An Agent-Based Approach to Modelling Public Transport Dynamics

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Outline

Concepts
1. PT assignment principles
2. Modelling PT dynamics
3. Agent-based simulation model

Applications
1. Congestion
2. Real-time travel information
3. Service disruptions
4. Control and operational strategies
PTA principles and approaches
Frequency-based: Assignment principles

- PT network is represented in terms of segments of lines
- Demand is assigned based on service frequencies
- Adopting concepts and solution methods from car traffic assignment
Frequency-based: Network representation
PT network is represented in terms of individual vehicle trips/runs following a timetable.

Demand is assigned to specific trips, takes into account time-dependent characteristics.

The concept of accumulative shortest path is not valid anymore.
Schedule-based: Network representation
Schedule-based: Stop topology

- line node
- stop node
- base node

- waiting arc
- boarding arc
- dwelling arc
- alighting arc
- pedestrian arc
- destination arc
- running arc
- stop arc

- run $r$ of line $\ell$

- $B_z^{\text{dest}}$, $\eta+1$
Traditional assumptions

• Travel times is equal on all lines riding the same arc (FB)
• Passengers arrive randomly at stops
• No capacity constraints
• Perfect reliability (regularity – FB; punctuality – SB)
• Passengers board the first arriving vehicle
• Perfect information
• Homogenous travellers’ population
Flow-dependent in-vehicle time

Flow-capacity ratio multiplier

- Already in the original presentation of optimal strategies
- on-board crowding
- Link travel time as a non-linear function of passenger flows
- Iterative network loading to obtain equilibrium
- BPR crowding function

\[
\gamma_{\ell s}(q_a) = 1 + \alpha_{\ell}^{run} \cdot \left( \frac{q_a}{f_{\ell s} \cdot \kappa_{\ell}^{veh}} \right)^{\beta_{\ell}^{run}}, \quad a = (N_{\ell s}^{dep}, N_{\ell s+\ell}^{arr}) \in A^{run}
\]

- \( q_a / (f_{\ell s} \cdot \kappa_{\ell}^{veh}) \) is the saturation rate of the vehicle on the line segment;
- \( \alpha_{\ell}^{run} \) and \( \beta_{\ell}^{run} \) are the BPR coefficient and exponent for running congestion.
Flow-dependent travel time

Effective frequency
- Assigning weights to waiting times
- Reliability effects and risk of denied boarding
- An infinite penalty when capacity is exceeded
- Reducing the nominal frequency by the BPR term

\[ f_{\ell s}^{\text{eff}} (q_a) = \frac{f_{\ell s}}{1 + \alpha_{\ell}^{\text{wait}} \left( \frac{q_a}{f_{\ell s} \cdot \kappa_{\ell}^{\text{veh}}} \right)^{\beta_{\ell}^{\text{wait}}}}, \quad a = \left( N_{\ell s}^{\text{dep}}, N_{\ell s+\ell}^{\text{arr}} \right) \in A^{\text{run}} \]

\[ t_{\ell s}^{\text{wait}} (q_a) = \frac{0.5}{f_{\ell s}^{\text{eff}} (q_a)} \cdot (1 + \sigma_{\ell s}) \]
Does not guarantee that capacity is not exceeded!

Average VOC ratio drops from 4.77 to 1.5
Number of over-saturated line segments drops from 45 to 10

Cpeda et al. (2006)
Failure-to-board probability

- FB: a quasi-dynamic model where *the share of passengers that exceeds the residual capacity* on the respective time period is transmitted to the next period.

- SB: guarantees that capacity constraints are *satisfied at the individual vehicle level* by introducing new arcs between successive vehicle trips.

- Queuing (FIFO, mingling)
Seating and priorities

- satisfy the set of priority rules and the seat capacity constraint
Main trends in developments of PT assignment models (Liu et al 2010)

- Consistently lagged behind developments in traffic modeling

- Expected and emerging developments
  - **Multi-agent** simulation models
  - **Dynamic** loading process
  - **Adaptive** user decisions
  - **Supply uncertainties**
2. 

Agent-based approach to PTA
Prominent research questions

- How does the **system perform** under various conditions?
- How can APTS be deployed most **effectively** to improve service operations?
- How to **mitigate** and manage service **disruptions**?
- How could service providers and users become more **adaptive** by taking advantage of the abundance of real-time data?
- What is the **impact** of APTS measures?
Agent-based TAM

- Represents individual vehicles and travellers
- Emerging solution based on agents interaction with each other throughout the simulation
- En-route decisions
- Day-to-day learning as proxy to equilibrium conditions
- Integration with traffic simulation models
Implementation: BusMezzo
Transit Assignment and Operations Simulation Model

• A framework for analyzing transit performance under various operational conditions and APTS

• **BusMezzo**: integrated into Mezzo, a mesoscopic traffic simulation model

• Agent-based
• Operations-oriented
• Sources of uncertainty
• Adaptive decision making
• System level analysis
A modelling framework for Analyzing Public Transport Operations

- Network
- Fleet
- Passenger Assignment
- Dynamic Loading
- Traveler Decisions
- Traveler Perception
- Traveler Strategy
- Traveller Population
- Automated Data Collection
- Real-Time Prediction
- Control Centre
- Service Planning
- Day-to-day
- Within-day
- Transit Performance
- Traffic Dynamics & Transit Operations
- Transit Performance
- Traveler Strategy
- Traveller Population
- Traveller Strategy
Network representation

- **Transit vehicle trajectory**
  - Ride
  - Queue
  - Dwell
  - Recover

- **Traveller trajectory**
  - Walk
  - Wait
  - On-board
Public Transport Dynamics

Joint car and PT; mode-specifics
Dwell times
Fleet; vehicle scheduling
Crowding and capacity

Operations planning
Control and management strategies
Adaptive route choice
Real-time information

Transit operations
Transit performance
Passengers decisions
Demand representation

- $\lambda_{od}(t, \tau)$ – Poisson arrival process
- Non-compensatory rule-based choice-set generation process

- En-route decisions
  - Assess the attributes of each available path
    \[ v_{i,n} = \beta_{i,n}X_{i,n} \]
  - Calculate the joint utility of the bundled paths
    \[ v_{l,n} = ln \sum_{i \in I} e^{v_{i,n}} \]

- Path: outcome of successive decisions

- Preserve passenger integrity from one day to the other
Reliability and Control

Real-time Information

Network Resilience

Congestion

Applications
Application: Increased capacity
The dynamics of reliability & congestion

- Route choice
- Service reliability
- Demand variation
How can the value of reduced congestion be quantified?
Evaluation of congestion effects

On-board crowding → Increased perceived in-vehicle time

Denied boarding → Increased waiting time

Reduced service reliability → Increased total travel time
Appraisal of Increased Capacity

- Crowding factor in static/dynamic model: +3%/+60%
- Value of increased capacity: underestimated in static models
- Overestimation in BusMezzo: currently incorporate crowding in the route choice model
Real-time Travel Information: Predicting, disseminating, rerouting
Modelling Impacts of Information

- Performance
- Prediction
- Provision
- Perception
- Path choice
Passengers’ Response to Service Reliability and Travel Information
Day-to-Day Learning of Service and Information Reliability

Final distribution of credibility coeff.

Example: evolution of credibility coeff.

\[ \alpha_{j,n}^\lambda(d + 1) = (1 - \kappa_n^\alpha) \times \alpha_{j,n}^\lambda(d) + \kappa_n^\alpha \times \left( \left( \left| \frac{t_{j,n}^{e(\lambda)}(d)}{t_{j,n}^\alpha(d)} - 1 \right| + 1 \right)^\nu \right) \]
Disruptions: impact and implications for strategic planning and operational management
What is the Weakest Link?

- Main determinants of network robustness?
- Potential benefits of real-time information dissemination?
- How incorporate vulnerability into network planning decisions?
- Requires non-equilibrium assignment
Capturing disruption dynamics

- Static model: underestimation of disruption effects
- En-route decisions, imperfect information
- Both passengers and operators can respond to disruptions

*Spill-over* – secondary effects caused by either supply processes or passenger rerouting

*Upstream* – vehicles progress until they queue upstream of the link closure

*Downstream* – can reconsider and revise their travel decisions

*Stranded passengers* – on-board passengers are unable to alight and have to wait until the service is restored
Criticality: Relative welfare loss

Disruption scenario

Change in total passengers welfare

-14% -12% -10% -8% -6% -4% -2% 0%

D1 D2 D3 D4 D5

No RTI Stop RTI Cluster RTI Network RTI

Research Seminar, Tokyo University, 11-08-2015
Value of Real-time information: Relative welfare gain
Normal operations

Disruption (D4)
Evaluation framework

- **Base Case (0,0)**
  - **Central Links**
    - Disruption \((\delta, 0)\)
    - Disruption
  - **Important Links**
  - **Overloaded Links**
    - Capacity enhancement \((\delta,h)\)
    - Capacity enhancement
    - Capacity enhancement
    - Capacity enhancement
  - **Effective Capacity Enhancement Scheme**
    - \(\Delta W\)
    - \(\Delta W\)
    - \(VOC, \Delta VOC\)
    - \(VSDM\)
VOC change due to disruptions

Disruption on 10-11, southbound

Disruption on 13-14, southbound
Where shall we increase capacity?
## Impact indicators

<table>
<thead>
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<th></th>
<th>$h = 0$</th>
<th>$h \neq 0$</th>
<th>$VCE$</th>
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<tbody>
<tr>
<td></td>
<td>Base network</td>
<td>Extended network</td>
<td>Value of capacity</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>enhancement</td>
</tr>
<tr>
<td>$\delta = 0$</td>
<td>$W(0,0)$</td>
<td>$W(0, h)$</td>
<td>$VCE(h</td>
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<td>Undisrupted</td>
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<tr>
<td>$PI$</td>
<td>$PI(\delta</td>
<td>0)$</td>
<td>$PI(\delta</td>
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<tr>
<td>Passenger importance</td>
<td>$= W(\delta, 0)$</td>
<td>$= W(\delta, h)$</td>
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<td></td>
<td>$- W(0,0)$</td>
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<tr>
<td>$VSDM$</td>
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### Evaluation example

<table>
<thead>
<tr>
<th>R – Stop-level</th>
<th>Disruption (D-Blue)</th>
<th>Value of strategic disruption mitigation</th>
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<tbody>
<tr>
<td></td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>Capacity</td>
<td>No</td>
<td>$w(0,0)$</td>
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<tr>
<td>enhancement</td>
<td>Yes</td>
<td>$w(0, h)$</td>
</tr>
<tr>
<td>(C-Green)</td>
<td></td>
<td>$w(\delta, h)$</td>
</tr>
<tr>
<td>Value of</td>
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<td></td>
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<tr>
<td>capacity</td>
<td>No</td>
<td>-24.67%</td>
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<tr>
<td>enhancement</td>
<td>Yes</td>
<td>-27.69%</td>
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Beyond a complete failure

- Most disruptions do not amount to complete breakdowns (maintenance and construction works, traffic incidents or cancelled services)

- Vulnerable systems - greater negative impacts in a disproportional relation to the increase in the original capacity reduction

- Non-linear properties of network effects, traffic dynamics and route choice -> non-trivial relation?

- Systems that operate close to capacity

- Line-level; full-scan; dynamic assignment
Relation between capacity reduction and change in societal cost

- Long and small rather than short and large capacity reductions
- The same capacity increase counts more when relieving a larger capacity reduction
On-going research

• Modelling
  ➢ Day to day congestion equilibrium conditions
  ➢ Habit formation and limited adaptation
  ➢ Passenger groups
  ➢ Real-time dynamic control optimization

• Applications
  ➢ Transfer coordination strategies
  ➢ Fleet management strategies
  ➢ Paris and Amsterdam networks
Thank you! Questions?

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