Toward More Sustainable Infrastructure: Project Evaluation for Planners and Engineers

Part I
Building Infrastructure to Serve the Needs of Society
Overview of Part I

Needs of Society

- Private Sector Focus
  - Financial Assessment (Chapter 2)
  - Economic Assessment (Chapter 3)
- Broader Public Sector Concerns
  - Social Assessment (Chapter 4)
  - Environmental Assessment (Chapter 4)

Project Selection or Approval (Chapter 5)

Martland, Toward More Sustainable Infrastructure, Chapter 2
Chapter 2 System Performance

- Introduction
- System Cost
- Profitability, Breakeven Volume and Return on investment
- Service
- Capacity
- Safety, Security, and Risk

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Aspects of Infrastructure Performance

**Infrastructure Performance**

- **Owners and Managers**
  - Investment Requirements
  - Maintenance Requirements
  - System Operating Cost
  - Usage Volume
  - Risks Associated with Construction and Operation

- **Users**
  - Price
  - Other Costs of Using the System
  - Service Quality
  - Accessibility and Availability
  - Risks Associated with Using the System

- **The Public**
  - Subsidies and Other Costs
  - Aesthetics and Land Use
  - Environmental Impacts
  - Risks to Abutters and the General Public
  - Other Social Impacts

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Infrastructure Management

Strategic Planning

Managing Infrastructure

**Operating Policy**
- Operating Capacity
- Hours of Operation (Availability of Service)
- Limits on Users
- Usage Volume
- Safety Plans

**Maintenance Policy**
- Inspections
- Desired Condition
- Disruptions to Service
- Limitations on Use
- Managing Risks with System Conditions

**Marketing Policy**
- Pricing
- Priority Market Segments
- Advertising & Sales
- Expansion Opportunities

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System Performance
Basic Cost & Revenue Concepts

1. Cost terminology
2. Breakeven volume and long-run cost functions
3. Cost, revenue and profitability
4. Present economy

*Can we afford to build a project based upon what customers or others are willing to pay?*

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1. Cost Terminology

A Simple, Linear Cost Function:

$$TC = a + bV = 50 + V, \quad 10 < V < 100$$
1. Cost Terminology

A Simple, Linear Cost Function:
Avg Cost = \( a/V + b = 50/V + 1 \)
Marginal Cost (V)= \( d(TC)dv = b = 1 \)
1. Cost Terminology

**Lifecycle Cost - A Key Concept for CEE Project**

![Graph showing lifecycle cost phases: Design, Construct, Expand, Operate, Decommission, Salvage.]

- **Design**
- **Owner and developer**
- **Construct**
- **Owner, users, and abutters**
- **Expand**
- **Operate**
- **Time**
- **Decommission**
- **Owner and abutters**
- **Salvage**

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1. Cost Terminology

Lifecycle Cost - Greatest Potential For Lifecycle Savings is in Design!

- Easy to modify design and materials
- Limited ability to modify infrastructure or operation
- Few options - cost already incurred

Still possible to make some modifications in design or materials

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3. Cost, Revenue and Profitability

**Breakeven Volume for Profitability**

Breakeven point P is where TR = TC

\[
\text{Total Cost} \quad \text{Revenue}
\]

\[
\begin{align*}
\text{Cost} & = 50 + V \\
\text{Revenue} & = 1.5 \, V
\end{align*}
\]

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5. Dimensions of space and time

Differing Perspectives of Economists & Engineers

• Economists
  – Assume that production function is known
  – Very elegant, calculus-based formulations of concepts
  – Great concern with prices and effects on volume
  – Often use sophisticated statistical techniques and historical data to estimate production functions

• Engineers
  – Must define the production function
  – Design and analysis of specific options
  – Great concern with costs and capacity
  – Often use models to estimate future costs
5. Dimensions of space and time

Complicating Factors for Projects

- Long lives
  - Demand can change substantially
  - Competition from other suppliers and new technologies can be expected
  - The time value of money becomes critical
  - Externalities are important

- Unique projects
  - Difficult to test supply & demand

- Equilibration takes place through what may be slowly evolving changes in land use and location decisions by firms and individuals

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## Transport Options, Early 19th Century

<table>
<thead>
<tr>
<th>Option</th>
<th>Capacity/Rate</th>
<th>Cost/Day per Tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough Road</td>
<td>1 ton/wagon 12 miles/day 12 tm/day/vehicle</td>
<td>$0.20 to $0.40/tm for freight rates</td>
</tr>
<tr>
<td>Turnpike</td>
<td>1.5 tons/wagon 18 miles/day 27 tm/d/v</td>
<td>$0.15 to $0.20/tm</td>
</tr>
<tr>
<td>Canal</td>
<td>10-100 tons/boat 20-30 miles/day 200-3000 tm/d/v</td>
<td>$0.05/tm</td>
</tr>
<tr>
<td>Railroad</td>
<td>500 tons/train 200 miles/day 100,000 tm/d/v</td>
<td>&lt;$0.05/tm</td>
</tr>
</tbody>
</table>

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Why Build Canals?

- Water is the most economical & efficient way to transport bulky, non-perishable goods
  - BUT - you need the waterway!
  - High volume of goods so long as speed is not a great factor
- Canals are built so that
  - Freight rates decline
  - Food can be delivered to cities
  - Cities can become trade centers

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Background on Canals

Capacity:
Gross tonnage/boat equals water displaced, so width and depth are key
Space is needed for two boats to pass
If canal is straight, rafts or barges can be linked

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Regent’s Canal, London
Excavation Costs Increase With the Size of the Canal

Doubling the width and depth of the canal can lead to major increases in excavation

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Locks Reduce Excavation, But Reduce Speed & Capacity
The length and width of canal boats were limited by the size of the locks.
Water Supply is Essential

A. Horizontal Alignment

B. Vertical Alignment

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China's Grand Canal

- Geography: N-S canal links major rivers
- Geopolitics: transport improvements help unit the empire
- Benefits
  - Steady supply of grain from south to north
    - 300,000 tons of grain per year in 7th century
- Costs:
  - 5.5 million laborers worked 6 years on one 1,500 mile stretch (20 man-years per mile)

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Bridgewater Canal

- Built in 1761 to link Manchester England with coal mines
- Benefits:
  - Halved the price of coal in Manchester (a direct benefit of increased efficiency of transport)
  - Helped Manchester become England's leading industrial center (development benefit for the region)
- Stimulation of infrastructure development
  - By 1840s, Britain had a network of 5,000 miles of canals & navigable rivers
  - Technological improvements: straighter, deeper, wider canals; aqueducts to cross rivers

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Potowmack Canal 1785-1802

- First extensive system of river navigation in US
  - George Washington was the "champion"
  - $750,000 investment

- Purpose
  - Open up the area west of Appalachia and linking to the Potomac River (current-day Washington DC)
  - Cut freight cost in half (relative to wagon)
  - 185 miles in 3 days with a 16-20 ton payload

- Problems
  - Construction: shaky economy; lack of skilled workers, weather
  - Operation: only navigable 3 mo/yr; sediments; wooden locks decayed

- Results
  - Spurred canal investment & development of west
  - $175,000 in debt by 1816

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Middlesex Canal 1793-1803

- **Purpose:**
  - Improve efficiency of existing system by providing a better link from NH to Boston (chartered by Massachusetts)
  - Reduced transfer from barge to wagon for delivery to Boston (cut costs by 75%)

- **Costs**
  - 50 bridges, 8 aqueducts, 27 locks
  - $528,000 investment = $20,000/mile = 3% of assessed value of Boston (an early Big Dig!)

- **Problems**
  - 1-way freight - and not much of it
  - Disruption of trade (Portsmouth & NH did not like this!)

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Erie Canal, 1817-1825

- First proposed in 1724; discussed widely in late 1700s and early 1800s
  - Thomas Jefferson: "A splendid project - for the 20th century."
- Purpose
  - Easiest way to cross Appalachian Mountains
- Constructed 363 miles of canal with 83 locks and 18 major aqueducts from Albany to Buffalo for $8 million
- Issues
  - How to finance
  - Which route (avoid Lake Ontario - too close to the British!)
  - Merchants using ground transport were against it
  - Lack of engineers - in fact this project created CE schools at RPI and Union College
Erie Canal - Results

- Problems
  - 1000 died from malaria
  - What depth: enough for freight, but no more than they could finance

- Results
  - Too many boats almost from day 1 - increased in 1835 to 70 ft wide with 7 ft depth (from 40 and 4)
  - Revenues exceeded all expectations
  - Opening up Lake Erie was "decisive impetus for commerce to move E-W rather than N-S"
  - Population growth - Rochester and Buffalo became boom towns
Morris Canal 1824-31

- **Purpose**: link coal fields of Lehigh Valley with NYC
- **Cost**: $2.1 million vs. $1 million estimate
  - Circuity: (99 mile canal to go 55 miles)
  - Elevation: (up 914 feet then down 750 feet)
- **Notable**
  - Use of rail cars to haul boats up an inclined plane
  - Acted as their own bank to finance canal
  - Interfered with salmon spawning
  - Speeds restricted to < 3 mph to avoid washing out banks
  - Needed to widen for wider boats (increased loads from 25 to 50-75 tons)
- **Results**
  - "Immediate and pronounced" - prices of coal and wood fell in NY, business was stimulated, towns grew
  - Peaked 1860-70, then overtaken by RR

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## Middlesex Canal vs. Erie Canal

<table>
<thead>
<tr>
<th></th>
<th>Middlesex</th>
<th>Erie</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost/mile</strong></td>
<td>$20,000</td>
<td>$22,000</td>
</tr>
<tr>
<td><strong>Hinterland</strong></td>
<td>New Hampshire</td>
<td>Northwest Territory</td>
</tr>
<tr>
<td><strong>Development</strong></td>
<td>Boston increases advantage over Portsmouth</td>
<td>NYC gains w.r.t. Boston; Rochester, Buffalo grow</td>
</tr>
<tr>
<td><strong>Financial</strong></td>
<td>Investors break even by 1860, replaced by RR</td>
<td>Vastly profitable; NYC becomes financial center of US</td>
</tr>
</tbody>
</table>

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User's Perspective

- Issue: if costs are lower, then we will use the facility
- Analysis: can we reduce cost/ton-mile by providing an opportunity for larger or better vehicles to operate over a better infrastructure
  - Compare equipment costs and operating costs for the current and the new options
Owner's Perspective

- Issue: should I build the facility?
- Analysis:
  - Compare annual revenues to annual costs
  - Cost:
    - Construction costs can be converted to annual payments on a loan
    - Maintenance costs
  - Revenue:
    - Tolls must be less than the savings that user gets from using the canal to attract traffic

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Investor's Perspective

- **Issue:** if we invest in this, will we be able to recover our investment plus a reasonable return?

- **Analysis:**
  - What will the project cost?
  - How long will it take?
  - How much revenue will it generate (and will the owner be able to repay our loans)
  - Do we have better options for investing?
Contractor's Perspective

- **Issue:** should we agree to build the facility for the amount proposed (or what should we bid?)

- **Analysis:**
  - Construction costs as a function of technology, methods, labor productivity, availability of materials, and costs
  - Is our estimated cost less than the proposed budget?
  - Is the estimated profit enough for us to accept the risks of construction?
Public Perspective

- Basic issue: should we assist (or protest) in the project by providing financial or legal support
- Analysis: what are the public benefits
  - Land use
  - Development
  - Environmental impact
- How can we help, if indeed we want to help?
  - Limit liability
  - Enforce ability to collect tolls
  - Use eminent domain to assemble land
  - Choice of route? scale of project?
- Possibly a major political issue!

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Summary - What Do We Learn From the Experience With Canals

- Ideas and concepts are around long before the means to build the infrastructure are available.
- Major projects can be decisive in directing development and population growth - but it is also possible to spend major resources on projects with modest potential.
- Changes in technology can kill projects (RRs killed both the turnpikes and the canals) or improve them (efficiency gains from larger boats justified enlarging canals).
- Financing is a major concern.

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## Transport Options, Early 21st Century

<table>
<thead>
<tr>
<th>Type</th>
<th>Capacity/Usage</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial Roads</td>
<td>10 tons/truck 100 miles/day 1000 tm/day/vehicle</td>
<td>$0.10 to $0.50/tm for freight rates</td>
</tr>
<tr>
<td>Interstate Highway</td>
<td>20 tons/trailer 1-3 trailers per tractor 500 miles/day 10,000/d/v</td>
<td>$0.15 to $0.20/tm</td>
</tr>
<tr>
<td>Canal &amp; waterway</td>
<td>1500 tons/barge Up to 40 barges/tow 50-200 miles/day 6 million tm/d/v</td>
<td>$0.01/tm</td>
</tr>
<tr>
<td>Railroad</td>
<td>5-15,000 tons/train 500 miles/day 5 million tm/d/v</td>
<td>$0.02/tm</td>
</tr>
</tbody>
</table>

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System Performance
Basic Concepts: Much More Than Cost

1. Service Measures
2. Capacity
3. Safety, Security and Risk
4. Cost Effectiveness

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Service Quality in Transportation

- Average trip time
- Trip time reliability
- Probability of excessive delays
- Comfort
- Convenience
Engineering-Based Service Functions

• Express service as a function of:
  – Infrastructure characteristics
  – Operating characteristics
  – Level of demand

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Estimating Commuting Time: Trip Segments

- Walk to bus stop
- Wait for bus (10 minute headways)
- Ride bus two miles to subway station
- Transfer from bus to subway platform
- Wait for subway train (5 minute headways)
- Ride train 3 miles (5 intermediate stops)
- Exit station and walk to destination

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Estimating Commuting Time:
Segment Times Based upon Personal Experience

- Walk to bus stop: 5 minutes
- Wait for bus (10 minute headways): 0 to 10 minutes
- Ride bus two miles to subway: 5 to 10 minutes (depending upon number of stops, road traffic, and weather)
- Transfer from bus to subway platform: 3 minutes
- Wait for train (5 minute headways): 0 to 5 minutes
- Ride train 3 miles (5 stops): 12 to 15 minutes
- Exit station and walk to destination: 7 minutes

- Total: 36-55 minutes; average ~ 45 minutes
Estimating Commuting Time: Segment Times Based Upon Trip Characteristics

- Time to walk to bus stop = Distance/average walking speed
- Wait for bus = Half of headway
- Time on bus = Distance/15 mph + 1 minute per stop
- Transfer from bus to subway platform = Distance/average walking speed in station plus time to buy ticket plus queue time
- Wait for subway train = half of headway
- Train time = Distance/30mph + 45 seconds per stop
- Exit station and walk to destination = Station time plus distance/average walking time

It is possible to develop an engineering-based service function that can be used to estimate average time for any trip.

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Estimating Commuting Time: Studying the Effects of Service Changes

• Possible changes designed to improve service
  – Extend bus routes or subway lines
  – Have more bus stops
  – Have more frequent bus or train operations
• Use the service function to compare service with and without the service improvements for a representative sample of users
• Sum results over all users to obtain average change in service

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Capacity

- Multiple measures are possible
- Network capacity can be constrained at bottlenecks
- Engineering-based capacity functions can be developed

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Capacity of a Highway Intersection: Theoretical Calculations

• Assumptions indicate:
  – One car in each direction every two seconds while light is green
  – If so, there should be 60 cars per minute

• Does this mean that theoretical capacity is:
  – 60 cars per minute?
  – 3600 cars per hour?
  – 84,400 cars per day?

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Capacity of a Highway Intersection: Measured Capacity

• Observation of intersection at rush hour:
  – The first car sometimes takes 4-5 seconds
  – Subsequent cars average a little more than 2 seconds
  – Maximum in one cycle: 56
  – Average in one cycle: 52

• Does this imply:
  – Theoretical capacity is at least 56 but less than 60 cars/minute?
  – Practical capacity is: 52 cars/minute or 3120/hour?
Capacity of a Highway Intersection: Insights from Commuters

• You need to consider performance over a much longer period because of problems related to:
  – Weather
  – Road maintenance
  – Emergency vehicles
  – Accidents
  – Gridlock (frustrated drivers may block the intersection when the light turns red)
Capacity of a Highway Intersection: Results of a More Thorough Study

• Average flow was 48 cars per minute in study that included extended rush hour observations in all seasons.
• Delays commonly averaged more than 5 minutes, which was believed to be unacceptable by both drivers and highway engineers.
• Does this imply that:
  – Capacity is 48 cars per minute?
  – Capacity is less than 48 cars/minute?
  – Capacity is inadequate?

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Capacity of a Highway Intersection: Lessons

- Practical capacity is well below theoretical capacity
- Capacity can be sharply restricted by common disruptions (accidents, bad weather, etc)
- During peak periods of operation, demand may exceed capacity of the system, resulting in delays
- Practical capacity is ultimately limited by what is believed to be “acceptable delay” or the “acceptable frequency of extreme delays”

- Three useful concepts:
  - **Maximum capacity**: maximum flow through the system when everything works properly
  - **Operating capacity**: average flow under normal conditions
  - **Sustainable capacity**: maximum flow that allows sufficient time for maintenance and recovery from accidents

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