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
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
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.
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.
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

<table>
<thead>
<tr>
<th>Health Effect</th>
<th>Annual Incidence Rate (millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Premature Mortality</td>
<td>2.4</td>
</tr>
<tr>
<td>Respiratory Hospital Admissions</td>
<td>2.5</td>
</tr>
<tr>
<td>Emergency Room Visits</td>
<td>51</td>
</tr>
<tr>
<td>Restricted Activity Days</td>
<td>5,720</td>
</tr>
<tr>
<td>Lower Respiratory Illness</td>
<td>143</td>
</tr>
<tr>
<td>Asthma Attacks</td>
<td>484</td>
</tr>
<tr>
<td>Respiratory Symptoms</td>
<td>38,500</td>
</tr>
<tr>
<td>Chronic Bronchitis</td>
<td>13</td>
</tr>
</tbody>
</table>
### Estimated per capita Health Costs (US$/year)

<table>
<thead>
<tr>
<th>Strata of Population</th>
<th>Low Estimate</th>
<th>High Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>By Location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Rural</td>
<td>1800</td>
<td>5600</td>
</tr>
<tr>
<td>• Slum</td>
<td>2000</td>
<td>7400</td>
</tr>
<tr>
<td>• Urban, non-slum</td>
<td>600</td>
<td>1500</td>
</tr>
<tr>
<td>By Gender</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Female</td>
<td>2000</td>
<td>6000</td>
</tr>
<tr>
<td>• Male</td>
<td>1400</td>
<td>4400</td>
</tr>
</tbody>
</table>

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).
• A 100 µg/m³ increase in TSP leads to 2.3% increase in deaths in Delhi.
• Mortality rates in Delhi would go down by 15% if air pollution levels were reduced to WHO prescribed levels.
• Highest contributors to vehicular pollution: two stroke engine three wheeler auto-rickshaws.
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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial</td>
<td>56</td>
<td>40</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>Vehicular</td>
<td>23</td>
<td>42</td>
<td>63</td>
<td>72</td>
</tr>
<tr>
<td>Domestic</td>
<td>21</td>
<td>18</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Concentration in Ambient Air</th>
<th>WHO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Industrial</td>
<td>Residential</td>
</tr>
<tr>
<td>SO₂</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>NOₓ</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>SPM</td>
<td>360</td>
<td>140</td>
</tr>
<tr>
<td>PM10</td>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>CO (mg/m³)</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

Ambient Air Quality in Delhi (annual average - µg/m³)

<table>
<thead>
<tr>
<th>Year</th>
<th>SO₂</th>
<th>NO₂</th>
<th>SPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>8.7</td>
<td>18.5</td>
<td>373</td>
</tr>
<tr>
<td>1990</td>
<td>10.2</td>
<td>22.5</td>
<td>338</td>
</tr>
<tr>
<td>1991</td>
<td>13.3</td>
<td>27.2</td>
<td>317</td>
</tr>
<tr>
<td>1992</td>
<td>18.4</td>
<td>30.4</td>
<td>377</td>
</tr>
<tr>
<td>1993</td>
<td>18.5</td>
<td>33.2</td>
<td>372</td>
</tr>
<tr>
<td>1994</td>
<td>19.5</td>
<td>33.0</td>
<td>377</td>
</tr>
<tr>
<td>1995</td>
<td>19</td>
<td>34.1</td>
<td>407</td>
</tr>
<tr>
<td>1996</td>
<td>19</td>
<td>33.7</td>
<td>387</td>
</tr>
<tr>
<td>1997 (Jan-Aug)</td>
<td>16.2</td>
<td>33.0</td>
<td>370</td>
</tr>
</tbody>
</table>
Actions taken so far (1):

• Euro I (June 1999) and now Euro II (04/2000) - All country Euro I since 04/2000
• all new LDV - Euro I with catalyst: 04/2000
• all new HDV - Euro I: 2000
• tight MC standards + catalysts: 2000
• phased out leaded gasoline: 09/1998 (entire country 02/2000)
• catalysts on all new cars: 10/1998
• low sulfur diesel (0.25% by weight): 08/1997
• low sulfur diesel (0.05% by weight): April 1, 2000 (both conventional and desulphurized petrol and diesel would be available)
• “no to diesel” but still in the Auto Expo 2000 at least 9 new diesel automobile models from more than 8 companies were presented
• convert all 8 year old diesel buses to CNG (1842 buses): should have been completed by March 31, 2000; extension asked for but not given
• Entire city buses (DTC and Private) to be steadily converted to single fuel mode on CNG by March 31st, 2000. (DTC had 3131 buses in 1999 and has 3200 buses (8.9% of total registered buses in Delhi) now in 2000, 57% of which are >8 years old and 24% are >10 years old.)
Actions taken so far (2):

- Also, all autorickshaws and taxis older than 10 years off Delhi’s roads as of March 31, 2000 (>17,200 TSRs and >1200 taxis were pre-1990 vehicles)
- Limit number of cars: Supreme Court limited the monthly number of car registration to 1500 (previously 4000 vehicles per month were being sold)
- Delhi government banned the registration of diesel taxis in the capital from January 2000 to control toxic particulate pollution in the capital.
- Delhi, which has experienced a massive growth in small-scale industries in the last 15 years, has been directed by the Supreme Court to relocate its 114 highly-polluting stone crushers to outside the city boundaries (WWF 1995).
- Restriction of the plying of the goods vehicles during the day
Delhi’s Vehicle Fleet (1)

Current and Projected Vehicle Population

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td># of vehicles</td>
<td>2,734,400</td>
<td>2,904,359</td>
<td>3,033,000</td>
<td>3,210,000</td>
<td>3,924,000</td>
<td>6,000,000</td>
</tr>
</tbody>
</table>

- Personal vehicles account for almost 90% of all vehicles in Delhi - largely single occupancy, therefore not very efficient as a transport mode.


- 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)

<table>
<thead>
<tr>
<th>Growth of Population and Registered Motor Vehicles in Delhi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>population</td>
<td>3.65</td>
<td>6.22</td>
<td>9.42</td>
<td></td>
</tr>
<tr>
<td># of vehicles</td>
<td>204,078</td>
<td>557,000</td>
<td>1,813,000</td>
<td>2,432,320</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
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<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td># of vehicles</td>
<td>2,734,400</td>
<td>2,904,359</td>
<td>3,033,000</td>
<td>3,210,000</td>
<td>3,924,000</td>
<td>6,000,000</td>
<td></td>
</tr>
<tr>
<td>population (million)</td>
<td></td>
<td></td>
<td>13.42</td>
<td>14.36</td>
<td>17.16</td>
<td>19.51</td>
<td></td>
</tr>
</tbody>
</table>
» People want freedom and flexibility in transportation.

» Due to timeliness, convenience, comfort, and reliability they want to buy cars to satisfy their transportation needs.

» But they want access to mobility at an affordable price.

» As a result, as per capita income grows motor vehicle ownership grows.

» Income elasticities are highest for passenger cars among other motor vehicles.

» So passenger cars will grow faster than other types of motor vehicles as per capita incomes grow.

» This will have the highest impact on more developed urban areas.

» And urban road systems will be faced with more rapidly growing demands.
• 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).

• 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.

- 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

<table>
<thead>
<tr>
<th>Year</th>
<th>Km of road / 1000 people</th>
<th># of vehicles / 1000 people</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>2.27</td>
<td>238</td>
</tr>
</tbody>
</table>


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.

Comparison of passenger trip mix among big cities in the world

<table>
<thead>
<tr>
<th>City</th>
<th>Buses</th>
<th>Cars</th>
<th>Light Rail/Subway</th>
<th>MC</th>
<th>NMV</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Seoul</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mexico city</td>
<td></td>
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<td></td>
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<tr>
<td>Buenos Aires</td>
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<tr>
<td>Rio de Janeiro</td>
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<tr>
<td>Bangkok</td>
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<tr>
<td>New York</td>
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<tr>
<td>London</td>
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<tr>
<td>Paris</td>
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<tr>
<td>Tokyo</td>
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</tbody>
</table>

Delhi, 1994

<table>
<thead>
<tr>
<th>Category</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>62.00%</td>
</tr>
<tr>
<td>Cars</td>
<td>6.94%</td>
</tr>
<tr>
<td>Light Rail/Subway</td>
<td>0.00%</td>
</tr>
<tr>
<td>MC</td>
<td>17.59%</td>
</tr>
<tr>
<td>NMV</td>
<td>6.61%</td>
</tr>
<tr>
<td>Others</td>
<td>6.86%</td>
</tr>
</tbody>
</table>

Others:

<table>
<thead>
<tr>
<th>Category</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autorickshaws</td>
<td>2.80%</td>
</tr>
<tr>
<td>Taxis</td>
<td>0.06%</td>
</tr>
<tr>
<td>Rail</td>
<td>0.38%</td>
</tr>
<tr>
<td>Others</td>
<td>3.62%</td>
</tr>
</tbody>
</table>
Comparison of Vehicle Ownership and Pollution in Big Cities in the World

![Bar chart and line graph showing vehicle ownership and NOx concentration in various cities.](image)

Data for Delhi vehicle number is in 1997, NOx 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 (µg/m³)

<table>
<thead>
<tr>
<th>City</th>
<th>TSP</th>
<th>SO₂</th>
<th>NO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>377</td>
<td>90</td>
<td>122</td>
</tr>
<tr>
<td>Delhi</td>
<td>415</td>
<td>24</td>
<td>41 (NOₓ 47.2)</td>
</tr>
<tr>
<td>Tokyo</td>
<td>49</td>
<td>18</td>
<td>68</td>
</tr>
<tr>
<td>Mexico City</td>
<td>279</td>
<td>74</td>
<td>130</td>
</tr>
<tr>
<td>London</td>
<td>25</td>
<td></td>
<td>77</td>
</tr>
<tr>
<td>New York</td>
<td>26</td>
<td></td>
<td>79</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>9</td>
<td></td>
<td>74</td>
</tr>
</tbody>
</table>
### Share of Air Pollutant Emissions from the Mobile Sector

<table>
<thead>
<tr>
<th>City</th>
<th>CO</th>
<th>HC</th>
<th>NO\textsubscript{x}</th>
<th>SO\textsubscript{2}</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mexico, 1994</td>
<td>100%</td>
<td>53.3%</td>
<td>70%</td>
<td>26.5%</td>
<td>4.3%</td>
</tr>
<tr>
<td>Santiago, 1992</td>
<td>94.2%</td>
<td>82.7%</td>
<td>84.6%</td>
<td>24%</td>
<td>11.5%</td>
</tr>
<tr>
<td>São Paulo, 1995</td>
<td>96.4%</td>
<td>90.9%</td>
<td>97.3%</td>
<td>85.5%</td>
<td>42.7%</td>
</tr>
<tr>
<td>Rio de Janeiro, 1978</td>
<td>96.4%</td>
<td>73.2%</td>
<td>69.6%</td>
<td>9.5%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Beijing, 1992</td>
<td>63.4%</td>
<td>73.5%</td>
<td>21.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beijing, 1995</td>
<td>86.2%</td>
<td>49.1%</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delhi, 1995</td>
<td>80.5%</td>
<td>95.2%</td>
<td>69.4%</td>
<td>4.6%</td>
<td>6.6%</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>1991</th>
<th>Road Supply (m/person)</th>
<th>Total Vehicles per km Road</th>
<th>Average Speed (km/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York</td>
<td>4.7</td>
<td>99</td>
<td>35</td>
</tr>
<tr>
<td>Paris</td>
<td>0.9</td>
<td>410</td>
<td>28</td>
</tr>
<tr>
<td>London</td>
<td>1.9</td>
<td>186</td>
<td>31</td>
</tr>
<tr>
<td>Tokyo</td>
<td>1.9</td>
<td>140</td>
<td>21</td>
</tr>
<tr>
<td>Beijing (1995)</td>
<td>0.944</td>
<td>49.9</td>
<td>23</td>
</tr>
<tr>
<td>Delhi (1992)</td>
<td>2.17</td>
<td>90</td>
<td>30</td>
</tr>
</tbody>
</table>


Delhi

<table>
<thead>
<tr>
<th>Year</th>
<th>Road length (km)</th>
<th># of vehicles (millions)</th>
<th>Speeds (km/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>8,380</td>
<td>0.214</td>
<td>23</td>
</tr>
<tr>
<td>1981</td>
<td>14,320</td>
<td>14,320</td>
<td>19</td>
</tr>
<tr>
<td>1991</td>
<td>21,670</td>
<td>21,670</td>
<td>18</td>
</tr>
<tr>
<td>1997</td>
<td>25,949</td>
<td>25,949</td>
<td>15</td>
</tr>
<tr>
<td>2001</td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

Road length increased by 3 times from 1972 to 1997 in Delhi while # of vehicles increased by 13 times!
In 1997, 1749 km of road per 100 km² in Delhi while 73 km/100 km² in India in 1996.

1994 Average Speeds in Large Cities

<table>
<thead>
<tr>
<th>City</th>
<th>Manila</th>
<th>Bangkok</th>
<th>Seoul</th>
<th>Shanghai</th>
<th>Jakarta</th>
<th>Tokyo</th>
<th>Singapore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Speed (km/hr)</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>8</td>
<td>14</td>
<td>14</td>
<td>30</td>
</tr>
</tbody>
</table>

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.

Health impacts

Air quality standards are being exceeded as a result of increased emissions

Fuel costs

Value of Time

Fuel Consumption

Total Emissions

1995 → 2020
All emissions grow by 2 to 3 times, while CO2 emissions rise by about 7 times

Concentrations
Vehicular Air Pollution Information System, Delhi (2)

Vehicle Growth: Delhi

- Trucks
- Buses
- Taxis
- Autos
- 2Str-2Wh
- Car

No. of Vehicles


10,000,000 15,000,000 20,000,000 25,000,000
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

- Cars: 26%
- 2Wh.2str: 64%
- Autos: 3%
- Taxis: 0%

Vehicle Population in 2020

- Cars: 43%
- 2Wh.2str: 50%
- Autos: 1%
- Taxis: 1%
- Buses: 1%
- Trucks: 4%

Bar charts showing the number of vehicles in 1995 and 2020 for various categories.
Vehicular Air Pollution Information System, New Delhi (5)

Delhi CO Emissions Overall

Delhi NOx Emissions Overall

Delhi HC Emissions Overall

Delhi SO2 Emissions Overall
Vehicular Air Pollution Information System, Delhi (6)

CO Emissions: Delhi Vehicles

NOx Emissions: Delhi Vehicles
Vehicular Air Pollution Information System, Delhi (7)

Percentage of Emissions by Vehicles in 1995

**CO Emissions (tons/day) by Vehicle Type**
- Cars: 44%
- Trucks: 14%
- Buses: 7%
- Taxis: 3%
- 2Wh.2str: 20%
- Autos: 12%

Total = 691 tons/day

**NOx Emissions (tons/day) by Vehicle Type**
- Trucks: 58%
- Buses: 29%
- Cars: 10%
- 2Wh.2str: 1%
- Autos: 1%
- Taxis: 1%

Total = 275 tons/day

Percentage of Emissions by Vehicles in 2020

**CO Emissions (tons/day) by Vehicle Type**
- Cars: 47%
- Trucks: 17%
- Buses: 7%
- Taxis: 3%
- 2Wh.2str: 17%
- Autos: 9%

Total = 1,509 tons/day

**NOx Emissions (tons/day) by Vehicle Type**
- Trucks: 59%
- Buses: 24%
- Cars: 14%
- 2Wh.2str: 1%
- Autos: 1%
- Taxis: 1%

Total = 740 tons/day
Vehicular Air Pollution Information System, Delhi (8)
Vehicular Air Pollution Information System, Delhi (9)

Percentage of Emissions by Vehicles in 1995

- **HC Emissions (tons/day) by Vehicle Type**
  - Cars: 25%
  - 2Wh.2str: 40%
  - Autos: 23%
  - Trucks: 7%
  - Buses: 4%
  - Taxis: 1%

Total = 220 tons/day

- **SO2 Emissions (tons/day) by Vehicle Type**
  - Cars: 4%
  - 2Wh.2str: 2%
  - Autos: 1%
  - Taxis: 0%
  - Buses: 30%
  - Trucks: 63%

Total = 19 tons/day

Percentage of Emissions by Vehicles in 2020

- **HC Emissions (tons/day) by Vehicle Type**
  - Cars: 26%
  - 2Wh.2str: 48%
  - Autos: 14%
  - Trucks: 7%
  - Buses: 3%
  - Taxis: 2%

Total = 497 tons/day

- **SO2 Emissions (tons/day) by Vehicle Type**
  - Cars: 20%
  - 2Wh.2str: 5%
  - Autos: 2%
  - Taxis: 1%
  - Buses: 21%
  - Trucks: 51%

Total = 41 tons/day
Vehicular Air Pollution Information System, Delhi (10)
Vehicular Air Pollution Information System, Delhi (11)
Percentage of Emissions by Vehicles in 1995

Percentage of Emissions by Vehicles in 2020

**TSP Emissions (tons/day) by Vehicle Type**
- **1995**
  - Trucks: 55%
  - Cars: 7%
  - 2Wh.2str: 6%
  - Autos: 5%
  - Taxis: 0%
  - Total: 42.4 tons/day

- **2020**
  - Trucks: 58%
  - Cars: 8%
  - 2Wh.2str: 8%
  - Autos: 1%
  - Taxis: 0%
  - Total: 84.7 tons/day

**PM10 Emissions (tons/day) by Vehicle Type**
- **1995**
  - Trucks: 55%
  - Cars: 7%
  - 2Wh.2str: 6%
  - Autos: 5%
  - Taxis: 0%
  - Total: 33.9 tons/day

- **2020**
  - Trucks: 58%
  - Cars: 8%
  - 2Wh.2str: 8%
  - Autos: 1%
  - Taxis: 0%
  - Total: 67.8 tons/day
Vehicular Air Pollution Information System, Delhi (12)
Vehicular Air Pollution Information System, Delhi (13)

Percentage of Emissions by Vehicles in 1995

- **CO2 Emissions (tons/day) by Vehicle Type**
  - Trucks: 44%
  - Cars: 25%
  - Buses: 21%
  - 2Wh.2str: 5%
  - Autos: 4%
  - Taxis: 1%

  **Total = 22,290 tons/day**

- **Pb Emissions (tons/day) by Vehicle Type**
  - Autos: 20%
  - 2Wh.2str: 20%
  - Cars: 57%

  **Total = 0.6 tons/day**

Percentage of Emissions by Vehicles in 2020

- **CO2 Emissions (tons/day) by Vehicle Type**
  - Trucks: 33%
  - Cars: 44%
  - Buses: 14%
  - 2Wh.2str: 5%
  - Autos: 4%
  - Taxis: 1%

  **Total = 141,716 tons/day**

- **Pb Emissions (tons/day) by Vehicle Type**
  - Autos: 15%
  - Taxis: 4%
  - Buses: 0%
  - Trucks: 0%

  **Total = 0.5 tons/day**
## Value of Time, Fuel Costs, & Health Costs from Passenger Transport in Delhi

<table>
<thead>
<tr>
<th></th>
<th>1995</th>
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<tbody>
<tr>
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<td>9,664.11</td>
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<tbody>
<tr>
<td><strong>million tons of carbon per year</strong></td>
<td>2.33</td>
<td>4.53</td>
<td>21.51</td>
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<td><strong># of premature deaths per year due to air pollution</strong></td>
<td>5,441</td>
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<td>31,427</td>
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## Value of Time, Fuel Costs, & Health Costs from Passenger Transport in Delhi

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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Unit Values for Each Category of Health Impact

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

Restricted activity days = daily wage

Source: Brandon and Hommann, 1995
Monetized Air Accounts for National Capital Territory – Delhi

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Damage Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Health Damage</td>
<td>867.6</td>
<td>1168.3</td>
</tr>
<tr>
<td>• Vegetation Damage</td>
<td>178.6</td>
<td>321.0</td>
</tr>
<tr>
<td>• Ecological Damage</td>
<td>15880</td>
<td>21390</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>16926.2</td>
<td>22978.3</td>
</tr>
<tr>
<td><strong>Avoidance Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Industrial Sector</td>
<td>107.8</td>
<td>143.2</td>
</tr>
<tr>
<td>• Power Sector</td>
<td>166.7</td>
<td>75.40</td>
</tr>
<tr>
<td>• Transportation Sector</td>
<td>577.50</td>
<td>804.00</td>
</tr>
<tr>
<td>• Domestic Sector</td>
<td>508.9</td>
<td>677.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1726.07</td>
<td>2182.3</td>
</tr>
<tr>
<td><strong>Willingness-to-pay for Good Air Quality AQI = 50</strong></td>
<td>3399.21</td>
<td>5089.81</td>
</tr>
</tbody>
</table>

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

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

Injuries and Death from Traffic Accidents in Delhi

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of Accidents</th>
<th>Killed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982</td>
<td>3,793</td>
<td>893</td>
</tr>
</tbody>
</table>

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 and Fuel Costs for Commuting to Work and Health Costs of Mobile Sources Emissions in New Delhi

<table>
<thead>
<tr>
<th>Millions $</th>
<th>1995</th>
<th>2000</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of Time</td>
<td>58.53</td>
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<td>1270.48</td>
<td>9664.11</td>
</tr>
</tbody>
</table>

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.

PM10 emissions from two stroke engine vehicles could cause up to 1510 premature deaths, 13 million restricted activity days, and 41 million respiratory symptoms each year. The associated minimum economic cost is $122million/year.

Transportation in Delhi

- Rapid pace of urbanization
- Growing motorization
- ↑ automobile ownership
- ↑ driving

- Inadequate traffic management
- Old vehicle stock and in poor condition
- Vehicle mix (large use of two stroke engine technology)
- Inefficient public transport system
- Poor land use management
- Lower fuel quality

- ↑ Income
- ↑ # of trips/day
- Inadequate public transport

- ↑ economic activities

- ↓ quality of life
- traffic congestion
- loss of productivity
- ↑ fuel consumption
- ↑ air pollution
- health impacts

- ↑ # of trips/day
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 \textit{energy use per passenger-km} modes

* use low \textit{emissions per passenger-km} modes

* use modes with low \textit{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.
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
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
\[
\text{MAX NET BENEFITS} = \text{Value of Time, Health and Materials Damages - Costs from Vehicular Air Pollution}
\]

\[
\text{MIN TOTAL COSTS}
\]

- air quality standards
- total emission limits
- demand constraint (pass-km)
- budget constraint
- fuel capacity limits
- logical constraints

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

Agree on Policy

Change Constraints
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\textsubscript{x}, SO\textsubscript{2}, HC, TSP, CO\textsubscript{2}/
- 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
• frt(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,f1,t): fraction of vehicle v age a fuel f switching to fuel f1 in year t
• SNV(v,a,f,f1,t): number of vehicles v of age a switching from fuel f to f1 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 +

= \sum\text{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

Cost from switching fuel & cost of control options utilized – cost of fuel savings
CONSTRANTS

• Sum of demand (pass-km) by each mode (t) ≤ Turnover projections (t)
• Annualized Infrastructure Investment Costs + Public Transport Vehicle Costs and their O&M costs + Costs of Control Options + Subsidies – Taxes ≤ Budget for each year allocated to the transportation sector
• Total Emissions (taking into consideration the reductions resulting from the use of different policy options) ≤ Air Quality Limits
• Concentration of Each Pollutant (as a function of emissions) ≤ 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 ≤ 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

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 f1 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)
Beijing’s TSP emissions lower than Delhi’s but concentrations close (ex. 1995 377 to 415) but higher % from vehicles in Beijing (25% vs 7%)

<table>
<thead>
<tr>
<th></th>
<th>1995</th>
<th>2000</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Value of Time</strong></td>
<td>182.33</td>
<td>743.63</td>
<td>19,514.94</td>
</tr>
<tr>
<td><strong>Fuel Costs</strong></td>
<td>641.00</td>
<td>1,569.22</td>
<td>19,509.85</td>
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<tr>
<td><strong>Health Costs</strong></td>
<td>975.18</td>
<td>1,898.65</td>
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<td><strong>million tons of carbon per year</strong></td>
<td>3.40</td>
<td>6.02</td>
<td>19.47</td>
</tr>
<tr>
<td><strong># of premature deaths per year due to air pollution</strong></td>
<td>10,405</td>
<td>15,267</td>
<td>46,123</td>
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Value of Time, Fuel Costs, & Health Costs from Passenger Transport in 2020 Under Different Scenarios for Beijing

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<th>At 6 km/hr 2020</th>
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<th>With Tokyo's pass-trip mix 2020</th>
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<td>Value of Time</td>
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<td>8,631.77</td>
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<td>Fuel Cost</td>
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