Topic Area:
A3 Urban and Inter-City Rail and Bus Transport

Abstract Number:
1153

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Title:
A schedule-based mode-service choice model for the assessment of the competition between air transport and high-speed services

Abstract:
This paper presents a mode-service choice model to assess competition between air transport, high-speed train services and private car at regional/national scale. It has been specified through a schedule-based approach which implies that the whole modeling system (demand, supply, path choice and assignment) has to consider service timetable explicitly. For this reason scheduled services have been represented by single runs instead of traditional service lines, and attributes at single run level for each scheduled transportation service have been taken into account to estimate the mode-service choice probabilities for a given O/D pair and user target time.

The mode-service choice model is defined in the framework of the Random Utility Model theory by using a nested-logit structure in which the systematic utility of scheduled services is assumed linear in both attributes and parameters. Among attributes composing systematic utility, a key role is played by the *early schedule penalty* or *late schedule penalty, w*hich represents the disutility that occurs because of the difference between user desired departure time and run scheduled departure time or between user desired arrival time at destination and run scheduled arrival; it can be calculated explicitly considering a schedule-based approach only.

The mode-service model has been specified and calibrated on the basis of a set of available data for Italy, and its application to the actual scenario allowed us to test its capability to reproduce the actual Italian market share between regional flights and high-speed trains, to be used as starting point for assessing future scenario forecasts.

The first part of the paper describes the schedule-based approach and presents the general structure of the proposed mode-service choice model; the latter part reports results of the application to the Italian case, in which the proposed model has been specified, calibrated and applied.

Keywords:
Mode choice, schedule-based, national models

Topic Area Code: A3

A SCHEDULE-BASED MODE-SERVICE CHOICE MODEL FOR THE ASSESSMENT OF THE COMPETITION BETWEEN AIR TRANSPORT AND HIGH-SPEED SERVICES

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1. Introduction

Different models have been proposed in literature for simulating mode choice for low frequency services, namely in the study of intercity trips. Most of them are characterised by logit or nested-logit specifications based on transit frequency models, which are part of larger systems of demand models (e.g. national models), or have been specified to explore different functional model structures and their implications (Koppelman and Bath, 2006).

Mode choice models are usually based on a static representation of the system, which implies that scheduled transport services, such as rail or bus, are modelled as service "lines", following an approach substantially similar to the one used to represent urban transit services. This approach, even though adequate for the long-term planning of new infrastructures, is not satisfactory to support operational market-oriented decisions, such as the definition of service timetable, or the setup of time-varying prices, because it does not consider differences in user behaviour underlying low-frequency services, for which users are more likely to choose a given mode-service if its timetable sufficiently adhere with his/her desired arrival time.

In other words, the alternatives to private modes are more likely to be the single service trips (runs) transit modes rather than transit modes themselves.

For this reason, joint mode-service choice models which take explicitly into account transit services through their schedule have been specified.

Cascetta and Papola presented a paper in (2003) formalising their modelling structure in the framework of Random Utility theory, assuming different forms for random residuals both closed (logit, nested-logit) and non-closed (probit, hybrid logit). Joint mode-service choice models have been specified and calibrated on the basis of a dataset of inter-urban trips in the Northeast Italy, considering the joint mode-service choice among private modes and transit services (bus and regional train). Different utility function specifications were tested with both nested and cross-nested correlation structures. The estimation results showed the importance in capturing the complex correlations existing among the alternatives for both service trips of the same mode (bus or train) and among service trips with the same kind of penalty (early or late). In order to assess benefits of the use of the schedule-based approach, this model was also compared with a "classic" mode choice model with three alternatives (car, bus and train) and frequency-based attributes used to reproduce transit mode dis-utilities. This comparison showed a significant increase in the goodness of fit of the proposed model that can be considered an empirical evidence of the better capability of the "schedule-based" model to simulate and reproduce the phenomenon with respect to a simpler ''frequency'' mode choice model.

This paper presents a mode-service choice model specified through a schedule-based approach that can be used to assess the competition between private car, air transport and high-speed train services at regional/national scale.

In the following, section 2 describes the schedule-based approach, while section 3 presents the proposed mode-service choice model that has been specified, calibrated and applied to evaluate competition between air transport and high-speed services in Italy, as reported in section 4.

2. The schedule-based approach

Scheduled transportation services are discrete both in time and space as they can only be accessed at certain times and certain locations such as airports and railway stations.

The schedule-based approach (Nuzzolo et al., 2003) for the modelling of such services is characterized by the specification of demand, supply, path choice and assignment models which take into account the timetable explicitly. It implies that scheduled services are represented by single runs which define individual connections with a given time schedule (e.g. a given train connection).

The schedule-based approach requires an explicit treatment for:

- temporal segmentation of the origin/destination matrix (as user's departure or arrival target time distribution has to be taken into account);
- supply modelling (as single runs with explicit departure/arrival times at airports have to be considered);
- path choice and assignment models (as they have to consider explicitly within-day time-dependence).

The following subsections will deal with these three main aspects and their specification for the simulation of air transport and high-speed railway services.

2.1. Time-varying demand

In order to consider the variation of the demand over time, the whole demand has to be splitted in time slices, according to the user target times defined as follows.

In the sphere of low-frequency services, such as air transport and high-speed railway trains, users have a Desired Arrival Time (*DAT*) at destination or a Desired Departure Time (*DDT*) from origin. Usually *DAT* is relative to home-living trips, for which users need to arrive in time to start their activities, while *DDT* concerns returning trips related to the end of user activities and to their desire to come back home.

The segmentation of the reference period usually entails a subdivision into n time slices, whose width $d\tau$ depends on the aim of the simulation (e.g. 60 min. in the case of long-distance trips). The generic time slice i covers time interval $[\tau_i - d\tau, \tau_i + d\tau[$ and a *DAT* and *DDT*, represented by τ_{Di} and τ_{Ai}, are associated with each interval i. Of course time intervals are such that

$$// \tau_{Di} - d\tau, \tau_{Di} + d\tau // = // \tau_{Di-1} - d\tau, \tau_{Di-1} + d\tau // \quad \forall i=2,\dots n \tag{1a}$$

$$// \tau_{Ai} - d\tau, \tau_{Ai} + d\tau // = // \tau_{Ai-1} - d\tau, \tau_{Ai-1} + d\tau // \quad \forall i=2,\dots n \tag{1b}$$

As an example, figure 1 describes a typical demand segmentation in *DAT* and *DDT* for business trips, where *DAT* are concentrated in the morning hours, while *DDT* are mainly located in the afternoon.

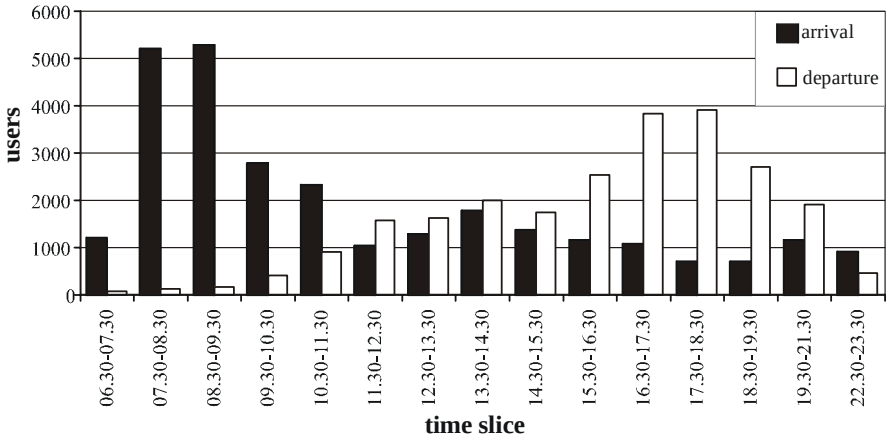

Figure 1. Example of demand segmentation in DAT and DDT

2.2. The diachronic supply model

Mode-service alternatives, and related level of service attributes, can be carried out by using a run-based supply model, and in particular a space-time network model known as *diachronic network* (Nuzzolo and Russo, 1993). The diachronic graph is similar to that traditionally set up to represent transit lines, for which the difference consists of representing each run with explicit consideration of arrival/departure times at stops, according to the timetable.

In particular, the diachronic graph Ω consists of three different sub-graphs (see figure 2) in which each node has an explicit time coordinate:

- a *service* sub-graph Ω_s, in which each run (representing a flight or a train) is defined both in space, through its stops, and in time, according to its arrival/departure times at stops (representing airports or railway stations);
- a *demand* sub-graph Ω_d, in which each node (temporal centroid) represents a *DDT* or *DAT,* in order to simulate the space-time characteristics of the trip;
- an *access/egress* sub-graph Ω_{ae}, which allows the demand connection of the demand sub-graph (zones) with access/egress stops.

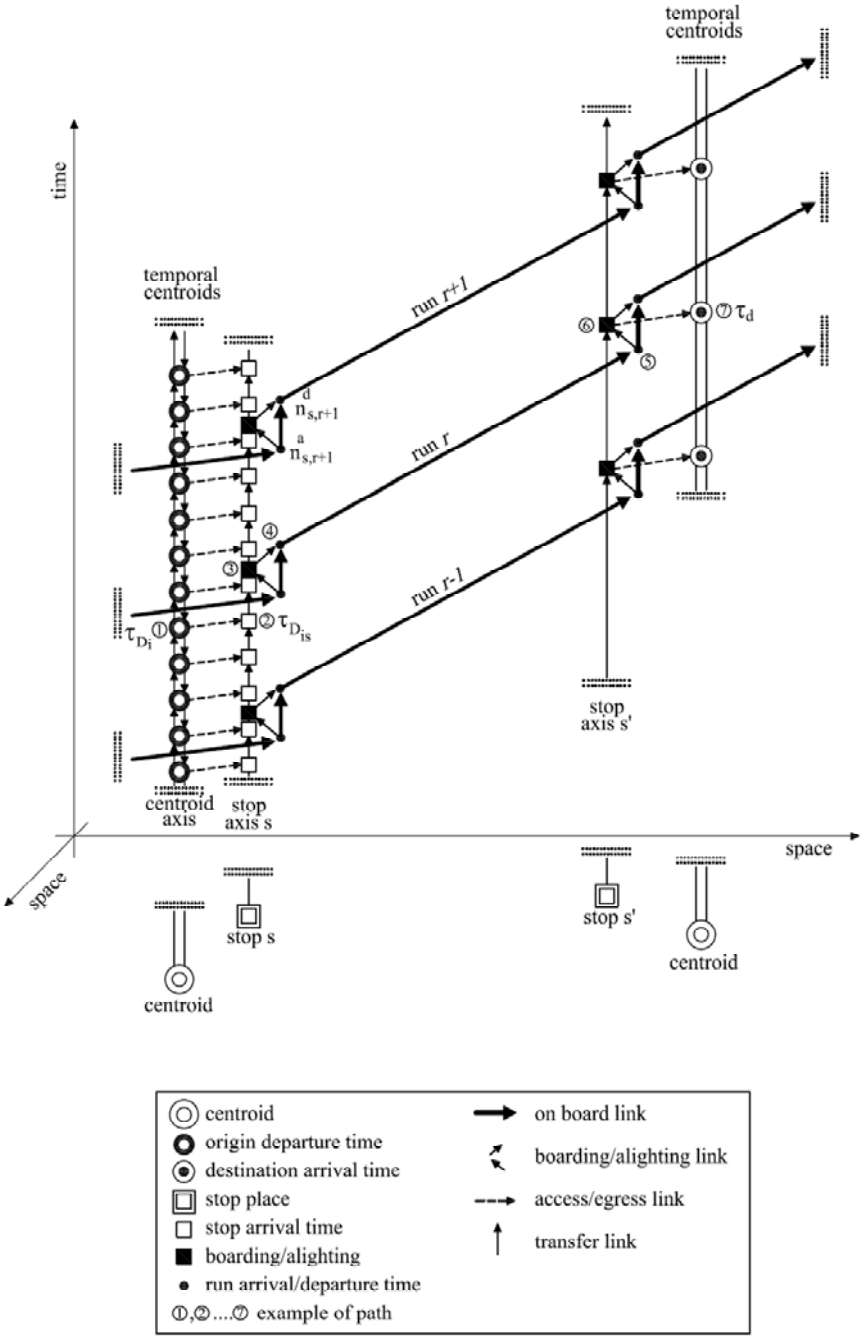

Figure 2. The diachronic graph

The *service* sub-graph Ω_s consists, in turn, of different sub-graphs $\Omega_{s,r}$ (one for each run of the scheduled services). Referring to the generic run *r*, the relative sub-graph $\Omega_{s,r}$ consists of nodes representing the arrival and departure times at stops, and links representing travel from one stop to another (run section) or the dwelling of the run at a given stop. Other nodes represent the time in which users board or alight from each run at the stop. These nodes are connected to the nodes representing run (flight or train) arrival and departure through boarding and alighting links. Finally, the whole sub-graph Ω_s is built by connecting all the sub-graphs $\Omega_{s,r}$ through links representing the users' transfer from one run to another at the same stop (*stop axis*).

The *demand* sub-graph Ω_d representing temporal demand segmentation is made up, in turn, by the same number of sub-graphs $\Omega_{d,c}$ as zones. For each spatial centroid *c* representing a given traffic zone, the sub-graph $\Omega_{d,c}$ consists of temporal centroids $n_o^{\tau_{TTi}}$, that are nodes located spatially in the position of the spatial centroid n_o and temporally according to the user target times τ_{TTi} (τ_{Di} for desired departure times and τ_{Ai} for desired arrival ones), representing the demand defined in section 2.1.

The *access/egress* sub-graph Ω_{ae} is made up of links representing access (egress) from (to) the centroids. The representation is made of direct links connecting nodes representing arrival/departure times on the demand subgraph and nodes representing arrival/departure times of runs at stops on the service subgraphs, as reported in figure 2. Access/egress attributes are associated with these links; they can be calculated in a more or less complex way by considering access/egress inclusive variables, which take into account the utility of each access/egress mode, or just access/egress times and costs.

Finally, the global diachronic graph Ω is obtained through

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

in which links connecting the three sub-graphs are properly adopted.

Link costs associated with diachronic graph are calculated on the basis of flow-dependent cost functions, for which the average link cost depends on the number of users on the link and, possibly, on other links of the graph (separable or not-separable cost functions). Different cost functions for different link types can be considered. As an example, for run and dwell links, we can use separable cost functions as

$$c_i(f_i) = k_1 + k_2 \cdot t_i + k_3\left(\frac{f_i}{cap_r}\right)^{k_4} \tag{2}$$

where f_i is the load on link *i*, t_i is its own travel time, cap_r is the capacity of run *r*, represented by link *i*, and $k_1 \geq 0$, $k_2 > 0$, $k_3 > 0$, $k_4 > 1$ are function parameters.

Values of parameter k_4 is such that link cost c_i goes to infinite when load f_i reach run (flight or train) capacity cap_r, leading to not-available alternatives that are sold out.

Performance attributes and generalized transportation cost (disutility) can be extended from links to paths. The path cost g_k is generally made up of the link-wise additive cost, g_k^{ADD}, and the non-additive cost, g_k^{NA}:

$$g_k = g_k^{ADD} + g_k^{NA} = \sum_a \delta_{ak} c_a + g_k^{NA} \tag{3}$$

or in matrix terms:

$$\underline{g} = \underline{\Delta}' \underline{c} + \underline{g}^{NA} \tag{4}$$

where $\underline{g}$ is the path cost vector, $\underline{g}^{NA}$ is the relative non-additive path cost vector, $\underline{c}$ is the link cost vector and $\underline{\Delta}$ is the link-path incidence matrix relative to graph Ω, whose element δ_{ak} is 1 if link *a* belongs to path *k* and is *0* otherwise. An example of non-additive cost could be the price structure that can be non linear with respect to distance (e.g. based on the *O/D* pair).

The diachronic graph is very useful as it allows efficient use of standard network algorithms (as least-cost paths) and allows a more straightforward treatment of congestion, if it is considered.

3. The schedule-based mode-service choice model

The mode-service choice model has been specified in the framework of the random utility theory (RUM approach) according to service characteristics (namely the medium-low service frequency) and user type.

In the schedule-based approach, a mode-service alternative can be defined through a path on the diachronic network representing services of the considered mode (air transport or high-speed railways). A path k is defined in both space and time and includes the space-time sequence: origin o with origin departure time τ_{Di}, access stop s with relative arrival time τ_{Dis}, run (or sequence of runs) with run departure time τ_r from access stop, egress stop s' and destination d with relative arrival time at destination τ_d. An example of path as sequence of links on the Ω diachronic graph is pictured in figure 2.

In order to describe the characteristics of the proposed mode-service (path) choice model, the following subsections will deepen the user behaviour assumptions, the choice set generation, as well as the specification of the model for the calculation of the choice probability of using each flight of the air transport services and each train of the high-speed railway services, for a given *od* pair and user target time τ_{TTi}.

3.1. Behavioural assumptions and choice set generation

Low-frequency scheduled services are usually characterised by regular service functioning and users behave considering all information at their disposal before starting the trip, which mainly concerns routes and timetable. According to the structure of the considered scheduled services (air transport and high-speed railways), it is common that only one access stop (airport or station) as well as a single egress stop are available, so stop choice can be easily simulated, while the run (flight or train) choice represents the crucial point.

The run choice is assumed fully pre-trip, in the sense that it is made before departing and includes the comparison of possible alternatives, including those of the alternative modes, as well as the choice of one of them on the basis of expected characteristics or attributes.

For what concerns the generation of alternatives (choice set), given an *od* pair and an user target time τ_{TTi} (desired departure times at origin, τ_{Di}, or destination arrival times at destination, τ_{Ai}), in addition to the private car alternative, the choice set includes the "nearest" paths in terms of minimum early and/or late times with respect to the user target time for each scheduled service (flights and high-speed trains).

Mode-service (path) alternatives for scheduled services can be generated using a selective approach based on the criteria of maximum earliness and lateness values that define a time slice around user target time, within which the path choice set is defined (e.g. at least two runs departing/arriving within 4 hours before/after the user target time).

The availability of early and/or late runs depends on the trip purpose, as well as

the maximum earliness/lateness value can be defined according to scheduled service characteristics.

As an example, if users are not strictly allowed to have a little delay in arrival, only the early runs (flights or trains) have to be considered, as well as the maximum earliness/lateness can be as closer to the target time (e.g. from the entire day up to 2 hours) as higher is the number of available flights for the considered *od* pair.

In the framework of random utility theory, users are assumed rational and behave with the aim of maximising their perceived utility U_r associated with each alternative.

The probability $p[r|od, \tau_{TTi}]$ of choosing run r, given the *O/D* pair *od* and user target time τ_{TTi} (Desired Departure Time τ_{Di} or Desired Arrival Time τ_{Ai}) can be written as

$$p[r|od,\ \tau_{TTi}] = prob(U_r > U_{r'}) = prob(V_r + \varepsilon_r > V_{r'} + \varepsilon_{r'}) \quad (5)$$

where the perceived disutility U_r associated with run (or sequence of runs) r can be written as the sum of a systematic utility V_r and a random term ε_r:

$$U_r = V_r + \varepsilon_r = \sum_j \beta_j X_{jr} + \varepsilon_r \quad (6)$$

Systematic utility V_r is a linear combination, through β_j parameters, of attributes X_{jr}. In addition to the usual level of service attributes X_{jr} (access and egress times and costs, on-board times; transfer times, number of transfers, monetary cost), a key role is given by the temporal gap between user Desired Departure Time and run scheduled departure time or between user Desired Arrival Time and run scheduled arrival. This gap (that for air transport and high-speed railways can be relevant) induces a further disutility component known as *early schedule penalty* or *late schedule penalty* that can be explicitly calculated considering a schedule-based approach only.

3.2. Model structure

Different path choice models can be specified according to the assumptions on random residuals ε_r.

Due to the complexity of air transport and high-speed railway networks, as well as considering the possibility to perceive scheduled alternatives of the same transport mode in a more structured way, this paper presents a nested-logit model. Nests are relative to mode alternatives (air transport, high-speed railways and private car), which include two elementary alternatives (runs) for each scheduled service, as pictured in figure 3.

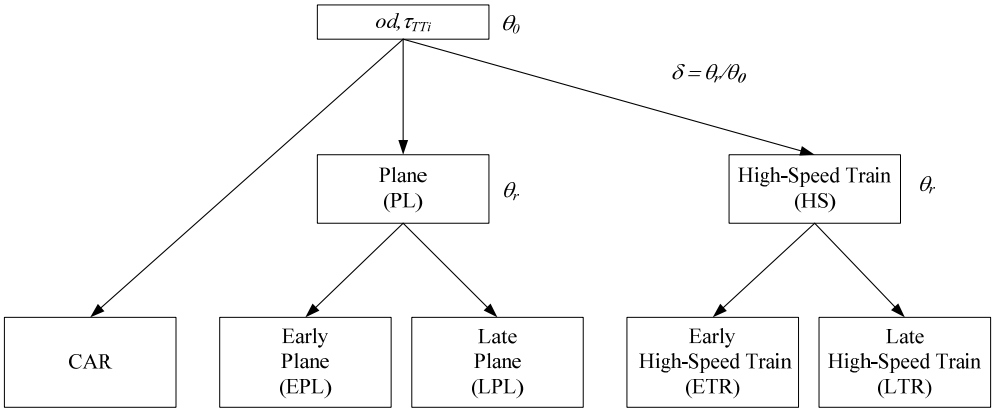

Figure 3. Model structure

Given an *od* pair and an user target time τ_{TTi}, the probability $p(r,m/od,\tau_{TTi})$ of choosing run *r* of scheduled service *m* can be written as

$$p(r,m/od,\tau_{TTi}) = p(m/od,\tau_{TTi})\,p(r/m,od,\tau_{TTi}) \qquad (7)$$

where the probability of choosing mode $m \in \{car, train, plane\}$ can be written as

$$p(m/od,\tau_{TTi}) = \frac{exp(\theta_r Y_m / \theta_0)}{\sum_{m'} exp(\theta_r Y_{m'} / \theta_0)} \qquad (8)$$

and the probability of choosing run *r* belonging to mode *m* can be written as

$$p(r/m,od,\tau_{TTi}) = \frac{exp(V_r / \theta_r)}{\sum_{r' \in m} exp(V_{r'} / \theta_r)} \qquad (9)$$

with $Y_m = ln \sum_{r' \in m} exp(V_{r'} / \theta_r)$ representing the logsum of available runs *r'* of mode *m*, and V_r representing the systematic utility associated with run *r*, made of specific run attributes (e.g., access and egress times and costs; on-board times; transfer times; number of transfers; monetary cost, early/late schedule delay, O/D distance, income level, and so on), calculated through the diachronic supply model described in section 2.

4. An application example

Aiming at verifying the specification and implementation of the proposed approach, an application of the presented models for the assessment of the competition between air transport and high-speed services has been carried out.

The mode-service model has been calibrated on the basis of a set of available data for Italy, and has been applied to the actual scenario to test its capability to reproduce the actual Italian market share between regional flights and high-speed trains.

The study area is defined by the part of Italy served by the high-speed train

services, which includes the main cities of the north and centre Italy (Naples, Rome, Florence, Bologna, Milan and Turin).

The demand in a typical workday for business purpose among these O/D pairs consists of about 34000 trips. In order to take into account *DAT* and *DDT*, the demand has been divided according to the hourly-based time-segmentation pictured in figure 4. Demand related to *DAT* is concentrated in the early morning for those which have to start their activities in the mid-morning (typical of Italian business meetings), and in the late morning for those who will start their activities in the early afternoon. For all business activities, which typically ends within a workday, the *DDT* is mainly concentrated in the evening (after 18.30), which represent the peak for *DDT* trips.

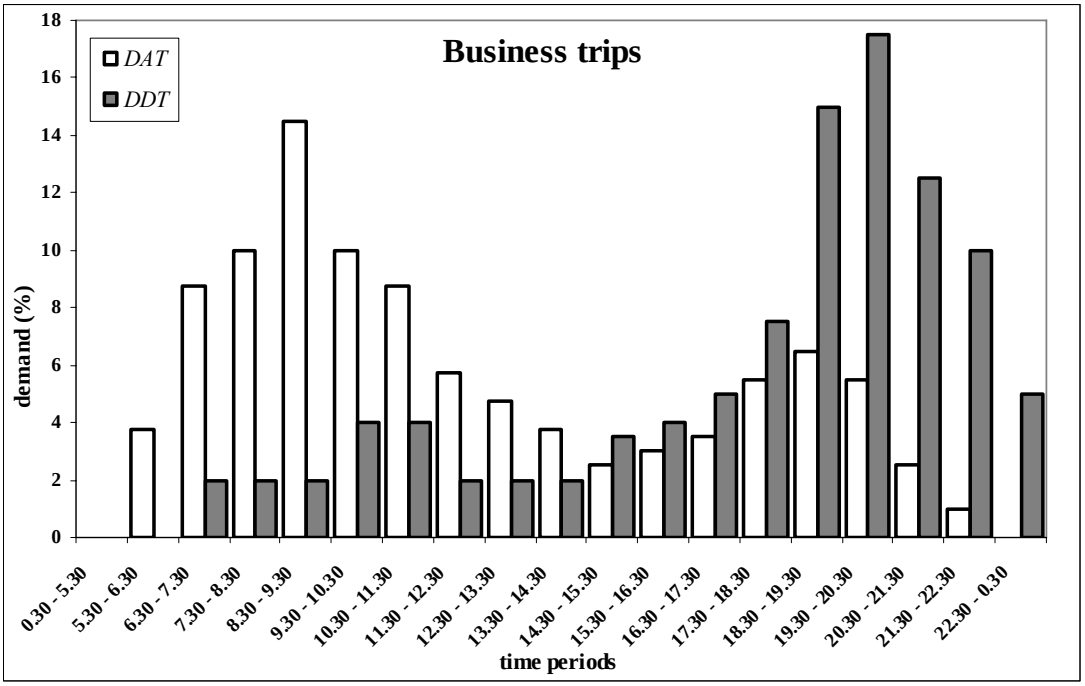

Figure 4. Demand time distribution (business trips)

Level of service attributes have been computed on specific modal networks. For the private car alternative they have been computed on the road supply model representing the Italian extra-urban road network. Travel costs have been estimated considering distance-based fuel consumptions and motorway tolls.

Level of service attributes for scheduled services have been carried out by using the diachronic network model described in section 2.

The considered air transport network is made of 6 airports through which 174 national flights are operated in a typical workday, while the high-speed railway network is defined through 6 stations served by 104 trains.

The diachronic graph Ω representing the air transport network is characterised by a service subgraph Ω_s of 707 nodes and 1212 links, while the same subgraph for the high-speed train services consists of 617 nodes and 1197 links.

The mode-service choice model has been specified on the basis of the nested-logit structure of section 3 using utility functions linear both in attributes and parameters. Table 1 reports alternatives and used attributes.

Table 1. Model specification: alternatives and attributes

		mode-service				
		car	early flights	late flights	early high-speed trains	late high-speed trains
attribute	**symbol**	**CAR**	**EFL**	**LFL**	**EHS**	**LTR**
Early Schedule Delay	ESD		X		X	
Late Schedule Delay	LSD			X		X
Scheduled Travel Time	STV		X	X	X	X
Scheduled Monetary Cost	SMC		X	X	X	X
Car Travel Time	CTV	X				
Car Monetary Cost	CMC	X				
Access Time	AT		X	X	X	X
Egress Time	ET		X	X	X	X
Number of Transfer	NT		X	X	X	X
Railways	RAIL				X	X
Private Car	CAR	X				

Scheduled service (flights and trains) alternatives have been generated by a selective approach in which the two closer early and late runs with respect to user target time have been considered.

Model parameters have been carried out by an aggregate calibration for business trip purpose by using a set of available data on the Italian transportation market.

In particular, the calibration has been carried out by a GLS approach in which revealed hourly O/D matrices have been compared with O/D matrices (target time segmented) obtained by models, that is:

$$\underline{\beta}^* = \arg\min(\hat{d}_{od,i}, \tilde{d}_{od,TT_i}) \qquad (10)$$

where $\hat{d}_{od,i}$ is the revealed *od* demand in time slice *i* and $\tilde{d}_{od,TT_i} = p(\underline{\beta}) \cdot d_{od,TT_i}$ is the estimated demand, in which $p(\underline{\beta})$ is given by eqn (7)

Calibration results are reported in table 2. It can be seen that all the coefficients have correct signs, the scale parameter associated to intermediate nodes is signicantly lower than 1, suggesting the presence of actual correlation among alternatives of the same scheduled service (note that, assuming the total variance θ_0 equal to 1, we have $\delta=\theta_r$). In particular, VOTs magnitudes are similar to those carried out in similar studies in Europe for business trips. VOT values also present both an internal congruence between early and late schedule delays coefficients (80 €/h vs. 103 €/h), with respect to the travel time one, and an external congruence, considering VOT values for scheduled services and private car (69€/h vs. 49 €/h).

Table 2. Calibration results (home-business)

attribute	symbol	units^{-1}	β	VOT (€/h)
Early Schedule Delay	ESD	h	-0.8	80
Late Schedule Delay	LSD	h	-1.032	103
Scheduled Travel Time	STV	h	-0.695	
Scheduled Monetary Cost	SMC	€	-0.01	69
Car Travel Time	CTV	h	-0.532	49
Car Monetary Cost	CMC	€	-0.011	
Access Time	AT	h	-1.6	
Egress Time	ET	h	-1.56	
Number of Ttransfer	NT		-0.07	
Railways	RAIL	0/1	0.30	
Private Car	CAR	0/1	2.68	
Scale Parameter	$\delta=\theta_r/\theta_0$		0.20	
Rho-squared			0.70	

Model validity was also tested by the application to different O/D pairs. As an example, in the following the Milan-Rome O/D pair with DAT at 12.00 a.m. is analysed. Table 3 describes mode-service alternatives, for which table 4 reports attributes and mode-service choice probabilities.

The aggregation of mode-service choice probability for each scheduled services, in terms of mode market share, and its comparison with the actual source market share, pictured in figure 5, shows the model capability to reproduce the actual Italian market share between private car, national flights and high-speed trains.

Table 3. Example of alternatives and attributes (Milan-Rome DAT=12.00)

High Speed Trains			**Air Transport**			**Car**
	Departure	Arrival		Departure	Arrival	
HS1	07.00	11.37	FL1	09.30	10.36	
HS2	08.00	12.37	FL2	10.00	11.06	
travel time: 4h 37min			**travel time:** 1h 06min			**travel time:** 6h 04min
fare: 55.8 €			**fare:** 81.5 €			**cost** (incl. tolls): 69 €

Table 4. Example of attributes and mode-service choice probabilities (Milan-Rome DAT=12.00)

		mode-service altervatives				
attributes		**car**	**Early High-Speed Train (HS1)**	**Late High-Speed Train (HS2)**	**Early Flight (FL1)**	**Late Flight (FL2)**
Arrival Time	**hh.mm**		11.37	12.37	10.36	11.06
Early Schedule Time	**min**	0	18	0	7	0
Late Schedule Time	**min**	0	0	12	0	53
Travel Time	**min**	364	277	277	66	66
Cost	**€**	69	55.8	55.8	81.5	81.5
Access Time	**min**	0	15	15	70	70
Egress Time	**min**	0	15	15	65	65
Railway	**0/1**	0	1	1		
Car	**0/1**	1			0	0
$p(r,m/od,\tau_{TTi})$		0.25	0.26	0.12	0.18	0.19

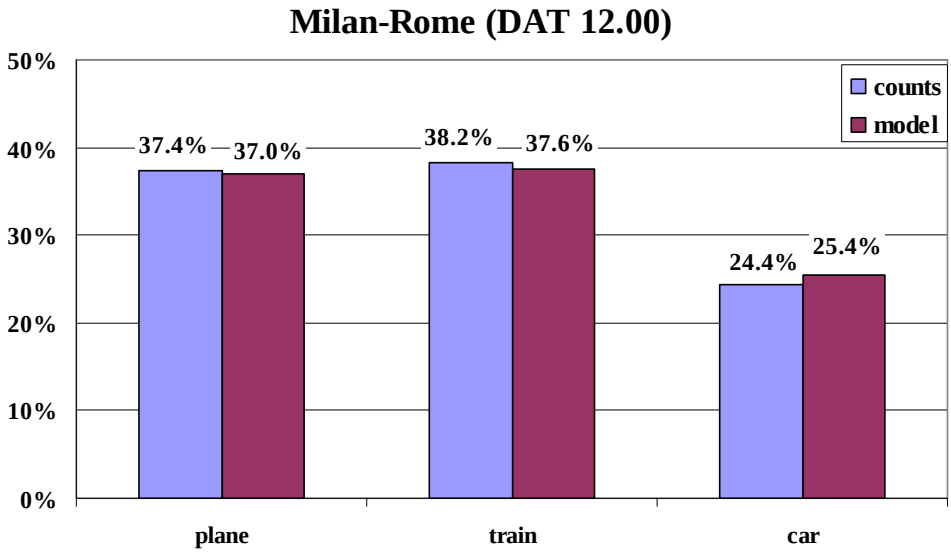

Figure 5. Example of mode-service choice probability

5. Conclusions

In this paper a mode-service choice model to assess competition between air transport and high-speed train services at regional/national scale has been presented. It has been specified through a schedule-based approach which implies that demand, supply, path choice and assignment models have to take into account the timetable explicitly. For this reason scheduled services have been represented by single runs instead of traditional service lines, and attributes at single run level for each scheduled transportation service have been considered to estimate mode-service choice probabilities for a given O/D pair and user target time.

The mode-service choice model has been specified using a nested-logit structure in which the systematic utility of scheduled services, linear in both attributes and parameters, includes the difference (that can be considerable) between desired user departure time and run scheduled departure time or between desired user arrival time at destination and run scheduled arrival, known as early schedule penalty or late schedule penalty, that can be explicitly calculated considering a schedule-based approach only.

The mode-service model has been specified and calibrated on the basis of a set of available data for Italy, and its application to the actual scenario allowed us to test its capability to reproduce the actual Italian market share between regional flights and high-speed trains, to be used as starting point for assessing future scenario forecasts.

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