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Series editor

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Modelling Public Transport Passenger Flows in the Era of Intelligent Transport Systems

COST Action TU1004 (TransITS)

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Notation

The notation utilized in this book copes with the following rules and assumptions.

A variable is a quantitative characteristic of an object/element; it is composed by the following:

- a variable identifier (only one letter, except for indicators), that specifies the nature of the characteristic (e.g., cost, flow, time, probability)
- some subscripts, that specify the referred object/element (e.g., node, origin, destination, mode, class, arc, line, run) which typically belongs to a discrete set; if the subscript is an integer index (e.g., 1, 2, …, n), it implicitly refers to the object/element at a certain position of an ordered list or vector
- a (possible) superscript, that specifies the sub-types of a same variable identifier (e.g., waiting time, in-vehicle time); the use of few letters ensures a self-explanatory notation

The following typographic rules also hold:

- the same symbol can be used as a variable, subscript or superscript, possibly in different contexts
- scalars, subscripts and superscripts are denoted in lower case, italic, not bold
- indicators (denoted possibly with one or more letters) are in upper case, italic, not bold
- set are denoted in upper case, italic, not bold
- vectors and matrices are denoted in lower case, not italic, bold
- square brackets can be used instead of subscripts to avoid nested subscripts
- parameters and coefficients are typically denoted with Greek letters

Notation Map

Subscripts

i, j	Node, vertex, generic indices
a, b	Arc, edge
$\breve{a}$	Hyperarc
o	Origin
d	Destination
z	Zone
m	Mode of transport, nest of alternatives
y	Turn
k, h	Route, path, hyperpath, tree, bush, generic choice alternative
ℓ	Line
s	Stop
r	Run
t, e	Time index, instant, interval referring to the initial instant
x	Space index, point, segment referring to the initial point
v	Vehicle
u	Person, user, individual, passenger, demand component
g	User class, person group, demand segment
f	Dictionary of parameters, arc type, function
c	Attribute
n	Iteration, year, outcome

Variables

q	Flow, volume, number of passengers, number of vehicles, cumulative flow
d	Demand
c	Cost, disutility
h	Headway, time interval
t	Travel time, elapsed time
τ, θ	Clock time; use τ for entry time and θ for exit time
κ	Capacity
f	Frequency
s	Speed
k	Density

l	Length, distance, travelled space
ξ	Space progressive
x	Generic input
y	Generic output
f	Generic function
p	Probability
u	Random utility
v	Systematic utility
w	Satisfaction, expected cost, minimum cost
ε	Random error term
a	Attribute, characteristic

Sets

$\Re, \Re_{+}, \Re_{++}, \Re_{-}, \Re_{--}$	Real numbers, non-negative, positive, non-positive, negative
$\Im, \Im_{+}, \Im_{++}, \Im_{-}, \Im_{--}$	Integer numbers, non-negative, positive, non-positive, negative
X	Generic set
N	Nodes
$A \subseteq N \times N$	Arcs
$O \subseteq N$	Origin (node)s
$D \subseteq N$	Destination (node)s
Z	Zones
M	Modes, nests
B	Vertices
E	Edges
H	Hyperarcs
Y	Turns
K	Routes, paths, hyperpaths, trees, bushes, choice set
L	Lines
S	Stops
R	Runs
$T = \{0, 1, \ldots, t, \ldots, \eta\}$	Instants of the time discretization, intervals
$\mathrm{T} = \{\tau_t : t \in T\}$	Clock times
$\aleph = \{0,1,\ldots, x, \ldots, \nu\}$	Points of the space discretization, segments
$\Xi = \{\xi_x : x \in \aleph\}$	Progressives
U	Users, individuals, demand components
V	Vehicles
G	Classes of users
F	Dictionaries, arc types, functions
C	Attributes, characteristics

Associations

$F_a \in F$	Parameters of edge $a \in E$
$F_g \in F$	Parameters of class $g \in G$
$F_s \in F$	Parameters of stop $s \in S$
$F_\ell \in F$	Parameters of line $\ell \in L$
$F_{\ell s} \in F$	parameters of stop $s \in S_\ell$ of line $\ell \in L$
$O_z \subseteq O$	Origin(s) of zone $z \in Z$
$D_z \in D$	Destination of zone $z \in Z$
$O_u \in O$	Origin of demand component $u \in U$
$D_u \in D$	Destination of demand component $u \in U$
$G_u \in G$	Class of demand component $u \in U$
$O_k \in O$	Origin of route $k \in K$
$D_k \in D$	Destination of route $k \in K$
$M_k \in M$	Mode of route $k \in K$
$L_a \in L$	Line of arc $a \in A$ (if any)
$L_r \in L$	Line of run $r \in R$

Operators

$\lvert X \rvert$	Cardinality of the generic set X, number of its elements
$Bool(\cdot)$	Boolean function; applies to a Boolean expression x: $Bool(x) = 1$, if x = TRUE, $Bool(x) = 0$, if x = FALSE
$Pr(\cdot)$	Probability; applies to an event or condition among random variables
$E(\cdot)$	Expected value; applies to a random variable
$Var(\cdot)$	Variance; applies to a random variable
$SD(\cdot)$	Standard deviation; applies to a random variable
$Cov(\cdot, \cdot)$	Covariance, applies to two random variables
$Max(\cdot)$, $Min(\cdot)$	Maximum, minimum; apply to a set or real numbers
$Sin(\cdot)$, $Cos(\cdot)$, $Tan(\cdot)$	Sine, cosine, tangent; apply to a real number
$Log(\cdot)$, $Exp(\cdot)$	Logarithm, exponential; apply to a real number
$\cup$, $-$, $\times$	Union, subtraction, product between two sets
$\leftarrow$	Assign value on the right of the arrow to variable on the left
$\Rightarrow$, $\Leftarrow$, $\Leftrightarrow$	Implications
$\varphi(\cdot)$	Probability density function
$\Phi(\cdot)$	(Cumulative) distribution function
$\bar{\Phi}(\cdot) = 1 - \Phi(\cdot)$	Complementary distribution function

Topology

$Z^{int} \subseteq Z$	Internal zones
$Z^{ext} \subseteq Z$	External zones
$(B, E \subseteq B \times B)$	Base network
$(N, A \subseteq N \times N)$	Assignment graph
$(a \in A) =$ $(i \in N, j \in N) = ij$	Generic arc
$A_m \subseteq A$	Arcs of mode $m \in M$
$a^- \in N$	Tail (initial node) of arc $a \in A$
$a^+ \in N$	Head (final node) of arc $a \in A$; in case of hyperarcs this is a set
$i^+ = \{a \in A: a^- = i\}$	Forward star of node $i \in N$; this is a set of arcs, not of nodes
$i^- = \{a \in A: a^+ = i\}$	Backward star of node $i \in N$; this is a set of arcs, not of nodes
$k = (N_k, A_k)$	Acyclic sub-graph (path, hyperpath, bush, tree)
$N_k \subseteq N$	Nodes of acyclic sub-graph k
$A_k \subseteq (A \cap N_k \times N_k)$	Arcs of acyclic sub-graph k
$i_k^+ = i^+ \cap A_k$	Successor arcs of $i \in N_k$
$i_k^- = i^- \cap A_k$	Predecessor arcs of $i \in N_k$
$k^- = \{i \in N_k : i_k^- = \emptyset\}$	Origin nodes of acyclic sub-graph k
$k^+ = \{i \in N_k : i_k^+ = \emptyset\}$	Destination nodes of acyclic sub-graph k
$od \in O \times D$	Generic OD pair
K_{odm}	Routes connecting on the network origin $o \in O$ to destination $d \in D$ on mode $m \in M$
$K_m = \cup_{od \in O \times D} K_{odm}$	Routes of mode $m \in M$
$K \in K_m \Rightarrow A_k \subseteq A_m$	Generic route on mode $m \in M$
$K = \cup_{m \in M} K_m$	Set of all routes defined on the multimodal network
Δ_{ak}	Number of times that a user travelling on route $k \in K$ passes through arc $a \in A$
$\Delta_{\breve{a}k}$	Probability of using hyperarc $\breve{a} \in H$ when traveling on route $k \in K$
$N^{div} \subseteq N$	Diversion nodes
$A^{div} = \{i^+ : i \in N^{div}\}$	Diversion arcs
$\breve{a} \subseteq i^+: i \in N^{div}$	A hyperarc is a set of arcs (its branches) exiting from a same diversion node
$H \subseteq \{\breve{a} \subseteq i^+: i \in N^{div}\}$	Set of hyperarcs
$(y \in Y) = (a \in A, b \in A)$ $= ab$	Generic turn
$y^- \in A$	Tail (initial arc) of turn $y \in Y$
$y^+ \in A$	Head (final arc) of turn $y \in Y$
$y^\circ \in N$	Centre (via node) of turn $y \in Y$
$Y_i \subseteq i^- \times i^+$	Turns of node $i \in N$
$t^+(\tau) \in T \cup \eta + 1$	The next time index of instant $\tau \geq \tau_0$

$t^{-}(\tau) \in T \cup \eta + 1$	The previous time index of instant $\tau \geq \tau_0$
$\tau_{\eta+1} = \infty$	Additional instant
h_t	Duration of interval $t \in T$

Symbols

Transit service

$S_\ell \subseteq S$	Stops sequence of line $\ell \in L$; an ordered set with no repetitions
$S_\ell^- \in S_\ell$	First stop of line $\ell \in L$
$S_\ell^+ \in S_\ell$	Last stop of line $\ell \in L$
$s_\ell^- \in S_\ell$	Previous stop of stop $s \in S_\ell - S_\ell^-$ of line $\ell \in L$
$s_\ell^+ \in S_\ell$	Successive stop of stop $s \in S_\ell - S_\ell^+$ of line $\ell \in L$
$R_\ell \subseteq R$	Runs sequence of line $\ell \in L$; an ordered set with no repetitions
$R_\ell^- \in R_\ell$	First run of line $\ell \in L$
$R_\ell^+ \in R_\ell$	Last run of line $\ell \in L$
$r^{-\ell} \in R_\ell$	Previous run of run $r \in R_\ell - R_\ell^-$ of line $\ell \in L$
$r^{+\ell} \in R_\ell$	Successive run of run $r \in R_\ell - R_\ell^+$ of line $\ell \in L$
τ_{rs}	Arrival time of run $r \in R_\ell$ at stop $s \in S_\ell - S_\ell^-$
θ_{rs}	Departure time of run $r \in R_\ell$ at stop $s \in S_\ell - S_\ell^+$
$\theta_r = \theta_{rs},\ s = S_\ell^-$	Scheduled departure of run $r \in R_\ell$
t_{rs}^{run}	Running time of run $r \in R_\ell$ on the line segment s from stop $s \in S_\ell - S_\ell^+$ to s_ℓ^+
t_{rs}^{dwell}	Dwelling time of run $r \in R_\ell$ at stop $s \in S_\ell - S_\ell^- - S_\ell^+$
$t_{\ell st}^{run}$	Running time of line segment s from stop $s \in S_\ell - S_\ell^+$ to $s_\ell{}^+$ during interval $t \in T$
$t_{\ell st}^{dwell}$	Dwelling time at stop $s \in S_\ell - S_\ell^- - S_\ell^+$ during interval $t \in T$
$B_{\ell s} \subseteq E$	Edge sequence of line segment $s \in S_\ell - S_\ell^+$; an ordered set with no repetitions
$l_{\ell s}$	Length of the line segment $s \in S_\ell - S_\ell^+$
l_a	Length of edge $a \in E$
s_a^{walk}	Walking speed of edge $a \in E$
s_{at}	Commercial speed of edge $a \in B$ during interval $t \in T$
t_ℓ^{stop}	Stop time of line $\ell \in L$
t_ℓ^{alight}	Alighting time of line $\ell \in L$
t_ℓ^{board}	Boarding time of line $\ell \in L$
t_ℓ^{do}	Door operation time of line $\ell \in L$

t_ℓ^{ab}	Minimum dwell time for alighting and boarding of line $\ell \in L$
$h_{\ell st}$	Headway of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$ during interval $t \in T$
$\varphi_{\ell st}^h(h)$	Headway distribution of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$ during interval $t \in T$
$h_{\ell s}^{max}$	Maximum headway of the distribution of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$
h_{rs}^{dep}	Departure headway of run $r \in R_\ell - R_\ell^-$ from stop $s \in S_\ell - S_\ell^+$
h_{rs}^{arr}	Arrival headway of run $r \in R_\ell - R_\ell^-$ to stop $s \in S_\ell - S_\ell^-$
α_{rs}	Headway deviation of run $r \in R_\ell - R_\ell^-$ to stop $s \in S_\ell - S_\ell^-$
$f_{\ell st}$	Frequency of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$ during interval $t \in T$
$f_{\ell s}^{dep}(\tau)$	Departure frequency of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$ at time τ
$f_{\ell s}^{arr}(\tau)$	Arrival frequency of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$ at time τ
f_a	Frequency of line $L_a \in L$ associated with arc $a \in A^{wait}$, otherwise ∞
$\sigma_{\ell st}$	Irregularity or variation coefficient of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$ during $t \in T$
$n_{\ell s}$	Parameter of the Erlang headway distribution of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$
$\varphi_{\ell st}^w(t)$	Waiting time distribution of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$ at instant $t \in T$
$t_{\ell st}^{wait}$	Expected waiting time of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$ at instant $t \in T$
κ_ℓ^{veh}	Vehicle capacity of line $\ell \in L$
κ_ℓ^{seat}	Seating capacity of line $\ell \in L$
κ_ℓ^{stand}	Standing capacity of line $\ell \in L$
κ_ℓ^{crush}	Crush capacity of line $\ell \in L$
κ_ℓ^{door}	Door capacity of line $\ell \in L$
κ_ℓ^{board}	Boarding capacity of line $\ell \in L$
κ_ℓ^{alight}	Alighting capacity of line $\ell \in L$
κ_s^{stop}	Stop capacity of stop $s \in S$
γ_{sg}^{stop}	Discomfort coefficient of stop $s \in S$ for class $g \in G$
$\gamma_{\ell g}^{line}$	Discomfort coefficient of line $\ell \in L$ for class $g \in G$
C^{cs}	Set of comfort attributes for each stop
C^{cl}	Set of comfort attributes for each line
a_{sc}	Value of comfort attribute $c \in C^{cs}$ for stop $s \in S$

$a_{\ell c}$	Value of comfort attribute $c \in C^{cl}$ line $\ell \in L$
β_{cg}^{stop}	Utility coefficient of stop comfort attribute $c \in C^{cs}$ for stop $s \in S$ and class $g \in G$
β_{cg}^{line}	Utility coefficient of line comfort attribute $c \in C^{cl}$ for line $\ell \in L$ and class $g \in G$
c_{kg}^{fare}	Fare of route $k \in K$ and class $g \in G$
$c_{\ell s}^{kfee}$	Kilometric fee of line segment $s \in S_\ell - S_\ell^+$
$c_{\ell s}^{bfee}$	Boarding fee of stop $s \in S_\ell - S_\ell^+$
α_ℓ^{dwell}	BPR coefficient for dwelling congestion of line $\ell \in L$
β_ℓ^{dwell}	BPR exponent for dwelling congestion of line $\ell \in L$
α_ℓ^{queue}	BPR coefficient for queuing congestion of line $\ell \in L$
β_ℓ^{queue}	BPR exponent for queuing congestion of line $\ell \in L$
χ_ℓ^{queue}	Exponent for the saturation of the remaining capacity of line $\ell \in L$
β_ℓ^{crowd}	BPR exponent for crowding congestion of line $\ell \in L$
β_s^{crowd}	BPR exponent for crowding congestion of stop $s \in S$

Public Transport Network

$E^{walk} \subseteq E$	Set of walkable edges
$B_z^{orig} \subseteq B$	Origin vertex associated with zone $z \in Z$
$B_z^{dest} \subseteq B$	Destination vertex associated with zone $z \in Z$
$B_s^{stop} \subseteq B$	Vertex associated with stop $s \in S$
N^{base}	Set of base nodes
N^{stop}	Set of stop nodes
N_ℓ	Set of line nodes of line $\ell \in L$
$N_{\ell s}^{arr}$	Arrival node of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^-$
$N_{\ell s}^{dep}$	D node of line $\ell \in L$ from stop $s \in S_\ell - S_\ell^+$
N_r	Set of run nodes of run $r \in R$
N_{rs}^{arr}	Arrival node of run $r \in R$ from stop $s \in S_\ell - S_\ell^+$
N_{rs}^{dep}	Departure node of run $r \in R$ from stop $s \in S_\ell - S_\ell^+$
$N_{\ell s}^{a\text{-}seat}$	Seating arrival node of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^-$
$N_{\ell s}^{d\text{-}seat}$	Seating departure node of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^-$

$N_{\ell s}^{a\text{-}stand}$ Standing arrival node of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^-$
$N_{\ell s}^{d\text{-}stand}$ Standing departure node of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^-$
$N_{\ell s}^{p\text{-}board}$ Board placing node of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^-$
$N_{\ell s}^{p\text{-}stand}$ Stand placing node of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^-$
$N_{\ell s}^{serv}$ Service node of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$
$N_{\ell s}^{que}$ Queue node of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$
A^{walk} Set of pedestrian arcs
A^{stop} Set of stop arcs
A^{run} Set of running arcs
A^{dwell} Set of dwelling arcs
A^{wait} Set of waiting arcs
A^{board} Set of boarding arcs
A^{alight} Set of alighting arcs
A^{trans} Set of transfer arcs
A^{dest} Set of destination arcs
$A^{r\text{-}seat}$ Set of seat running arcs
$A^{p\text{-}seat}$ Set of seat placing arcs
$A^{d\text{-}seat}$ Set of seat dwelling arcs
$A^{a\text{-}seat}$ Set of seat alighting arcs
$A^{r\text{-}stand}$ Set of stand running arcs
$A^{d\text{-}stand}$ Set of stand dwelling arcs
$A^{p\text{-}stand}$ Set of stand placing arcs
$A^{a\text{-}stand}$ Set of stand alighting arcs
$A^{p\text{-}switch}$ Set of switch seating arcs
$A^{p\text{-}keep}$ Set of keep standing arcs
A^{fail} Set of failing arcs
A^{serv} Set of service arcs
A^{que} Set of queuing arcs
H^{wait} Set of waiting hyperarcs
H^{board} Set of boarding hyperarcs
H^{dwell} Set of dwelling hyperarcs
H^{serv} Set of service hyperarcs

Class Parameters

γ_g^{vot} Value of time for users of class $g \in G$
γ_g^{walk} Walking discomfort coefficient for users of class $g \in G$
γ_g^{wait} Waiting discomfort coefficient for users of class $g \in G$

c_g^{tran}	Transfer cost for users of class $g \in G$
γ_g^{risk}	Risk-averseness coefficient for users of class $g \in G$
γ_g^{mfee}	Fee multiplier for users of class $g \in G$
γ_g^{del}	Delay coefficient for users of class $g \in G$
γ_g^{adv}	Anticipation coefficient for users of class $g \in G$
t_g^{ant}	Maximum anticipation wrt desired departure time for users of class $g \in G$
t_g^{del}	Maximum delay wrt desired departure time for users of class $g \in G$
α_g^{crowd}	Overcrowding congestion coefficient for users of class $g \in G$
α_g^{learn}	Cost learning exponential filter for users of class $g \in G$
α_g^{choup}	Choice updating exponential filter for users of class $g \in G$
α_g^{cred}	Credibility exponential filter for users of class $g \in G$
t_g^{wmax}	Maximum walking time on the pedestrian network for users of class $g \in G$
t_g^{stop}	Reference stop time for users of class $g \in G$
γ_g^{loss}	Discomfort coefficient for lost opportunities for users of class $g \in G$

Performances

c_{ag}	Generalized cost of arc $a \in A$ for users of class $g \in G$
c_{ag}^{nt}	Non-temporal cost of arc $a \in A$ for users of class $g \in G$
t_a^0	Free-flow travel time of arc $a \in A$
t_a	Travel time of arc $a \in A$
γ_{ag}	Value of time on arc $a \in A$ for users of class $g \in G$
c_{kg}	Generalized cost of route $k \in K$ for users of class $g \in G$
c_{kg}^{na}	Non-additive cost of route $k \in K$ for users of class $g \in G$
$\tilde{c}_{kg}^{n}$	Forecasted cost of path $k \in K$ for users of class $g \in G$ in day n
$p_{a\|\breve{a}(dgm)}$	Diversion probability of using branch $a \in \breve{a}$ of hyperarc $\breve{a} \in H$ (for users of class $g \in G$ that travel on mode $m \in M$ to destination $d \in D$)

$t_{a\|\breve{a}}$ (dgm)	Conditional travel time for using branch $a \in \breve{a}$ of hyperarc $\breve{a} \in H$ (for users of class $g \in G$ that travel on mode $m \in M$ to destination $d \in D$)
$t_{\breve{a}\ (dgm)}$	Combined travel time of hyperarc $\breve{a} \in H$ (for users of class $g \in G$ that travel on mode $m \in M$ to destination $d \in D$)
γ_{ig}	Value of time on arcs exiting the diversion node $i \in N^{div}$ for class $g \in G$ users
$c_{a\|\breve{a}\ g}$	Conditional cost of using branch $a \in \breve{a}$ of hyperarc $\breve{a} \in H$ for class $g \in G$ users
$c_{\breve{a}g}$	Combined cost of hyperarc $\breve{a} \in H$ for users of class $g \in G$
$c_{\breve{a}dgm}$	Combined cost of hyperarc $\breve{a} \in H$ for users of class $g \in G$ that travel on mode $m \in M$ to destination $d \in D$
γ_{sgt}^{crowd}	Crowding discomfort coefficient of class $g \in G$ user at stop $s \in S$ at instant $t \in T$
$\gamma_{\ell sg}^{crowd}$	Crowding discomfort coefficient of segment $s \in S$ of line $\ell \in L$ for class $g \in G$
γ_{rsg}^{crowd}	Crowding discomfort coefficient of segment $s \in S$ of run $r \in R_\ell$ for class $g \in G$
$f_{\ell s}^{eff}$	Effective frequency of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$
$p_{\ell s}^{fail}$	Fail-to-board probability of line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$
$c_{\ell s}^{fail}$	Additional cost in the case of fail-to-board line $\ell \in L$ at stop $s \in S_\ell - S_\ell^+$
$\theta_a(\tau)$	Exit time from arc $a \in A$ of a passenger who enters it at time τ
θ_{at}	Exit time from arc $a \in A$ of a passenger who enters it at instant $t \in T$
m_{aet}	Share of users that enter arc $a \in A$ during interval $e \in T$ and exit it during $t \in T$
$\kappa_a(\tau)$	Instantaneous remaining capacity at time τ available at the end of arc $a \in A^{que}$
$\kappa_a^{cum}(\tau)$	Cumulative remaining capacity of arc $a \in A^{que}$ at time τ
$n_a(\tau)$	Number of carriers passengers must let go before being able to board each line $\ell = L_a$, if queuing on arc $a \in A^{que}$ starts at a given time τ
ρ_{br}	Time when the last passenger that achieves boarding run r arrives at the stop and enters the waiting arc $b \in A^{wait}$

Route Generation

c_k^{imp}	Search impedance of path $k \in K$
t_k^{tot}	Total travel time of path $k \in K$
n_k^{trans}	Number of transfers of path $k \in K$
c_k^{fare}	Fare of path $k \in K$
β^{time}, β^{trans}, β^{fare}	Attribute multipliers
α^{imp}	Relative tolerance wrt the least impedance path
χ^{imp}	Additive absolute tolerance wrt the least impedance path
χ^{trans}	Maximum number of transfers

Attributes and Information

$\hat{a}_{kcu}^{n}$	Value of attribute $c \in C$ on path $k \in K_u$ forecasted by traveller $u \in U$ for day n
$\alpha_u^{PK\ n}$	Weight of Prior Knowledge in day n for traveller $u \in U$
$\alpha_u^{TE\ n}$	Weight of Travel Experience in day n for traveller $u \in U$
α_u^{RTI} n	Weight of Real-Time Information in day n for traveller $u \in U$
$\tilde{a}_{kcu}^{1}$	Value of attribute $c \in C$ on path $k \in K_u$ prior known by traveller $u \in U$ for day 1
$\tilde{a}_{kcu}^{n}$	Value of attribute $c \in C$ on path $k \in K_u$ anticipated by traveller $u \in U$ for day n
$\tilde{a}_{kcu}^{RTI}$	Value of attribute $c \in C$ on path $k \in K_u$ got from RTI by traveller $u \in U$ for day n

Stop and Run Choices

t_{is}^{walk}	Walking time on the shortest path from i to B_s^{stop} on the pedestrian network
v_s^{idgt}	Systematic utility of stop $s \in S$ for passengers of class $g \in G$ directed toward destination $d \in D$ that at instant $t \in T$ are in vertex $i \in B$
p_s^{idgt}	Probability of choosing stop $s \in S$ for passengers of class $g \in G$ directed toward destination $d \in D$ that at instant $t \in T$ are in vertex $i \in B$

$v_{r\|r'}^{sdgt}$	Systematic utility of run r conditional on arrival of run r' for users of class $g \in G$ directed to destination $d \in D$ who reached stop $s \in S$ at instant $t \in T$
$p_{r'\|r'}^{sdgt}$	Probability of run r conditional on arrival of run r' for users of class $g \in G$ directed to destination $d \in D$ who reached stop $s \in S$ at instant $t \in T$
p_r^{sdgt}	Unconditional probability of run r for users of class $g \in G$ directed towards destination $d \in D$ who reached stop $s \in S$ at instant $t \in T$

Flows and Route Choice

$d_{odmg(t)}$	Flow of class $g \in G$ users that travel on mode $m \in M$ (and depart during time interval $t \in T$) from origin $o \in O$ directed to destination $d \in D$
$\mathbf{d}_{ODmg(t)}$	O-D matrix of class $g \in G$ users that travel on mode $m \in M$ (and depart during time interval $t \in T$)
q_{kg}	Flow of class $g \in G$ users that travel on route $k \in K$
$\tilde{q}_{kg}^{n}$	Flow of class $g \in G$ on route $k \in K$ given by the Route Choice Model in day n
q_{ag}	Flow of class $g \in G$ users travelling on arc $a \in A$
q_{ag}^{nlm}	Flow of class $g \in G$ users on arc $a \in A$ given by the Network Loading Map
q_a	Volume of arc $a \in A$
ω_{ag}	Equivalency coefficient on arc $a \in A$ for class $g \in G$ users
q_a^0	Base volume of arc $a \in A$
p_{kg}	Probability that class $g \in G$ users take (choose) route $k \in K$
p_{admg}	Probability that class $g \in G$ users that travel on mode $m \in M$ directed to destination $d \in D$ take (choose) arc $a \in A$ conditional on being at its tail
w_{idmg}	Expected cost to reach destination $d \in D$ from node $i \in N$ perceived by users of class $g \in G$ that travel on mode $m \in M$
q_{idmg}	Flow traversing *node* $i \in N$ of class $g \in G$ users that travel on mode $m \in M$ directed to destination $d \in D$ users
w_{admg}	Remaining cost to reach destination $d \in D$ from node $a^- \in N$ for class $g \in G$ users that travel on mode $m \in M$ and take (choose) arc $a \in A$

$p_{\breve{a}dmg}$	Probability that class $g \in G$ users that travel on mode $m \in M$ directed to destination $d \in D$ take (choose) hyperarc $\breve{a} \in H$ conditional on being at its tail
$w_{\breve{a}dmg}$	Remaining cost to reach destination $d \in D$ from node $\breve{a}^- \in N$ for class $g \in G$ users that travel on mode $m \in M$ and take (choose) hyperarc $\breve{a} \in H$
$q_{ag}^{out}(\tau)$	Outflow of class $g \in G$ users from arc $a \in A$ at time τ
$q_{ag}^{int}(\tau)$	Inflow of class $g \in G$ users to arc $a \in A$ at time τ
$q_{ag}^{cout}(\tau)$	Cumulative outflow of class $g \in G$ users from arc $a \in A$ at time τ
$q_{ag}^{cint}(\tau)$	Cumulative inflow of class $g \in G$ users to arc $a \in A$ at time τ

Optimal Strategies

$\bar{A}_{(dg)} \in A$	Set of arcs in the solution hypertree provided by the (deterministic) route choice model (for passengers of class $g \in G$ directed to destination $d \in D$)
$\bar{A}_i^+ = i^+ \cap \bar{A}$	Arcs exiting from node $i \in N$ and belonging to the solution hypertree
$w_i(\breve{a})$	Expected cost to reach the destination from stop $i \in N$ as a function of the attractive set $\breve{a} \subseteq i^+$
x_a	Binary variable denoting if arc $a \in A$ belongs to the solution hypertree $\bar{A}$
ω_i	Total wait time at stop $i \in s$ (for a given class and destination)
μ_a	Dual variable of arc $a \in A$ in the optimal strategies solution
$p_{\breve{a}\|a}(t)$	Probability that the line $L_a \in L$ of arc $a \in \breve{a}$ is boarded after a wait time t
$t_{\breve{a}}^{max}$	Minimum headway among the attractive lines $\breve{a}$
$\breve{a}_x$	Attractive set formed by the first x lines at the stop in terms of remaining costs
$\breve{a}_{x(\tau)}$	Attractive set that will be considered by the passenger at time $\tau \geq t$ of the wait after the elapsed wait time $t \geq 0$
$w_i(t)$	Expected cost after the elapsed wait time $t \geq 0$ resulting from the future application of the dynamic attractive set $\breve{a}_{x(\tau \geq t)}$

τ_k	Elapsed wait time after which the kth line exits from the attractive set
$p_k(\tau\|t)$	Probability that the kth line is boarded at time τ after an elapsed wait time t

Demand Models

d_{og}^{gen}	Flow of class $g \in G$ users produced (or generated) from origin $o \in O$
d_{dg}^{att}	Flow of class $g \in G$ users attracted from destination $d \in D$
d_{odg}	Flow of class $g \in G$ users that travel from origin $o \in O$ to destination $d \in D$
w_{odg}	Satisfaction of class $g \in G$ to travel from origin $o \in O$ to destination $d \in D$
w_{odmg}	Satisfaction of class $g \in G$ to travel on mode $m \in M$ from origin $o \in O$ to $d \in D$
a_{zc}^{zone}	Value of landuse attribute $c \in C^{zone}$ in zone $z \in Z$
C^{zone}	Set of zone landuse attributes
β_{cg}^{gen}	Coefficient of generation attribute $c \in C^{zone}$ for class $g \in G$
β_{cg}^{att}	Coefficient of attraction attribute $c \in C^{zone}$ for class $g \in G$
a_{mgc}^{mod}	Value of modal split attribute $c \in C^{mod}$ for mode $m \in M$ and class $g \in G$
C^{mod}	Set of modal split attributes
β_{cg}^{mod}	Coefficient of modal split attribute $c \in C^{mod}$ for class $g \in G$
β_{g}^{mod}	Coefficient of generalized cost for mode choice of class $g \in G$
β_{g}^{route}	Coefficient of generalized cost for route choice of class $g \in G$

Estimation of Assignment

$\mathbf{d}$, $\mathbf{d}^0$, $\mathbf{d}^{LB}$, $\mathbf{d}^{UB}$	Vectors of demand parameters: calibrated, initial, lower bound, upper bound
$\boldsymbol{\delta}$, $\boldsymbol{\delta}^0$, $\boldsymbol{\delta}^{LB}$, $\boldsymbol{\delta}^{UB}$	Vectors of supply parameters: calibrated, initial, lower bound, upper bound
$\mathbf{q}$, $\mathbf{q}^m$	Vectors of arc flows: resulting from the assignment model, measured on the field

$q(\mathbf{d},\boldsymbol{\delta})$, $t(\mathbf{d},\boldsymbol{\delta})$	Functionals of the assignment model in terms of: traffic flows and travel times
z_1, z_2, z_3, z_4	Distance functions
ψ_1, ψ_2, ψ_3, ψ_4	Weights of the distance functions in the objective function
$\mathbf{M}$, $m_{a\ od}$	Assignment matrix; its elements are the fractions of demand d_{od} using each arc a

Prospect Theory

N	Set of outcomes
p_n	Objective probability of the nth outcome
v_{kn}	Utility of alternative $k \in K$ in the nth outcome
v_k^0	Reference point of alternative $k \in K$
Δv_{kn}	Gain or loss in the nth outcome wrt the reference point of alternative $k \in K$
$\pi(p)$	Pi function
$h(\Delta v)$	Value function
w_{kn}^+, w_{kn}^-	Cumulative probability of positive/negative the nth outcome of alternative $k \in K$
γ, δ	Parameters of the pi function
λ, α, β	Parameters of the value function

Random Utility

K_u	Choice set of alternatives (e.g., paths) considered by traveller $u \in U$
u_{uk}	Perceived utility by traveller $u \in U$ for alternative $k \in K_u$
v_{uk}	Systematic utility for traveller $u \in U$ associated to alternative $k \in K_u$
ε_{uk}	Random error term for traveller $u \in U$ associated to alternative $k \in K_u$
p_{uk}	Probability that traveller $u \in U$ chooses alternative $k \in K_u$
w_u	Satisfaction (or Expected Maximum Utility) of traveller $u \in U$
a_{ukc}	Value of the attribute $c \in C$ associated to alternative $k \in K_u$
β_c	Coefficient of attribute $c \in C$
θ	Scale parameter of the MNL model

$\delta_m = \theta_m/\theta_0$	Ratio of scale parameters of nest $m \in M$ in the NL and CNL model
α_c	Transformation parameter of attribute $c \in C$ in the Box-Cox model
CF_k	Commonality factor of alternative $k \in K$
SC_{kh}	Similarity coefficient of two alternatives $k \in K$ and $h \in K$
α_{mk}	Degree of inclusion of alternative $k \in K$ in nest $m \in M$
π_{uk}	Observed probability that traveller $u \in U$ chooses alternative $k \in K_u$
$L(\boldsymbol{\beta})$	Likelihood function
$LL(\boldsymbol{\beta})$	Log-likelihood function
σ_c	Standard deviation of parameter $c \in C$
t_c	t-test of parameter $c \in C$
LR	Likelihood ratio
ρ^2	Rho-square
MRS_{cj}	Marginal rates of substitution between attributes $c \in C$ and $j \in C$
ELA_{kch}	Elasticity of alternative $k \in K$ wrt an attribute $c \in C$ of alternative $h \in K$

Indicators

$K_s \subseteq K$	Set of routes which include boarding at stop $s \in S$
$K_\ell \subseteq K$	Set of routes which include running on line $\ell \in L$
$A_\ell^{run} \subseteq A^{run}$	Set of running arcs of line $\ell \in L$
q_{ktg}	Flow on route $k \in K$ of class $g \in G$ users departing during interval $t \in T$
VOL_{kt}	Volume of route $k \in K_{od}$ during interval $t \in T$
VOL_k	Volume of route $k \in K_{od}$
PBS_s	Passengers Boarding (at) Stop $s \in S$
PRL_ℓ	Passengers Riding Line $\ell \in L$
PKR_k	Passenger-Kilometres of Route $k \in K$
PKL_ℓ	Passenger-Kilometres of Line $\ell \in L$
SKL_ℓ	Service-Kilometres of Line $\ell \in L$
ALL_ℓ	Average Loading of Line $\ell \in L$
DIS_k	Distance of route $k \in K$
ATD_{od}	Average Travelled Distance for origin-destination pair $od \in O \times D$
t_{kt}	Travel time of route $k \in K$ for passengers departing at instant $t \in T$

ATT_{odt}	Average Travel Time for origin–destination pair $od \in O \times D$ and interval $t \in T$
c_{ktg}	Generalized cost of route $k \in K$ for passengers of class $g \in G$ departing at $t \in T$
AGC_{odgt}	Average Generalized Cost for pair $od \in O \times D$ class $g \in G$ and interval $t \in T$

Cost Benefit Analysis

NPV	Net Present Value
B_t	Benefits in year t
C_t	Costs in year t
r	Discount rate
PVB	Present Value of future Benefits
PVC	Present Value of future Costs
BCR	Benefit-Cost Ratio
IRR	Internal Rate of Return

Introduction

This book is the main output of the COST Action TU1004: Modelling Public Transport Passenger Flows in the Era of Intelligent Transport Systems, which was called TransITS for short.

Cost Actions are projects funded by the EU to support a network of researchers. The focus is in this case on transit assignment and ITS technologies. In very productive four years of cooperation, more than 100 researchers from all continents have been involved in TransITS with various roles.

The specific purpose of this book is to provide to a wide community of possible readers, ranging from policy makers to practitioners, from master and Ph.D. students to researchers, a comprehensive source to understand how transit assignment can support the appraisal of investments in ITS technologies for operators and passengers. This is a unique contribution that is really missing in the literature.

The book is not a simple collection of papers. It is really a joint work of multiple hands with a very precise structure, where about 40 different authors (see the List of Contributors for more details) accepted to give a specific contribution with a uniform style and notation (which is not trivial). Of course, a huge coordination and sometimes rewriting effort by the Editorial Board (Guido Gentile, Fabien Leurent, Klaus Noekel, Francesco Viti) was necessary to achieve the desired result. Each chapter and section of the book then went through the careful reading of cross-reviewers. This ambitious project was concluded successfully, and we are all very proud of this book.

The result is a relevant piece of work, with around 700 dense pages articulated in 4 Parts and 10 Chapters (see the Table of contents for more details).

Part I introduces the use of ITS in public transport. The motivations for improving public transport in the context of sustainable cities and regions together with the importance of ITS technologies are first discussed (Chap. 1). The forms of public transport are then illustrated not only presenting the different types of systems and vehicles but also including organization and product issues (Chap. 2). Finally, the state of the art of ITS solutions for public transport is presented with several examples and applications, together with the conceptual link to the variables of the transit assignment models that are used for the appraisal of such innovative systems (Chap. 3).

Part II introduces the idea of planning and modelling public transport. Modelling is presented not as a means in itself, but as a tool for rational decision-making about investment into transport. Passenger route choice models, the core of this book, form just a part of a hierarchy of travel demand models. An overview of this hierarchy is given and the common mathematical framework explained. Particular emphasis is given to random utility models (Chap. 4). The stage is set for Part 3 by defining a standard terminology for the input and output data of such models. The final section describes how ITS produces a large part of these data and how they can be used to build and validate models (Chap. 5).

Part III presents the theory of transit assignment and discusses the basic modelling frameworks: schedule-based, frequency-based, simulation-based. Particular emphasis is given to the representation of strategic behaviour through hyperpaths and to the dynamic aspects of transit simulation including within-day and day-to-day assignment models (Chap. 6). The focus is more on the demand and supply requirements rather than on equilibrium algorithms. The proposed models contain several advancements and original contributions which are designed to capture in the models the effects of real-world phenomena such as passenger information, vehicle capacity and operational stability (Chap. 7).

Part IV examines how transit modes interact with other modes in reality, both competing and complementing, and how these effects can be reflected in multimodal networks (Chap. 8). A review of which models presented in the book have found their way from theory into practice, in the form of both commercially available software and of prototypical academic implementations is presented; their use is also illustrated with the help of two case studies (Chap. 9). Finally, open challenges are described and directions for future research are proposed (Chap. 10).

We want to thank the Cost Office in Bruxelles (Thierry Goger, Carmencita Malimban, Mickael Pero, Andrea Tortajada) for continuously assisting our work with precise indications on managing the Action and the EU Commission for granting a suitable budget, in particular for this book.

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Guido Gentile
Klaus Noekel

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COST (European Cooperation in Science and Technology) is a pan-European intergovernmental framework. Its mission is to enable break-through scientific and technological developments leading to new concepts and products and thereby contribute to strengthening Europe's research and innovation capacities. It allows researchers, engineers and scholars to jointly develop their own ideas and take new initiatives across all fields of science and technology, while promoting multi- and interdisciplinary approaches. COST aims at fostering a better integration of less research intensive countries to the knowledge hubs of the European Research Area. The COST Association, an International not-for-profit Association under Belgian Law, integrates all management, governing and administrative functions necessary for the operation of the framework. The COST Association has currently 36 Member Countries (www.cost.eu).

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