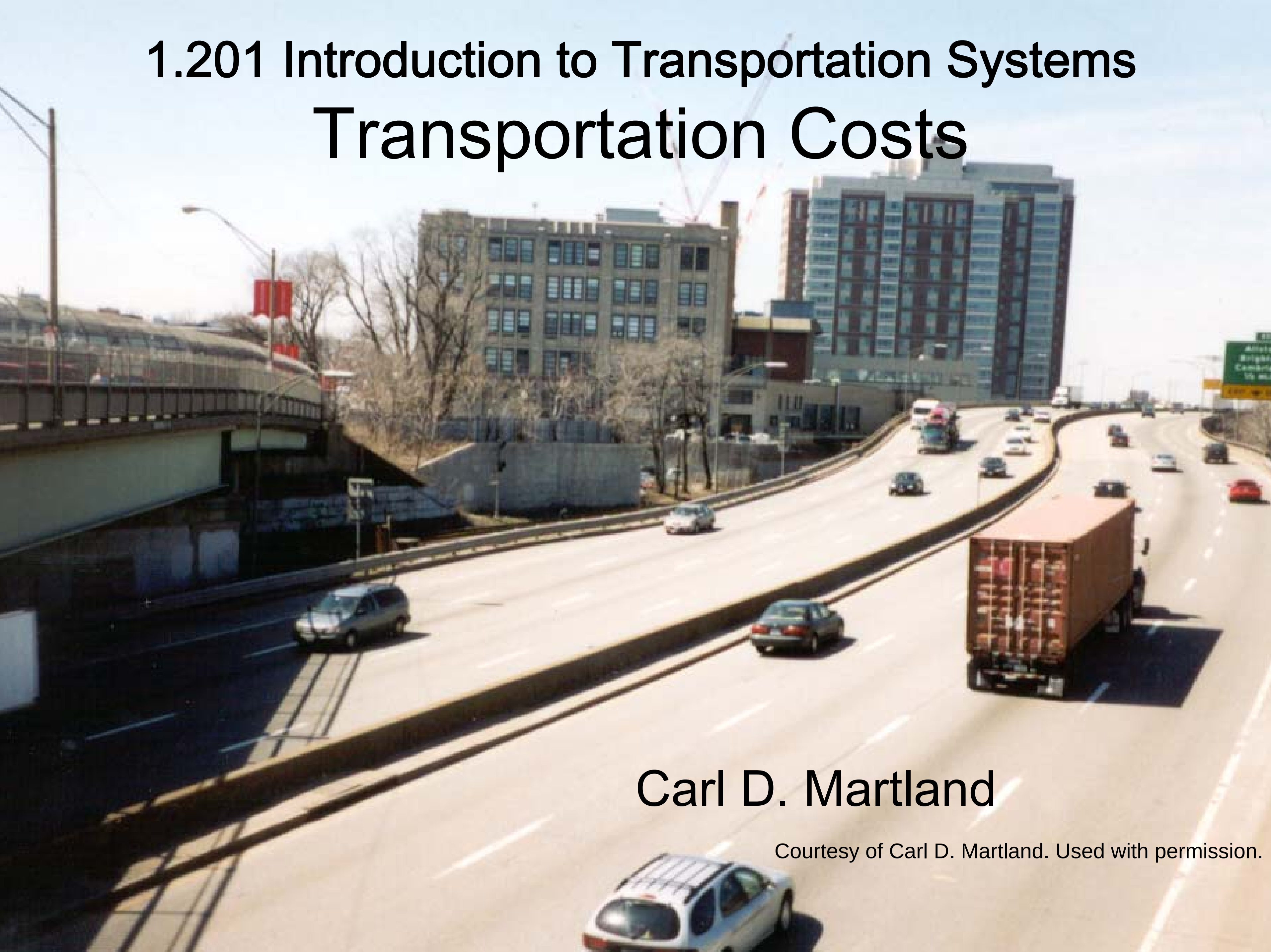
1.201 Introduction to Transportation Systems
Transportation Costs



Carl D. Martland

Transportation Costs

- Introduction & Motivation
- Duality of Production Functions & Cost Functions
- Types of Cost Functions
- Engineering Cost Functions

High Costs & Poor Productivity

Peak Traffic Demands Cause Delays at Bottlenecks

Clark Junction, CTA

Photo: C.D. Martland, January 2003

High Costs & Poor Productivity: Capacity for Peak Loads

Tate Modern Subway Station, London

Photo: C.D. Martland, October 2002)

High Costs & Poor Productivity: Limits on Vehicle Size/Weights

Photos: C.D. Martland

Improving Costs & Productivity: Tailoring Services to Demand

San Juan, Puerto Rico (Photo: C.D. Martland)

Improving Costs & Productivity: Information & Control

Photo: C.D. Martland

Improving Costs & Productivity: Increasing Vehicle Size/Weight

Photos: C.D. Martland

Duality of Costs & Productivity

- Cost Function
  - Minimize cost of resources required to produce desired services
- Production Function
  - Maximize value of output obtained from given resources

Basic Economic Concepts- Differing Perspectives of Economists and Engineers

- Production functions
  - Economists either assume this is known or try to estimate a very aggregate model based upon actual performance
  - Engineers are constantly trying to "improve productivity", i.e. find better ways to use resources to produce more or better goods and services
- Cost functions
  - Both use total, average, variable, and marginal costs; engineers go into much greater detail than economists
  - Short-run and long-run cost functions
    - Economists typically focus on effects of volume and prices
    - Engineers typically focus on costs and capacity
- Duality of production and cost functions

Using Average and Marginal Costs

- Profitability/Subsidy Requirements
  - Comparison of average costs and average revenue
    - Average revenue per trip is a natural way to look at revenue, so this becomes a useful way to look at costs
- Profitablity of a particular trip
  - Comparison of marginal cost and marginal revenue
- Economic efficiency (or business common sense)
  - Price = MC (Price > MC)
- Regulation of industries with declining costs
  - May need to segment markets and have differential pricing in order to cover total costs

Fixed vs. Variable Costs

- Fixed Costs
  - Unaffected by changes in activity level over a feasible range of operations for a given capacity or capability over a reasonable time period
  - For greater changes in activity levels, or for shutdowns, the fixed cost can of course vary
  - Examples: insurance, rent, CEO salary
- Variable Costs
  - Vary with the level of activity
  - Examples: construction labor, fuel costs, supplies
- Incremental Costs
  - Added costs for increment of activity

Fixed, Variable, and Incremental Costs

Total Cost (V) = Fixed Cost + f(volume)

Avg. Cost (V) = Fixed Cost/V + f(volume)/V

Incremental Cost(V0,V1) = f(V1) - f(v0)

Marginal Cost (V) = d(Total Cost)/dV = f'(V)

(Assuming we in fact have a differentiable function for variable costs!)

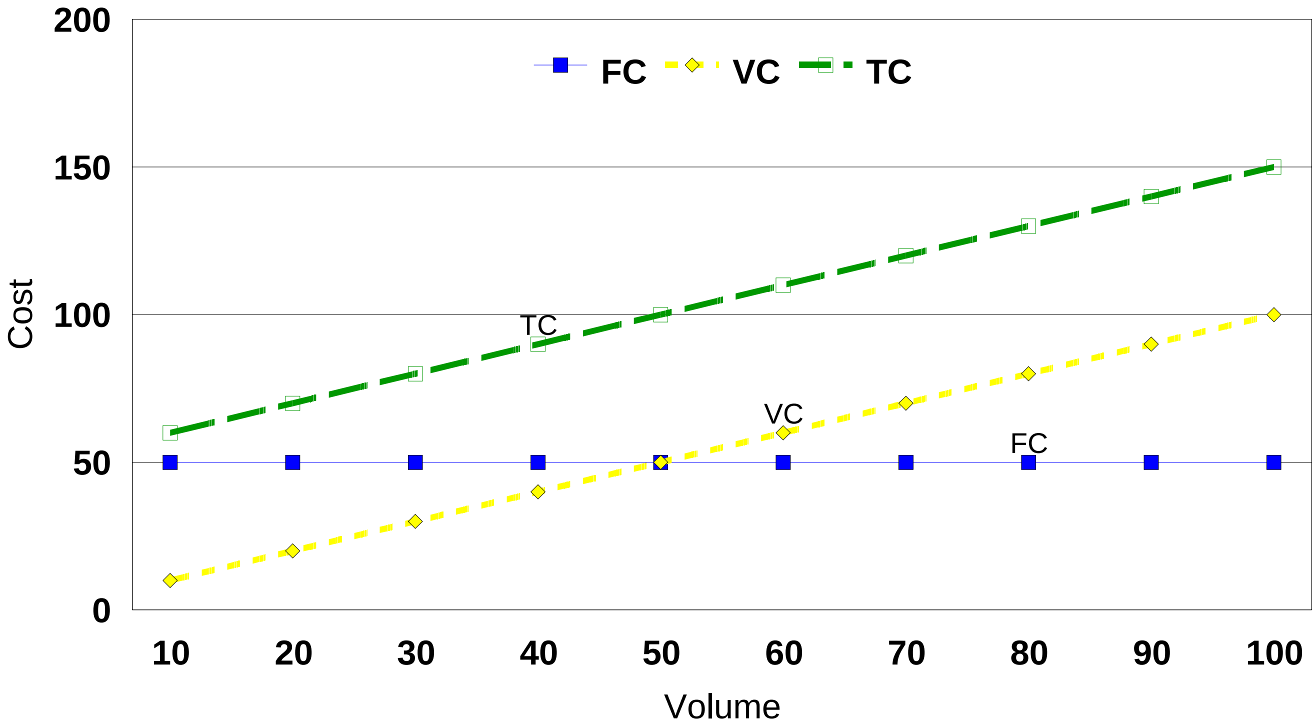
Long-Run & Short-Run Costs

- Long-run costs
  - All inputs can vary to get the optimal cost
  - Because of time delays in reaching equilibrium and the high costs of changing transportation infrastructure, this may be a rather idealized concept in many systems!

- Short-run costs
  - Some (possibly many) inputs are fixed
  - The short-run cost function assumes that the optimal combination of the optional inputs are used together with the fixed inputs

A Simple, Linear Cost Function:

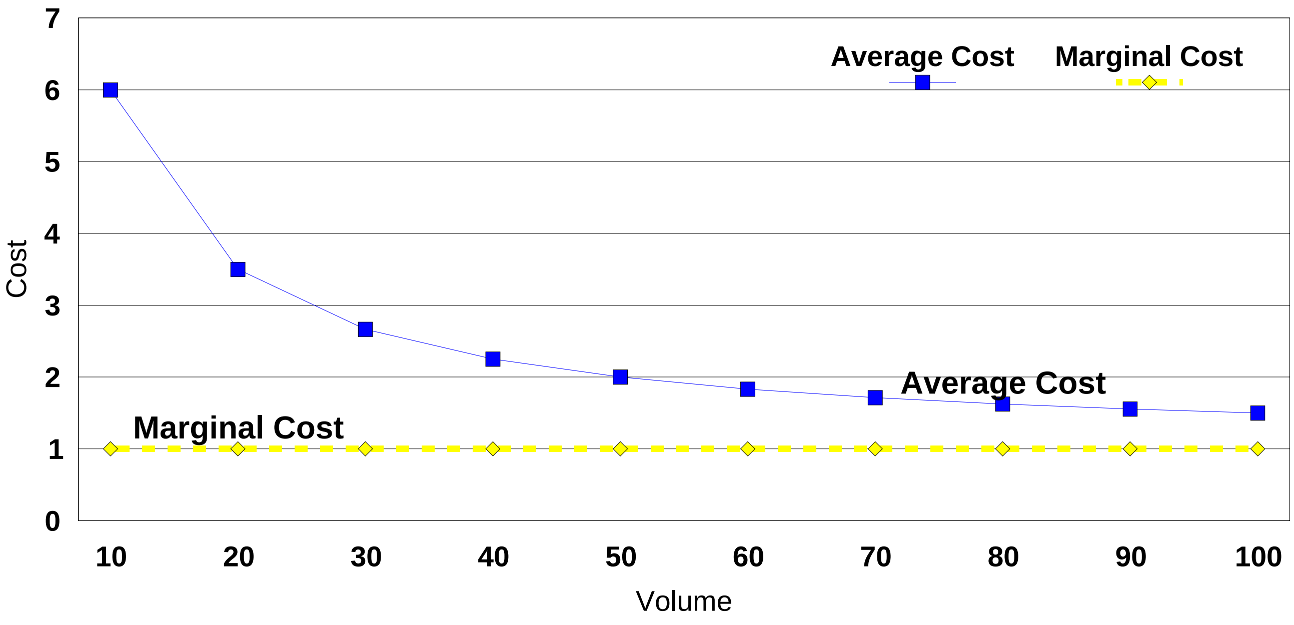
TC = a + bV = 50 + V, 10 <V<100



A Simple, Linear Cost Function:

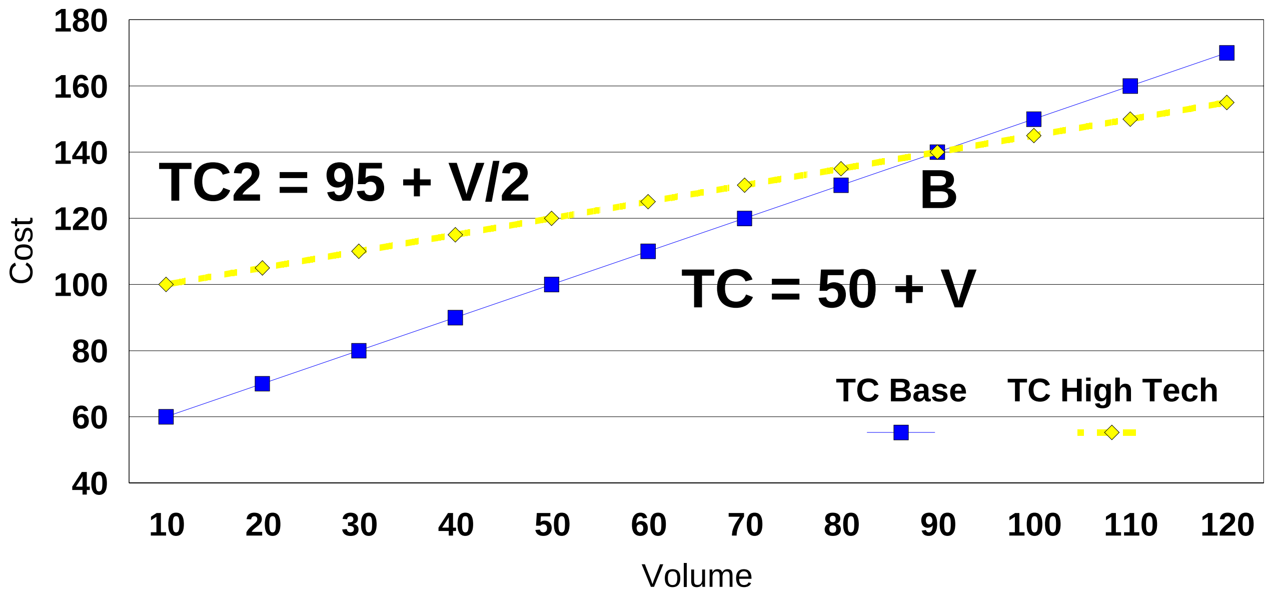
Avg Cost = a/V + b = 50/V + 1

Marginal Cost (V)= d(TC)dv = b = 1



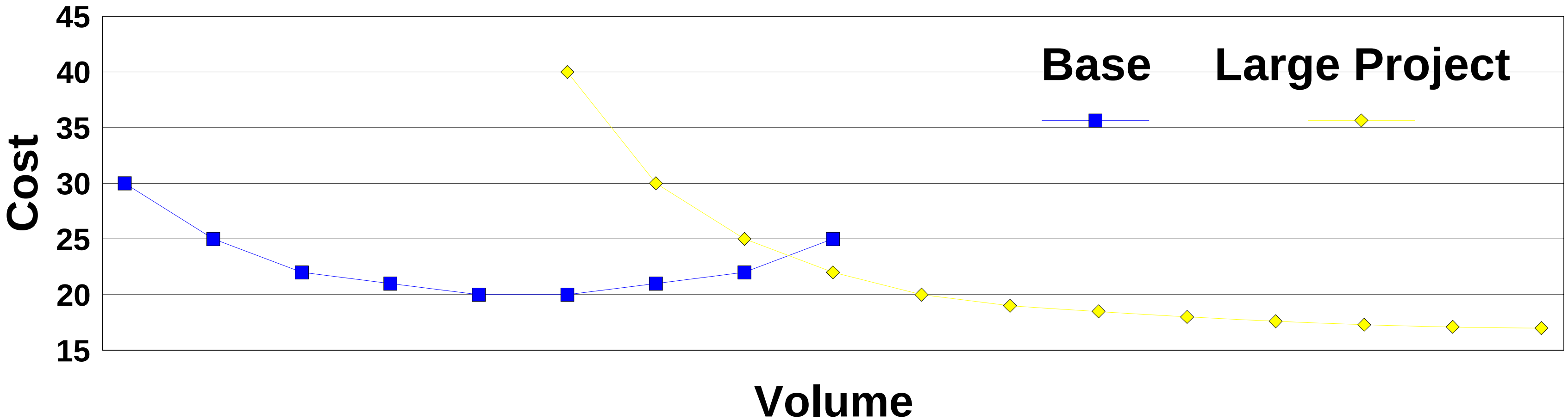
Classic Tradeoff: Can we afford higher fixed costs in order to get lower variable costs?

Breakeven point B is where TC1 = TC2



More Comments - CEE Projects

- Typical major projects reduce both marginal and average costs **per unit of capacity**
- Will there be sufficient demand to allow prices that cover average costs?
- In general, smaller projects will be better at low volumes until poor service and congestion hurt performance



Some Other Cost Terminology

- **Opportunity Cost**
  - **A key economic concept! What else could be done with these resources?**
- Sunk Cost
  - Expenditures that cannot be recovered and that are common to all options and therefore can be ignored ("focus on the differences")
- Direct, Indirect, and Standard Costs
  - Direct - easily related to a measurable activity or output
    - Excavation cost/cu. yd.
  - Indirect (or overhead or burden) -ther costs related to the overall operation
    - Utilities, marketing, property tax
  - Standard costs - used in budgeting, estimating & control

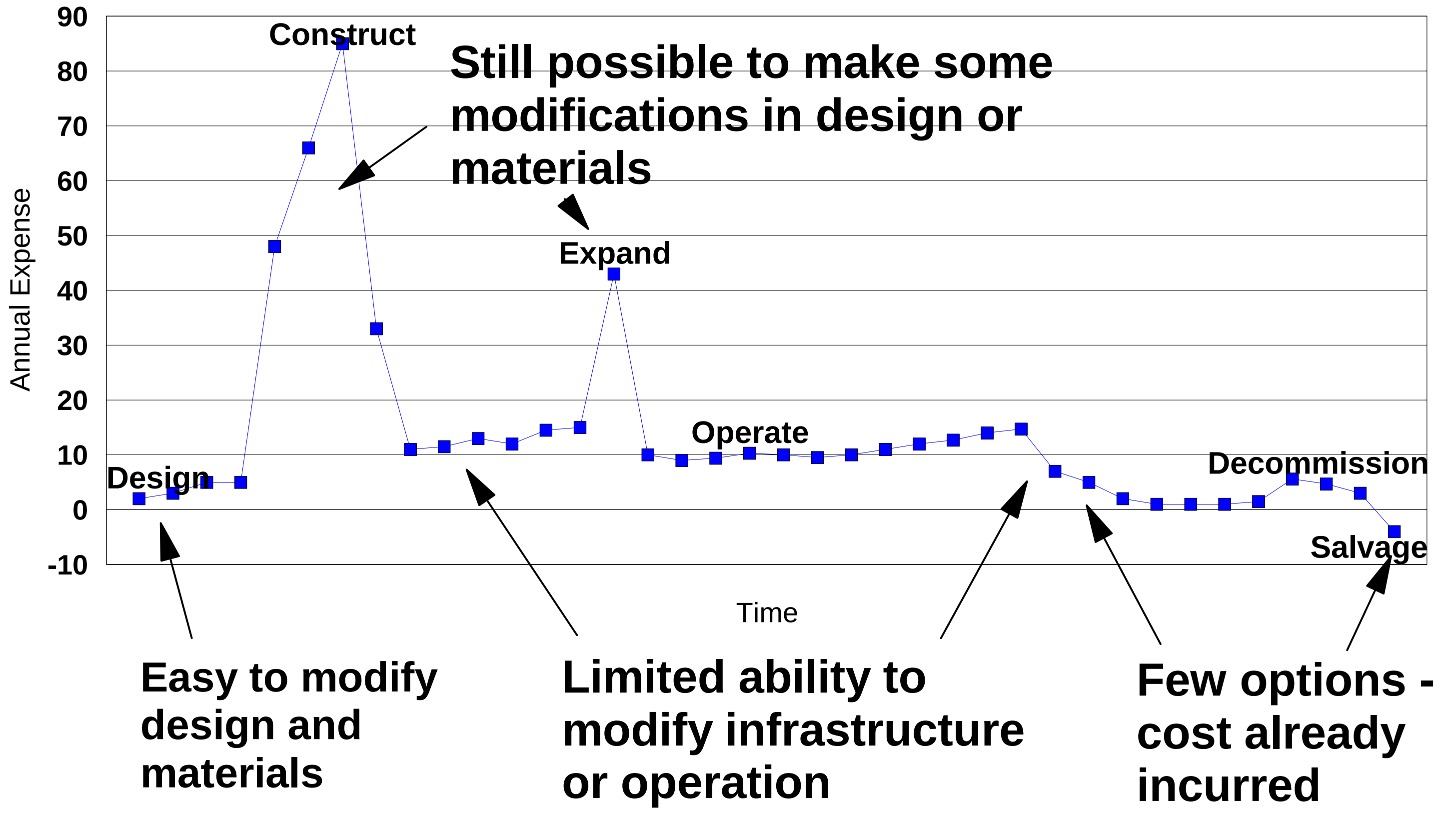
Even More Cost Terminology

- Recurring vs. Non-recurring costs
  - Recurring - repetitive; could be fixed or variable
  - Non-recurring - typically the one-time expense of getting started
- Cost vs. Expense
  - "Expense" is a specific cash or other expenditure that can be followed in the accounting system
    - Depreciation is a non-cash expense - according to tax rules
    - Repayment of principal on a loan is definitely cash, but not a current expense item
  - "Cost" can refer to non-financial matters, such as lost time, aggravation, or pollution

Special Characteristics of Transportation Costs

- Infrastructure and equipment last a long time:
  - Life cycle costing
  - Deterioration rates, condition assessment, and need for maintenance and rehabilitation
- Transportation takes place over a network: space is critical!
  - Cost of network vs. cost of operation
  - Congestion
- Output is complex

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



Net Present Value (NPV)

The NPV is an estimate of the current value of future net benefits:

Given:

Future Value (t) = B(t) – C(t)

Discount Rate = i

Then

NPV(t) = (B(t) – C(t))/(1 + i)^t after t years

NPV(cash flows) = Σ((B(t) – C(t))/(1 + i)^t)

Annuity

An annuity is a sequence of equal payments over a period of time. To find an annuity that is equivalent to an arbitrary sequence of cash flows

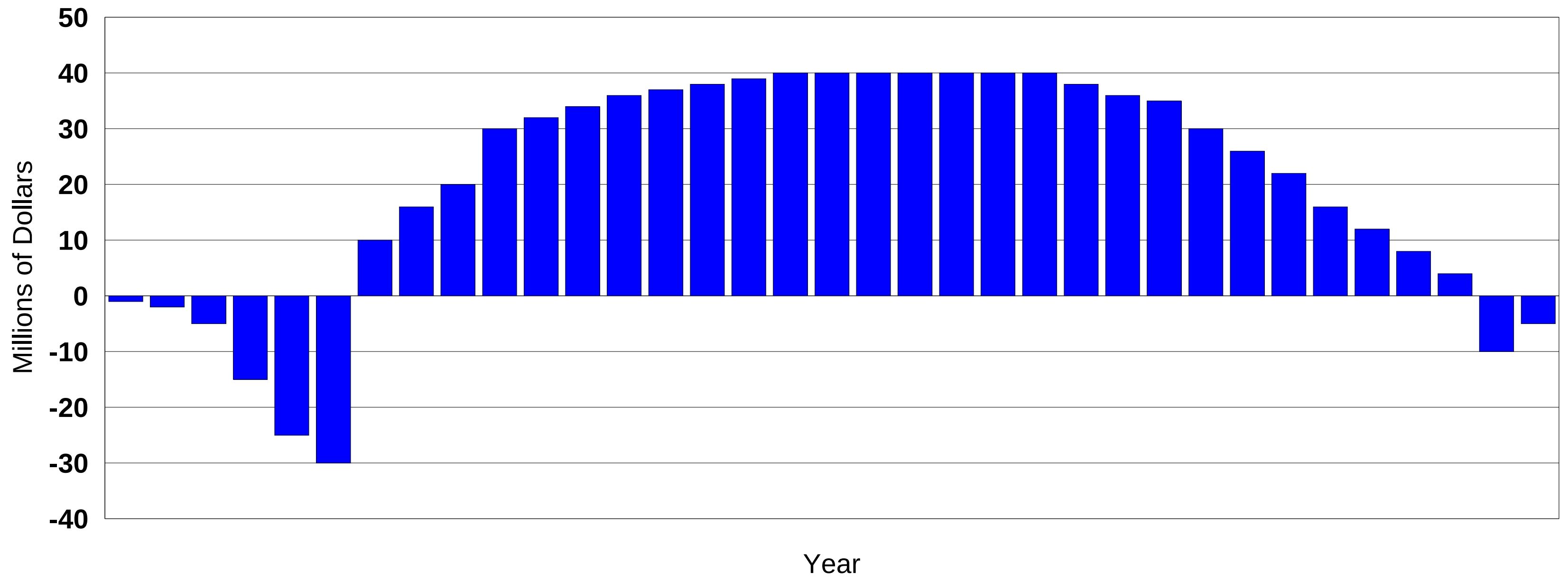
- Step 1: convert cash flows to NPV
- Step 2: convert NPV to an annuity A:

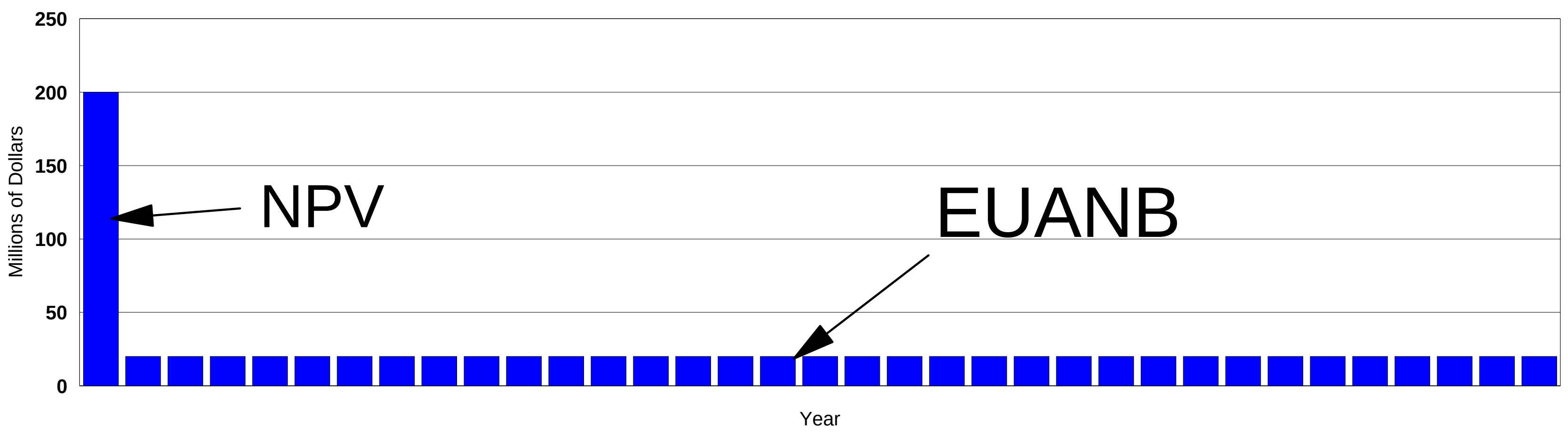
$$A = NPV * (A/P, i, N)$$

$$= NPV * i * (1+i)^N / ((1+i)^N - 1)$$

= PMT(NPV, i , N) *(in Excel)*

Cash Flows, NPV, and Equivalent Uniform Annual Net Benefits



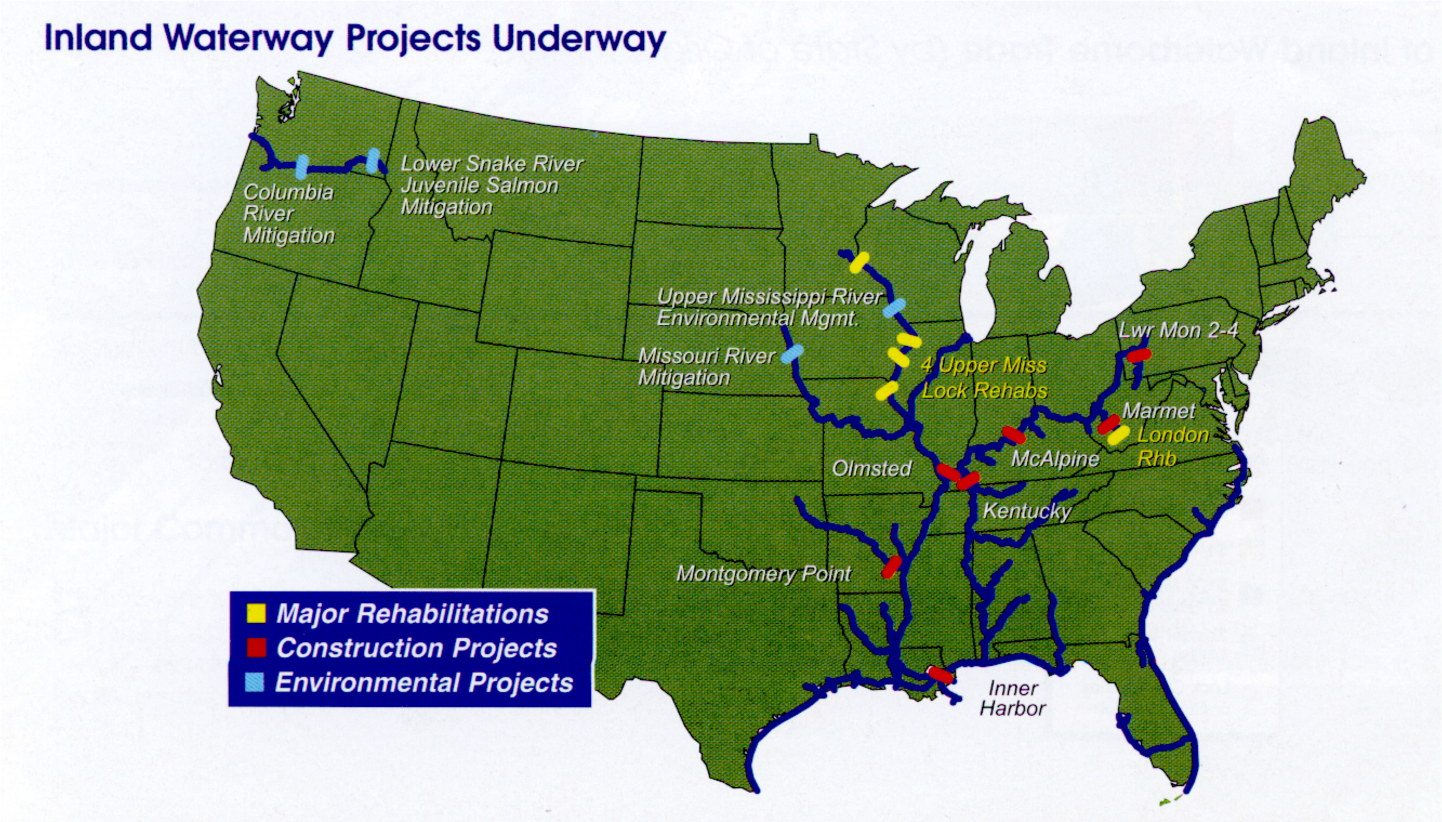


Network Considerations

- How best to structure the network?
  - Economies of scale
  - Economies of density
  - Economies of scope
- Congestion
  - Cost to users
  - Cost to operators
  - Relationship to capacity

Economies of Scale

Average costs may decline and markets expand if the network is larger. Corps of engineers is responsible for all inland waterway projects, including extending portions available handle larger shipments.



Source: US Army Corps of Engineers

Economies of Density

Photograph of tracks leading to grain elevator. Image removed due to copyright restrictions.

It may be cheaper to handle traffic on one facility rather than two:

$$C(V1 + V2) < C(V1) + C(V2)$$

Larger grain elevators, fewer branch lines, longer truck trips from the farm

Photograph of coal trains on parallel tracks. Image removed due to copyright restrictions.

Coal trains at UP fueling facility in North Platte; triple track line handles 150 trains/day

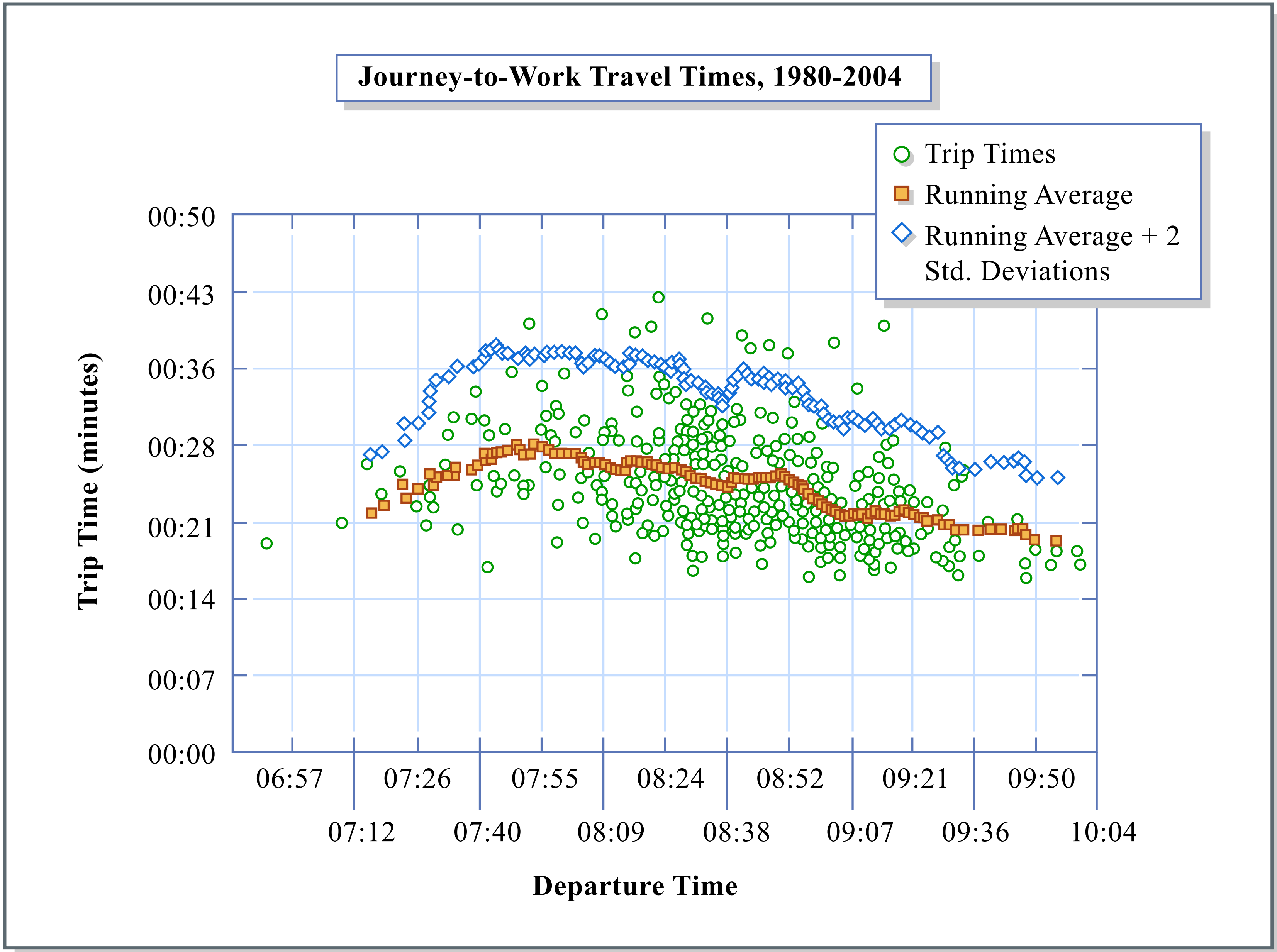


Figure by MIT OCW.

Economies of Scope

Photograph removed due to copyright restrictions.

Triple transport tiers in a gorge – interstate plus bike path on opposite side of river from Amtrak (Colorado)

It may be cheaper to provide facilities for multiple services than to provide separate facilities for both. Highways serve auto, bus and many kinds of trucks; transport projects can service multiple modes, plus fiber optics, and other functions.

Output is Complex – What Measures Are Needed?

- Cost per trip?
- Cost per passenger or per ton?
- Cost per vehicle-mile?
- Cost per passenger-mile or ton-mile?

All will be useful for something!

Methods of Estimating Costs

- Accounting
  - Allocate expense categories to services provided using:
    - Detailed cost data from accounting systems
    - Activity data from operating MIS
- Engineering
  - Knowledge of technology (possibly new technology) and operating capabilities
  - Prices of inputs
- Econometric
  - Knowledge of total costs for a varied set of firms or conditions
  - Aggregate data representing inputs and system characteristics

Accounting Costs

- Every company and organization will have some sort of accounting system to keep track of expenses by (very detailed) categories
- These costs can readily (and possibly correctly or at least reasonably) be allocated to various activities, such as:
  - number of shipments
  - number of terminal movements
  - vehicle-miles
- This allows a quick way to estimate the average costs associated with each activity, which can be used to build a cost model (which can be quite useful even though they tend to be disparaged by both engineers and economists!)
- Refinements can reflect which elements of expense are fixed and which are variable

Example of the Accounting Approach

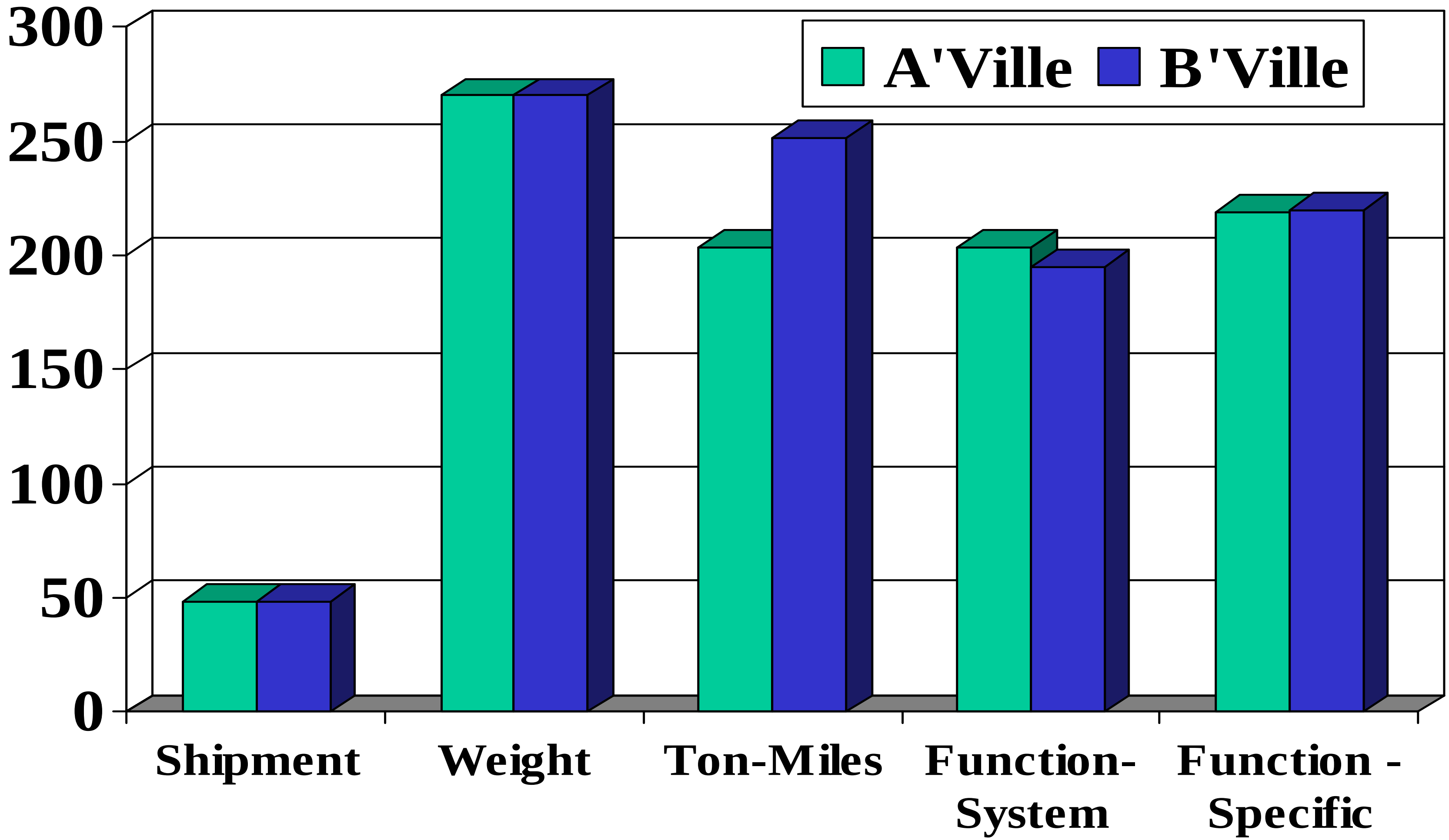
D.L. Shrock, "The Functional Approach to Motor Carrier Costing: Application and Limitations", 1986

Functional Category	Relevant Service Unit
Pickup & Delivery Expense	60% to shipments (running time) 40% to CWT (stop time)
Platform Expense	Weight moved across the terminal dock
Line Haul Expense	Traffic moved and distance, i.e. ton-miles
Other Expense (Clerical)	Shipments

Trucking Example, Continued

Function	**Shipment Attribute**	**Expense Factor**	**Shipment Expense**
Pick up			
Running	1 shipment	$3.37/shipment	$3.37
Stop	5 CWT	0.3140/CWT	$1.57
Platform –O	5 CWT	0.7413/CWT	$3.71
Line Haul	87.5 ton-mi	0.0874/ton-mi	$7.65
Platform - D	5 CWT	0.7413	$3.71
Delivery			
Running	1 shipment	3.37/shipment	$3.37
Stop	5 CWT	0.3140/CWT	$1.57
Other	1 shipment	13.90/shipment	$13.90
Total			$38.85

Trucking Example: Significant Differences Depending Upon Method Used

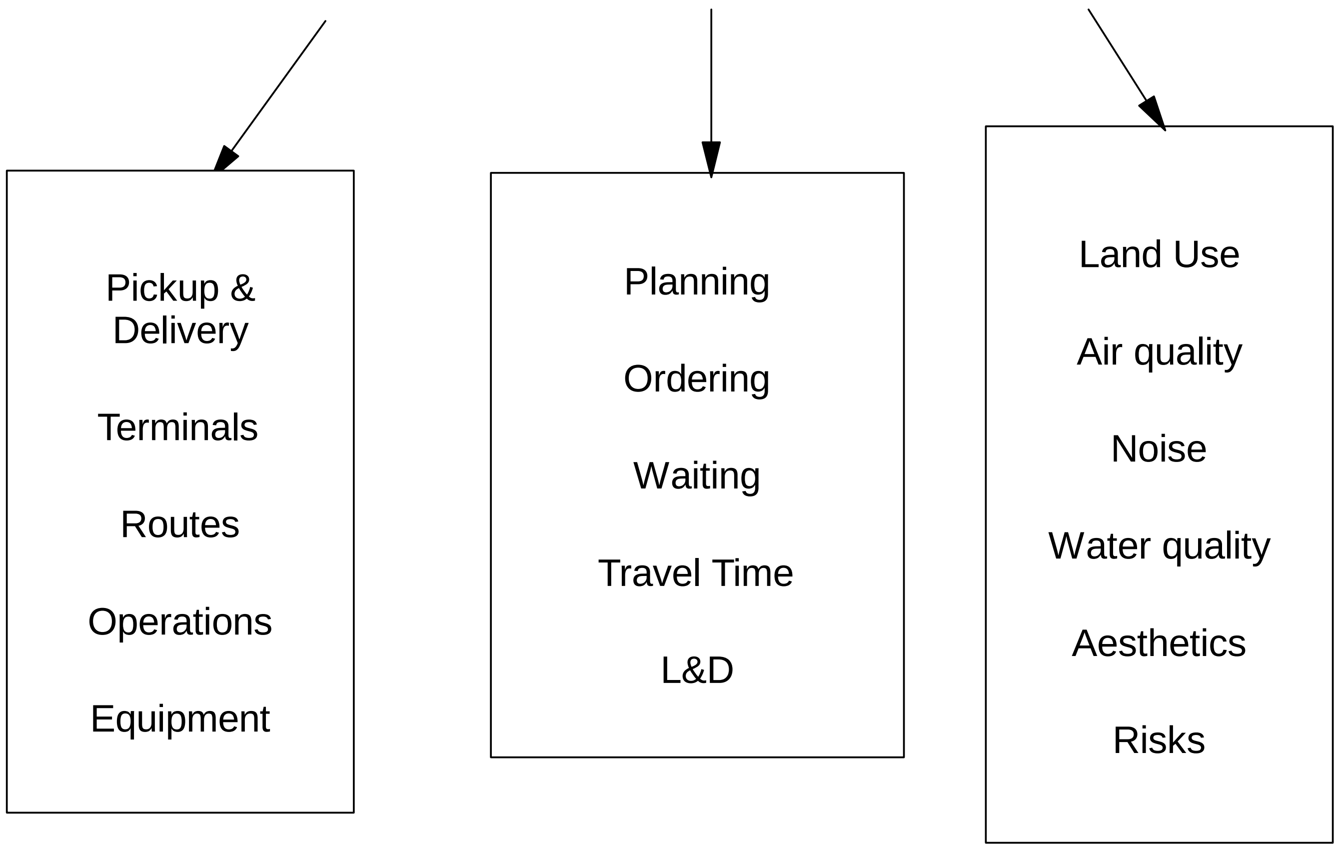


Engineering Costs

- Engineers need to examine the costs of different technologies and operating strategies, so historical costs may not be relevant
- When pushing the limits of technology (e.g. heavy axle loads or congested highways), it is necessary to include some science in the cost models
- Engineering models can go to any required level of detail, so long as there is some scientfic or historical evidence available
- Most researchers work with some sort of engineering models as they examine the performance of complex systems

Engineering Cost:
Cost Elements to Consider

Cost = Carrier Cost + User Cost + Externalities



Econometric Cost Models

- Deal with the complexity problem by assuming a simplified, more aggregate cost model
  - Calibrate using available data
  - Structure so that it can be calibrated using standard regression analysis
  - Structure so that its parameters are in themselves interesting, e.g. the marginal product of labor
  - Focus on specific parameters of interest in current policy debates

Summary: Comparison of Costing Methods

	Main Uses	Strengths	Weaknesses
Accounting	Internal costing systems, Planning	Actual data Consistent with MIS	Limited to historical experience and technologies; Limited by structure of MIS
Engineering	Investment planning Technology assesment, Service design, Strategic planning	Can deal with new technologies, operating practice, or networks	May not match history Analysis may be "idealized"
Statistical	Public policy research, Pricing strategy, Strategic planning	Can estimate eonomic parameters; Minor data requirements	Limited to historical conditions; not meaningful to managers

Is There a "Transportation" Cost Model

- In principle, a generic cost model could be developed for application to any mode
- In practice, specialized models are often used for each mode
  - Different costs dominate for different modes
  - Key players (e.g. port authorities) are concerned with only part of the system
  - Simplifying assumptions used in one mode won't work in another context
    - A bus stop is a very simple terminal
  - Complexities in one mode won't be needed in another
    - A rail right-of-way has complex deterioration relationships that aren't relevant in water transport
  - Specifying generic functions may not be (or seem) worth the effort

Selected Cost & Productivity Issues:
The Details are Critical!

- How will heavy axle loads affect costs related to track maintenance, vehicles, and operations?
- How will better communications help improve control?
- Will better inspection techniques allow lower lifecycle costs?
- Is it worth investing in communications-based train control in order to improve safety or operations?
- What changes should a railroad seek in labor agreements in order to improve labor productivity?
- How can we change our organizations & institutions to improve control over equipment utilization?

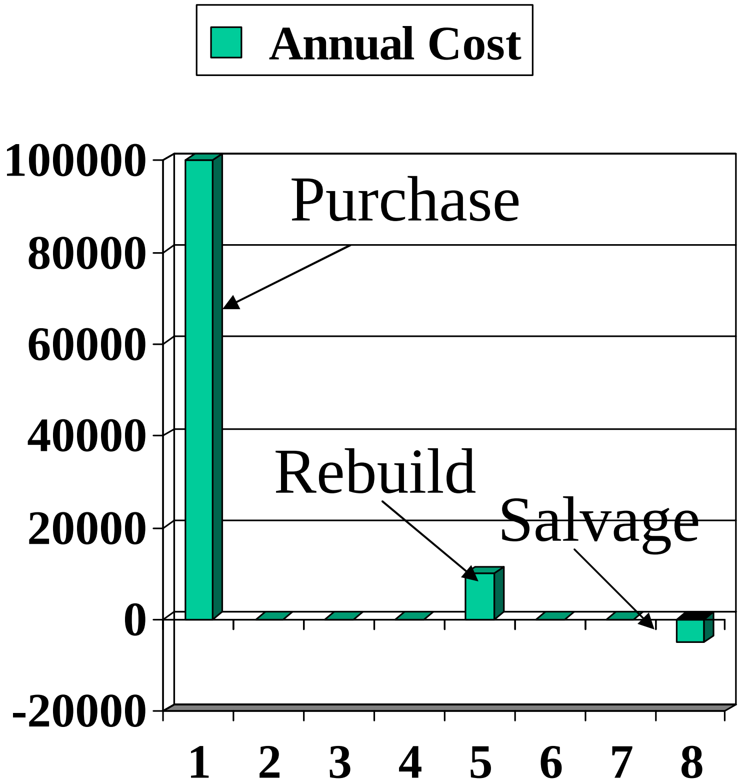
Key Costs for Selected Transport Services

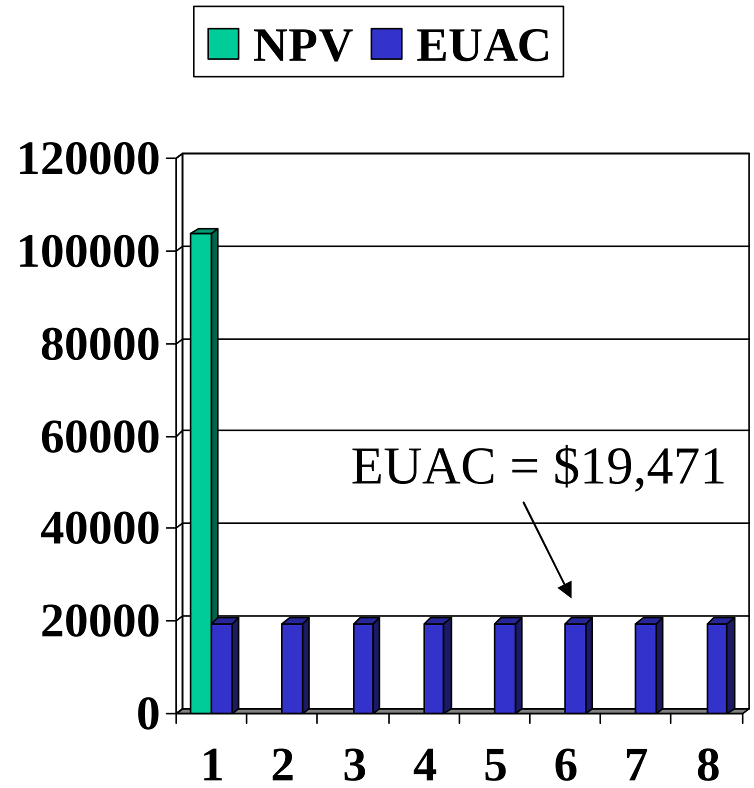
	Car Pools	Rail Bulk	Air Freight	Transit
PU & D	High	Low	High	none
Terminals	none	none	High	High
Route		High	none	High
Crews	none	High	low	
Vehicles		High		
Ordering	High	Low	High	None
Waiting	High	Low		High
Travel time		Low		High

Vehicle Costs

- Estimating cost per trip or per shipment
  - Cycle time and load factors
  - Life cycle cost (purchase, maintenance, rehab scrap)
  - Equivalent uniform annual cost
  - Equivalent hourly cost, at achievable utilization levels
  - Allocation of costs to specific shipments or passengers based upon veh-hrs required
- Economic cost/hour: best alternative use

Example: Convert Life Cycle cost for A Truck to an Equivalent Truck Cost per Day (i = 10%)





Cost/day = EUAC/(365*% utilization * % serviceability)

= $11.98/day @ 95% utilization & 95% serviceability

A More Expensive Vehicle May Have Better Operating Cost

- Value of Fuel efficiency, assuming 100,000 mile/year and fuel @ $2.50/gallon
  - 5 mpg => 20,000 gallons or $50,000/yr
  - 6 mpg => 16,700 gallons/yr or $42,000/yr
- NPV of savings of $8,000 per year for 8 years is $43,000 => willing to pay a lot more for a truck with better mileage

A Larger Vehicle Can Earn More Revenue

- Standard Trailer Used in N. America
  - 1960s: 35’
  - 1970s: 40’
  - 1980s: 40’ & 45’
  - Early 1990s: 40 & 45’
  - Late 1990s to date: 45’, 48’,53’
- 10% Larger Payload => 10% more revenue per trip (~ $10,000 per year @ 100,000/yr)

Horse-drawn Wagons competed successfully with Trucks into the 1930s

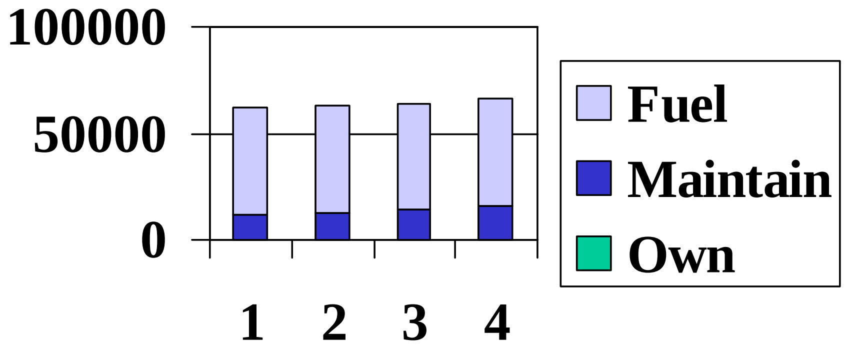
Black-and-white photograph of horse-drawn carriages. Image removed due to copyright restrictions.

Source: Leonard Reich, “Dawn of the Truck”, Invention & Technology, Fall 2000, p. 19

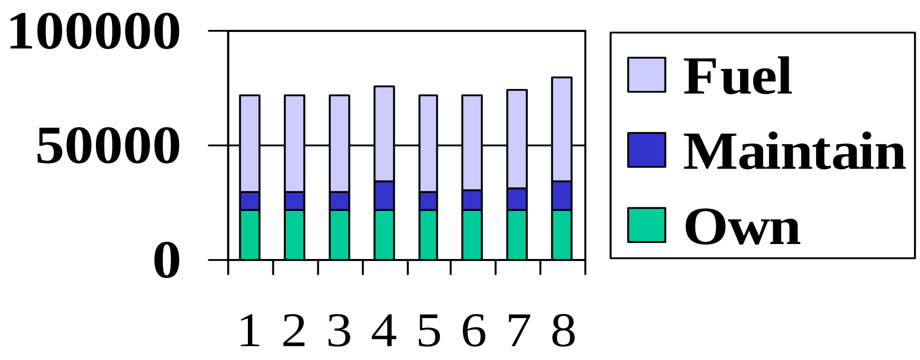
When Is Equipment Obsolete?

- Compare expected EUAC for vehicle ownership & operations over the remaining life of the vehicles (assuming you plan to be in business that long)

Current Truck - 5 mpg



New Truck - 6 mpg



Vehicle Cost & Design Issues

- Larger vehicles generally have lower cost per unit of capacity
  - 747s, articulated buses, containerships
- Lightweight materials increase payload or reduce operating costs
  - Aluminum, plastics, composites
- Improved reliability extends vehicle life
  - Automobiles
- Coordination among carriers and customers can allow higher utilization
- Lower interest rates reduce costs/hr

Vehicle Examples

- Automobile
  - First car can be justified for use in shopping, visiting friends & relatives, vacations, and emergencies
  - Marginal cost for commuting may just include gas, tolls, and maintenance
  - Second car may be harder to justify, but may also be cheaper (simply retain older car and use as needed – lower value, lower usage, lower insurance & taxes)
- Transit
  - Larger vehicles have lower cost per seat-mile, but smaller vehicles support more frequent service

Photo: C.D. Martland

Route Costs

- Opportunity cost of using the land is in fact an economc cost (i.e. value of the corridor for other services, value of the land for agriculture or development)
- Depreciation (which can be based in part upon time and in part upon usage) is a real cost
- Purchase cost or construction cost (except as reflected in depreciation) is a sunk cost for economic decision-making (i.e. we can and should ignore it)
- Maintenance cost (some activities vary with time, some with area, and some with usage)
- Note:
  - Accounting rules will be established by professional societies and/or governments; these rules may be more or less complicated than what is suggested here and they will be unlikely to reflect physical deterioration of the facility. In extreme cases, the accounting rules will bear little or no relation to reality!

Estimating Route Costs

Photo: C.D. Martland

- Identify route maintenance activities:
  - Inspection = f(time, condition, type of use)
  - Minor repairs = f(time, condition, amount of use)
  - Periodic maintenance = f(usage)
  - Renewal = f(time, usage)
- Estimate frequency, unit costs, and net present value of future costs for each acctivity for base traffic levels
  - Note: if we have a route where the activities have reached steady state, then the annual activities will be the same each year, and we can deal with average annual costs per unit of traffic instead of the more complex NPV analysis
- Estimate frequency, unit costs, and NPV for new traffic level
- Estimate the marginal cost as the increased cost for the increased traffic

Structuring the Analysis of a Rail Route

Safety Standards
Traffic
Technology

Track
- Rail
- Ties
- Fastening syste
- Ballast

Turnouts

Crossings

Bridges

Signals & communications

Installation:
- Rail cost
- Transport cost
- Installation cost

Maintenance
- Inspection
- Grinding
- Defect repair

Factors Influencing Costs

- Ability of components to withstand stresses
- Probability and impacts of component failure
- Traffic mix and volume
  - Requirements for comfort or L&D (lateral & vertical accelerations
  - Static & dynamic axle loads
  - Size and materials for wheels
- Technological options
  - Materials & design of components
  - Materials & design of vehicles

Route Costs:
Adding 100 cars/day to a rail service

	1 Train/wk	10 Trains/day	100 Trains/day
BASE Inspection Frequency	Monthly	Weekly	Daily
Inspection Cost $/day	5	25	200
Minor repairs $/day	5	100	300
Periodic repairs $/day	none	50	500
Renewal $/day	none	25	500
Total Cost $/day	**10**	**200**	**1500**
Avg. Cost/train	**70**	**20**	**15**
NEW(add 100 cars/day) Inspection	Bi-weekly 5	Weekly 25	Daily 200
Minor repairs $/day	30	110	303
Periodic repairs $/day	5	55	505
Renewal $/day	10	27.5	505
Total Cost $/day	**55**	**217.5**	**1513**
Avg. Cost/train	**48**	**19.8**	**15**
Incremental cost (TC1-TC2)	***45***	***17.5***	***13***

Fleet Management


Photo: C.D. Martland

- Fleet sizing
  - Ability to provide service during peak
  - Low level of utilization during off-peak
- Fleet management
  - Acquisitions and retirements
  - Maintenance and rehabilitation
  - Allocation of vehicles to services
  - Empty vehicle distribution
- “Contribution to overhead and profit per veh-hr” vs. cost per veh-hr: framework for mgt

Crew Cost

- Allocate crew cost to volume handled on the vehicle (or possibly to the base load {i.e.only the market segment for which the service was initiated}

- Crew cost is inversely proportional to the expected load:
  - Crew$/unit = Crew$ / (capacity)(capacity utilization)

- Crew$ varies with the size of the crew and wage rate
  - Importance of work rules
  - Union vs. non-union wage rates
  - Crew size relates to workload and safety, which ultimately determiie the required crew size

- Marginal costs depend upon utilization:
  - 0 in short run if there is room
  - May be 0 in medium run if the minimum service is underulized
  - Usually assumed to equal allocated cost at desired level of utilization in the long run

Crew Cost Example:

Marginal Costs of Adding 100 Cars/Day to a Rail Service

	A	B	C	D
Base trains/day	.15	1	10	100
Base cars/train	35	20	100	90
Base cars/day	5	20	1000	9000
Short-run change:				
New cars/day	105	120	1100	9100
New trains/day	.85	0	1	0
New cars/train	105	120	100	91
Δ Crews/100 cars	.85	0	1	0
Long-run change				
Cars/train	100	100	100	90
New trains/day	1.05-.15	1.2-1	11-10	101.1-100
Δ Crews/100 cars	.9	.2	1	1.1

Examples of Productivity Issues Related to Crew Costs

- Truck driver shortage and extremely high turnover (40% and up) for TL companies
  - Deregulation created tremendously competitive market, depressing prices and thereby limiting wage increases
  - Substitution of non-union for union drivers as TL companies split off from trucking companies
  - No shortages in LTL, where union agreements have maintained wages
- Incursion of low priced drivers after formation of international trade pacts (e.g. NAFTA, EU)
  - Pressure to open up national markets & to protect national drivers
- Increasing vehicle size (aircraft, buses, trains)
  - Economies available ***IFF*** the added capacity can be utilized
  - Focus on vehicle and operating costs may hurt service and other elements of cost

Pickup & Delivery Cost

- Time, rather than speed or vehicle capacity is the key:
  - How many customers can be served by one crew within a single shift?
  - Cost/unit = (Crew$ + Veh $)/Units handled per shift
  - Units handled per shift = (Units/Customer)(Customers/shift)
- Marginal costs can be very high
  - Fully utilized PUD operation may require a new crew
  - Distant PUD operation may require excessive time
- Marginal costs can also be very low
  - Multiple units from one location

Photo: C.D. Martland

PU & D Examples

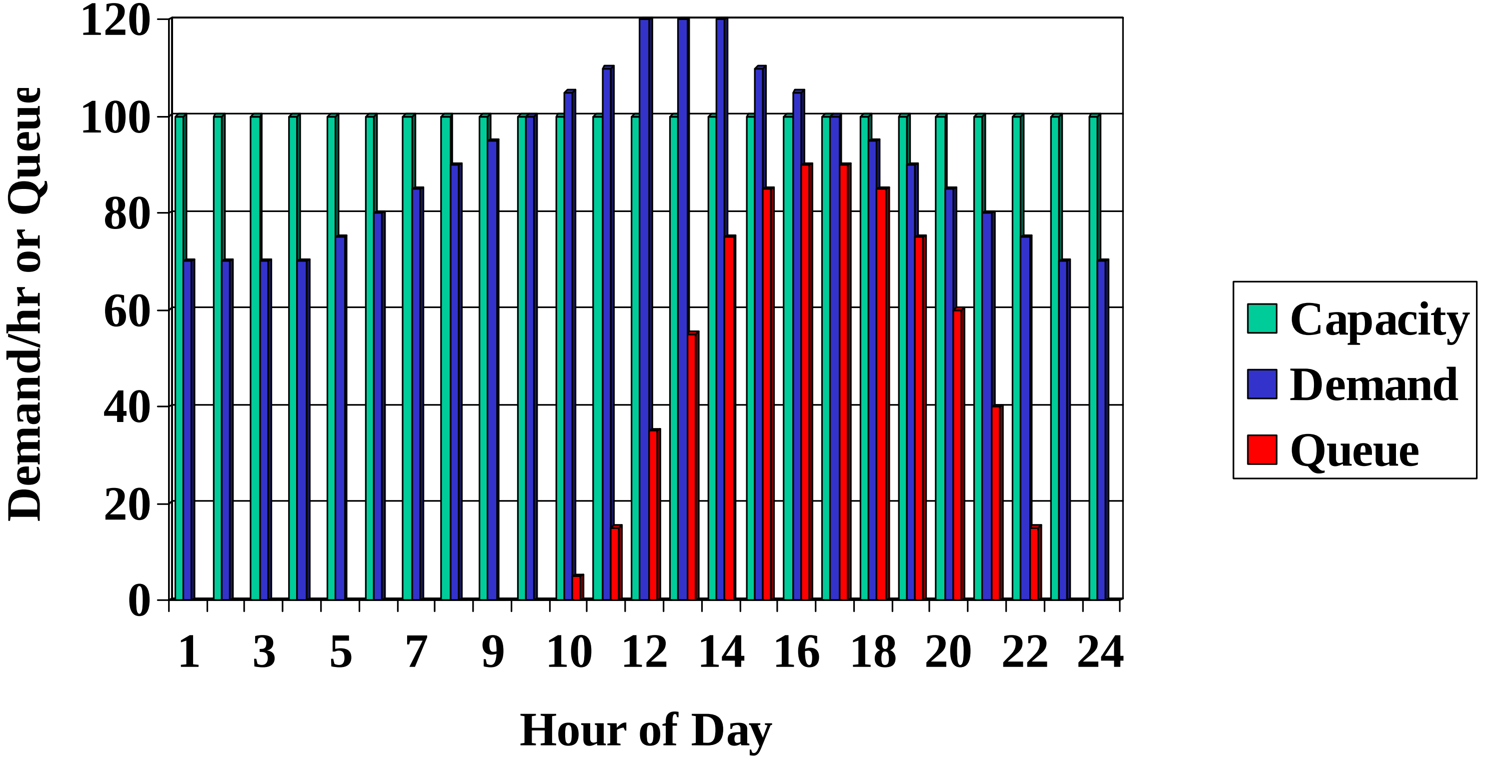
- Rail boxcar service to customers on light density lines
  - Per unit costs are so high that this traffic is more efficiently served by truck, which led to abandonment of roughly a third of the rail network
- Express parcel service is a leading user of technology
  - To make the PU&D work, they need to minimize the time and effort required (for customer and carrier)
- Strategic alliances are possible
  - Airborne express focuses on business customer for overnight services
  - USPS already has a vast delivery network to residences
  - Airborne and USPS have teamed up for priority small package services
- The highly visible airport access problem is a problem of PU&D of airline passengers

Terminal Costs

- Construction and land (as for route)
- Maintenance
- Crew and equipment (fixed plus variable)
- Management & clerical
- Detention time for road vehicles and their crews
- Detention time for passengers or freight

Goal: maximum utilization up to capacity constraint (delays during peak period must be acceptable)

Classic Problem of Terminal Management: Cost of Capacity vs. Cost of Delay

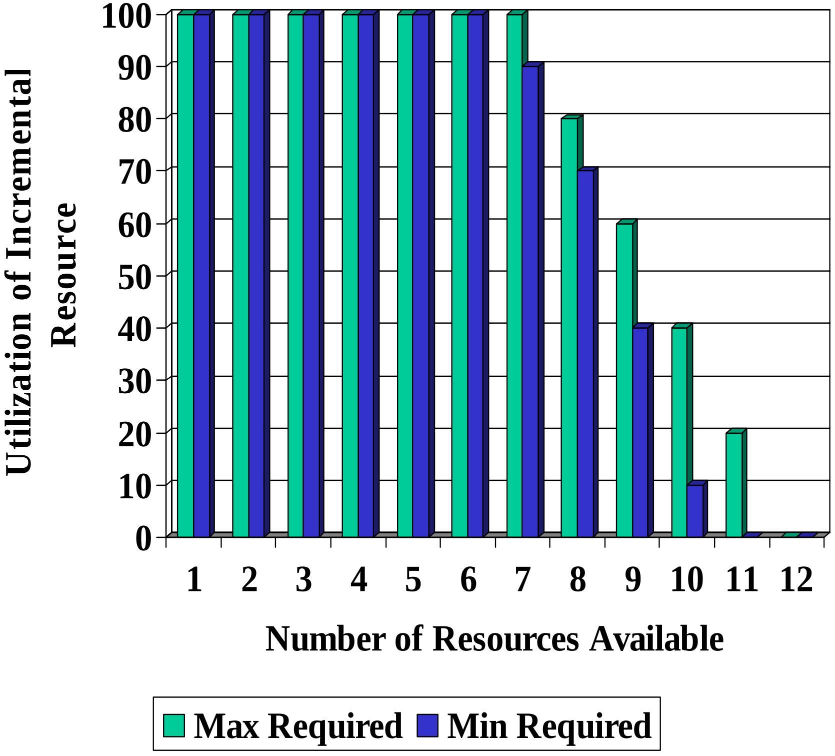


Classic Problem of Terminal Management: Cost of Capacity vs. Cost of Delay

- Size of Facility
- Personnel: supervisors, crews, etc.
- Ability to handle queues
- Ability to divert traffic to other terminals
- Time required in terminal
  - Crews
  - Vehicles
  - Passengers or Freight
- Quality and timeliness of information

Classic Problem of Terminal Management: Cost of Capacity vs. Cost of Delay

- Resources & their unit costs
- Incremental utilization rate
- Sustainable utilization rate for the facility (time for maintenance, recovery from incidents, and dealing with peak demands)
  - Managers and planners: 90%
  - Practical limit: 70%
- Incremental benefit for each resource
- Add resources if incremental benefit justifies incremental cost



Terminal Examples

- Ocean container shipping
  - Carriers want very large ships that are larger than what the ports can handle
    - What is best for the system?
- Airports located far from downtown may be only option, but these increase access costs
- LTL companies created vast networks with 600+ terminals across the US in order to highlight local presence - but costs proved too high and they have since consolidated

Transportation Costs & Productivity

- Important
- Complex
- Interesting

Photograph of roads and highways at the base of mountains. Image removed due to copyright restrictions.