Contents

1 Introduction

1.1 Transit right now

- Ridership is increasing, but small
- Strong financial support from
- Trends in modal split
  - Auto is above 80%
  - Transit 2-3%
  - Biking and walking are the same as transit

1.2 Funding

- In North America, it's divided into captial and operating expenses
- Fares only pay ~1/3 of operational expenses
- Lots of federal support for capital expenses - almost 40%
  - Since operating expenses are funded less, this encourages more building and less maintenance
- Fuel taxes in NA are 10-20% of what they are in Europe

1.3 Traditional Arguments Supporting Transit

- Equity: travel for those who can't drive
- Congestion
  - Not such a good argument, papers don't support it. The capacity released it quickly filled again
- Better for the environment
  - Actually, effort it better spent making cars cleaner since they're like 80% of transport

1.4 Critical assessment

- Transport has been stabilized
- Success stories (NYC, Houston(?), Seattle)
- Institutional changes are occurring slowly

1.5 Future influences

- Urban form
- More old people
- Better tech to improve performance
- Public has higher expectation (you know exactly when the bus is coming)

1.6 Ingredients for future success

- Maintain supportive coalition
- Expand the definition of public transport
- Greater private sector involvement
- Aggressive implementation of new technology

2 Data Collection Techniques and Program Design

2.1 Summary of current practice

- Used to be manual
- Now is collected with IoT devices
- **Automated Data Collection Systems (ADCS)**
  - **Automated Fare Collection Systems (AFC)**
    - Tapping your card on/off the vehicle
  - **Automatic Vehicle Location Systems (AVL)**
    - GPS tracking for buses, train tracking based on circuit occupancy
  - **Automatic Passenger Counting Systems (APC)**
    - Sensors in bus doors
      - Use break beam sensors to tell if you're getting on or off (out of 2 beams which do you break first)
    - Counts from fare barriers
    - Load weight calculators on trains
      - In trains the brakes apply force proportional to the load in each car (lighter cars need less braking, heavier cars need more, so they dont run into each other)

2.2 Passenger counting techniques

- Manual - checker (a person)
  - Ride check (on the bus, on/off counts and running time)
  - Point check (load on board, headway - time between buses)

2.3 Sampling

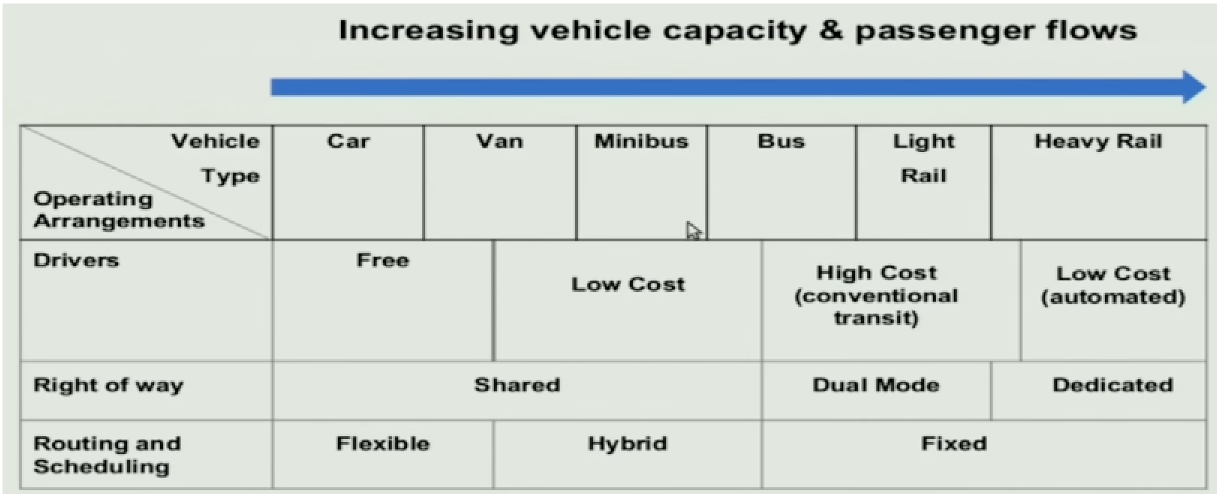
- **Simple random sampling**
- **Systematic sampling** - every 6 days, etc
- **Cluster sampling** - do as much data collection as possible
- **Ratio estimation/Conversion factors**
- **Stratified sampling** - sample sizes for each thing separately
  - E.g. you want information about students: get a large sample size on routes that serve universities

2.4 Tolerance and confidence level

- Accuracy has 2 dimensions
  - Relative tolerance: $\pm 10\%$
  - Absolute tolerance: ± 3.3

3 Modal Characteristics and Roles

3.1 Spectrum of services


Increasing vehicle capacity & passenger flows

Operating Arrangements \ Vehicle Type	Car	Van	Minibus	Bus	Light Rail	Heavy Rail
Drivers	Free	Low Cost		High Cost (conventional transit)		Low Cost (automated)
Right of way	Shared			Dual Mode		Dedicated
Routing and Scheduling	Flexible	Hybrid		Fixed		

3.2 Transit categories

- Rights of way - degree of separation
  - Surface with mixed traffic (light rail/buses)
  - Longitudinal separation by at grade crossing (light rail/bus rapid transit)
  - Full separation (at grade/tunnel/elevated)
- Technologies
  - Support (how they contact the groups)
    * Rubber tire on concrete (cars, buses, some rail like Paris Metro)
    * Steel wheel on steel rail
    * Maglev
    * Suspended cars
    * Water
    * Others
  - Guidance (lateral control)
    * Steered by driver
    * Guided by track
    * Others
  - Energy and propulsion
    * Combustion engine
    * Electric
    * Compressed natural gas (CNG)
    * Hybrid
    * Others
  - Control (longitudinal)
    * Manual/visual
    * Manual/signal
    * Automatic

3.3 Basics of train control

- Divide the system into blocks
  - If a train is occupying a section, do not let any trains in the section immediately before
  - For each block further, slowly increase speed limit in that block from nothing (0, 10, 25, 40,. . .)
- Block system constrains the frequency of service
- Moving block system increases capacity, usually used with automatic driving systems

3.4 Levels of automated protection

- None - advisory way signals
- Manual setting of speed below speed limit - train will be automatically braked if over speed limit
- Automatic train supervision/regulation
- Full automation - sometimes has operators, needs to have platform screen doors to keep people off of track
- Capacity increased through moving block or communication based train control

3.5 What is a bus?

- Vehicle size - 10-250 passengers
- Floor height (high floor/low floor)
  - Low floor is better for accessibility, has lower dwell time
- Right of way - all options available
- Guidance - often manual, sometimes systems
- Propulsion - all options available
- Fare payment - pay outside, or pay in the bus

3.6 Examples of bus systems

- Bi-articulated buses are a thing
- In Curitiba, bi-articulated buses have high floors, and have to be boarded at specific stations with fare gates
- The Cambridgeshire Guided Busway has buses operating on dedicated “tracks” of pavement

  - Buses can also be optically guided, following a line on the floor with a camera

3.7 Light Rail

- Vehicle design
  - High/low floor
  - Articulated or not
- Right of way
  - All options available
- Operation
  - Automated or manual
- Power
  - Overhead catenaries
  - Third rail
    * On street rails, the third rail is electronically controlled and is only powered when the train is coming

3.8 Heavy Rail

- Length
  - Limited by station length
  - In some cases (like in London) they allow the last door of the last car to stay in the runnel
- Turning radius

- Right of way
  - At-grade
  - Elevated
  - Tunnel
- Station spacing
- Control
- Power

3.9 Commuter Rail

- Vehicles operating in trains with long station spacing
- Fare collection strategies
- Line length
- Through routing in CBD [central business district] (cross through city or go there and back)
  - Where to put trains when you're done
- Station spacing
- Parking capacity

3.10 Traditional and new service concepts

- Traditional
  - Bus on shared right of way
  - Streetcar on shared right of way
  - Heavy rail on exclusive ROW
  - Commuter/regional rail on semi-exclusive ROW
- New
  - Bus rapid transit
  - Light rail on exclusive ROW

3.11 Increasing diversity

- Driver arrangements
  - Part timers (cover peaks), 10 hour day (to cover peaks that are 8 hours apart), payment by vehicle type
- Routing and scheduling
- Vehicle types
- control options
- Priority options
- Dual mode operation

3.12 Bus vs rail comparison

- Rail advantages
  - Higher capacity
  - Lower unit operating cost
  - Better service quality
  - Stronger land use influence
  - Fewer negative externalities
- Bus advantages
  - Low capital costs
  - Wide network coverage
  - Single vehicle trips
  - Flexibility
  - Dual mode nature

4 Short Range Planning

4.1 Public transit planning

- Long range (>3 years)
  - Major capital investments, infrastructure
  - Usually in collaboration with government
- Medium range (1-3 years)
  - Fleet size, network size, fare policy
  - Usually in collaboration with government
- Short range (<1 year)
  - Route structure, service frequency
  - Incremental changes
  - Can be handled only by the transit authority
- Control (real time)
  - Revise schedule and route of specific vehicle

4.2 Operational planning process

- Right of way + demand => bus route design => routes and stops
- Service + demand => set timetables => departure times
- Travel time constraints => scheduling vehicles => vehicle schedules
- Operator and union constraints => scheduling drivers => crew schedules

4.3 Transit service guidelines

- Goals => objective => measures => standards
- Early arrivals are not considered on time, because it may still cause people to miss connections
- Purpose
  - Communicate to the public and their representatives how decisions are made on changes in the transit network and the allocation of resources
  - Ensure acceptable level of service quality
  - Provide a consistent and fair bases for
    * Evaluating existing services
    * Considering new services
  - Balance impreovements with efficient use of resources

4.4 Aspects covered by service guidelines

- Service design
  - Factors that are important to riders:
    * Frequency
    * Waiting time
    * Reliability
    * Access
  - Why are frequency and waiting time both here?
    * Waiting time can be independent of waiting time - if a bus comes early, it will change waiting time
- Operating perfornace
  - Service quality

4.5 Service design: schedule

- Two main components
  - Maximum (policy) headways
  - Maximum passenger crowding
    * Usually for peak corridors

5 Short Range Planning, con't.

5.1 Service reliability

- Walk up service
  - Schedule free
  - Headway-based, <10 minutes
  - Performance based on headway
- Scheduled service
  - >= 10 minute headway
  - Performance measurement based on punctuality

5.2 Alternative benefit measures

- Revenue
  - Relevant to financial concerns and willingness to pay, discounts reduced fare trips and favors higher income passengers
- Passengers
  - Reflects number of people who benefit, values each passenger equally, but doesn't reflect trup length or linked trips
- Passenger miles
  - Weights longer trips more, but hardest to measure since most systems don't have an exit
- Net cost
  - Usually most directly constrained, but hardest to estimate (if you're planning a new service, you won't know revenue)
- Cost
  - Also directly constrained, but hard to estimate
- Vehicle miles
  - Easy to measure, only reflects ~30% of bus costs and penalized fast service
- Vehicle hours
  - Easy to measure, related to >50% bus costs, but doesn't reflect cost differences between peak and off-peak

6 Modal Capacities and Costs

6.1 Simple calculation analysis

- Given
  - P_c = population density at CBD
  - dP = rate of decrease of population density with distance from CBD
  - θ = angle served by corridor
  - r = distance from CBD
  - L = corridor length
  - t = number of one-way trips per person per day
  - c = share of trips inbound to CBD
  - m = transit market share for CBD-bound trips
  - p = share of CBD-bound transit trips in peak hour
- Then
  - Population in corridor $= \int_0^L r\theta(P_c - dPr)dr$
  - Peak passenger flow $= L^2\theta(\frac{P_c}{2} - \frac{dPL}{3})tcmp$
  - Maximum access distance to transit line $= \frac{L\theta}{2}$

6.2 Theoretical capacities

- Rail
  - 10 car trains
  - 200 passengers per car
  - 2 minute headway
  - = 60,000 passengers/hr
- Bus
  - 70 passengers/bus
  - 30 second headway
  - = 8,400 passengers/hr
- BRT
  - 200 passengers/bus
  - 20 second headways
  - = 36,000 passengers/hr
- Light Rail
  - 2 car trains
  - 150 passengers/car
  - 1 minute headway
  - 18,000 passengers/hr

6.3 Capital costs

- In the US, $18.2 billion was spent in capital costs in 2013
  - By type
    * 25% for vehicles
    * 59% infrastructure and facilities
    * 16% other
  - By mode
    * 25% bus
    * 34% heavy rail
    * 17% commuter rail
    * 19% light rail
    * 5% other (mostly paratransit)
  - Capital costs don't vary as much as you would expect year to year, because a) there are a lot of cities with new projects and b) the projects are gradual and can span years

	Bus	Heavy Rail	Commuter Rail	Light Rail
Vehicles	52%	10%	17%	7%
Infrastructure, facilities, and other	48%	90%	83%	93%
Total (billion USD)	4.5	6.2	3.0	3.5

6.4 Infrastructure cost

- Type of construction (increasing in cost)
  - at grade
  - elevated
  - subway
    * shallow tunnel (cut and cover)
    * deep tunnel (tunnel boring machine)
- Land acquisition and clearance
- Number, size, complexity and length of stations
- Systems complexity

6.5 Typical capital costs per passenger mile

- For all modes
  - Vehicle cost per pass. mile: $0.05-0.10
  - Infrastructure cost per pass. mile: $0.01-1.00i (because there are so many different ways of doing it)

6.6 Operating costs

- In the US, $42.2 billion was spent on operating costs in 2013
  - By type
    * 44% for vehicle operations
    * 16% for vehicle maintenance
    * 11% for non-vehicle maintenance
    * 16% for administration
    * 14% for purchased transportation (hiring third parties, mostly for paratransit)
  - By mode
    * 49% for buses
    * 19% for heavy rail
    * 13% for commuter rail
    * 4% for light rail
    * 12% for paratransit
    * 3% for other modes

7 Cost Estimation

7.1 Roles

- Predict cost change associated with service change
  - Marginal or incremental cost
  - Sensitive to time periods
- Predict cost changes with production process
  - Introduce part time operators

  - Contract out maintenance, suburban routes
  - New fare technology
- Subsidy allocation among jurisdictions

7.2 Types of cost models

- Fully allocated causal factor models
  - Not sensitive to time periods
- Temporal variation models
- Incremental fixed/variable cost models

7.3 Fully allocated causal factor models

- Select causal factors: vehicle hours, miles, peak vehicles
- Assign each expense type to an appropriate factor
- Calculate average costs per unit of Factor A, B, C
- Define cost model as: $A \times \text{vehicle hours} + B \times \text{vehicle miles} + C \times \text{peak vehicles}$

7.4 Temporal variation models

- Follow fully allocated causal factor model procedure for all except operator costs
- To estimate operator costs, for each 30 min time period t,
  - identify all runs, i, with at least 15 minutes of vehicle time in period t
  - for each run i, compute the average pay per vehicle hour by dividing daily pay W_i by vehicle hours H_i
  - find the minimum, average and maximum pay per vehicle hour in period t. Average given by:

$$W_i = \frac{\sum_{i=1}^{n}(\frac{W_i}{H_i})}{n}$$

8 Ridership Forecasting

8.1 Roles

- Predicting ridership as a result of changing fares
- Predicting ridership for general agency planning and budgeting
- Predicting ridership as a result of service changes

8.2 Factors Affecting Transit Ridership

- Exogenous
  - Auto ownership availability
  - Gas prices
  - Demographics
  - Usually can be assumed to be “fixed” in the short run

- Endogenous
  - Fare
  - Headways
  - Route structure (walk time, ride time)
  - Crowding
  - Reliability

8.3 Route Ridership Prediction

- Traditional approach is reactive
  - Exogenous change: monitor ridership change
  - Endogenous change: modify system accordingly

8.4 Professional Judgement

- Widely used
- Based on experience and local knowledge
- No evidence of accuracy or reproducability
- Lack of faith in data, etc.

8.5 Survey-based Methods

- Non-committal survey
  - Non recommended
- Stated preference surveys
  - Provide comparisons between A and B instead of A vs not-A
  - People contradict themselves, and you can then adjust for biases

8.6 Cross-sectional Model

- Use route and demographic data to explain route ridership
- Many methods
  - Rules of thumb
  - "Similar routes" method
  - Multiple factor trip rate model
  - Aggregate route regression models

8.7 Typical Transit Elasticities

- Elastic = more sensitive to change
- Small cities have larger fare elasticities than large cities (fewer number of people)
- Bus travel is more elastic than commuter/rapid rail (there are more alternatives for short distances)
- Off peak fare elasticities are double that of peak fare
- Short distance trups are more elastic than long distance

- Fare elasticities rise with income and fall with age
- Work trips are the most inelastic

9 Origin, Destination, and Transfer Inference

9.1 Intro

- Using automatically collected data
- Infers destinations (in open systems – i.e. no tapping off)
- Infers transfers

9.2 Key Automated Data Collection Systems (ADCS)

- Automatic Vehicle Location (AVL)
- Automatic Fare Collection (AFC)
- Automatic Passenger Counting (APC)

9.3 OD Matrix Estimation

- Why do we need to know about inference?
  - The real destination might be on route 2 if they have to start with route 1
  - For service planning, you want to know what people actually want to do

9.4 Origin Inference

- Is tap close to a time when the AVL says it was at one of the stops?

9.5 Destination Inference: Closest Stop

- Key assumptions
  - Destination of the trip segment is close to the origin of the following trip segment
  - No intermediate private transportation mode trip segment
  - Passengers will not walk long distances
  - Last trip of a day ends at the origin of the day

9.6 Destination Inference: Minimum Cost Path

- Calculate minimum cost path
- Useful for open systems

9.7 Trip Linking Assumptions (i.e., this is a transfer)

- Temporal conditions - interchange time (distance), maximum bus wait time (headways)
- Spatial conditions - Maximum interchange distance, circuity between stages, ending journey near origin
- Logical conditions - Must not continue at same station, same route

10 Vehicle Scheduling

10.1 Timetable Development

- Translating frequencies into a timetable
  - Equal headways
    - Peak Period Duration / N
  - Balanced load - more frequent service during peaks
    - Total Passenger Flow / N
  - Clockface or not - do headways repeat every hour?

10.2 Fleet Size Required

- Salzborn's Fleet Size Theorem
  - Given
    - $l(k,t,s)$ = number of departures from terminal k by time t following schedule s
    - $a(k,t,s)$ = number of arrivals "
    - $d(k,t,s) = l(k,t,s)$ - $a(k,t,s)$
  - Assumptions
    - no trip shifting
    - no deadheading
  - $N(s) = \sum_{k \in K} \max_t(d(k,t,s))$

10.3 Vehicle Scheduling Problem

- Objective
  - Define vehicle blocks covering revenue and non-revenue trips to
    - Minimize fleet size
    - Minimize non-revenue time/mileage
  - Observation
    - These are proxies for cost, but a large portion of cost will depend on crew duties, which are currently unknown
- Input
  - Vehicle revenue trips
  - Possible layover arcs
  - Possible deadhead arcs (pull-outs from depot to start point, pull-ins from end point to depot)
- Variations
  - Restricting vehicles to one line vs. interlining
  - Single vs multi depot
  - Vehicle fleet size at depot level
  - Routes assigned to specific depot
  - Vehicle types