Transportation Decision-making
Principles of Project Evaluation and Programming

Transportation Cost Estimation

Kumares C. Sinha and Samuel Labi
Transportation Costs

- Classification of Costs
- Agency Costs
- User Costs/Community Costs
- Cost Functions
  - Highway
  - Transit
  - Air
- Issues in Cost Estimation
Classification

By Incurring Party
- Agency
- User
- Nonuser or Community Costs
Cost categories

- Transportation Costs
  - Agency/Owner Facility Costs
  - Operator's Facility Costs
  - User Costs
    - Operator's Usage Costs
  - Community or Nonuser Costs
Cost Categories – Details of User Costs

User Costs
  Operator’s Usage Costs
    Facility Usage Fees
      Operators: License Fees, Permits, etc.
      Users: Fares/Tolls, Taxes, etc.
    Costs of Operating the Transportation Vehicle
      Energy Sources: Gasoline, Jet Fuel, Electricity, etc.
      Consumable Parts and Fluids: Tires, Brake pads, Oil, etc.
    Delay and Travel Time Costs
      Cost of Delay at Nodes (Terminals, Ports, Stations, Intersections) and Links.
    Security/Safety Costs
      Cost of Consequences of Failed Security/Safety (User)
Cost Categories – Details of Community Costs

- Community or Nonuser Costs
  - Air Pollution Costs
  - Noise Pollution Costs
  - Other Environmental Resource Costs
Cost Variation with Output Volume

\[ TC (V) = k + f(V) \]

- \( k \) = Fixed Cost
- \( f (V) \) = Variable Cost
- \( V \) = Output

Ratio of Variable Cost to Fixed Cost
- Is an Indicator of Economy of Scale
By the Expression of Unit Cost

- Average Total Cost, $ATC = \frac{TC}{V}$
- Average Fixed Cost = $\frac{FC}{V}$
- Average Variable Cost = $\frac{VC}{V}$

Marginal Cost Vs. Average Cost

- Ratio of Small Increment of Cost to a Small Increment of Output
  - $MC = \frac{\delta C}{\delta V}$
MC and AC can differ significantly
- $10 million to build a 10-mile highway
- $10.5 million for 11-mile
AC’s are $1 million and $0.954 million
MC of additional 0.5 mile $0.5 million

- MVC = \( \frac{\delta VC}{\delta V} \)
- MTC = \( \frac{\delta TC}{\delta V} = \frac{\delta FC}{\delta V} + \frac{\delta VC}{\delta V} = \frac{\delta VC}{\delta V} = MVC \)
Table E4.1

<table>
<thead>
<tr>
<th>Function</th>
<th>Linear $TC = k + a \times V$</th>
<th>Quadratic $TC = k + a \times V^2$</th>
<th>Exponential $TC = k + a \times e^V$</th>
<th>Cubic $TC = k + a \times V^3$</th>
<th>Logarithmic $TC = k + a \times \ln V$</th>
<th>Power $TC = k + a \times b^V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Fixed Cost $= FC/V$</td>
<td>$k/V$</td>
<td>$k/V$</td>
<td>$k/V$</td>
<td>$k/V$</td>
<td>$k/V$</td>
<td>$k/V$</td>
</tr>
<tr>
<td>Average Variable Cost $= VC(V)/V$</td>
<td>$a$</td>
<td>$a \times V$</td>
<td>$a \times e^V/V$</td>
<td>$a \times V^2$</td>
<td>$a \times \log V/V$</td>
<td>$a \times b^V/V$</td>
</tr>
<tr>
<td>Average Total Cost $= TC(V)/V$</td>
<td>$k/V + a$</td>
<td>$k/V + a \times V$</td>
<td>$k/V + a \times e^V/V$</td>
<td>$k/V + a \times V^2$</td>
<td>$k/V + a \times \log V/V$</td>
<td>$k/V + a \times b^V/V$</td>
</tr>
<tr>
<td>Marginal Variable Cost $= VC(V) - VC(V-1)$</td>
<td>$a$</td>
<td>$2a \times V$</td>
<td>$a \times e^V$</td>
<td>$3a \times V^2$</td>
<td>$a/V$</td>
<td>$a \times \ln (b) \times b^V$</td>
</tr>
<tr>
<td>Marginal Total Cost $= TC(V) - TC(V-1)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Example: Historical record of operating costs for a metropolitan bus system

- Total Average and Marginal Costs
- Significance of the interaction between AC and MC
Illustration- Variation of Different Cost Types
Illustration- Variation of Different Cost Types
Illustration - Variation of Different Cost Types

- Average Total Costs
- Marginal Total Costs

Costs ($M) vs. Output (V, in millions)
Solution: When MC < AC, scale economies

Revenue is maximum at the ridership level when MC = AC (@3.7 million)
TC ($M) = 1.2 + 150V^2, V = monthly output in million of tons

AC = 1.2/V + 150 V

MC = 300 V

Optimal Output = 0.09 million tons
Illustration

Average Total Costs

Marginal Total Costs

Output ($V$), in millions of tons

Cost ($\text{millions}$)
Cost classification by By Position in Facility Life Cycle

- Initial or Construction Costs
- Subsequent Costs e.g. Maintenance, Operation and Preservation Costs
- Life Cycle Costs
Other Classifications of Costs

- In-House vs. Contract
- Preventive vs. Corrective
- Routine vs. Periodic
Transportation Agency Costs

- For Facilities
  - Advance Planning
  - Preliminary Engineering
  - Final Design
  - R-O-W Acquisition and Preparation
  - Construction
  - Operations
  - Preservation and Maintenance
  - Salvage or Disposal

- For Rolling Stocks
  - Acquisition
  - Operation
  - Preservation
  - Maintenance
  - Salvage or disposal
A. Disaggregate Approach

- By Pay Items
  - $ per length, area, or volume or weight of finished product, reported separately for materials, labor and supervision, and equipment use.
- At planning stages, level of identifying pay items and their costing is quite coarse.
- Cost models as a function of facility attributes.
B. Aggregate Approach

1. An average rate per unit output – for various subcategories.

2. A statistical model.

Example: Unit cost per lane-mile-station in $M

\[ = 3.9 \times L^{0.702} \times U^{1.08} \times ST^{-0.36} \]

L = number of line-miles
U = fraction underground
ST = number of stations
Risk as an Element of Agency Cost

Is due to Uncertainties in Estimation
- possible outcomes
- probability of each outcome
- consequences of decisions
- expected value
- Monte Carlo sampling
- defined probability distribution
Due to Disasters

- Natural or Man-made
- Vulnerability Cost =

\[
\sum (\text{Probability of Disaster} \times \text{Cost of Damage})
\]
User Costs

- Travel Time
- Safety
- Vehicle Operating
- Noise, Air and Water Pollution
Demand and User Cost Interaction

Demand is Inelastic
Figure 4.3

Elastic, Induced Trips
Figure 4.4

Elastic Demand - Generated Trips
Figure 4.5

[Diagram showing supply and demand curves with points labeled W, X, Y, Z, and axes for unit cost of travel and quantity of travel.]
Additional Consumer Surplus May Not be Equal to Change in User Cost

Change in (UC) > Change in (CS)

\[
\text{Change(UC)} = (Y + Z) - (X + Y) = Z - X
\]

\[
\text{Change(CS)} = (K+X) - W
\]
Figure 4.6
### Table: Possible Variables for Agency Cost Functions or Rate

<table>
<thead>
<tr>
<th>Physical Infrastructure</th>
<th>Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavements – cost per lane-mile of new pavement, cost per volume of laid/cast material</td>
<td>Congestion/Mobility – cost per travel time reduction, cost per unit resource for incident management,</td>
</tr>
<tr>
<td>Highways Bridges – cost per area of new or rehabilitated bridge (measured using deck area)</td>
<td>Safety – cost per unit reduction in fatal and injury crashes</td>
</tr>
<tr>
<td>Bus/Rail Transit</td>
<td>Cost per passenger, cost per passenger-mile, cost per revenue vehicle</td>
</tr>
<tr>
<td>Cost per bus or railcar, cost per route-mile</td>
<td>Cost per passenger, cost per enplanement</td>
</tr>
<tr>
<td>Rail Freight</td>
<td>Cost per passenger, cost per terminal, cost per floor area (of terminals). Yards – cost per yard area</td>
</tr>
<tr>
<td>Track – cost per line-mile.</td>
<td></td>
</tr>
<tr>
<td>Air Travel</td>
<td>Cost per area of passenger terminals, cost per runway length, cost per runway area</td>
</tr>
<tr>
<td>Cost per ton load of freight, cost per passenger</td>
<td></td>
</tr>
<tr>
<td>Marine Ports</td>
<td>Cost per area of facility, cost per dock</td>
</tr>
<tr>
<td>Cost per passenger-mile, Cost per freight ton-mile</td>
<td></td>
</tr>
</tbody>
</table>
Highway Cost Models


Variables
- Number of Crossings
- R-O-W
- Environmental Impacts
- Soil and Site Conditions
- Project Size
- Project Complexity
- Construction Delivery Method
- Urban/Rural Location

Historical Cost Database by Pay Items
Transit Cost Models

- High Speed Rail
- Heavy Rail
- Commuter Rail
- Light Rail
- Monorail
- BRT
- Urban Bus Transit
Unit Cost of Heavy (Rapid) Rail Construction

\[ UC = 3.906 \times LM^{-0.702} \times PU^{1.076} \times ST^{-0.358} \]

\[ R^2 = 0.94 \]

Where

UC = Cost Per Line-Mile-Station in $ M(2005)
LM = number of Line-Miles
PU = Percentage of System Underground
ST = Number of Stations
Example 1: Heavy Rail

- Given
  - 12 Line-Miles
  - 4 Stations
  - 85% Above Ground

- Total Cost
  \[
  = (12)(4)[3.906(12^{-0.702})(15^{1.076})(4^{-0.358}]
  = $367.68 \text{ M}
  \]
### Table 4.5
**Light Rail Construction Cost per Mile**

<table>
<thead>
<tr>
<th>Light Rail Project</th>
<th>Cost per mile (millions of 2005$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baltimore Central Line Phase 1</td>
<td>18.8</td>
</tr>
<tr>
<td>Baltimore Central Line – three extensions</td>
<td>16.4</td>
</tr>
<tr>
<td>Dallas DART – S&amp;W Oak Cliff</td>
<td>31.3</td>
</tr>
<tr>
<td>Dallas DART – Park Lane</td>
<td>58.6</td>
</tr>
<tr>
<td>Denver RTD – Central Corridor</td>
<td>24.4</td>
</tr>
<tr>
<td>Denver RTD – Southwest Extension</td>
<td>20.3</td>
</tr>
<tr>
<td>Los Angeles MTA – Blue Line</td>
<td>43.4</td>
</tr>
<tr>
<td>Los Angeles MTA – Green Line</td>
<td>49</td>
</tr>
<tr>
<td>Portland Tri-Met – Banfield</td>
<td>26.6</td>
</tr>
<tr>
<td>Portland Tri-Met – Westside</td>
<td>56.7</td>
</tr>
<tr>
<td>Sacramento RTD – Original Line</td>
<td>12.4</td>
</tr>
<tr>
<td>Sacramento RTD – Mather Field Road Extension</td>
<td>15.4</td>
</tr>
<tr>
<td>Salt Lake City UTA – South Line</td>
<td>21.4</td>
</tr>
<tr>
<td>St. Louis MetroLink – Phase 1</td>
<td>20.8</td>
</tr>
<tr>
<td>San Diego Trolley – Blue Line</td>
<td>31.3</td>
</tr>
<tr>
<td>San Diego Trolley – Orange Line</td>
<td>23.5</td>
</tr>
<tr>
<td>Santa Clara County (VTA) – Guadalupe Corridor</td>
<td>26.2</td>
</tr>
<tr>
<td>Santa Clara County (VTA) – Tasman Corridor</td>
<td>43.8</td>
</tr>
<tr>
<td><strong>Average Cost per Mile</strong></td>
<td><strong>36.6</strong></td>
</tr>
</tbody>
</table>

*Adapted from US GAO (2001)*
Guideways for Light Rail

- Guideway construction accounts for 16-38% of overall capital costs of LRT

- Guideway Cost
  \[ \text{Guideway Cost} = \exp(-1997.92 + 1448.22 \cdot \text{Length}^{0.0005} + 553.55 \cdot \text{Stations}^{0.0005}) \]
  \[ R^2 = 0.61 \]
Example 2: Light Rail

Two Alternatives
- Alternative 1: 21 Miles, 13 Stations
- Alternative 2: 38 Miles, 22 Stations

Total Guideway Cost
- Alternative 1:
  \[ \exp(-1997.92 + 1448.22 \times 21^{0.0005} + 553.55 \times 13^{0.0005}) \]
  \[ = \$868.35 \text{ M} \]
- Alternative 2:
  \[ \exp(-1997.92 + 1448.22 \times 38^{0.0005} + 553.55 \times 22^{0.0005}) \]
  \[ = \$1544.71 \text{ M} \]

Average Cost
- Alternative 1: \[ \$868.35 \text{ M} / (21)(13) = \$3.18 \text{ M/mile-station} \]
- Alternative 2: \[ \$1544.71 \text{ M} / (38)(22) = \$1.84 \text{ M/mile-station} \]
Stations and Yards for LRT

a. Passenger Station Costs per Station

b. Maintenance Yards and Shops per Unit of Capacity

c. Capacity = Max. Number of Vehicles that can be held in Maintenance Yard.
Example: Subway LRT

Given: 20 Passenger Stations; 60 Vehicle Capacity

Average Cost of Passenger Station for Subway LRT
\[= \$26,982,000\]

Cost of Stations
\[= 20 \times 26,982,000 = \$539,640,000\]

Average Cost of Maintenance Yard
\[= \$600,000 \text{ per unit capacity}\]

Cost of 60 Capacity Yard
\[= 60 \times 600,000 = 36,000,000\]

Total Capital Cost for Stations and Yards
\[= \$575,640,000\]
## Rolling Stock Capital Costs for Rail Transit

<table>
<thead>
<tr>
<th>Type</th>
<th>Avg. Cost/Car ($ Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Rail</td>
<td>2.3</td>
</tr>
<tr>
<td>LRT</td>
<td>2.6</td>
</tr>
<tr>
<td>Commuter Rail</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Rolling Stock Rehabilitation

Avg. Cost/Car
($ Millions)

- Heavy Rail: 0.84
- Commuter Rail: 0.99
BRT Capital Costs

- Depend on Location, Type, and Complexity of Construction
  - Independent at-grade 7.5 million/mile
  - Arterial Busways on Median $6.6
  - Mixed Traffic and/or Curb Bus lanes 1.0

- Many Times Higher When Tunnels and Other Features for Exclusive Guideways are involved

- See Table 4.11
Rail Transit Operating Costs

- As a Function of Supply-Based Measures
  - Op. cost per mile, per vehicle, per expected VMT

- As a Function of Demand-Based Measures
  - Op. cost per passenger, per passenger-hour or passenger-mile

- Personnel cost is 70 – 80%

- Heavy Rail has the Lowest Op. Cost per Passenger-mile

- See Tables 4.12 and 4.13
Example:

A LRT with 20 cars @ 330 miles/day

From Table 4.12,

Expected Revenue Vehicle-Miles / Year = (330)(365)(20)

Estimated Total Op. Cost / Year
= (2,409,000) (11.02) = $26,547,000
Bus Transit Capital Costs

- Acquisition and Rehabilitation of Buses
- Construction and Preservation of Terminals, Stations and Maintenance Facilities
- Bus Acquisition Costs – Table 4.14
- Bus Rehabilitation Costs – Table 4.15
- Facilities - $120-140/sq. ft.
Bus Transit Operating Costs

Cost per Vehicle-Mile = 2.625S^{0.184} PBR^{0.029}

S = Number of Buses in Maximum Service.
PBR = Peak Buses/Off-peak Buses

Unit Op. Cost by System Size and PBR – Table 4.16

Average Capital and Operating Costs by City Size –
Tables 4.17 – 4.19
How to Update Costs?

- Use of Price Indices
  - FHWA Federal-Aid Highway Price Index
  - FHWA Highway Maintenance and Operating Cost Index
  - FTA Cost Adjustment Factors

- FHWA State Cost Factors (Table 4.20)
Cost Adjustments for Economies of Scale

- The Greater the Project Size, the Lower is the Unit Cost (e.g. Cost per Lane-Mile)

- Adjustment for Economics of Scale on the Basis of Unit Aggregate Cost of a Project and Unit Aggregate Cost Function for all Projects of Same Type

- Unit Cost Function can be Developed from Historical Contract Data
Example:

Two Alternative Types, A & B

40-Mile Transit System

\[ C_A = -1.05 \ln(x) + 5.2 \] \[ \bar{c}_A = $207,000 / mile \]

\[ C_B = \frac{30}{x^{0.95}} \] \[ \bar{c}_B = $285,000 / mile \]

where, \( x \) = number of line-miles
Figure E4.11 p. 92

Cost per line-mile \( f(L) \)

Transit System Type A: \( C_A = -1.05 \cdot \ln(X) + 5.2 \)

Transit System Type B: \( C_B = \frac{30}{X^{0.95}} \)
From Cost Function, Unit Cost to be Used Instead of Given Average Cost Values.

System A = $133,000/mile

System B = $90,000/mile
Problem of Cost Overruns

- 5-14% Underestimation at Planning Stage
- Design Revisions
- Unexpected Site Conditions
- Construction Errors
- Weak Estimates of Inflation

Include a Realistic Contingency Amount