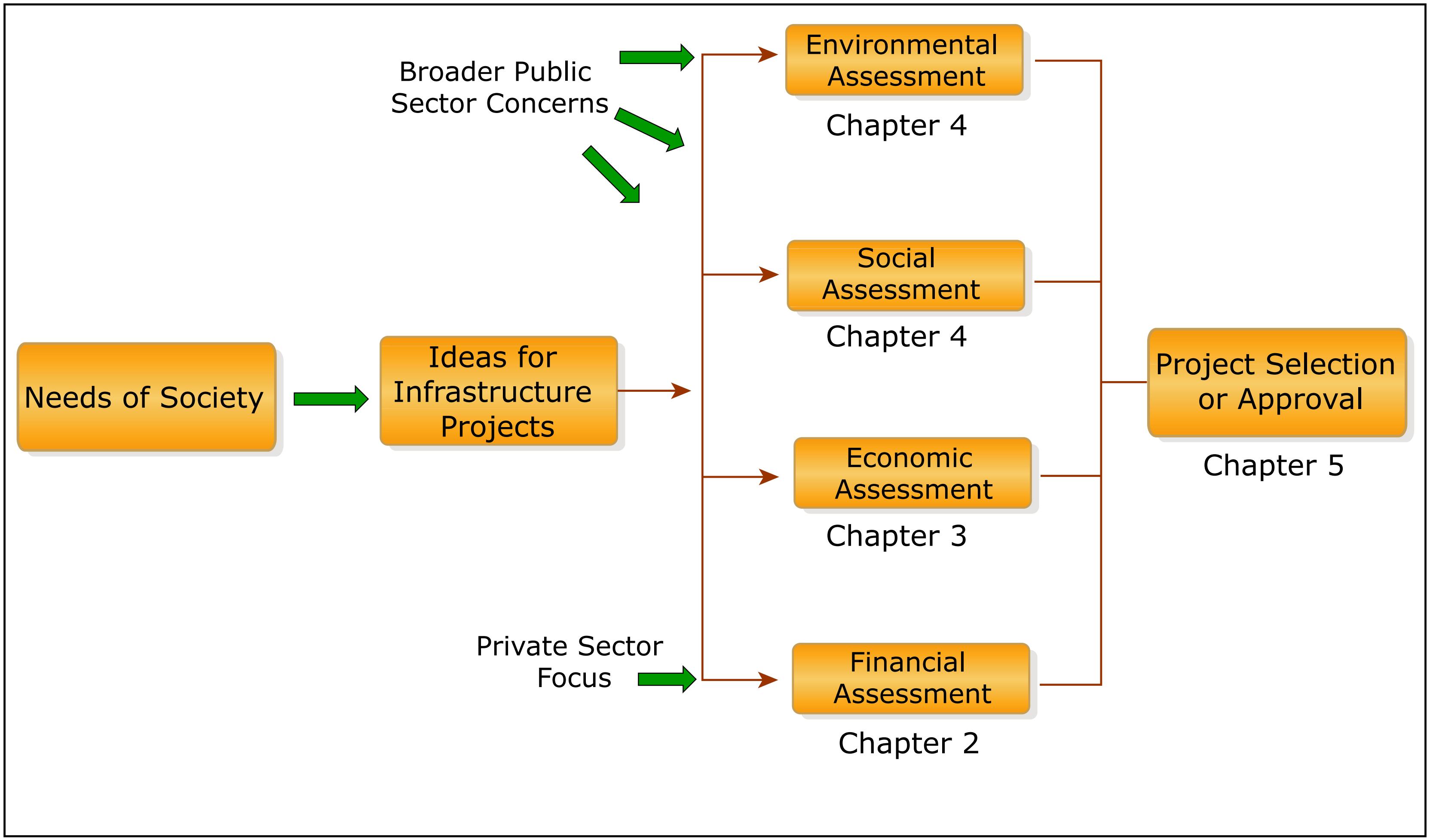
Toward More Sustainable Infrastructure: Project Evaluation for Planners and Engineers

Part I

Building Infrastructure to Serve the Needs of Society

Overview of Part I



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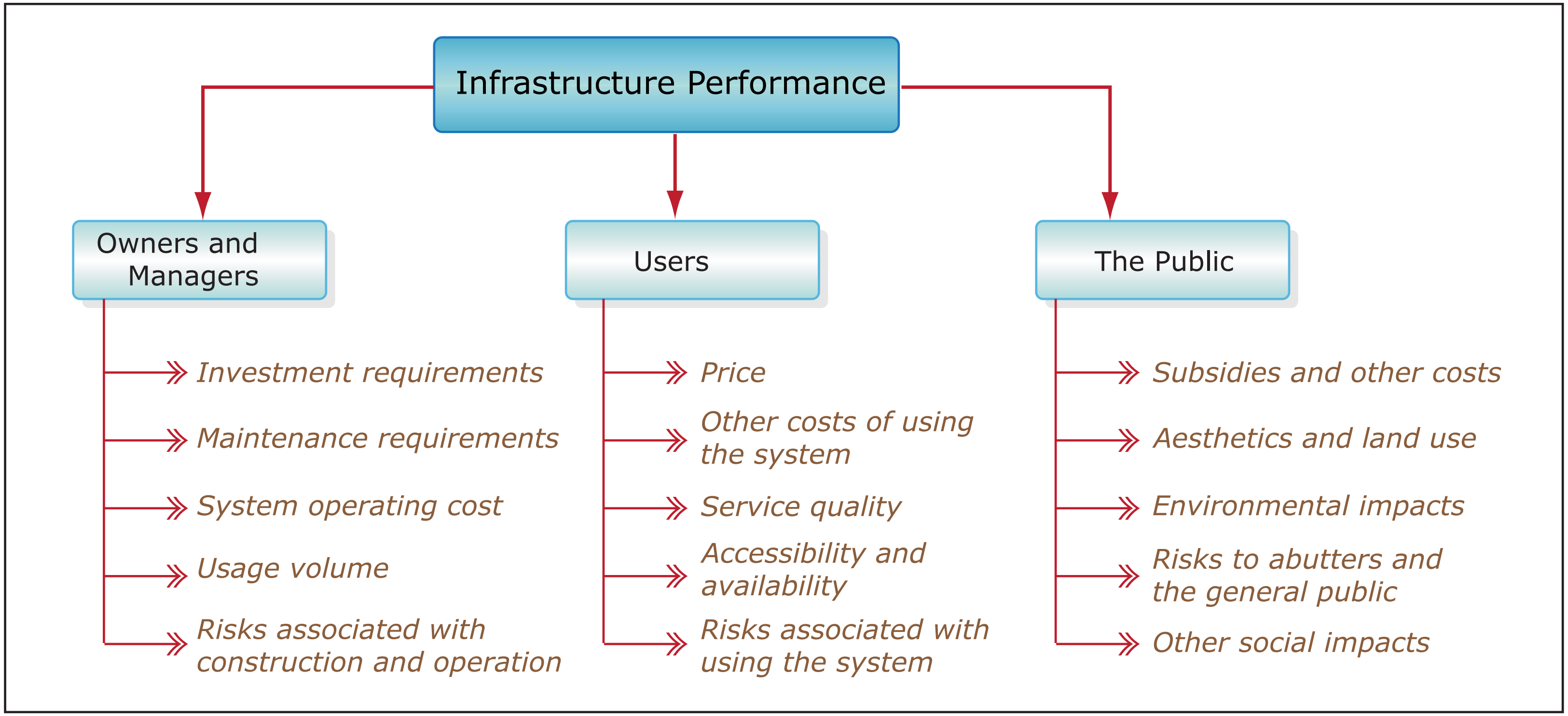
Chapter 2 System Performance

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

Aspects of Infrastructure Performance



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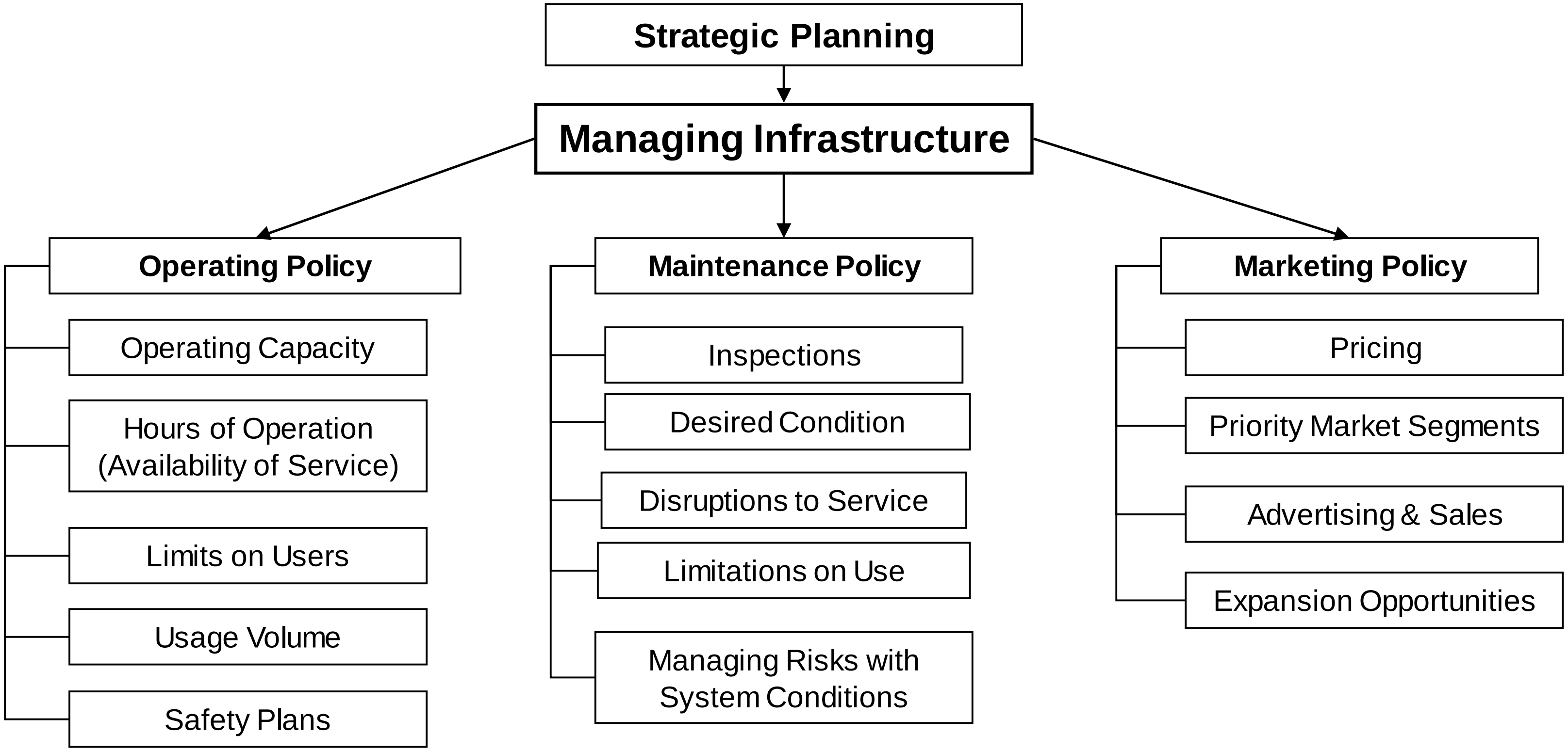
Infrastructure Management



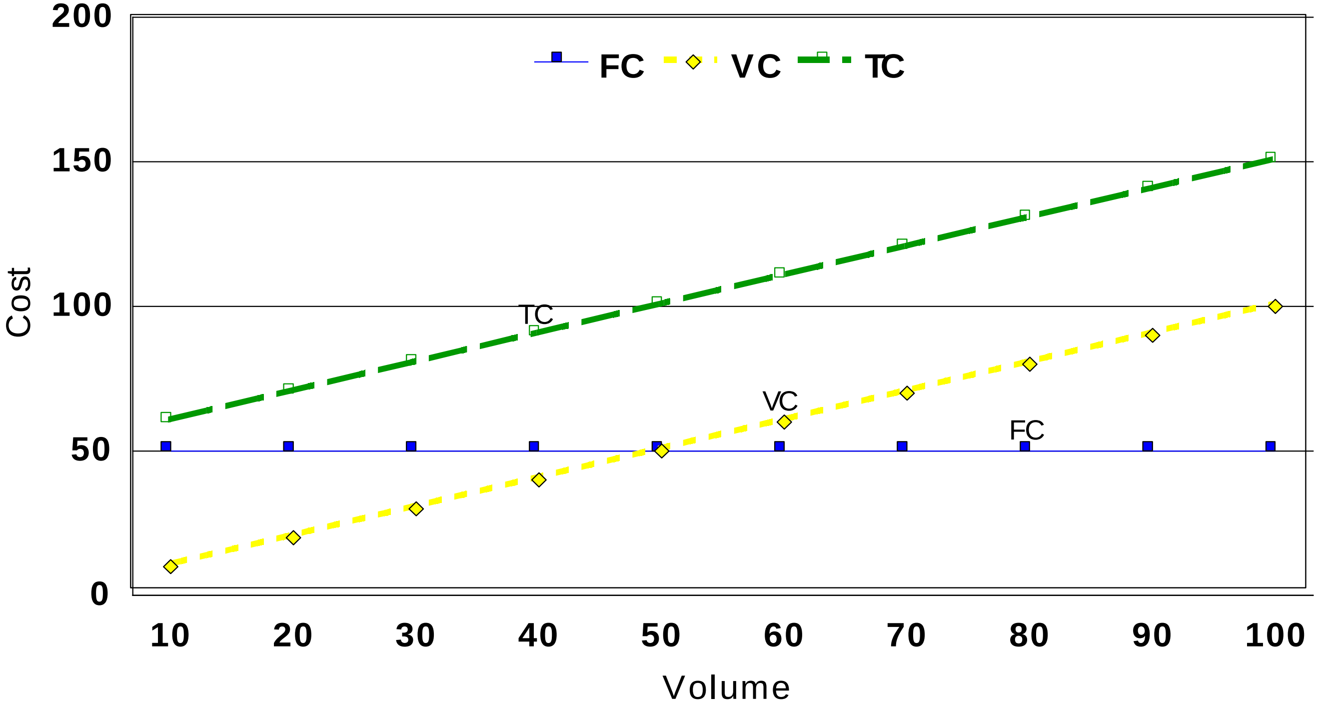
System Performance
Basic Cost & Revenue Concepts

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?

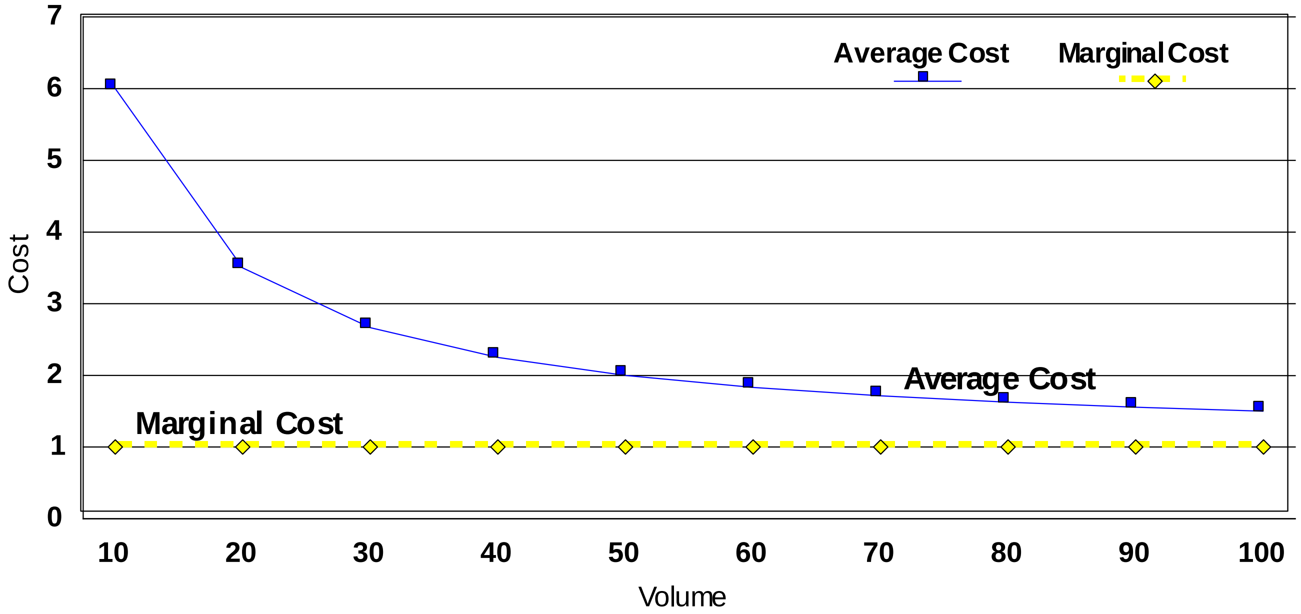
1. Cost Terminology

A Simple, Linear Cost Function:
TC = a + bV = 50 + V, 10 <V<100



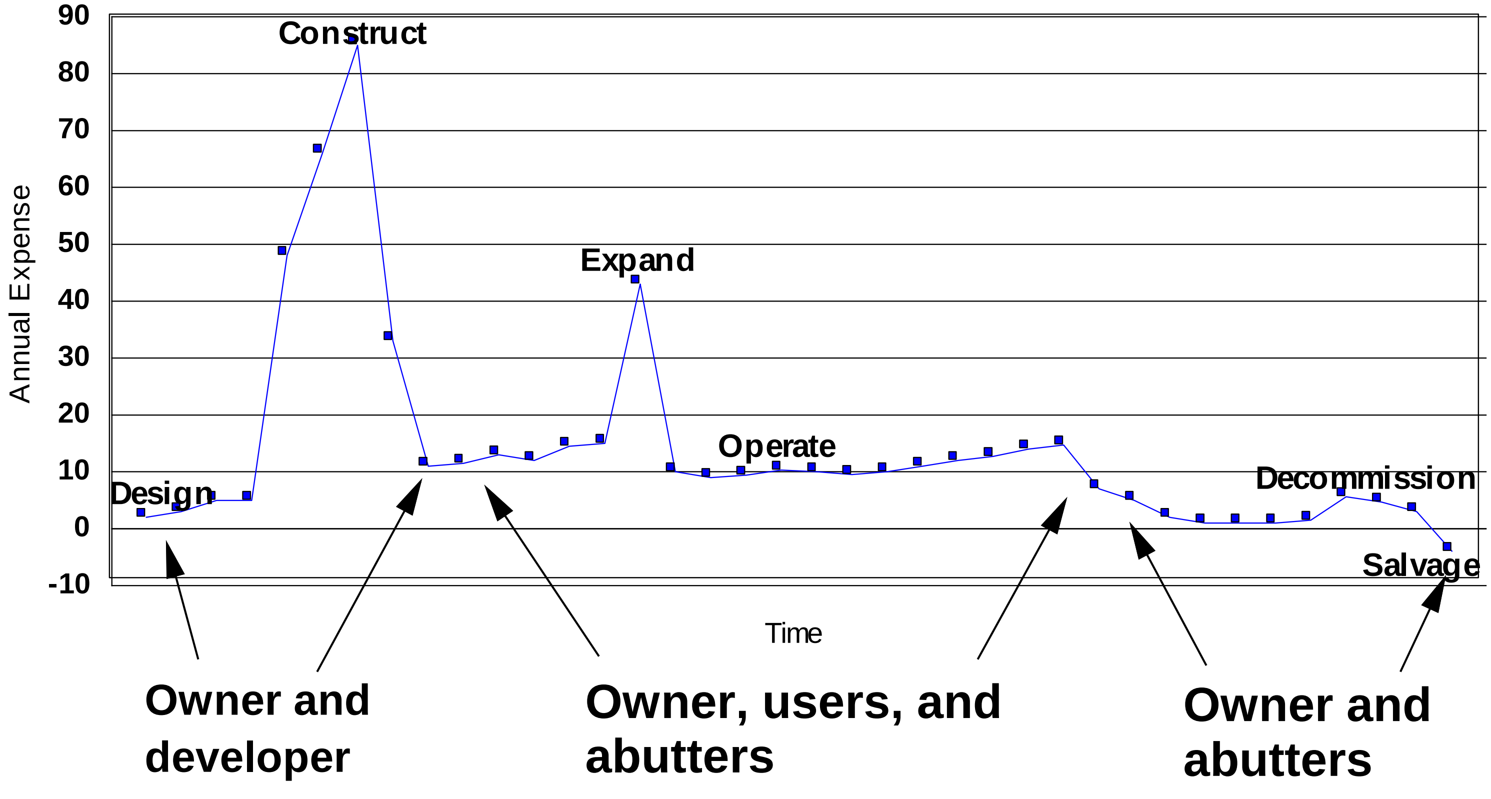
1. Cost Terminology

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



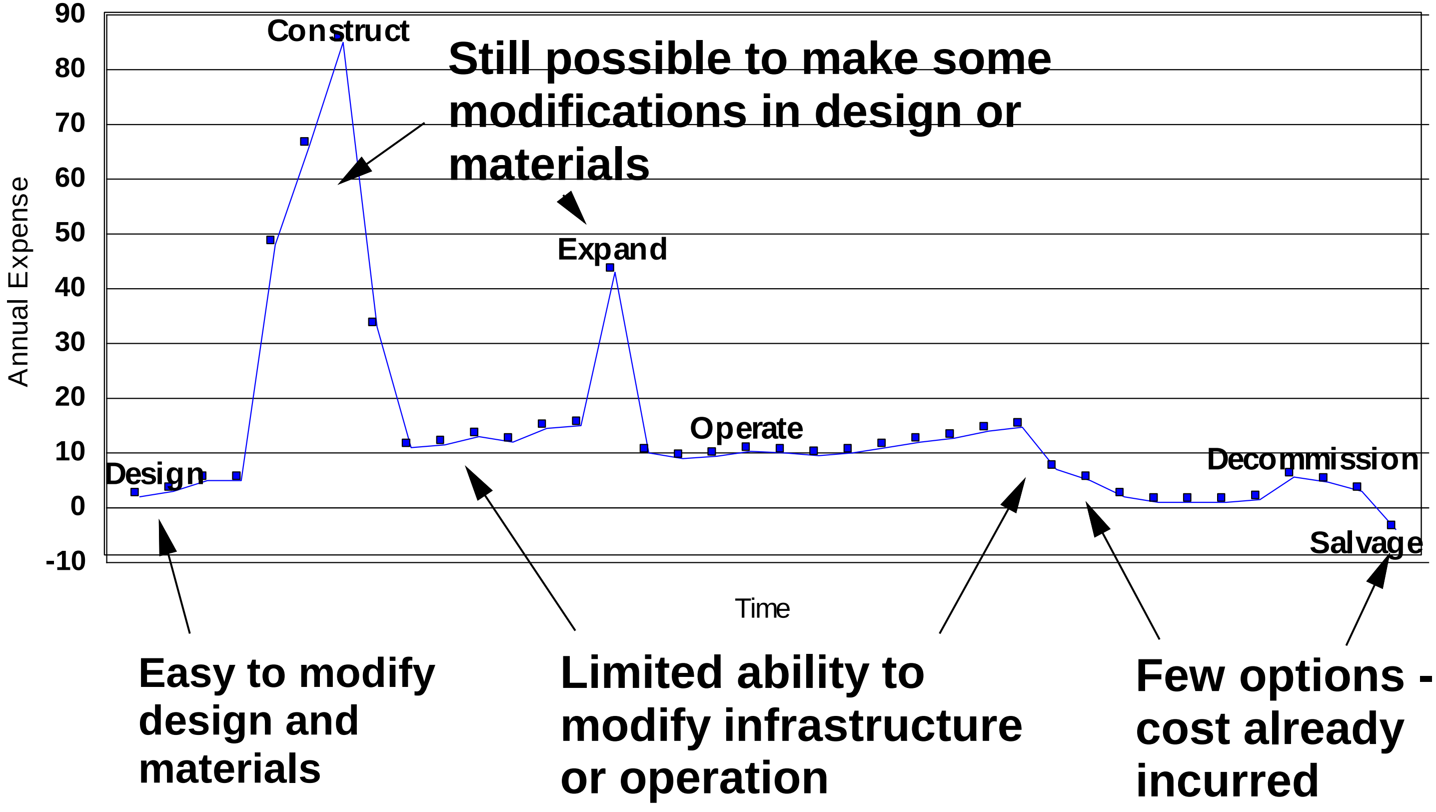
1. Cost Terminology

Lifecycle Cost - A Key Concept for CEE Project

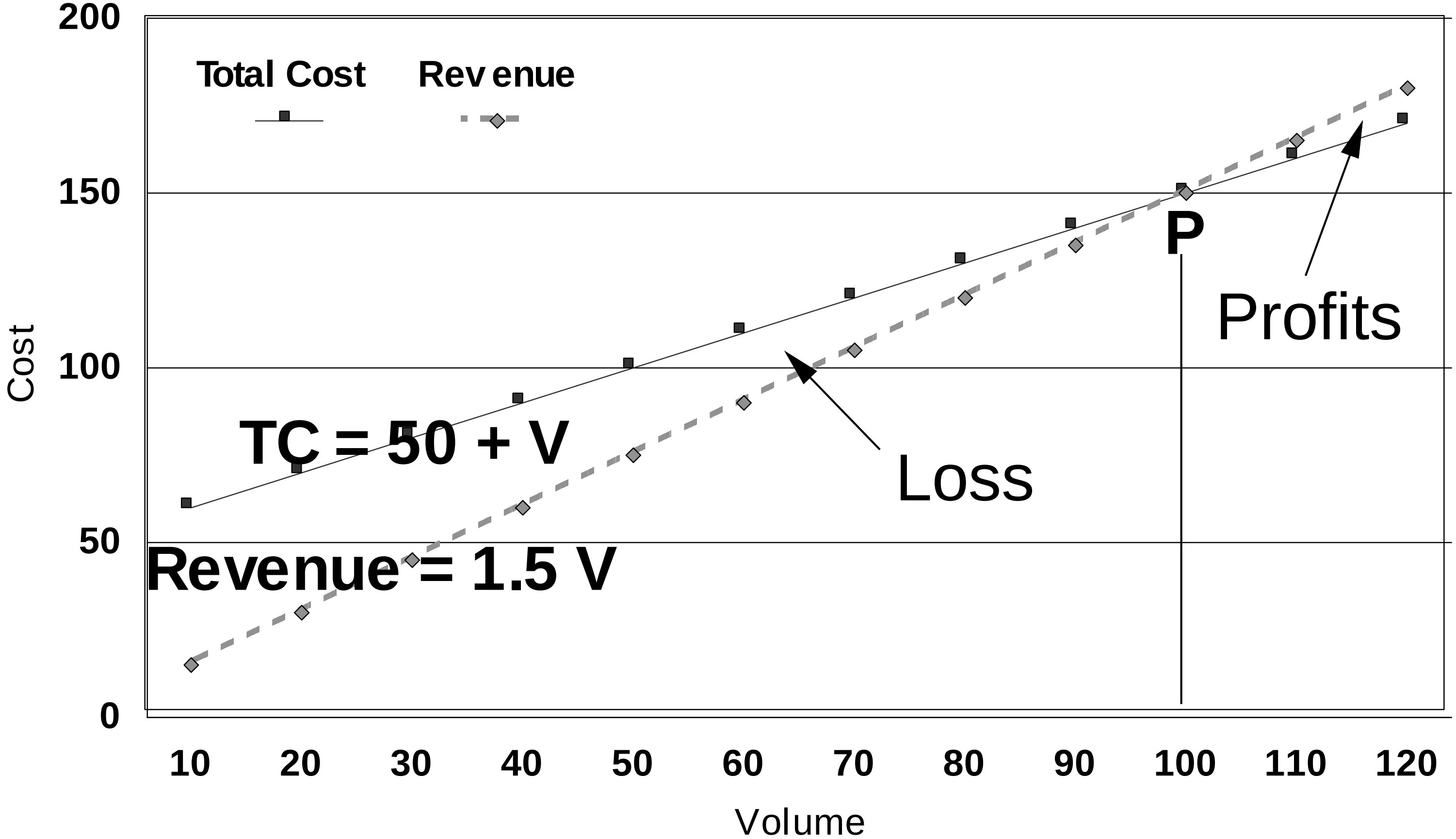


1. Cost Terminology

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



Breakeven Volume for Profitability
Breakeven point P is where TR = TC



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

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

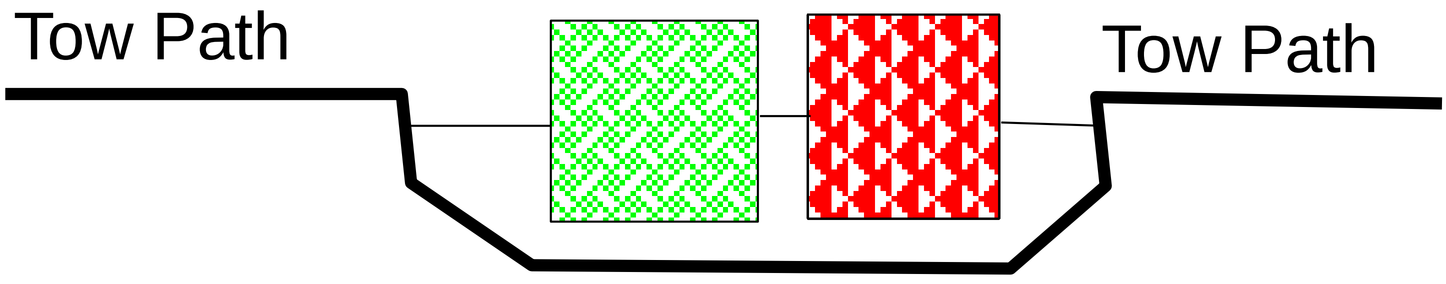
Transport Options, Early 19th Century

Rough Road $1-2,000/mile to construct	1 ton/wagon 12 miles/day 12 tm/day/vehicle	$0.20 to $0.40/tm for freight rates
Turnpike $5-10,000/mile	1.5 tons/wagon 18 miles/day 27 tm/d/v	$0.15 to $0.20/tm
Canal >$20,000/mile	10-100 tons/boat 20-30 miles/day 200-3000 tm/d/v	$0.05/tm
Railroad $15-50,000/mile	500 tons/train 200 miles/day 100,000 tm/d/v	<$0.05/tm

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

Background on Canals



Capacity:

Gross tonnage/boat equals water displaced, so width and depth are key

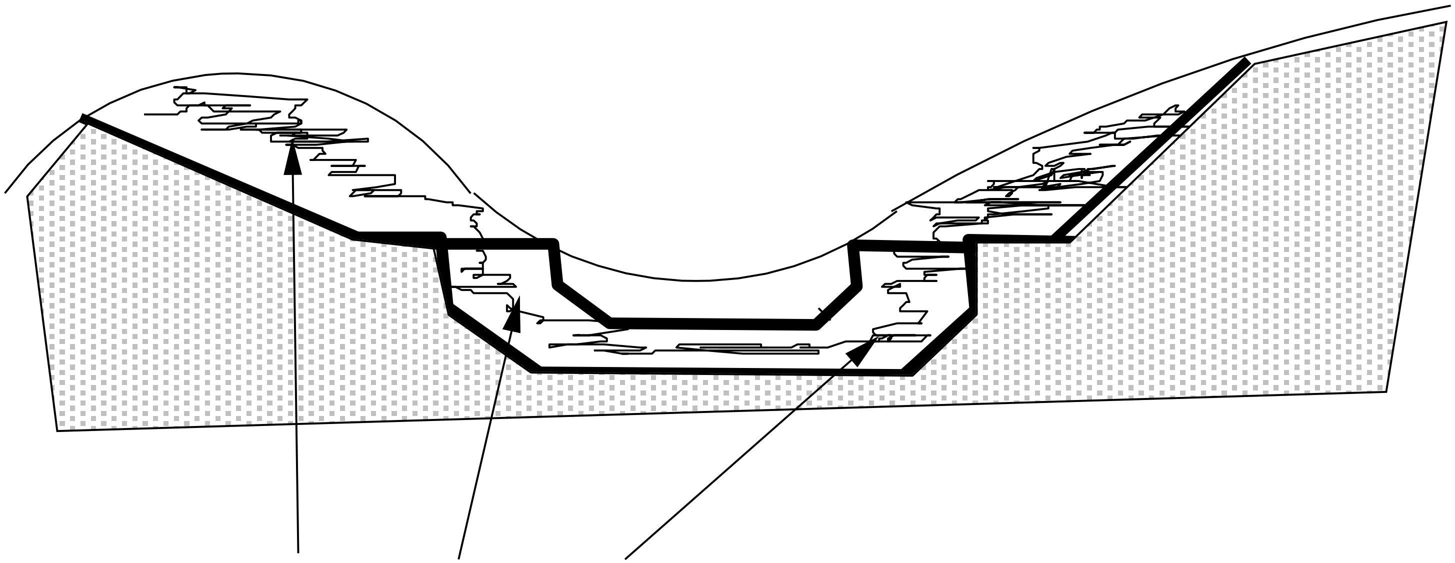
Space is needed for two boats to pass

If canal is straight, rafts or barges can be linked

Regent's Canal, London

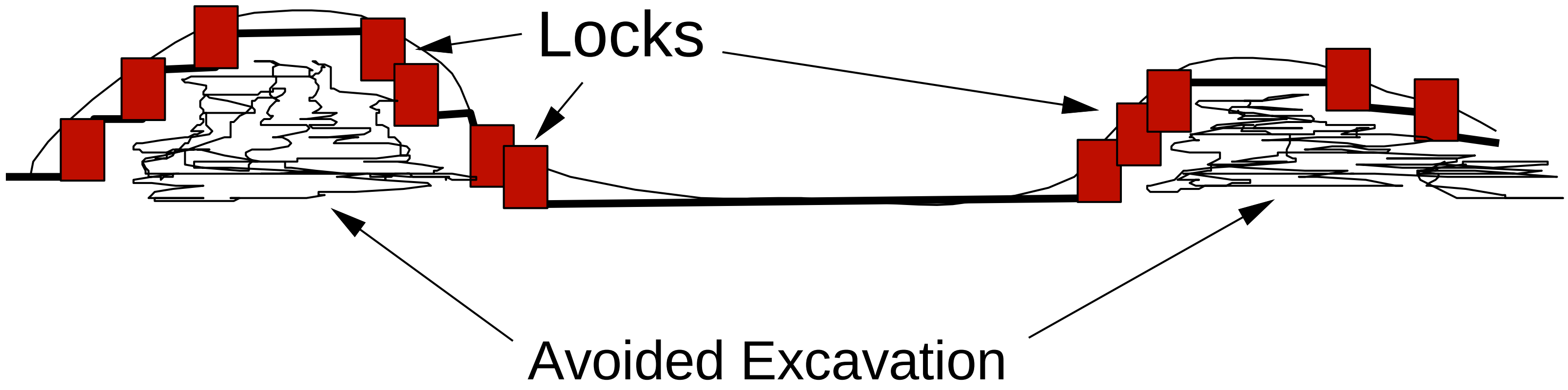
Courtesy of Tino Morchel on Flickr.

Excavation Costs Increase With the Size of the Canal



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

Locks Reduce Excavation, But Reduce Speed & Capacity

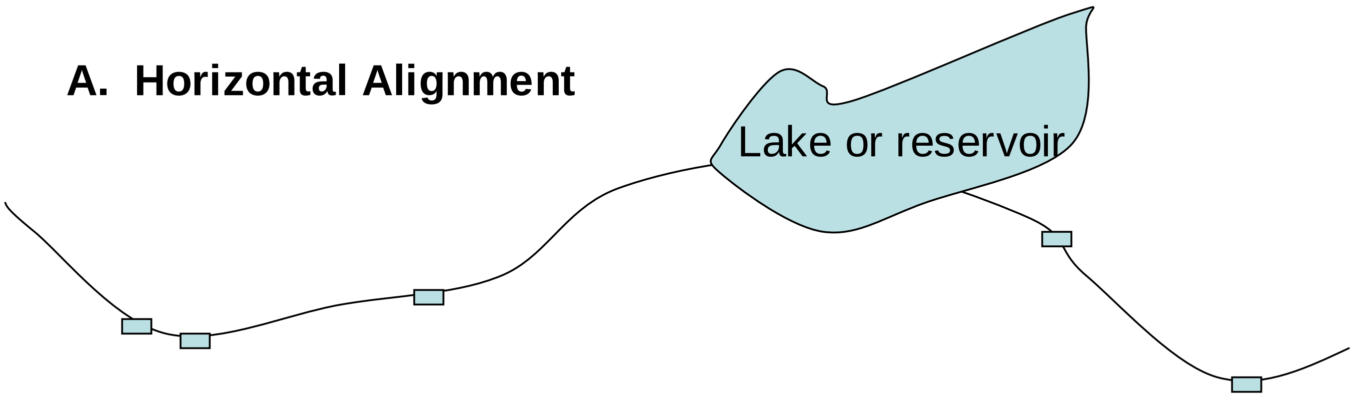


C&O Canal Washington, D.C.

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

Locks

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)

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

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

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!)

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 was $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

Middlesex Canal vs. Erie Canal

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

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

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 emminent domain to assemble land
  - Choice of route? scale of project?
- Possibly a major political issue!

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

Transport Options, Early 21st Century

Arterial Roads $1-5 million/mile to construct	10 tons/truck 100 miles/day 1000 tm/day/vehicle	$0.10 to $0.50/tm for freight rates
Interstate Highway $5-100 million/mile	20 tons/trailer 1-3 trailers per tractor 500 miles/day 10,000/d/v	$0.15 to $0.20/tm
Canal & waterway >Highly variable - few built	1500 tons/barge Up to 40 barges/tow 50-200 miles/day 6 million tm/d/v	$0.01/tm
Railroad $0.5-5 million/mile	5-15,000 tons/train 500 miles/day 5 million tm/d/v	$0.02/tm

System Performance

Basic Concepts: Much More Than Cost

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

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

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

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.

Estimating Commuting Time:
Studying the Effects of Service Changes

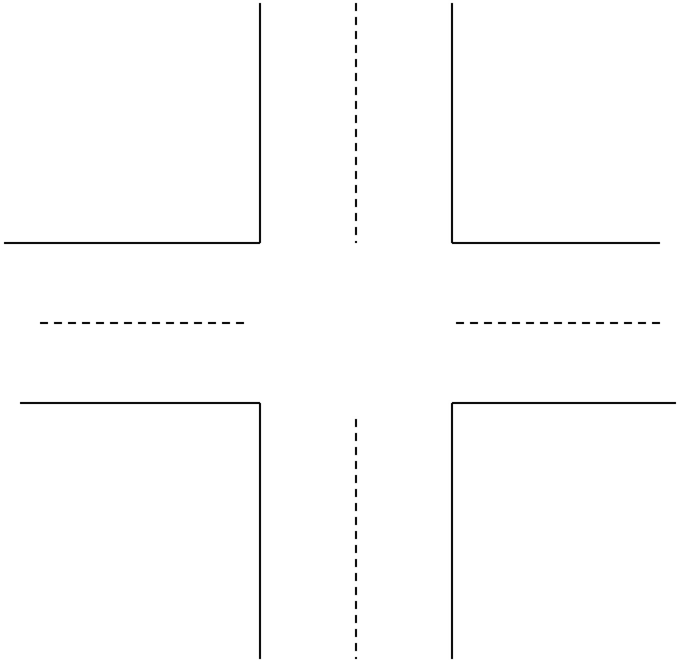
- Possible changes designed to improve service
  - Extend bus routes or subway lines
  - Have more bus stops
  - Have more frequent bus or train operations
- Use the service function to compare service with and without the service improvements for a representative sample of users
- Sum results over all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

Capacity

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

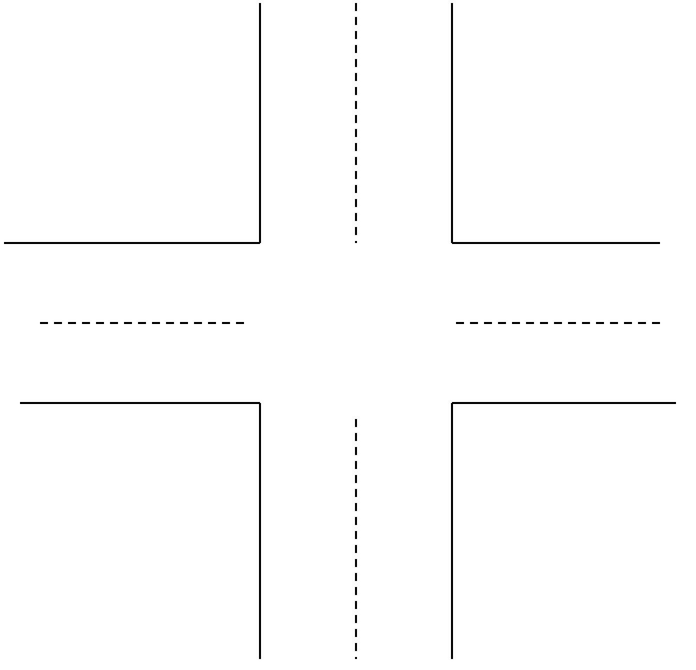
Capacity of a Highway Intersection: Theoretical Calculations

- 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?



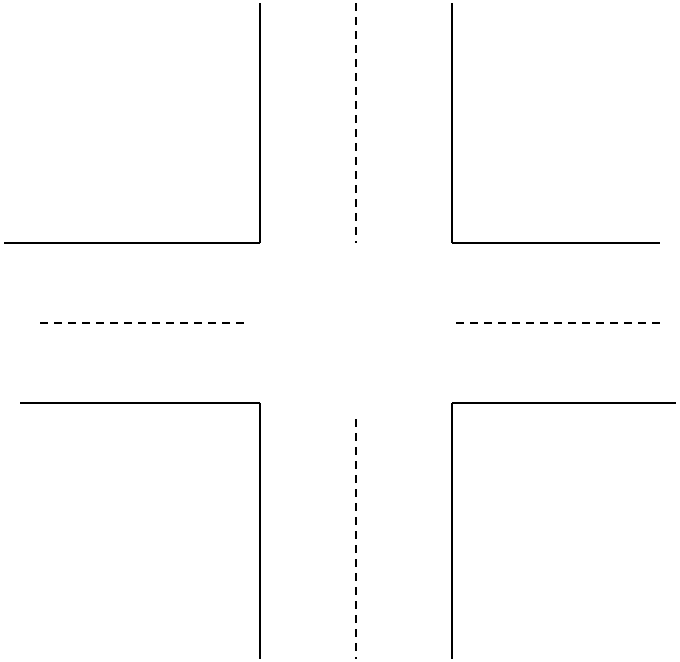
Capacity of a Highway Intersection: Measured Capacity

- 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?



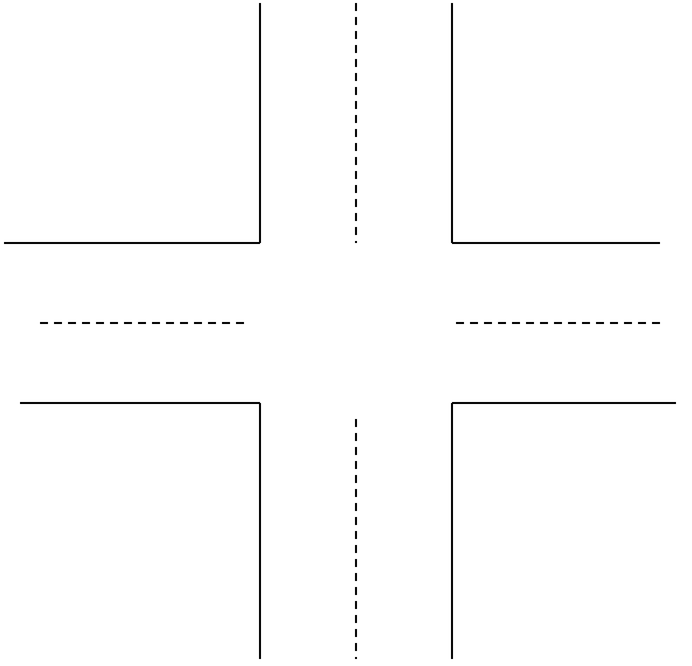
Capacity of a Highway Intersection: Insights from Commuters

- 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?



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