Transportation and Environment

Problems in Delhi

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Presentation Outline

★ Transportation system characteristics and air quality in Delhi

★ Spreadsheet vehicular air pollution information system for Delhi
  ★ Effects of technological improvements and congestion

★ An optimization model
  ★ Different cases, results, and implications
Delhi’s Transportation System

- Inadequate traffic management
- Inefficient public transport system
- Increasing incomes and economic activities
- Mostly personal vehicles (cars and two wheelers) with largely single occupancies
- Growing motorization: increasing number of trips per person and average trip distances
Delhi’s Vehicle Fleet and Population

• Total # of motor vehicles per 1000 people in 1998 was 238 (expected 305/1000 in 2005).
• Largest vehicle population in the country: number of vehicles increased by 15 times in the past three decades (currently about 3 million vehicles for close to 14 million people)
• Highest road length in India: 1284km/100km² area (26,379km of total length in 1998/99).
  • But no traffic segmentation and lane discipline
  • ~10,000 accidents/yr: 10,000 injuries, 2,000 deaths
• Most congested city in India!
• Expected population for 2020: 22,000,000
Effect of Speed on Emission Factors and Fuel Efficiencies for Cars in Beijing

Even a small reduction in speeds from 20km/hr to 15km/hr increases fuel consumption by 25% (Stares and Liu, 1996).

Stop and go driving substantially increases vehicle emissions (very high emissions during accelerating and decelerating).

Increased congestion levels creating reduction in speeds will result in higher emissions and fuel consumption from transport activities!

Also more time will be spent in traffic!

As fuel efficiencies decrease due to reduced speeds, emissions of other pollutants will also increase!
WHO named Delhi as the 4th most polluted city in the world in terms of suspended particulate matter.

Particulate pollution was reported to kill 1 person per hour in 1995 in Delhi (CSE, 1997).
Transport Institutions & Data

- Need for institutional and regulatory reform (multiple institutions are responsible for urban transport planning)
- Lack of coordination and poor enforcement
- Publicly available data very few and with questionable credibility
- Private organizations do not share their data
Spreadsheet Simulation

- 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 vehicular emissions when current growth rates are maintained into the future.

- Cases:
  - Case 1: Continuous technological advancement to meet fuel efficiency, emissions factors, and fuel quality improvements until 2020.
  - Case 2: Maintain 2000 technologies into the future.
  - Case 3: Case 1 with the effects of reduced speeds and congestion on fuel efficiencies and emissions factors.
Delhi’s Vehicle Fleet

Age Distribution of All Vehicles in Delhi (1995-2020)

Vehicle Growth: Delhi

Percent of Vehicles Older Than 15 Years in Delhi’s Vehicle Fleet

<table>
<thead>
<tr>
<th></th>
<th>cars</th>
<th>2W</th>
<th>autorickshaws</th>
<th>taxis</th>
<th>buses</th>
<th>trucks</th>
<th>total</th>
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<tbody>
<tr>
<td>1995</td>
<td>12.30</td>
<td>0.00</td>
<td>7.35</td>
<td>28.05</td>
<td>21.97</td>
<td>20.11</td>
<td>4.91</td>
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<tr>
<td>2000</td>
<td>7.82</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>17.48</td>
<td>3.20</td>
</tr>
<tr>
<td>2001</td>
<td>7.90</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.43</td>
</tr>
</tbody>
</table>
Although cars and two wheelers make up close to 95% of total vehicles in 2020, they meet about 45% of the PKM demand.

Buses will continue to meet most of the transport demand in Delhi (less than 0.5% of total fleet in 2020 still satisfying about 40% of the PKM demand).
Emissions from the 3 Cases

- **CO Emissions**
  - Case 1
  - Case 2
  - Case 3

- **HC Emissions**
  - Case 1
  - Case 2
  - Case 3

- **CO₂ Emissions**
  - Case 1
  - Case 2
  - Case 3

- **PM10 Emissions**
  - Case 1
  - Case 2
  - Case 3
Value of Time, Fuel Costs, and Health Impacts of Vehicular Air Pollution

<table>
<thead>
<tr>
<th>Year</th>
<th>Value of Time</th>
<th>1995</th>
<th>2000</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 3</td>
<td></td>
<td>162.79</td>
<td>391.04</td>
<td>16,536.75</td>
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<table>
<thead>
<tr>
<th>Year</th>
<th>Premature Deaths due to air pollution</th>
<th>1995</th>
<th>2000</th>
<th>2020</th>
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<tbody>
<tr>
<td>Case 1</td>
<td></td>
<td>4,027</td>
<td>4,827</td>
<td>6,614</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td>4,027</td>
<td>4,827</td>
<td>8,009</td>
</tr>
<tr>
<td>Case 3</td>
<td></td>
<td>4,027</td>
<td>4,963</td>
<td>10,463</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Health Costs</th>
<th>1995</th>
<th>2000</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td></td>
<td>495.15</td>
<td>800.73</td>
<td>2,918.64</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td>495.15</td>
<td>800.73</td>
<td>3,532.15</td>
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<tr>
<td>Case 3</td>
<td></td>
<td>495.15</td>
<td>823.08</td>
<td>4,617.93</td>
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<table>
<thead>
<tr>
<th>Year</th>
<th>Total Fuel Consumption</th>
<th>1995</th>
<th>2000</th>
<th>2020</th>
</tr>
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<tbody>
<tr>
<td>Case 1</td>
<td></td>
<td>1,602</td>
<td>1,949</td>
<td>5,726</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td>1,602</td>
<td>1,949</td>
<td>7,410</td>
</tr>
<tr>
<td>Case 3</td>
<td></td>
<td>1,602</td>
<td>2,008</td>
<td>9,123</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Fuel Costs</th>
<th>1995</th>
<th>2000</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td></td>
<td>586.7</td>
<td>882.67</td>
<td>7,452.50</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td>586.7</td>
<td>882.67</td>
<td>9,787.14</td>
</tr>
<tr>
<td>Case 3</td>
<td></td>
<td>586.7</td>
<td>909.89</td>
<td>12,029.16</td>
</tr>
</tbody>
</table>
Conclusions & Summary of Simulation Model Results

- Projection of the vehicle fleet at current growth rates will result in more than 13 million vehicles, mostly cars and two wheelers, for a population of close to 22 million people by the year of 2020.
- Buses satisfy a very large amount of the transport demand despite the fact that their numbers are so small. So measures directed to facilitate their operation are a must.
- Even though the vehicle fleet becomes younger and cleaner due to lower retirement ages, strict fuel efficiencies and emissions standards, and fuel quality improvements, costs of externalities from this growing transportation system will increase by large amounts.
- Although technological improvements are necessary and they attain large reductions in health costs and fuel costs, the effects of traffic congestion and reduced speeds on emissions and fuel consumption from vehicles are even higher. Therefore, appropriate measures should be taken to reduce these adverse effects of reduced speeds and increase the efficiency of the transport system.
Optimization Model Structure

Fuel Cost + Vehicle and OM Costs + Infrastructure Cost + Options Cost + Social Costs → Minimum

Parameters:
- Economic
- Technical
- Environmental
- Social

Constraints:
- Air Quality
- Social Costs
- Budget

Road, rail, subway

Traffic mgt, Parking mgt, Ride sharing, Telecommuting, I/M, Subsidies

Gasoline, Diesel, Methanol, Ethanol, CNG, LPG, Hybrid, Electricity, NMV

Cars, 2W, Autorickshaws, Taxis, Buses, Light Rail, Subway, Bicycle, Tricycle

PKM Demand
General Equilibrium Analysis of the Maximization of Producers’ and Consumers’ Surplus

Price: \( \text{cost/pkm} \ (v,t) \)
Quantity: \( \text{pkm} \ (v,t) \)

Welfare = Area under the Demand Function
- Area under the Supply Function
= Consumers’ surplus \( (W) \)
+ Producers’ surplus \( (X) \)

Demand and Supply Relationships for Welfare Maximization
Optimization Model Cases

- Minimizing Total Costs of Transportation System
- Maximizing Welfare from Transportation

PKM Demand

5% annual increase

Spreadsheet simulation equivalent

Minimize Costs

- With Additional Options
  - With Social Costs in Obj
    - Limited Buses
  - No Social Costs in Obj
    - No Bus Limit

- No Additional Options
  - With Social Costs in Obj
    - Limited Buses
  - No Social Costs in Obj
    - No Bus Limit

Maximize Welfare

- Welfare (v,t)
  - With Additional Options
    - Limited Buses
  - No Social Costs in Obj
    - No Bus Limit

- Aggregate Demand-Supply (t)
  - With Additional Options
    - Limited Buses
  - No Social Costs in Obj
    - No Bus Limit
Cases Analyzed

• **Case 1:** Minimizing total costs without social costs with only the first three control options for vehicle technologies, fuels, and rail infrastructure with SET 1 PKM demand

• **Case 2:** Case 1 with SET 2 PKM demand

• **Case 3:** Case 2 with social costs

• **Case 4:** Case 2 with all the traffic control options

• **Case 5:** Maximizing welfare without social costs with only the first three control options for vehicle technologies, fuels, and rail infrastructure with SET 2 PKM demand

• **Case 6:** Case 5 with an aggregate demand and supply curve for total motor vehicles

• **Case 7:** Case 1 with limited number of buses (35,000)

• **Case 8:** Case 2 with limited number of buses (50,000)

• **Case 9:** Case 5 with limited number of buses (50,000)

• **Case 10:** The spreadsheet simulation

  SET 1: 5% annual growth rate in travel demand over base year 2000.
  SET 2: Spreadsheet simulation equivalent travel demands.
Transportation System Costs in Delhi for Case 1

Breakdown of PDV of Engineering and Social Costs of Transport

Breakdown of PDV of Engineering Costs of Transport

Costs of Transportation

2000 Cost per Pkm

2000 overall system cost per PKM: 2.22 cents/PKM

Because there is no light rail or subway in Delhi yet its cost is not calculated.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cost per Pkm</th>
</tr>
</thead>
<tbody>
<tr>
<td>tricycle</td>
<td>0.03</td>
</tr>
<tr>
<td>bicycle</td>
<td>0.05</td>
</tr>
<tr>
<td>subway</td>
<td></td>
</tr>
<tr>
<td>light rail</td>
<td></td>
</tr>
<tr>
<td>trucks</td>
<td>3.96</td>
</tr>
<tr>
<td>buses</td>
<td>0.29</td>
</tr>
<tr>
<td>taxis</td>
<td>1.86</td>
</tr>
<tr>
<td>autorickshaws</td>
<td>4.41</td>
</tr>
<tr>
<td>2W</td>
<td>2.59</td>
</tr>
<tr>
<td>cars</td>
<td>6.15</td>
</tr>
</tbody>
</table>
VKT, PKM, and Energy Use Breakdown by Travel Mode for Case 1

**Vehicle-km Breakdown by Vehicle in Each Year**

- **2020**:
  - Cars: 1,267,537
  - Two wheelers: 1,000,000
  - Autorickshaws: 25,000
  - Buses: 71,210
  - Trucks: 244,435

- **2015**:
  - Cars: 1,267,537
  - Two wheelers: 1,000,000
  - Autorickshaws: 25,000
  - Buses: 71,210
  - Trucks: 244,435

- **2010**:
  - Cars: 1,267,537
  - Two wheelers: 1,000,000
  - Autorickshaws: 25,000
  - Buses: 71,210
  - Trucks: 244,435

- **2005**:
  - Cars: 1,267,537
  - Two wheelers: 1,000,000
  - Autorickshaws: 25,000
  - Buses: 71,210
  - Trucks: 244,435

- **2000**:
  - Cars: 1,267,537
  - Two wheelers: 1,000,000
  - Autorickshaws: 25,000
  - Buses: 71,210
  - Trucks: 244,435

**Passenger-km Breakdown by Vehicle in Each Year**

- **2020**:
  - Cars: 38.17%
  - Two wheelers: 48.38%
  - Autorickshaws: 95.00%
  - Buses: 2.72%
  - Trucks: 9.33%

- **2015**:
  - Cars: 38.17%
  - Two wheelers: 48.38%
  - Autorickshaws: 95.00%
  - Buses: 2.72%
  - Trucks: 9.33%

- **2010**:
  - Cars: 38.17%
  - Two wheelers: 48.38%
  - Autorickshaws: 95.00%
  - Buses: 2.72%
  - Trucks: 9.33%

- **2005**:
  - Cars: 38.17%
  - Two wheelers: 48.38%
  - Autorickshaws: 95.00%
  - Buses: 2.72%
  - Trucks: 9.33%

- **2000**:
  - Cars: 38.17%
  - Two wheelers: 48.38%
  - Autorickshaws: 95.00%
  - Buses: 2.72%
  - Trucks: 9.33%

**% Energy Use by Transport Mode**

- **2020**:
  - Cars: 95.00%
  - Two wheelers: 44.00%
  - Autorickshaws: 2.72%
  - Buses: 9.33%
  - Trucks: 9.33%

- **2015**:
  - Cars: 95.00%
  - Two wheelers: 44.00%
  - Autorickshaws: 2.72%
  - Buses: 9.33%
  - Trucks: 9.33%

- **2010**:
  - Cars: 95.00%
  - Two wheelers: 44.00%
  - Autorickshaws: 2.72%
  - Buses: 9.33%
  - Trucks: 9.33%

- **2005**:
  - Cars: 95.00%
  - Two wheelers: 44.00%
  - Autorickshaws: 2.72%
  - Buses: 9.33%
  - Trucks: 9.33%

- **2000**:
  - Cars: 95.00%
  - Two wheelers: 44.00%
  - Autorickshaws: 2.72%
  - Buses: 9.33%
  - Trucks: 9.33%
PKM, CO₂, CO, and PM10 Emissions breakdown by travel mode for Case 1
Fuel consumption by mode & energy use and CO$_2$ emissions per PKM for Case 1

Because there is no light rail or subway used in this case its MJ/PKM is zero - not calculated.
Minimizing Costs vs Maximizing Welfare: Vehicle Fleet Breakdown (# of vehicles)

### Minimize Costs

**Case 2**
- **2020**
  - cars: 1,267,537
  - 2W: 1,000,000
  - 3W: 25,000
  - taxis: 11,600
  - buses: 103,635
  - trucks: 244,435
  - subway: -
  - light rail: -
  - bicycle: 4,597,534
  - tricycle: 210,000

### Maximize Welfare

**Case 5**
- **2020**
  - cars: 2,242,478
  - 2W: 1,000,000
  - 3W: 25,000
  - taxis: 128,000
  - buses: 94,470
  - trucks: 244,435
  - subway: -
  - light rail: -
  - bicycle: 2,200,000
  - tricycle: 82,812
### Vehicle Fleet Distribution by Type in 2020 in Delhi for the 10 Cases

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7</th>
<th>Case 8</th>
<th>Case 9</th>
<th>Case 10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>total motor vehicles</strong></td>
<td>2,619,781</td>
<td>2,652,206</td>
<td>2,652,206</td>
<td>2,641,187</td>
<td>3,734,383</td>
<td>2,648,425</td>
<td>6,066,004</td>
<td>12,186,843</td>
<td>8,165,821</td>
<td>13,556,004</td>
</tr>
<tr>
<td><strong>cars</strong></td>
<td>1,267,537</td>
<td>1,267,537</td>
<td>1,267,537</td>
<td>1,267,537</td>
<td>2,242,478</td>
<td>1,267,537</td>
<td>1,267,537</td>
<td>1,267,537</td>
<td>1,286,409</td>
<td>6,580,560</td>
</tr>
<tr>
<td><strong>two wheelers</strong></td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>4,229,432</td>
<td>10,200,000</td>
<td>1,000,000</td>
<td>7,044,943</td>
</tr>
<tr>
<td><strong>autorickshaws</strong></td>
<td>25,000</td>
<td>25,000</td>
<td>25,000</td>
<td>25,000</td>
<td>25,000</td>
<td>25,000</td>
<td>25,000</td>
<td>25,000</td>
<td>25,000</td>
<td>121,510</td>
</tr>
<tr>
<td><strong>taxis</strong></td>
<td>11,600</td>
<td>11,600</td>
<td>11,600</td>
<td>11,600</td>
<td>128,000</td>
<td>11,600</td>
<td>11,600</td>
<td>11,600</td>
<td>128,000</td>
<td>265,826</td>
</tr>
<tr>
<td><strong>buses</strong></td>
<td>71,210</td>
<td>103,635</td>
<td>103,635</td>
<td>92,615</td>
<td>94,470</td>
<td>99,853</td>
<td>35,000</td>
<td>50,000</td>
<td>50,000</td>
<td>53,569</td>
</tr>
<tr>
<td><strong>trucks</strong></td>
<td>244,435</td>
<td>244,435</td>
<td>244,435</td>
<td>244,435</td>
<td>244,435</td>
<td>244,435</td>
<td>244,435</td>
<td>244,435</td>
<td>244,435</td>
<td>406,557</td>
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<tr>
<td><strong>subway</strong></td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>78</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>175</td>
</tr>
<tr>
<td><strong>light rail</strong></td>
<td>-</td>
<td>-</td>
<td>101</td>
<td>-</td>
<td>-</td>
<td>289</td>
<td>667</td>
<td>667</td>
<td>108</td>
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<tr>
<td><strong>bicycle</strong></td>
<td>2,200,000</td>
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<td>2,200,000</td>
<td>2,200,000</td>
<td>2,200,000</td>
<td>13,000,000</td>
<td>13,000,000</td>
<td>2,200,000</td>
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</tr>
<tr>
<td><strong>tricycle</strong></td>
<td>60,000</td>
<td>210,000</td>
<td>210,000</td>
<td>166,493</td>
<td>82,812</td>
<td>60,000</td>
<td>210,000</td>
<td>210,000</td>
<td>702,382</td>
<td></td>
</tr>
</tbody>
</table>

- **Case 1:** Min Cost SET 1 PKM
- **Case 2:** Min Cost SET 2 PKM
- **Case 3:** Case 2 + Social Costs
- **Case 4:** Case 2 + All Options
- **Case 5:** Max Welfare SET 2 PKM
- **Case 6:** Case 5 with aggregate D-S
- **Case 7:** Case 1 + 35,000 Buses
- **Case 8:** Case 2 + 50,000 Buses
- **Case 9:** Case 5 + 50,000 Buses
- **Case 10:** Spreadsheet Simulation

**SET 1:** 5% annual growth rate in travel demand over base year 2000.
**SET 2:** Spreadsheet simulation equivalent travel demands.
Value of Time, Health Costs, and Fuel Costs in 2020 for 10 Cases

Case 1: Min Cost SET 1 PKM
Case 2: Min Cost SET 2 PKM
Case 3: Case 2 + Social Costs
Case 4: Case 2 + All Options
Case 5: Max Welfare SET 2 PKM
Case 6: Case 5 with aggregate D-S
Case 7: Case 1 + 35,000 Buses
Case 8: Case 2 + 50,000 Buses
Case 9: Case 5 + 50,000 Buses
Case 10: Spreadsheet Simulation

SET 1: 5% annual growth rate in travel demand over base year 2000.
SET 2: Spreadsheet simulation equivalent travel demands.
Tradeoff Curves for PKM vs Costs, Emissions, and Number of Vehicles in Case 8:

It is very important to forecast a fairly exact travel demand for the future, but as long as the demand is below the elbow point of these tradeoff curves, it would be possible to plan for a rather cost-effective transport system with the suggested model solutions.
Main Model Formulations and Their General Outcomes

Model Formulations

Minimize Total Engineering Costs

Minimize Engineering + Social Costs

Maximize Welfare

Characterization of Outcomes

Buses and non-motorized vehicles meet increasing demand. CNG taxis, hybrid buses and trucks

Buses, tricycles, and light rail. Cleaner vehicle technologies.

Larger total number of motor vehicles, fewer buses and non-motorized vehicles but more cars and taxis. Mix of alternative fuel and clean technologies for vehicles. Higher system costs.
Conclusions & Summary of Optimization Model Results

- Less repetitive work involved in optimization – an integrated way of looking at an extensive list of control options.

- Cleaner vehicles need to be adopted due to emissions reduction requirements included in the optimization model. Competitive vehicle technologies in the cost minimizing cases turn out to be: CNG taxis, hybrid buses and trucks, electric, LPG, and CNG autorickshaws, gasoline and CNG cars, and ethanol, LPG, and CNG two wheelers. A mixture of alternative fuels and clean vehicle technologies are chosen in welfare maximizing cases still maintaining widely the choice of CNG for taxis and hybrid for buses and trucks.

- The total # of motor vehicles are higher in welfare maximizing cases compared to their parallel cost minimizing cases. In general more cars and taxis and fewer buses are used in these cases.

- Addition of social costs in the objective function results in some cases with the use of more light rail, less bicycles, and lower VoT, and in almost all the cases in the use of cleaner vehicle technologies and consequently lower health costs.
**Conclusions & Summary of Optimization Model Results**

- Addition of all the control options in the optimization results in less total # of motor vehicles, higher speeds, and lower value of time and health costs to achieve a social optimum.

- Most cost-effective mode of transport chosen by the optimization model is Buses! Buses are Delhi’s future!
  - When buses are limited, a lot more vehicles in all the other modes are required to meet the transport demand. As a result, social costs are higher.
  - More two wheelers, autorickshaws, bicycles, subway, and light rail are used in cost minimizing cases. More cars, taxis, and tricycles meet the left over demand in welfare maximizing cases.

- A very well planned public transport system, with dedicated bus lanes and bus priorities, is essential for developing a sustainable transportation system in Delhi!
The End

Thank You!