Public Transportation Models I: Framework and Low Frequency Services

Ennio Cascetta

Modeling and Simulation of Transportation Networks

Boston, July 30, 2015

Outline

- Introduction
  - Types of transportation services
- Supply models
  - Definitions and modeling approaches
- Demand models
  - Users’ behavior assumptions
  - Path choice models
  - Mode-service choice models
- Supply-Demand Interaction (Assignment) models
- Applications
Outline

✓ Introduction
  Types of transportation services
✓ Supply models
  Definitions and modeling approaches
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  Mode-service choice models
✓ Supply-demand interaction (assignment) models

✓ Applications

INTRODUCTION

Types of transportation services
In relation to space & time dimensions, Transportation Systems can be classified in:

✓ Continuous services
  are available at every instant and can be accessed from a very large number of points (e.g. individual modes: car, walking, ....)

✓ Discrete services (e.g. Scheduled Services)
  can be accessed only at given points and are available only at given times

×Passengers services
  ➢ Bus
  ➢ Plane
  ➢ Train
  ➢ ...

×Freight services
  ➢ Railway
  ➢ Combined transport
  ➢ Maritime Transport: Ro-Ro
  ➢ ...
  ➢ ...
Scheduled Services modelling approaches
Scheduled Services can be modelled using two different approaches:

✓ Frequency-based approaches
  × line-based representation of services
  × modal choice and path choice models that give the mode and the line probability in relation to service frequency
  × assignment models that give the average flow of each line

✓ Schedule-based approaches
  × run-based supply models with explicit consideration and representation of services timetable
  × modal choice and path choice models give the mode and the run choice probability in relation to run attributes
  × assignment models that give the average flow of each run

Definitions

✓ Run \( r \)
  individual connection among stops with a given scheduled arrival/departure time at each stop
  A run is defined by the route and the (scheduled) arrival and departure times at stops

<table>
<thead>
<tr>
<th>run</th>
<th>Line</th>
<th>service type</th>
<th>initial station</th>
<th>departure time</th>
<th>Intermediate Stops</th>
<th>terminal station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AA</td>
<td>INTERCITY</td>
<td>A</td>
<td>9.30</td>
<td>-</td>
<td>D</td>
</tr>
<tr>
<td>2</td>
<td>BB</td>
<td>REGIONAL</td>
<td>A</td>
<td>9.50</td>
<td>B/C</td>
<td>D</td>
</tr>
<tr>
<td>3</td>
<td>AA</td>
<td>INTERCITY</td>
<td>A</td>
<td>10.30</td>
<td>-</td>
<td>D</td>
</tr>
<tr>
<td>4</td>
<td>CC</td>
<td>INTERCITY</td>
<td>A</td>
<td>11.30</td>
<td>D</td>
<td>E</td>
</tr>
</tbody>
</table>

✓ Line \( l \)
  set of runs with the same characteristics (route and stops, average travel times, quality of services, etc.).
  A line is defined by the route and the frequency (average number of runs in the unit of time)
Outline

✓ Introduction
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✓ Supply models
  Definitions and modeling approaches

✓ Demand models
  Users’ behavior assumptions
  Path choice models
  Mode-service choice models

✓ Supply-demand interaction (assignment) models

✓ Applications

SUPPLY MODELS

Definitions

✓ Line-based supply models ➔ services are represented by lines

✓ Run-based supply models ➔ services are represented by runs
SUPPLY MODELS

Line-based approach

taken from:

SUPPLY MODELS

Run-based approach

Diachronic graph:

- nodes representing events taking place at a given instant (nodes have explicit time coordinate);
- allows using network algorithms similar to those used for static continuous networks.
TRANSIT SUPPLY MODELS

Run-based models

*Diachronic graph - Definition*

The diachronic graph $\Omega$ consists of three different sub-graphs in which each node has an explicit time coordinate:

- a *service sub-graph* $\Omega_s$;
- a *temporal centroids sub-graph* $\Omega_d$;
- an *access-egress sub-graph* $\Omega_{ae}$.

**DIACHRONIC SUPPLY MODELS**

Service sub-graph

*Definition*

The *service sub-graph* $\Omega_s$ represents transit services, in which each run of each line is defined both in space, through its stops, and in time, according to its arrival/departure times at stops.
**DIACHRONIC SUPPLY MODELS**

Service sub-graph

**Representation**

<table>
<thead>
<tr>
<th>Run</th>
<th>Terminal s arr</th>
<th>Terminal s dep</th>
<th>Terminal s’ arr</th>
<th>Terminal s’ dep</th>
</tr>
</thead>
<tbody>
<tr>
<td>line 1</td>
<td>7.55</td>
<td>8.00</td>
<td>8.55</td>
<td>9.00</td>
</tr>
<tr>
<td>line 1</td>
<td>9.55</td>
<td>10.00</td>
<td>10.55</td>
<td>11.00</td>
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<tr>
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<td>11.55</td>
<td>12.00</td>
<td>12.55</td>
<td>13.00</td>
</tr>
</tbody>
</table>

1. boarding/alighting
2. run arrival/departure time
3. run/dwell link
4. boarding/alighting links
5. transfer link

---

**DIACHRONIC SUPPLY MODELS**

Service sub-graph

**Representation**

<table>
<thead>
<tr>
<th>Run</th>
<th>Terminal s arr</th>
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Service sub-graph

**Representation**

<table>
<thead>
<tr>
<th>Run</th>
<th>Terminal s</th>
<th></th>
<th>Terminal s'</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>arr</td>
<td>dep</td>
<td>arr</td>
</tr>
<tr>
<td>line 1 - run 5</td>
<td>7.55</td>
<td>8.00</td>
<td>8.55</td>
</tr>
<tr>
<td>line 1 - run 6</td>
<td>9.55</td>
<td>10.00</td>
<td>10.55</td>
</tr>
<tr>
<td>line 1 - run 7</td>
<td>11.55</td>
<td>12.00</td>
<td>12.55</td>
</tr>
</tbody>
</table>

- Date:
- Time:
- Line:
- Run:
- Transfer:
- Diagram:

**Notes:**
- Boarding/alighting
- Run arrival/departure time
- Run/dwell link
- Boarding/alighting link
- Transfer link
Service sub-graph

Representation

<table>
<thead>
<tr>
<th>run</th>
<th>Terminal s</th>
<th>Terminal s'</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1 - Run 5</td>
<td>7.55 8.00</td>
<td>8.55 9.00</td>
<td></td>
</tr>
<tr>
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<td>9.55 10.00</td>
<td>10.55 11.00</td>
<td></td>
</tr>
<tr>
<td>Line 1 - Run 7</td>
<td>11.55 12.00</td>
<td>12.55 13.00</td>
<td></td>
</tr>
</tbody>
</table>

- boarding/alighting links
- run arrival/departure time
- run/dwell link
- transfer link
## Service sub-graph Representation

### TIMETABLE

<table>
<thead>
<tr>
<th>Run</th>
<th>Terminal s</th>
<th>Terminal s’</th>
</tr>
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<tbody>
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</tr>
<tr>
<td>Line 1 - run 6</td>
<td>10.55</td>
<td>11.00</td>
</tr>
<tr>
<td>Line 1 - run 7</td>
<td>12.55</td>
<td>13.00</td>
</tr>
</tbody>
</table>

### Diagram

- **Boarding/alighting**: passenger access and departure
- **Run/dwell link**: passenger movement during movement
- **Transfer link**: passenger transfer between services

**Notes**

- Stop times
- Axis positions
- Stop s
- Stop s’
## DIACHRONIC SUPPLY MODELS

### Service sub-graph Representation

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<td>11.00</td>
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<td>run 7</td>
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<td>12.00</td>
<td></td>
<td>12.55</td>
<td>13.00</td>
<td></td>
</tr>
</tbody>
</table>

- ♦ boarding/alighting
- ▲ run arrival/departure time
- ▲ run/dwell link
- ♦ boarding/alighting links
- ▲ transfer link

---

### TIMETABLE

#### Terminal a
- Arr.: 7.55, Dep.: 8.00
- Arr.: 9.55, Dep.: 10.00
- Arr.: 11.55, Dep.: 12.00

#### Terminal b
- Arr.: 8.55, Dep.: 9.00
- Arr.: 10.55, Dep.: 11.00
- Arr.: 12.55, Dep.: 13.00

#### Terminal a’
- Arr.: 8.00, Dep.: 10.00
- Arr.: 12.00, Dep.: 13.00

#### Line 1 - Runs 5, 6, 7
- Stop 8.00, Stop 9.55, Stop 11.55

---

### DIACHRONIC SUPPLY MODELS

### Service sub-graph Representation

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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- Arr.: 11.55, Dep.: 12.00

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- Arr.: 8.55, Dep.: 9.00
- Arr.: 10.55, Dep.: 11.00
- Arr.: 12.55, Dep.: 13.00

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- Arr.: 8.00, Dep.: 10.00
- Arr.: 12.00, Dep.: 13.00

#### Line 1 - Runs 5, 6, 7
- Stop 8.00, Stop 9.55, Stop 11.55

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### Diagram

- Stop a, Stop b, Stop a’
- Time axis, Space axis
DIACHRONIC SUPPLY MODELS

Service sub-graph Representation

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<td>11:55</td>
<td>12:00</td>
</tr>
</tbody>
</table>

DIACHRONIC SUPPLY MODELS

Temporal centroids sub-graph Definition

The temporal centroids sub-graph \( \Omega_d \) represents user departure/arrival times or an user target times (DDT - Desired Departure Time and Desired Arrival Time - DAT).
Temporal centroids sub-graph

Representation

Access-Egress sub-graph

Definition

The access-egress sub-graph $\mathcal{Q}_{ae}$ represents the connection between centroids and stops, and among stops.

It allows the connection between the demand sub-graph and the service sub-graph.
DIACHRONIC SUPPLY MODELS

Access-Egress sub-graph
Representation
DIACHRONIC SUPPLY MODELS

The diachronic graph

$$\Omega = \Omega_s \cup \Omega_d \cup \Omega_{ae}$$

Outline

✓ Introduction
  Types of transportation services
✓ Supply models
  Definitions and modeling approaches
✓ Demand models
  Users' behavior assumptions
  Path choice models
  Mode-service choice models
✓ Supply-demand interaction (assignment) models
✓ Applications
DEMAND MODELS

Services classification

Frequency:

✓ **Low**: av. headway > 30 mins (e.g. non-urban transit services)

✓ **High**: av. headway <12-15 mins (urban transit)

Regularity:

✓ **Low** (e.g. urban transit services): average delays “large” compared to the average headways

✓ **High** (e.g. airlines, intercity train services) : average delays “small” compared to the average headways

<table>
<thead>
<tr>
<th>Frequency</th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irregular Service</td>
<td>URBAN</td>
<td></td>
</tr>
<tr>
<td>Regular Service</td>
<td>REGIONAL INTERCITY</td>
<td></td>
</tr>
</tbody>
</table>

DEMAND MODELS

Modelling approaches

Different specifications for modal choice, path choice and assignment models:

✓ **Frequency-based** approach
  - for **High-frequency** services

✓ **Schedule-based** approach
  - for **High-frequency** services

- for **Low-frequency** services

See lecture *Public transportation II: Schedule-based Models for High Frequency Services*
DEMAND MODELS

Schedule-Based models for low frequency services

Behavioural assumptions

✓ pre-trip choice of the stop (station, airport) and of the run

✓ users segmentation according to the user target time (TT), i.e.:
  - desired departure time (DDT) or
  - desired arrival time (DTT)

DEMAND MODELS

Schedule-Based models for low frequency services

User Target Time

Times in which users desire/need to start or to complete their trips:

✓ desired departure times (DDT),
  times in which users would like to depart from their origin

✓ desired arrival times (DAT),
  times in which users would like to arrive at their destination

user target times (TT), due to low frequency, generate early or late schedule delays, producing a further disutility component (early/late schedule penalty) in mode and path choice
DEMAND MODELS

Schedule-Based models for low frequency services

Example of early/late schedule delay

DEMAND MODELS

Schedule-Based models for low frequency services

Example of User Target Time distribution

Regional trips

<table>
<thead>
<tr>
<th>Time Slice</th>
<th>Users</th>
<th>Arrival</th>
<th>Departure</th>
</tr>
</thead>
<tbody>
<tr>
<td>06.30-07.30</td>
<td>6000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>07.30-08.30</td>
<td>6000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>08.30-09.30</td>
<td>6000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>09.30-10.30</td>
<td>6000</td>
<td></td>
<td></td>
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<tr>
<td>10.30-11.30</td>
<td>6000</td>
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<td>11.30-12.30</td>
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<td>12.30-13.30</td>
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<td>13.30-14.30</td>
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<td>14.30-15.30</td>
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<td>15.30-16.30</td>
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<td>16.30-17.30</td>
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<td>17.30-18.30</td>
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<td>21.30-22.30</td>
<td>6000</td>
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</tr>
</tbody>
</table>
DEMAND MODELS

Schedule-Based models for **low frequency** services

*Demand Temporal Segmentation*

Time-dependent O/D matrix

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**DEMAND MODELS**

Schedule-Based models for **low frequency** services

**O-D segmentation: other criteria**

**Trip purposes:**
- ✓ Home-based (from/to)
  - ✓ work
  - ✓ business
  - ✓ study
  - ✓ other
- ✓ Non home-based
  - ✓ secondary

**Users’ segmentation:**
- ✓ Income level;
- ✓ Reimbursement or not;
- ✓ Party size;
- ✓ Car availability.
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    Mode-service choice models

✓ Supply-demand interaction (assignment) models

✓ Applications
  Commercial software packages
  Application example to Regione Veneto

DEMAND MODELS

Path choice models
estimate the probability of choosing a path on the diachronic network given the origin-destination pair and the user’s target time
DEMAND MODELS

Path choice models

Choice set defined by the following rules:

✓ **maximum earliness and lateness band**
  (e.g. all the runs within a given temporal band)

✓ **feasibility rules**
  (e.g. max schedule delay, max number of interchanges)

✓ **Dominance rules**
  (e.g. no paths leaving earlier and arriving later)

\[ \tau_j \text{ = departure target time} \]
\[ K^* = \text{path choice set} \]

---

**Example of Random Utility path choice model**

**Pre-trip** choice of run \( r \) with maximum perceived utility \( U_r \) in relation to target time \( \tau_{TT} \)

\[ U_r(\tau_{TT}) = \beta_{TB} TB_r + \beta_{TC} TC_r + \beta_{MC} MC_r + \beta_{CFB} CFB_r + \beta_{ESP} ESD_r + \beta_{LSP} LSD_r + \epsilon_r \]

where:

✓ **TB**, on-board time;
✓ **TC**, transfer time;
✓ **MC**, monetary cost;
✓ **CFB**, on-board comfort;
✓ **ESD**, early schedule delay;
✓ **LSD**, late schedule delay;
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Applications

DEMAND MODELS

**Mode-service choice models**

*estimate the joint probability of choosing a mode and a service (e.g. train-first class) on a given OD pair for a given user’s target time*

**Service characteristics**

- single or multiclass on the same vehicle or group of vehicles
  (e.g. business and economy for plane, First and second class for train))

- single or multiservice on different vehicles (train)
  (e.g. High-speed, Intercity, Interregional)

- different fare structures
  (e.g. different prices for O/D pair, service and class)
**DEMAND MODELS**

Mode-service choice model

*Example of model structure*

```
<table>
<thead>
<tr>
<th>O/D pair</th>
<th>User Target Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>od, τ_{TT}</td>
</tr>
</tbody>
</table>

Early Run

- Individual
- Mode k
- Mode j
- ... Mode n

Late Run

- Mode j
- ... Mode n
```

**DEMAND MODELS**

*Example of mode-service choice model*

Model specification

\[ p(j) = p(j/k) \cdot p(k) \]

\[ p(j/k) = \frac{\exp(V_j / \theta_0)}{\sum_{m \in I_k} \exp(V_m / \theta_0)} \]

\[ p(k) = \frac{\exp(\theta Y_k / \theta_0)}{\sum_h \exp(\theta Y_h / \theta_0)} \]

\[ V_j = \sum_i \beta_i \cdot X_{ij} \] systematic utility of j-th alternative

\[ \beta_i \] model parameters

\[ X_{ij} \] i-th attribute of j-th alternative

\[ Y_h = \ln \sum_{m \in I_h} \exp(V_m / \theta) \] logsum variable of h-th group
DEMAND MODELS

Example of Mode-service choice model

Model Structure

O/D, target time

EARLY RUNS

LATE RUNS

Car
Early Bus
Early Train (bus+train)
Early Park-Ride
Late Bus
Late Train (bus+train)
Late Park-Ride

DEMAND MODELS

Example of Mode-service choice model

Alternatives & Attributes

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>CAR</th>
<th>EB</th>
<th>ET</th>
<th>EPR</th>
<th>LB</th>
<th>LT</th>
<th>LPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>description</td>
<td>car</td>
<td>early bus</td>
<td>early train</td>
<td>early park &amp; ride</td>
<td>late bus</td>
<td>late train</td>
<td>late park &amp; ride</td>
</tr>
<tr>
<td>TB</td>
<td>transit travel time</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>TC</td>
<td>car travel time</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>C</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>EP</td>
<td>early schedule Delay</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>LP</td>
<td>late schedule Delay</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>A/E</td>
<td>access/ egress time</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</tr>
<tr>
<td>HI</td>
<td>high income user</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>PR</td>
<td>park&amp;ride dummy</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>CAR</td>
<td>car dummy</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>EBUS</td>
<td>early bus dummy</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Department of Transportation Engineering
University of Naples “Federico II”
**DEMAND MODELS**

### Example of mode-service choice model

**Estimation results**

<table>
<thead>
<tr>
<th>Attribute</th>
<th>$\beta$</th>
<th>t Stud</th>
</tr>
</thead>
<tbody>
<tr>
<td>On board time</td>
<td>-1.4805</td>
<td>-2.154</td>
</tr>
<tr>
<td>Car time</td>
<td>-2.6050</td>
<td>-1.964</td>
</tr>
<tr>
<td>Monetary cost</td>
<td>-0.2371</td>
<td>-1.989</td>
</tr>
<tr>
<td>High income</td>
<td>2.0066</td>
<td>1.895</td>
</tr>
<tr>
<td>Park&amp;Ride</td>
<td>-0.31</td>
<td>-2.113</td>
</tr>
<tr>
<td>Purpose</td>
<td>-1.5911</td>
<td>-2.109</td>
</tr>
<tr>
<td>Center</td>
<td>-2.3510</td>
<td>-2.322</td>
</tr>
<tr>
<td>Center2</td>
<td>-1.1253</td>
<td>-1.866</td>
</tr>
<tr>
<td>Car</td>
<td>5.0109</td>
<td>2.343</td>
</tr>
<tr>
<td>Early arrival penalty</td>
<td>-2.6152</td>
<td>-2.876</td>
</tr>
<tr>
<td>Late arrival penalty</td>
<td>-5.2426</td>
<td>-2.856</td>
</tr>
<tr>
<td>Urban acc/egr</td>
<td>0.7333</td>
<td>1.972</td>
</tr>
<tr>
<td>Early bus</td>
<td>0.3465</td>
<td>1.633</td>
</tr>
</tbody>
</table>

| log-likelihood          | -264.11  |
| $\rho^2$                | 0.6834   |
| $\delta$                | 0.2032   |

### Outline

- **Introduction**
  - Types of transportation services
- **Supply models**
  - Definitions and modeling approaches
- **Demand models**
  - Users' behavior assumptions
  - Path choice models
  - Mode-service choice models
- **Supply-demand interaction (assignment) models**

- **Applications**
ASSIGNMENT MODELS

Demand-Supply interaction models

Classification

<table>
<thead>
<tr>
<th></th>
<th>Path Choice Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit network</td>
<td>Assignment approach</td>
</tr>
<tr>
<td>uncongested [c=cost]</td>
<td>Network Loading</td>
</tr>
<tr>
<td>congested [c=c(t)]</td>
<td>Equilibrium</td>
</tr>
<tr>
<td></td>
<td>Dynamic</td>
</tr>
</tbody>
</table>

AON=All or Nothing; SNL=Stochastic Network Loading; DUE=Deterministic User Equilibrium; SUE=Stochastic User Equilibrium; DDP=Deterministic dynamic process; SDP=Stochastic dynamic process.

Schedule-based Assignment Models for low frequency services

within-day dynamic network loading model (WD-DNL)
Within-day Dynamic Network Loading

The within-day dynamic network loading model (WD-DNL) allows to obtain the network loading map, i.e. loads $f_{e,t}$ at each time $\tau$ on day $t$.
APPLICATION EXAMPLE

• The base scenario

• The methodology for demand forecasting
  - Modeling specifications
  - Validation

• Simulation of strategic operations of a new entrant

• The opening of competition the HSR
APPLICATION EXAMPLE

The base scenario

**HSR lines**
- lengths and travel times

<table>
<thead>
<tr>
<th>High Speed Railways</th>
<th>1.355 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total National Railways Network</td>
<td>24.179 km</td>
</tr>
</tbody>
</table>

APPLICATION EXAMPLE

Current Scenario
The study area: The catchment area of the station of the Italian HSR
APPLICATION EXAMPLE

➢ **December 2009:** was completed and opened to the public the director High Speed Turin-Milan-Naples-Salerno: 1,000 km long

<table>
<thead>
<tr>
<th>Distance</th>
<th>Travel time before HSR</th>
<th>Travel TIME after HSR</th>
<th>Δ</th>
<th>Δ%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torino-Milano</td>
<td>125</td>
<td>1h 33'</td>
<td>54'</td>
<td>39'</td>
</tr>
<tr>
<td>Torino-Roma</td>
<td>640</td>
<td>6h 30'</td>
<td>4h 30'</td>
<td>2h</td>
</tr>
<tr>
<td>Milano-Roma</td>
<td>515</td>
<td>4h 30'</td>
<td>3h 1h 30'</td>
<td>-33%</td>
</tr>
<tr>
<td>Milano-Napoli</td>
<td>720</td>
<td>6h 30'</td>
<td>4h 55'</td>
<td>1h 35'</td>
</tr>
<tr>
<td>Milano-Bologna</td>
<td>182</td>
<td>1h 40'</td>
<td>65' 35'</td>
<td>-35%</td>
</tr>
<tr>
<td>Bologna-Firenze</td>
<td>79</td>
<td>59’</td>
<td>37’ 22’</td>
<td>-37%</td>
</tr>
<tr>
<td>Roma-Napoli</td>
<td>205</td>
<td>1h 45’</td>
<td>1h 10’</td>
<td>35’</td>
</tr>
</tbody>
</table>

December 2009: was completed and opened to the public the director High Speed Turin-Milan-Naples-Salerno: 1,000 km long

APPLICATION EXAMPLE

➢ **2012 incoming of a new operator**
  o TRENITALIA: (Italian National Operator)
  o NTV: (expect entry time: Dec 2001)
APPLICATION EXAMPLE

• The base scenario

• The methodology for demand forecasting
  - Modeling specifications
  - Validation

• Simulation of strategic operations of a new entrant

• The opening of competition the HSR
APPLICATION EXAMPLE

Supply models

220 zones:
- each Province in the catchment area split into two zones (i.e. the main city and the rest of the province)
- the regions Abruzzo, Molise, Trentino-Alto Adige and Valle d’Aosta one zone
- the main Italian cities (Rome, Milan, Naples, Turin, Florence, Bologna) cities split into multiple zones
APPLICATION EXAMPLE

Supply models

the road graph

1900 nodes
7000 links
(representing 35000 Km)

the railways graph

2600 nodes
5500 links
(representing 14500 Km)

APPLICATION EXAMPLE

Supply models

The services simulated using a diachronic network includes:

- 800 daily domestic flights between major Italian airports

- the following railway services:
  • 111 High-Speed and Eurostar trains;
  • 232 intercity trains;
  • 4.466 interregional and regional trains

The diachronic network consists of:

- 126.526 nodes
- 329.657 links

Space
APPLICATION EXAMPLE

The run-based mode choice model
estimating the market share of different OD transportation modes, including
alternative rail services (HSR vs Intercity; 1st vs. 2nd class) and individual flight
and trains (runs) characterized by different scheduled timetables.

Requires the specification of
• Desired Departure Time-of-day (DDT) demand distribution

• Mode-service-run choice model

APPLICATION EXAMPLE

Desired Departure Time-of-day (DDT) distribution
Reference period: 5.00 – 21.30 (⇒ 990 minutes corresponding to the values of the
functions to be estimated)
Non-parametric uni-variate Kernel function:
\[ \hat{f}_h(x) = \frac{1}{n} \sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right) \]
being:
• \(x_i\) the DDT revealed by respondent \(i\)
• \(K()\) the Epachenikov function:
  \[ K(u) = 0.75 \left(1 - u^2\right) \] if \(|u|<1\); 0 otherwise
• \(h\) the length of the generic time period

Estimation methods: Max Likelihood (2079 obs)
APPLICATION EXAMPLE

Desired Departure Time-of-day (DDT) distribution

The estimated DDT distribution functions by OD distance (<400Km and >400Km) and by travel purpose (Business vs. Other)

APPLICATION EXAMPLE

The mode-service-run choice model: RP-SP survey

The RP data contacts recruited at home, stations and airports

<table>
<thead>
<tr>
<th># observations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Airports</strong></td>
</tr>
<tr>
<td><strong>Stations</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>cities with HSR stations</th>
<th>Air</th>
<th>79</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train</td>
<td>166</td>
<td></td>
</tr>
<tr>
<td>Auto</td>
<td>709</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>sampled at home from the population of travelers</th>
<th>1332</th>
</tr>
</thead>
<tbody>
<tr>
<td>cities with Air</td>
<td>23</td>
</tr>
<tr>
<td>other cities</td>
<td>369</td>
</tr>
<tr>
<td>Train</td>
<td>44</td>
</tr>
<tr>
<td>Auto</td>
<td>302</td>
</tr>
</tbody>
</table>

Total 3341
APPLICATION EXAMPLE

**The mode-service-run choice model: RP-SP survey**

The SP data
445 contacts gathered via web with 6 experiments per respondent to test
- fare levels
- L.o.S. attributes (travel time + access/egress)
- Run departure time
- New HSR operator (i.e. NTV)

<table>
<thead>
<tr>
<th># scenarios completed</th>
<th># respondents</th>
<th>%</th>
<th># observations</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>82</td>
<td>18%</td>
<td>82</td>
<td>4%</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>4%</td>
<td>40</td>
<td>2%</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>2%</td>
<td>33</td>
<td>2%</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>1%</td>
<td>24</td>
<td>1%</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>1%</td>
<td>15</td>
<td>1%</td>
</tr>
<tr>
<td>6</td>
<td>323</td>
<td>73%</td>
<td>1938</td>
<td>91%</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>445</strong></td>
<td><strong>100%</strong></td>
<td><strong>2132</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

APPLICATION EXAMPLE

**The mode-service-run choice model: RP-SP survey**

The SP survey: example of train schedule submitted to respondent

<table>
<thead>
<tr>
<th>origin</th>
<th>destination</th>
<th>Dep. Time</th>
<th>Arr. Time</th>
<th>Travel Time</th>
<th>Base fare</th>
<th>off-peak reduction</th>
<th>7-day advanced purchasing</th>
<th>14-day advanced purchasing</th>
<th>return fare</th>
</tr>
</thead>
<tbody>
<tr>
<td>Napoli Centrale</td>
<td>Milano</td>
<td>7:30</td>
<td>12:00</td>
<td>4h 30 min</td>
<td>114</td>
<td>90</td>
<td></td>
<td></td>
<td>154</td>
</tr>
<tr>
<td>Napoli Centrale</td>
<td>Reggio</td>
<td>8:00</td>
<td>13:00</td>
<td>5h 00 min</td>
<td>114</td>
<td>90</td>
<td></td>
<td></td>
<td>154</td>
</tr>
<tr>
<td>Napoli Centrale</td>
<td>Milano</td>
<td>8:00</td>
<td>13:00</td>
<td>4h 30 min</td>
<td>65</td>
<td>49</td>
<td></td>
<td></td>
<td>194</td>
</tr>
<tr>
<td>Napoli Centrale</td>
<td>Reggio</td>
<td>8:30</td>
<td>13:00</td>
<td>4h 30 min</td>
<td>114</td>
<td>90</td>
<td></td>
<td></td>
<td>154</td>
</tr>
<tr>
<td>Napoli Centrale</td>
<td>Milano</td>
<td>9:30</td>
<td>14:30</td>
<td>5h 00 min</td>
<td>114</td>
<td>90</td>
<td></td>
<td></td>
<td>154</td>
</tr>
<tr>
<td>Napoli Centrale</td>
<td>Reggio</td>
<td>9:30</td>
<td>14:30</td>
<td>5h 00 min</td>
<td>114</td>
<td>90</td>
<td></td>
<td></td>
<td>154</td>
</tr>
<tr>
<td>Napoli Centrale</td>
<td>Milano</td>
<td>10:30</td>
<td>15:30</td>
<td>5h 00 min</td>
<td>114</td>
<td>90</td>
<td></td>
<td></td>
<td>194</td>
</tr>
<tr>
<td>Napoli Centrale</td>
<td>Reggio</td>
<td>10:30</td>
<td>15:30</td>
<td>5h 00 min</td>
<td>114</td>
<td>90</td>
<td></td>
<td></td>
<td>154</td>
</tr>
<tr>
<td>Napoli Centrale</td>
<td>Milano</td>
<td>11:30</td>
<td>16:00</td>
<td>4h 30 min</td>
<td>114</td>
<td>90</td>
<td></td>
<td></td>
<td>154</td>
</tr>
<tr>
<td>Napoli Centrale</td>
<td>Reggio</td>
<td>11:30</td>
<td>16:00</td>
<td>4h 30 min</td>
<td>114</td>
<td>90</td>
<td></td>
<td></td>
<td>154</td>
</tr>
</tbody>
</table>
APPLICATION EXAMPLE

The mode-service-run choice model
Nested logit models with a nesting structure to capture higher degrees of substitutions among specific subsets of modal alternatives, particularly the HSR alternatives provided on the same route by different operators, NTV vs. High Speed Trentitalia (AVTR).

APPLICATION EXAMPLE

The mode-service-run choice model: choice set analysis
Hp 1: choice set includes the run before and the run after the Desired Departure Time (DDT)

<table>
<thead>
<tr>
<th></th>
<th>AIR</th>
<th>HSR Trentitalia</th>
<th>HSR NTV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage ratio</td>
<td>77%</td>
<td>64%</td>
<td>59%</td>
</tr>
</tbody>
</table>

Hp 2: choice set includes all the runs departing in a time window of a given length

Hp 3: choice set includes all the non-dominated runs w.r.t. travel time, cost and early/late penalty
### APPLICATION EXAMPLE

#### The mode-service-run choice model

**Statistics**

<table>
<thead>
<tr>
<th></th>
<th>Business</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>acc-egress time / travel time</td>
<td>0.5</td>
<td>3.4</td>
</tr>
<tr>
<td>travelling alone</td>
<td>34.7</td>
<td>23.2</td>
</tr>
<tr>
<td>travelling with party</td>
<td>21.3</td>
<td>10.7</td>
</tr>
<tr>
<td>train/air if reimbursed</td>
<td>53.8</td>
<td>18.0</td>
</tr>
<tr>
<td>train/air if not reimbursed</td>
<td>28.2</td>
<td></td>
</tr>
<tr>
<td>early dep. penalty / travel time</td>
<td>1.5</td>
<td>2.9</td>
</tr>
<tr>
<td>late dep. penalty / travel time</td>
<td>0.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Values comparable with those found in the literature, e.g. a study on HSR in Japan (Yao et al. 2005)

<table>
<thead>
<tr>
<th></th>
<th>Business</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>access time/travel time</td>
<td>0.8</td>
<td>2.1</td>
</tr>
<tr>
<td>VOT (converted in Euro/h)</td>
<td>59.7</td>
<td>21.2</td>
</tr>
</tbody>
</table>

### APPLICATION EXAMPLE

#### The mode-service-run choice model

Delta ASC's for the two HSR operators by distance band, trip purpose and service class

<table>
<thead>
<tr>
<th></th>
<th>Business</th>
<th>delta NTV-Trenitalia</th>
<th>Other</th>
<th>delta NTV-Trenitalia</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>trenitalia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;400Km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st class</td>
<td>-2,58</td>
<td>-1,45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd class</td>
<td>-2,48</td>
<td>-1,35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st class</td>
<td>-3,33</td>
<td>-0,75</td>
<td>-1,79</td>
<td>-0,34</td>
</tr>
<tr>
<td>2nd class</td>
<td>-2,73</td>
<td>-0,25</td>
<td>-1,52</td>
<td>-0,17</td>
</tr>
<tr>
<td>&lt;400Km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st class</td>
<td>-1,75</td>
<td>-1,18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd class</td>
<td>-1,42</td>
<td>-0,69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st class</td>
<td>-2,85</td>
<td>-1,10</td>
<td>-2,14</td>
<td>-0,96</td>
</tr>
<tr>
<td>2nd class</td>
<td>-1,76</td>
<td>-0,33</td>
<td>-0,93</td>
<td>-0,24</td>
</tr>
</tbody>
</table>
APPLICATION EXAMPLE

MODEL VALIDATION: Scatter diagram of assigned and counted flows

MODEL VALIDATION: Scatter diagram of counted flows in May and October 2010
APPLICATION EXAMPLE

• The base scenario

• The methodology for demand forecasting
  - Modeling specifications
  - Validation

• Simulation of strategic operations of a new entrant

• The opening of competition the HSR

Strategic policies tested
  Services and Rolling Stock

Operational policies tested
  Fares
  Timetable setting
APPLICATION EXAMPLE

Reference Scenario (2012)

- additional services of the new operator, i.e. NTV
- Incumbent As Is

<table>
<thead>
<tr>
<th>Year</th>
<th>Pax-km/year (mil.)</th>
<th>Ref. scenario (2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>NTV</td>
<td>3.569</td>
</tr>
<tr>
<td></td>
<td>Trentitalia</td>
<td>9.791</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>10.697</td>
</tr>
</tbody>
</table>

Demand generated by the additional NTV services: 5.9%

• Assumptions on GDP and

<table>
<thead>
<tr>
<th>Year</th>
<th>GDP yearly growth (%)</th>
<th>Cumulated GDP growth (%)</th>
<th>Cumulated demand growth (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>1.16%</td>
<td>1.16%</td>
<td>1.42%</td>
</tr>
<tr>
<td>2012</td>
<td>1.34%</td>
<td>2.70%</td>
<td>3.30%</td>
</tr>
<tr>
<td>2013</td>
<td>1.44%</td>
<td>4.14%</td>
<td>5.06%</td>
</tr>
<tr>
<td>2014</td>
<td>1.30%</td>
<td>5.44%</td>
<td>6.65%</td>
</tr>
<tr>
<td>2015</td>
<td>1.66%</td>
<td>6.70%</td>
<td>8.20%</td>
</tr>
</tbody>
</table>

APPLICATION EXAMPLE

Strategic policies tested: services and rolling stock

NTV

<table>
<thead>
<tr>
<th>Rolling stock</th>
<th>Ref. Scenario (2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td># runs /day</td>
<td>20</td>
</tr>
<tr>
<td>trainsKm / day</td>
<td>51</td>
</tr>
<tr>
<td>Pax-km/year (mil.)</td>
<td>3.593</td>
</tr>
</tbody>
</table>

The HSR network
**APPLICATION EXAMPLE**

**Strategic policies tested: service and rolling stock**

Alternative scenario:
No services between Napoli and Salerno + new services on the “Torino-Milano-Venezia”

+ new services on the Adriatic corridor

---

<table>
<thead>
<tr>
<th></th>
<th>Ref. scenario</th>
<th>Alternative scenario</th>
<th>Delta %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>To-Mi-Na</td>
<td>To-Mi-Ve</td>
</tr>
<tr>
<td>Rolling stock</td>
<td>20</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td># runs /day</td>
<td>51</td>
<td>42</td>
<td>6</td>
</tr>
<tr>
<td>trainsKm / day</td>
<td>35.238</td>
<td>28.455</td>
<td>2.484</td>
</tr>
<tr>
<td>Pax-km/year (mil.)</td>
<td>3.593</td>
<td>3.110</td>
<td>263</td>
</tr>
</tbody>
</table>
APPLICATION EXAMPLE

Operational policies tested: **fares**
Fares “war” among the two HSR competitors

<table>
<thead>
<tr>
<th>HSR Service supply (invariant)</th>
<th>Ref. Scenario</th>
<th>Alternative scenario 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st class</td>
<td>2nd class</td>
</tr>
<tr>
<td>Transitalia</td>
<td>78.162</td>
<td>43.9</td>
</tr>
<tr>
<td>NTV</td>
<td>35.238</td>
<td>15.9</td>
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<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>HSR Service supply (invariant)</th>
<th>Ref. Scenario</th>
<th>Alternative scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st class</td>
<td>2nd class</td>
</tr>
<tr>
<td>Transitalia</td>
<td>78.162</td>
<td>43.9</td>
</tr>
<tr>
<td>NTV</td>
<td>35.238</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

APPLICATION EXAMPLE

Operational policies tested: **timetable**
Example of timetable setting to increase flows

![Timetable Diagram]
APPLICATION EXAMPLE

Operational policies tested: timetable
Example of timetable setting to balance train loads

Assignment matrices

HSR supply growth

Runs/day

<table>
<thead>
<tr>
<th>Year</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st class</td>
<td>95</td>
<td>113</td>
<td>125</td>
<td>139</td>
<td>130</td>
</tr>
<tr>
<td>2nd class</td>
<td>111</td>
<td>120</td>
<td>132</td>
<td>145</td>
<td>140</td>
</tr>
<tr>
<td>Total</td>
<td>206</td>
<td>233</td>
<td>257</td>
<td>284</td>
<td>270</td>
</tr>
</tbody>
</table>

+95%

Trains-km/day

<table>
<thead>
<tr>
<th>Year</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>120,000</td>
<td>128,400</td>
<td>136,800</td>
<td>145,200</td>
<td>153,600</td>
</tr>
</tbody>
</table>

+106%
HSR demand growth

- Passengers/day
- Passengers-Km/day

APPLICATION EXAMPLE

Modal shares between 2009-2012