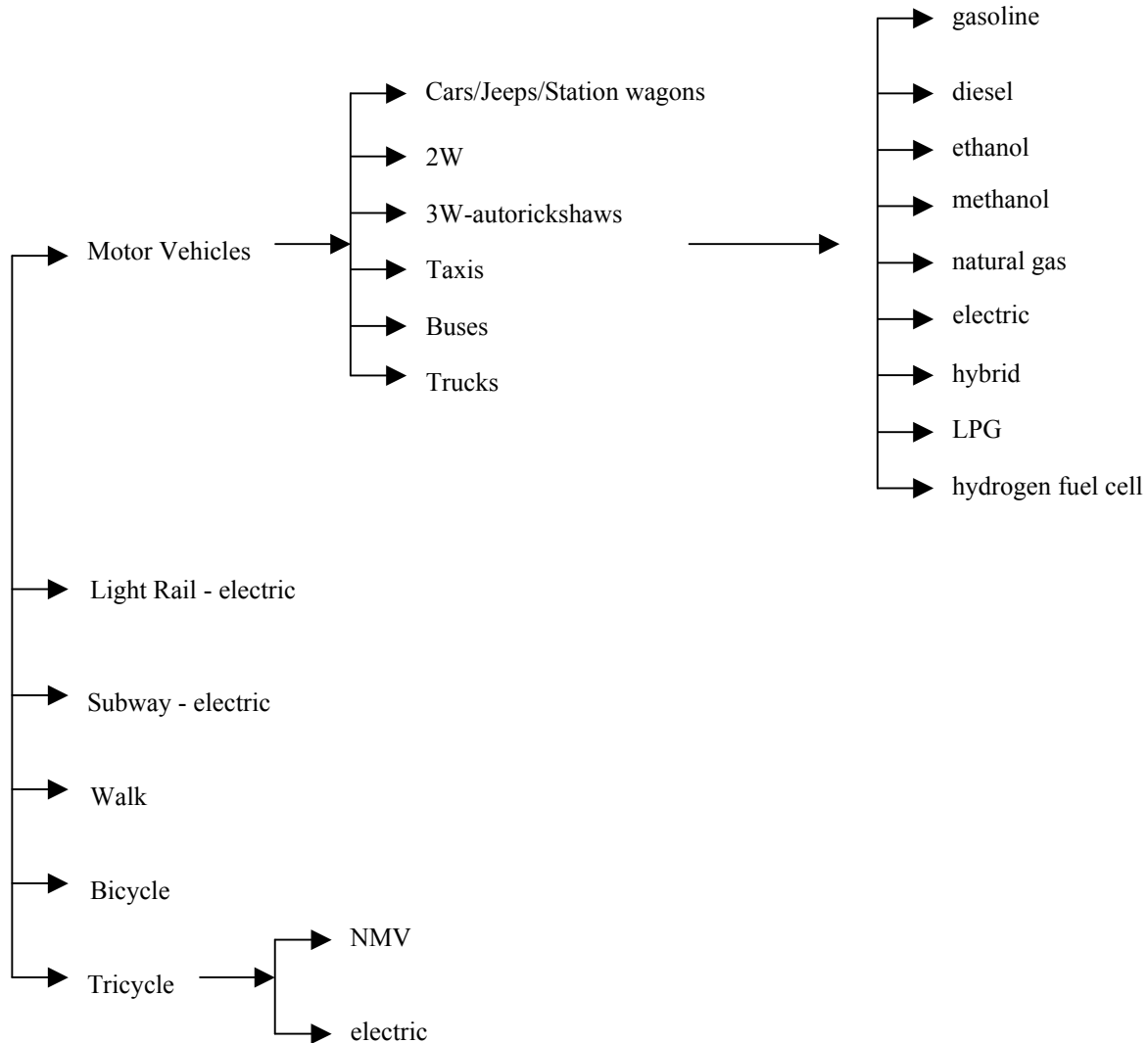
Pollution Control Options for The Transportation Sector

- Technology options (such as new vehicle emission standards, fuel reformulation, alternative fuels) alone are not enough - standards will still be exceeded
- Infrastructure investments (build roads and develop infrastructure to sustain the growth in transportation) - road area in Beijing is 6.1% whereas in other developed cities goes up to 30%
- Traffic management options to reduce congestion and increase speeds (a set of transportation system improvements such as arranging the traffic flow direction, and installation and better coordination of traffic signals)
- Employer based controls such as giving transit passes, arranging telecommuting programs, providing ride-matching information and services, and modified work schedules
- Enhanced I/M and accelerated vehicle retirement programs
- Improve public transit as a good alternative for the commuters and also by options such as parking management and road fees discourage extensive use of cars
- Environmental education and awareness programs
- Land use management

MATHEMATICAL MODEL

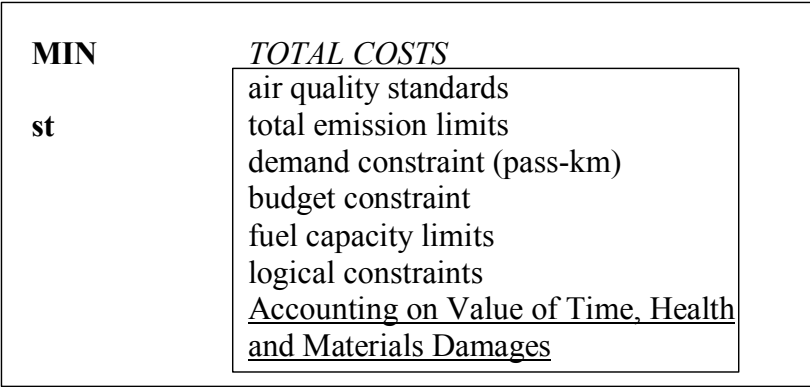
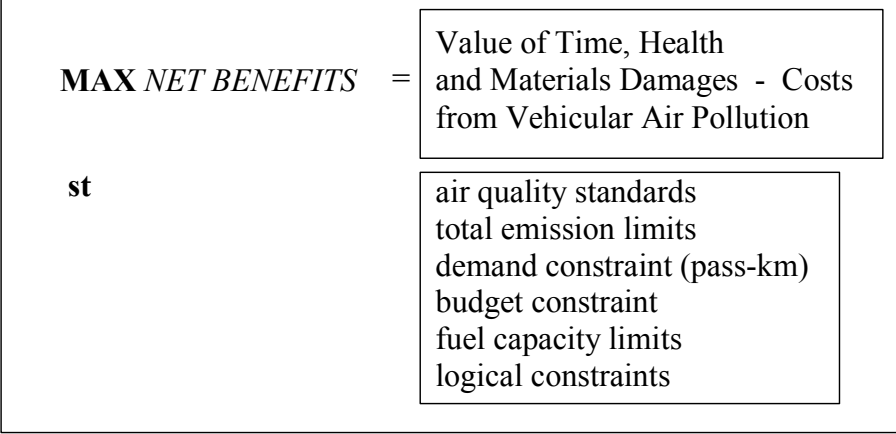
- Include all modes of transportation
- Include different types of fuels and technologies for each mode
- Include investment opportunities in infrastructure for all transportation modes
- Include different control options

TRANSPORTATION MODES FOR DELHI



Control Options To Be Considered in The Model

- Pricing Measures:
 - tax measures
 - subsidize transit services
 - subsidize clean fuels
- Incentive related and educational policy options
 - education and driver behavior
 - encourage air quality monitoring and research on health effects of pollutants
 - ride sharing
 - telecommuting
- Technical policy options
 - engine designs
 - improve fuel quality
 - catalytic converters
 - fuel switching
 - decrease scrappage rate
 - infrastructure investments
 - increase transit services
- TDM measures
 - I/M programs
 - traffic management
 - parking management
 - provide HOV and bus lanes



Look at results of \$, Health, Time, and Other Damages.

Change Constraints

Agree on Policy

SETS

- v vehicle types /cars, taxis, LDV, buses, HDV, MC, tricycles, light-rail, subway, bicycle/
- a age of vehicles /0, 1, 2, ..., 22/
- t time horizon of the model /1995, 1996, ..., 2030/
- p pollutants from vehicle emissions /CO, NO_x, SO₂, HC, TSP, CO₂/
- f fuel types /gasoline, diesel, electric, methanol, ethanol, LPG, hydrogen, natural gas, coal/
- m transportation modes /road, subway, railroad/
- oo control options /I/M programs, catalytic converters, HOV and bus lanes, traffic management (arrange traffic directions according flows), education and driver behavior, ride sharing, telecommuting, parking management/
- e health effects of pollutant concentrations in the air /premature mortality, respiratory hospital visits, emergency room visits, restricted activity days, lower respiratory illnesses, asthma attacks, chronic bronchitis, chest discomfort/

PARAMETERS

- Fuel costs
- Vehicle costs
- O&M costs
- Infrastructure costs
- Fuel switching costs
- Various costs of control options
- Effects of control options on emissions, fuel efficiencies, congestion, fuel prices, occupancy
- Emission factors
- Background concentrations and base year concentrations
- Fuel efficiencies
- Limits on emissions and air quality standards
- Projections of passenger-km demand
- Occupancy and VKT per yr per vehicle
- # of vehicles in base year
- Upper bounds on # of vehicles and fuel capacity for the transport sector
- Restrictions on infrastructure building & control option utilization ratios
- Population projections
- Dose response coefficients
- Average commute time
- Average wages
- Health effects and costs of air pollution
- Materials damages from air pollution

VARIABLES

- TC: present value of total costs
- SC(t): social cost of air pollution from transportation at year t
- EF(p,v,a,t): emission factors of vehicle v age a for pollutant p in year t
- NV(v,a,f,t): number of vehicles v in year t, of age a and using fuel f
- emiss(p,t): emissions of pollutant p in year t (tons/yr)
- conc(p,t): concentration of pollutant p in year t
- AM(m,t): miles of road/railroad/subway built in year t
- capcostyr(m,t): annual capital cost of infrastructure investments and land costs
- FUEL(f,v,t): fuel f used by vehicle v in year t
- firt(v,t): fractional reduction in commute time with vehicle v in year t due to newly built infrastructure of mode m including the effect of increased number of vehicles on roads
- fvaf(v,a,f,t,oo): fraction of vehicle v age a fuel f in time t using control option oo
- frac(v,a,f,fl,t): fraction of vehicle v age a fuel f switching to fuel fl in year t
- SNV(v,a,f,fl,t): number of vehicles v of age a switching from fuel f to fl in year t
- FS1(f,t): amount of fuel saved from the use of ride sharing option
- FS2(f,t): amount of fuel saved from the use of telecommuting option
- RA(t): total road area (km²) in year t
- Speed(v,t): average velocity (km per hr)
- FE(v,f,t): fuel efficiencies at time t for vehicle v using fuel type f

Total Costs = Costs of Implementing a Package of Policy Options

= Fuel Costs + Cost of Vehicle + Infrastructure Investments

+ Other Operations and Maintenance Costs + cost from switching fuel & cost of control options utilized – cost of fuel savings

= Σ present value of all annualized costs

- repairs, maintenance, tires, oil,...
- parking costs
- ownership costs (insurance, license, registration, taxes, depreciation, finance charge)

- Technology options
- Fuel options
- Management options
- Legislative options
- Incentive related and educational options
- Pricing measures

- Construction costs
- Land costs

For example: lifetime for highways may be assumed to be 35 years and for railroads 50 years.

For example for rail:

- Capital expenditure for electrification
- Signals and train control facilities
- Per mile road bed trackage costs
- Terminal costs
- Operations and maintenance costs

CONSTRAINTS

- Sum of demand (pass-km) by each mode (t) \leq Turnover projections (t)
- Annualized Infrastructure Investment Costs + Public Transport Vehicle Costs and their O&M costs + Costs of Control Options + Subsidies – Taxes \leq Budget for each year allocated to the transportation sector
- Total Emissions (taking into consideration the reductions resulting from the use of different policy options) \leq Air Quality Limits
- Concentration of Each Pollutant (as a function of emissions) \leq Air Quality Standards
- Logical Constraints (example: sum of fraction of vehicle v using option oo equals 1)
- Age distribution, emission factors calculation, fuel efficiencies, calculation of electricity use by electric vehicle v, speeds, fuel consumption, # of vehicles in each year, infrastructure construction, and utilization of control options
- Bounds on vehicle numbers for different types & fuel switching option for vehicles
- Calculation of fractional reduction of commute time from investments into infrastructure (keeping in mind the increase in the total # of vehicles)
- Fuel Capacity Limits (example: Total use of NG in transportation sector in year i \leq Total available NG supply for the transportation sector for that year)
- Social Cost Equation (\$) = Value of Time + Health Impacts of Air Pollution + Materials Damages from Air Pollution

Pollution

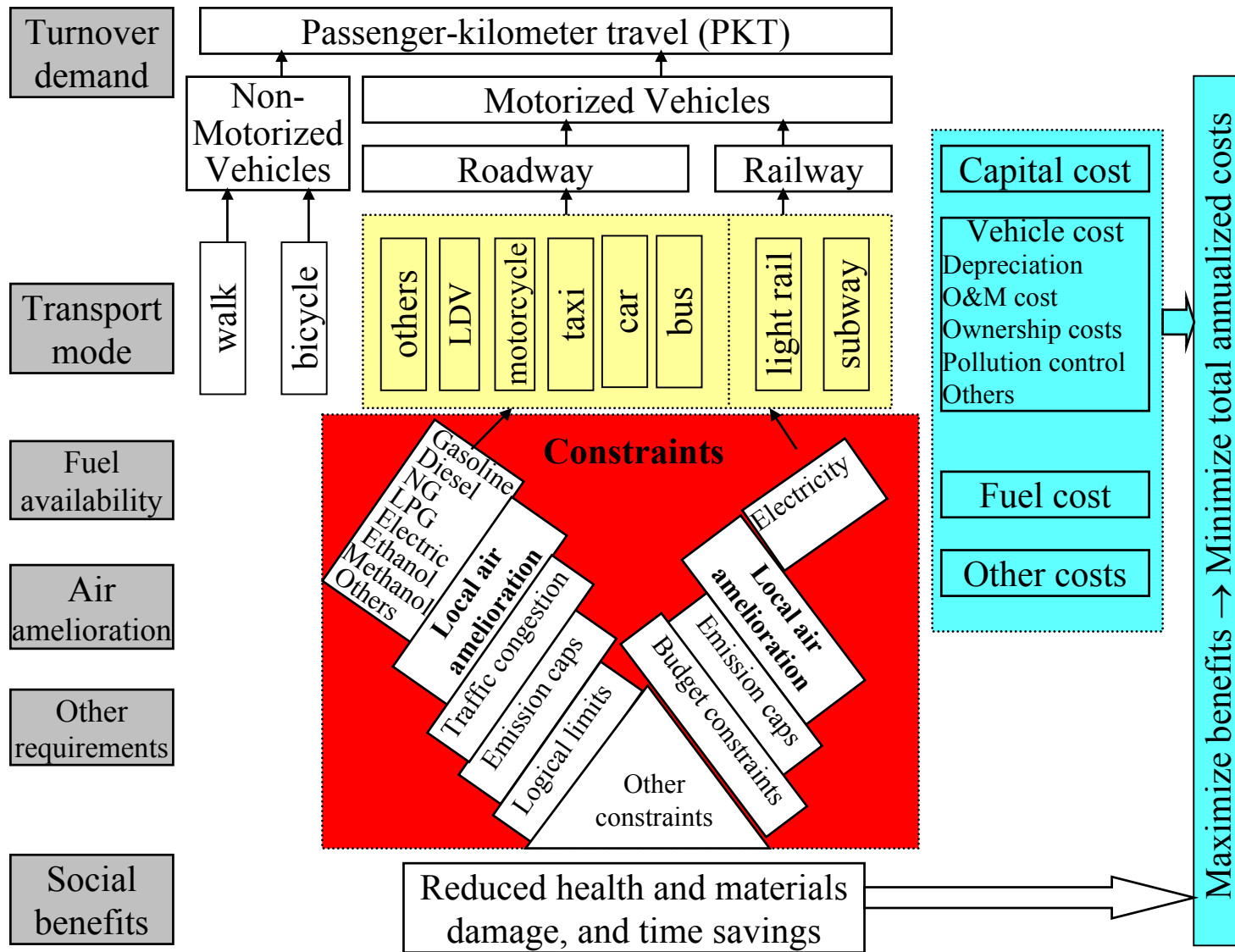
In traffic time each hour may be assumed to be worth 50% of your wage

Increase in concentration of pollutants due to mobile sources emissions result in health and materials damages.



Types of Results from The Model

- * *Optimization of urban transportation systems for minimum overall cost and least environmental damage meeting all economic, technical, and policy constraints will yield the following information:*
 - Obtain trade-off curves for cost, emissions, and pass-km demand
 - Average vehicle emission factors, fuel efficiencies, vehicle population (type, age, fuel), land use patterns, fuel consumption
 - Breakdown of turnover (% of pass-km demand and VKT being satisfied by each mode)
 - Cost breakdown (%) of the optimal system over the model time horizon: vehicle costs, O&M costs, fuel costs, infrastructure investments, fuel switching costs, costs of control options utilized
 - Investment into different control options each year
 - % of fuel switching of vehicle v from fuel type f to f_1 and extent of control options utilized each year and over the total model time horizon
 - Total emissions of pollutant p from mobile sources exhaust emissions from each vehicle type v
 - Resulting concentrations from these emissions and health impacts
 - Social costs: health and materials damages from air pollution caused by vehicle emissions and value of time spent in traffic
 - Energy consumption by each mode
 - Shadow prices of constraints
 - Vehicle growth rates, mode choice, road area, number of vehicles per km of road, average road speeds



The transportation system should emphasize the movement of people, not vehicles.

ADVANTAGES

- Simulation vs Optimization
- Extensive list of control options
- Passenger-km demand as the driving force
- Time frame (annual) evaluation - not one step future
- Valuation of future costs and accounting on social costs
- User friendly design at the fingertips of the decision maker
- Visual representation of final optimal set of options (GIS)