Capacity Estimation Methods

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Content

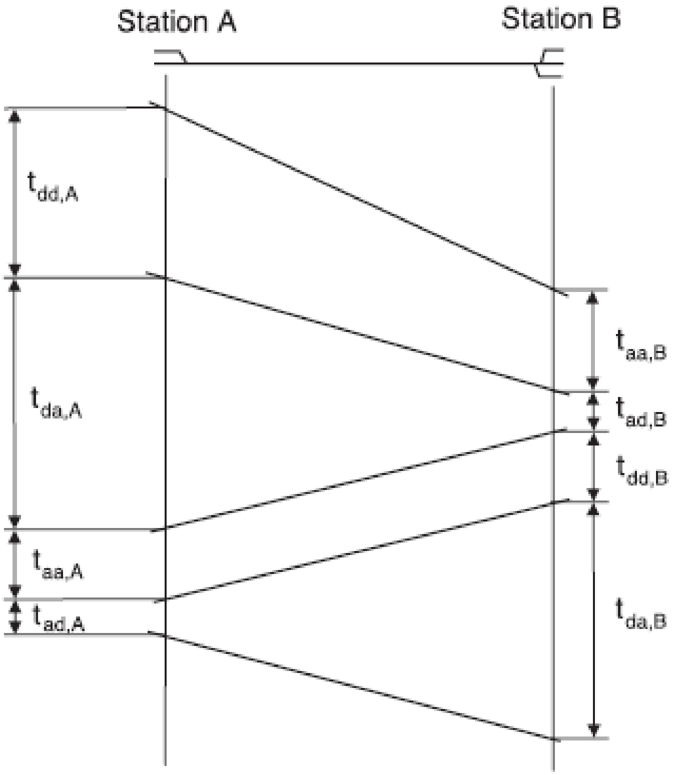
Definition of Capacity

Maximum number of trains N that may be operated using a defined part of the infrastructure at the same time during a defined time period $[1/T]$; T: Time period [24 h = 1440 min; 1 h = 60 min]

- Theoretical capacity $C = T/\sum(t_{h\,min}+\Delta t)$
  Maximum number of trains N_T at scheduled order and speed without timetable margins; $t_{h\,min}$: minimum headway time
  Δt : running time difference between successive trains
- Practical capacity $C_p = T/\sum(t_{h\,min}+\Delta t + t_b)$
  Maximum number of trains N_P at scheduled order and speed including running time supplements t_r , buffer times t_b and track possession time for infrastructure inspection and maintenance

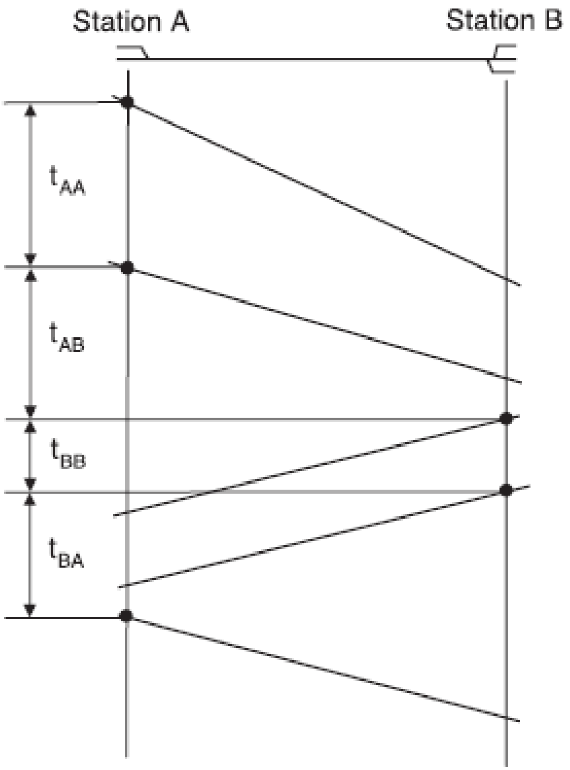
Assignment of headway times

A. To stations

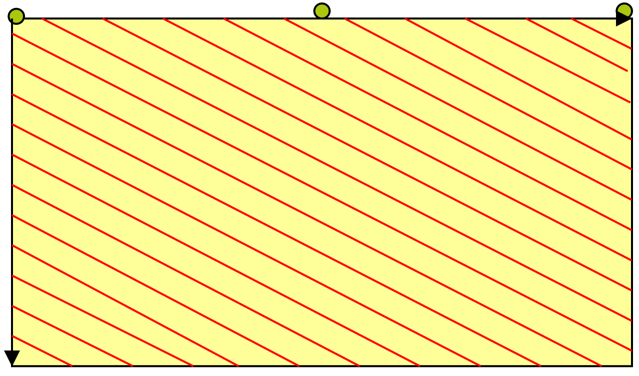


$t_{dd,X}$ "depart-depart" headway at station X
$t_{da,X}$ "depart-arrive" headwayat station X
$t_{aa,X}$ "arrive-arrive" headway at station X
$t_{ad,X}$ "arrive-depart" headway at station X

B. To track sections



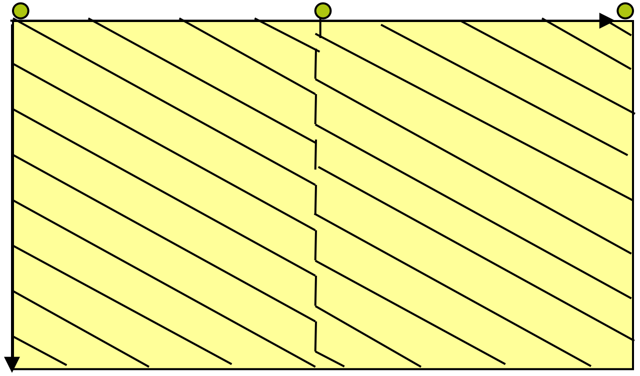
Impact of speed and number of tracks on capacity



12 1 fast line 0 double track 12

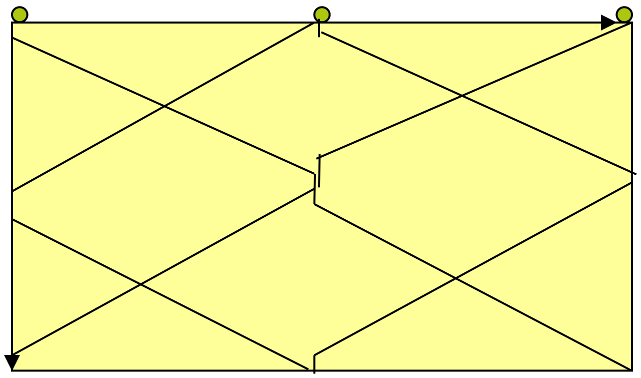
12/h

T= 60 min



8 1 slow line 8 8

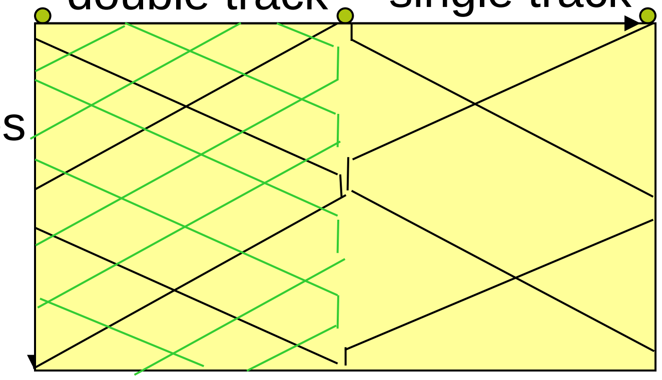
8/h



single track, sidings

2/h

1 line



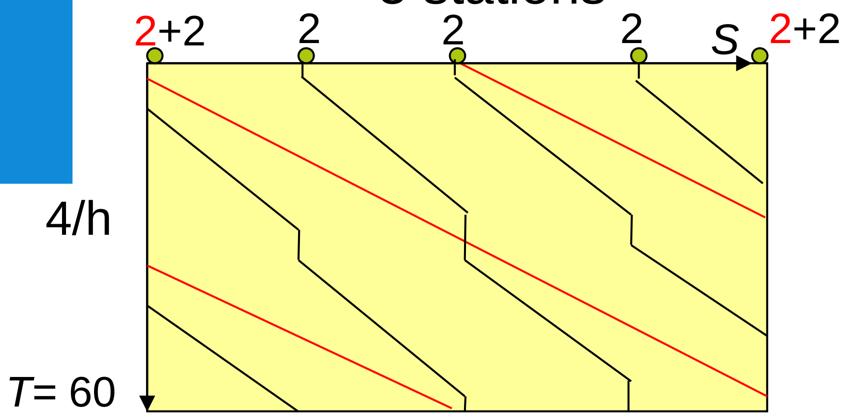
2+3 double track single track 2

2 lines 5/h

1 line

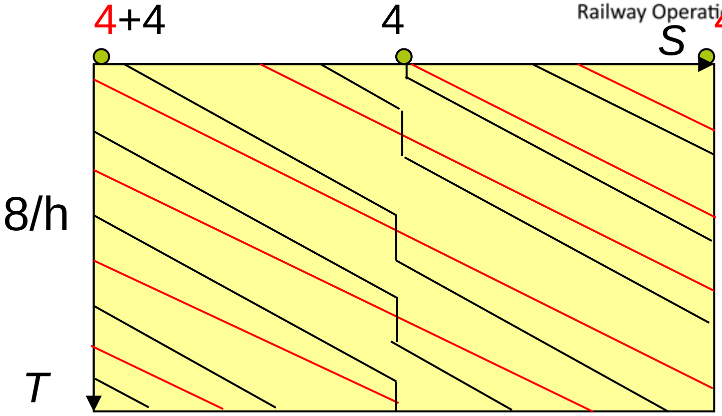
Impact of station density, service pattern and overtakings on capacity

5 stations



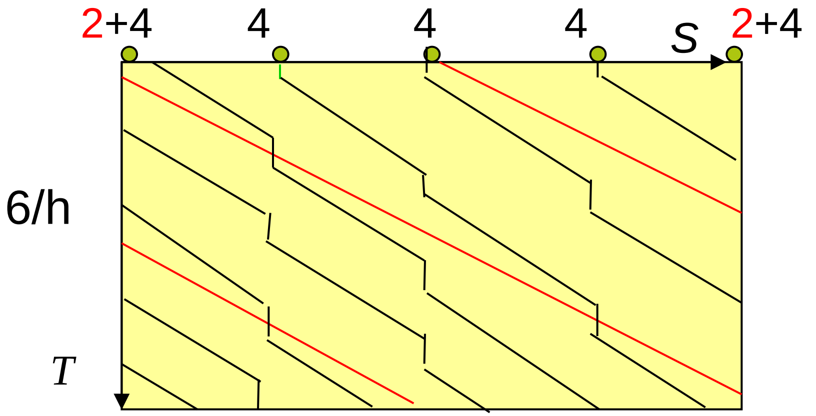
min

1 overtaking



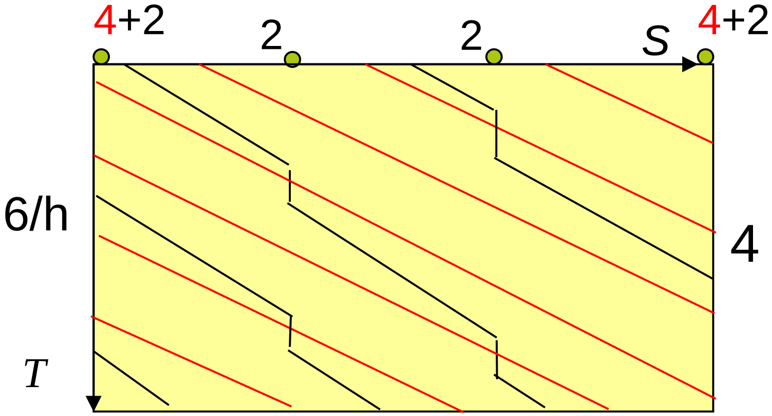
3 stations

1 overtaking



3 overtakings

2 lines



4 stations

2 overtakings

2 lines

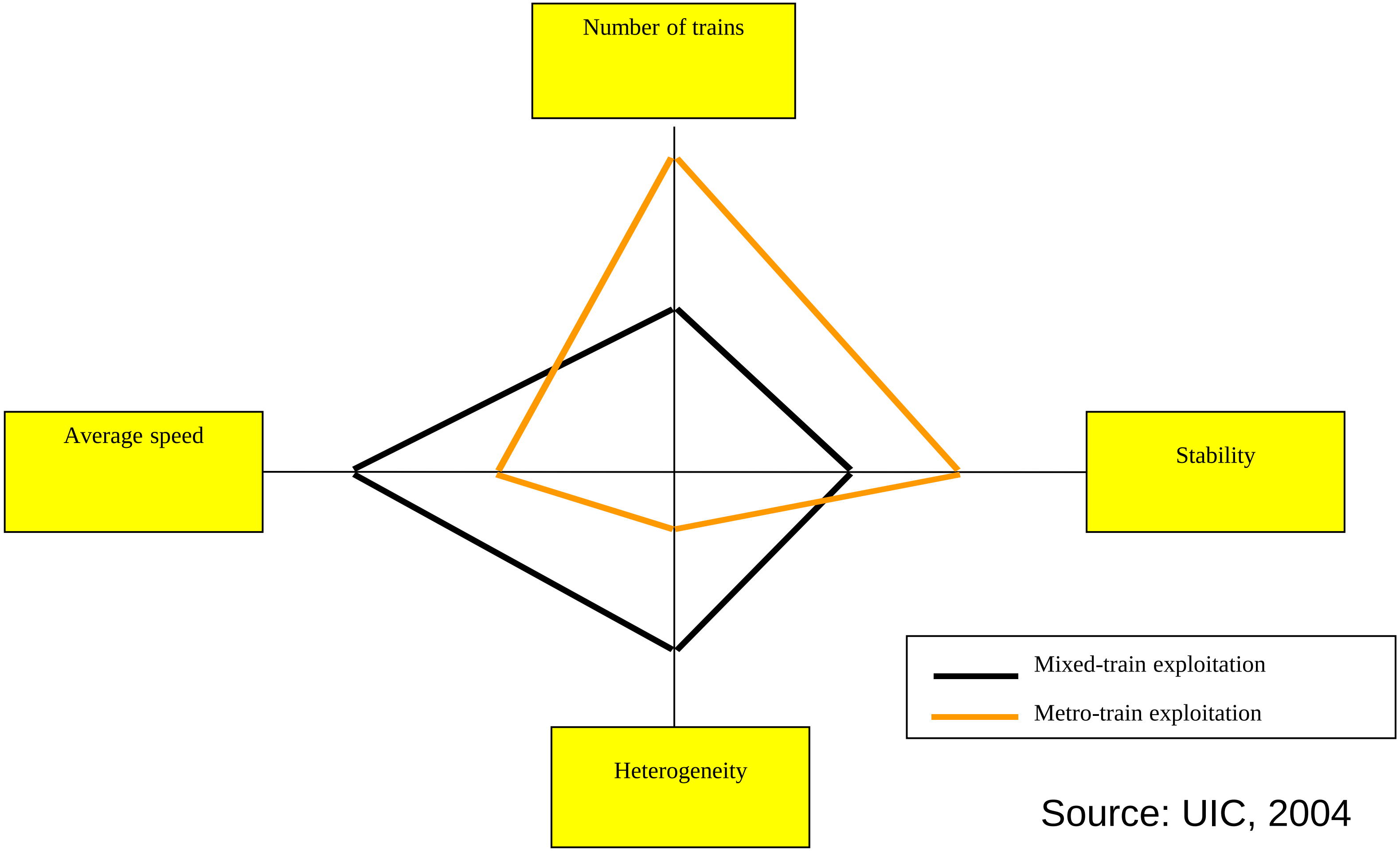
Capacity depends on

- Timetable
  - Train speed and homogeneity
  - Train order
- Infrastructure
  - Alignment
  - Number and length of tracks
  - Number of stations
  - Number of lines
  - Signalling & safety system

- Rolling stock
- Weather
- Human behavior

  - Travel time differences
  - Minimum headways
  - Timetable margins
  - At-grade crossings, flyovers, speed reductions, steep gradients
  - Single (bidirectional), passing loop
  - Double, merging/diverging/crossing, terminal, stabling
  - Fixed block {one-section/multiple track sections}
  - Automatic Train Protection (ATP)
  - Automatic Train Control (ATC)
  - Automatic Train Operation (ATO)
  - Moving block

Capacity balance



Number of trains

Average speed

Stability

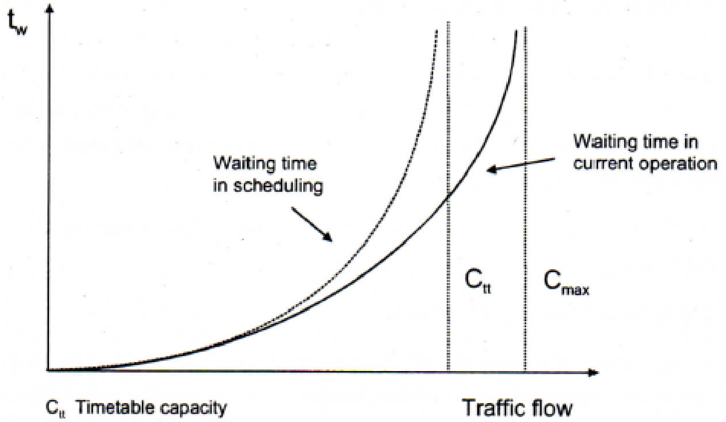
Heterogeneity

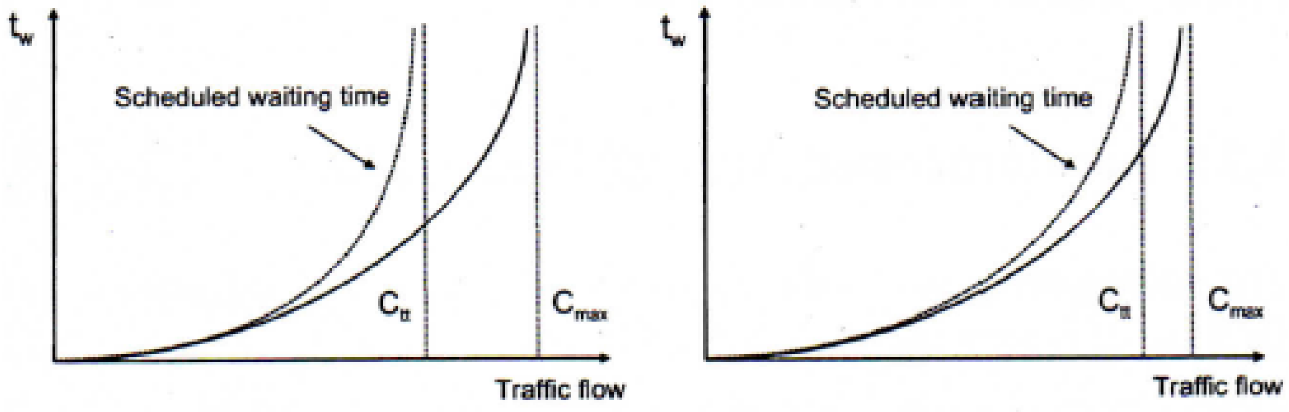
Mixed-train exploitation

Metro-train exploitation

Source: UIC, 2004

Trade-off between waiting time and capacity





a) High variation of minimum line headways

b) Low variation of minimum line headways

Classification of capacity estimation models

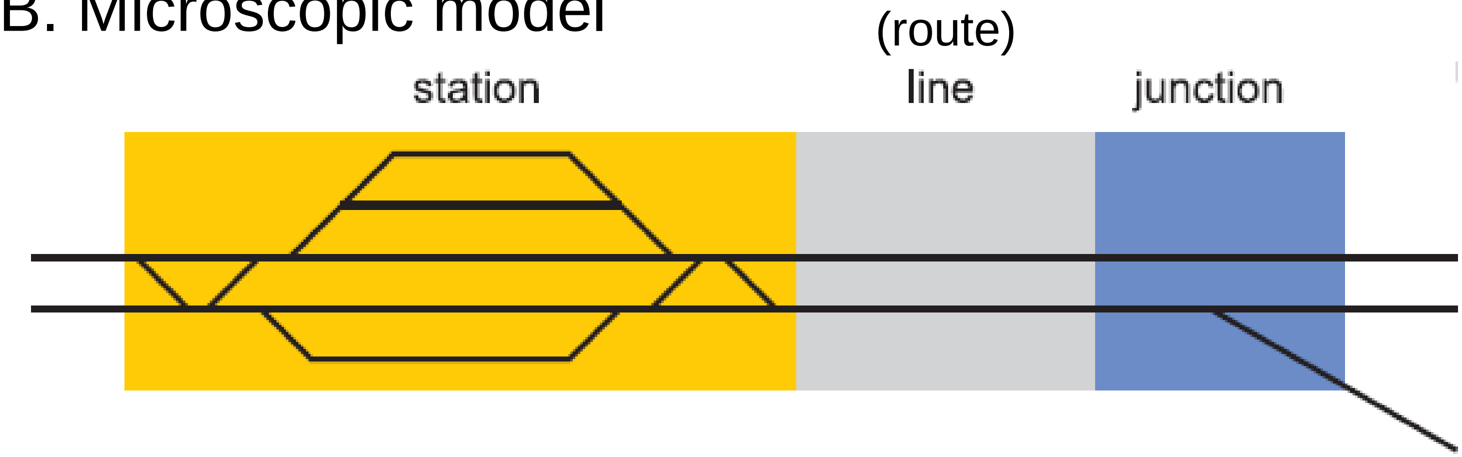
IAROR
International Association of Railway Operations Research

	Open track	Station	Network
A. Graphical (rule based)			
❖ Train diagramming	✓	✓	✓
B. Analytical			
❖ Track occupation	✓	✓	-
❖ Waiting time, stability margin	✓	(✓)	(✓)
❖ Queueing	✓	(✓)	-
C. Simulation			
❖ Macroscopic	✓	✓	(✓)
❖ Microscopic	✓	✓	((✓))
D. Combinatorial Optimisation			
❖ (Mixed) Integer Linear Programming	✓	(✓)	(✓)
❖ Heuristics (local search, genetic, tabu search)			
❖ Stochastic programming, Light robustness, Recoverable robustness, ...			

Infrastructure model

A. Macroscopic model

B. Microscopic model

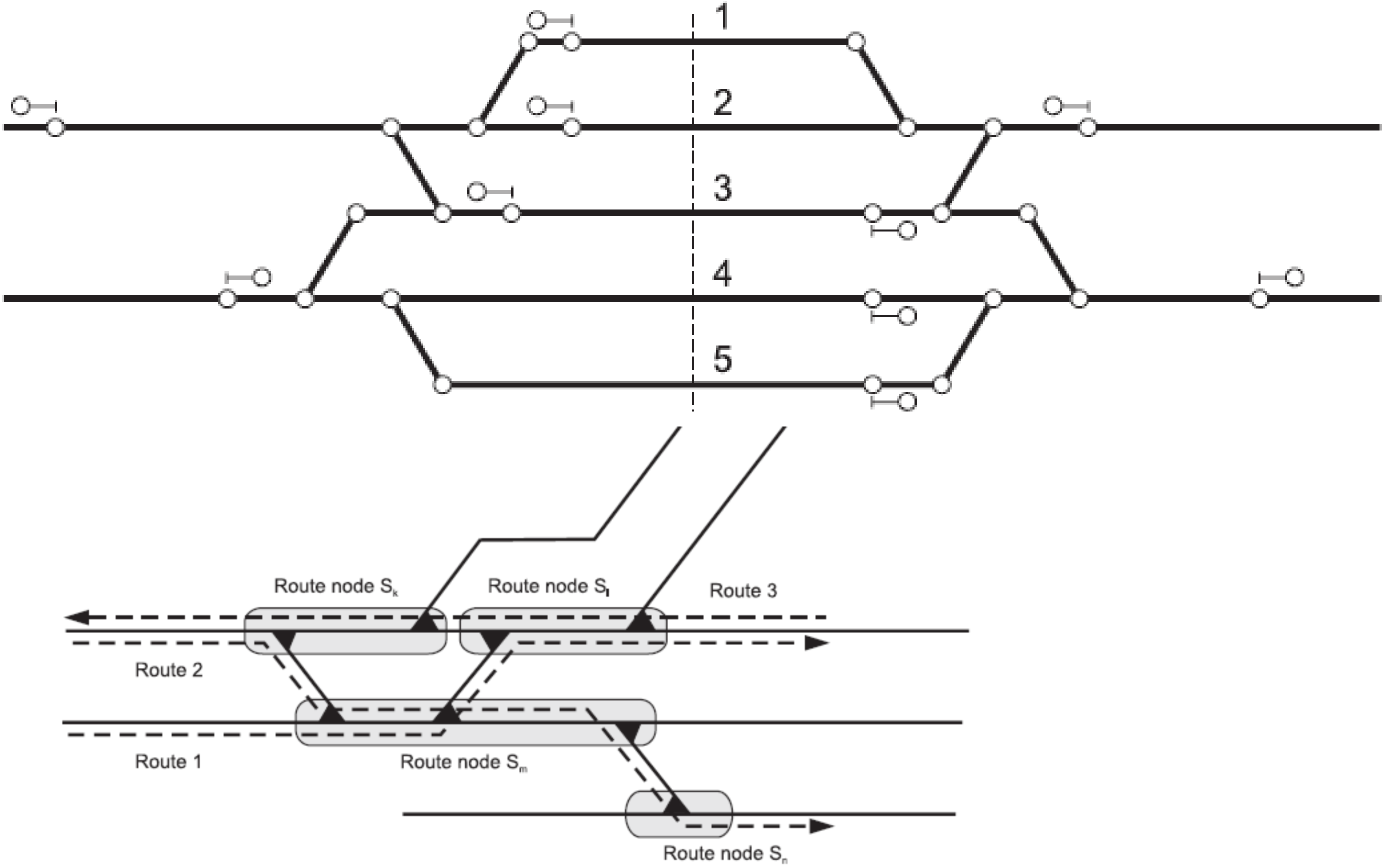


Drawbacks of macroscopic capacity estimation model

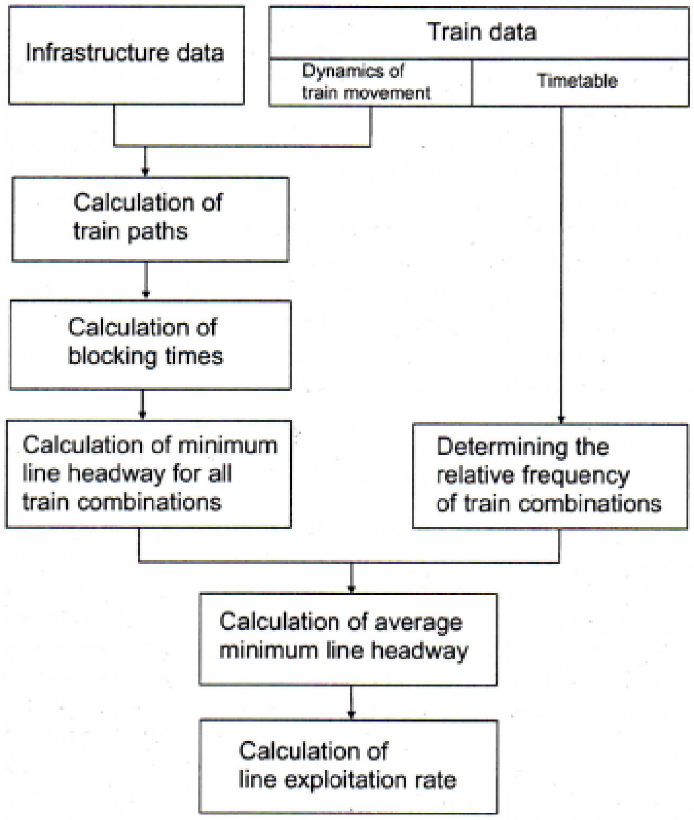
- Inaccuracy of scheduled travel (running and dwell) times
  - Linear train graphs: time loss due to acceleration, coasting and deceleration unknown/not disaggregated
  - Scale: rounded-up to full minutes
  - Discrete point modelling of trains: variation of train length neglected
- Validation of scheduled minimum time headways missing
  - Use of given standard minimum headway values (safety constraints)
  - Variation of train speed and minimum headway times neglected
  - Impact of ATP, ATC neglected
- Timetable margins unknown
  - Standard running time supplements not verified nor differentiated
  - Amount of buffer times unknown

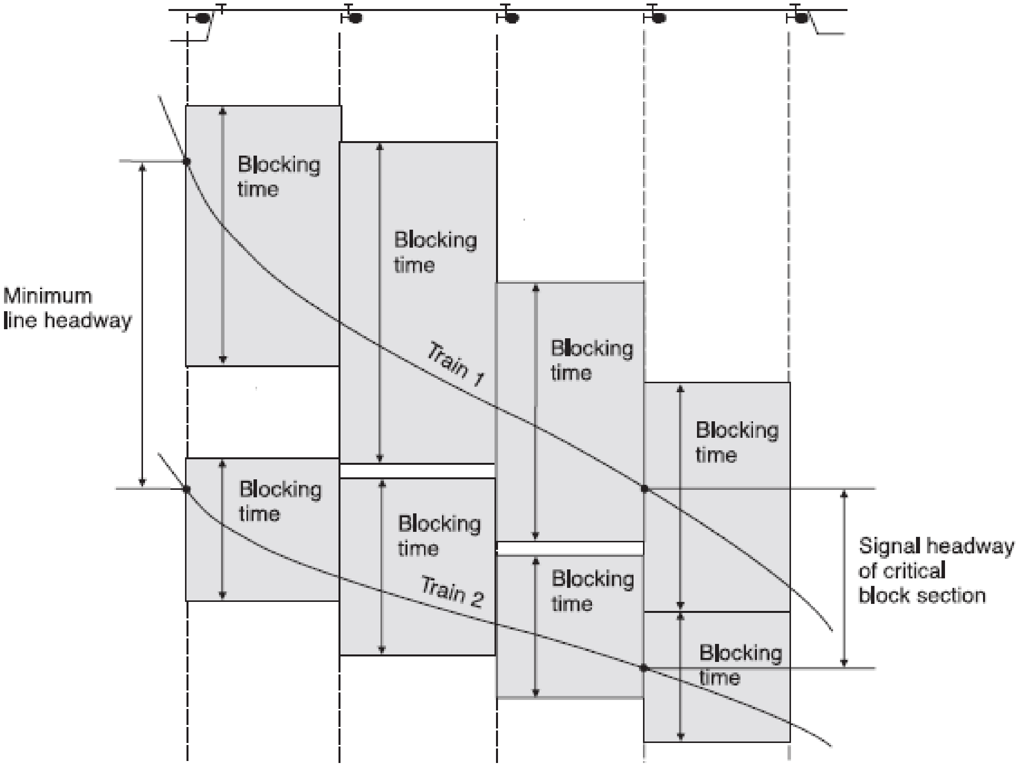
⇒ Insufficient precision and reliability of capacity estimation!

Microscopic model of station track yard and route nodes



Analytical capacity estimation





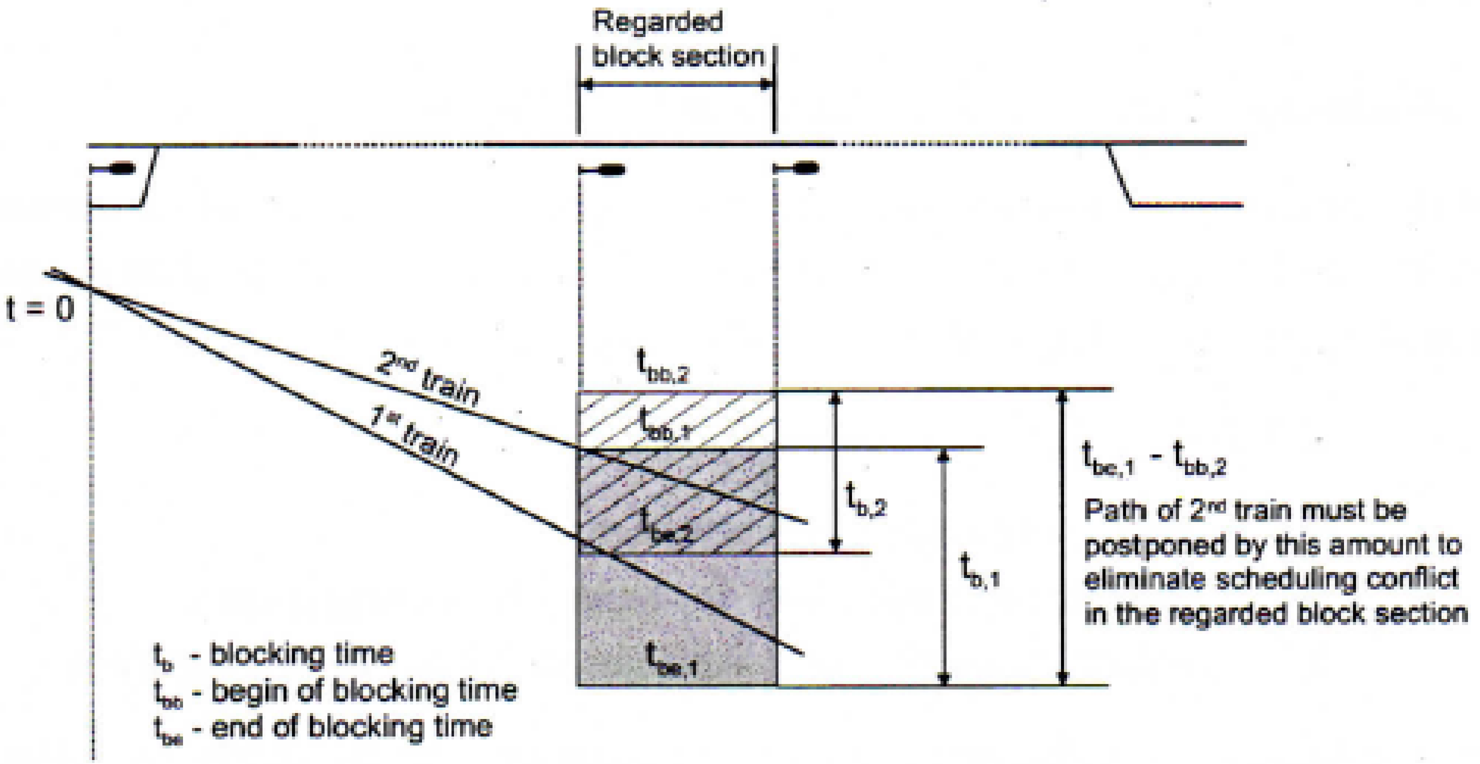
Microscopic infrastructure and rolling stock model

International Association of Railway Operations Research

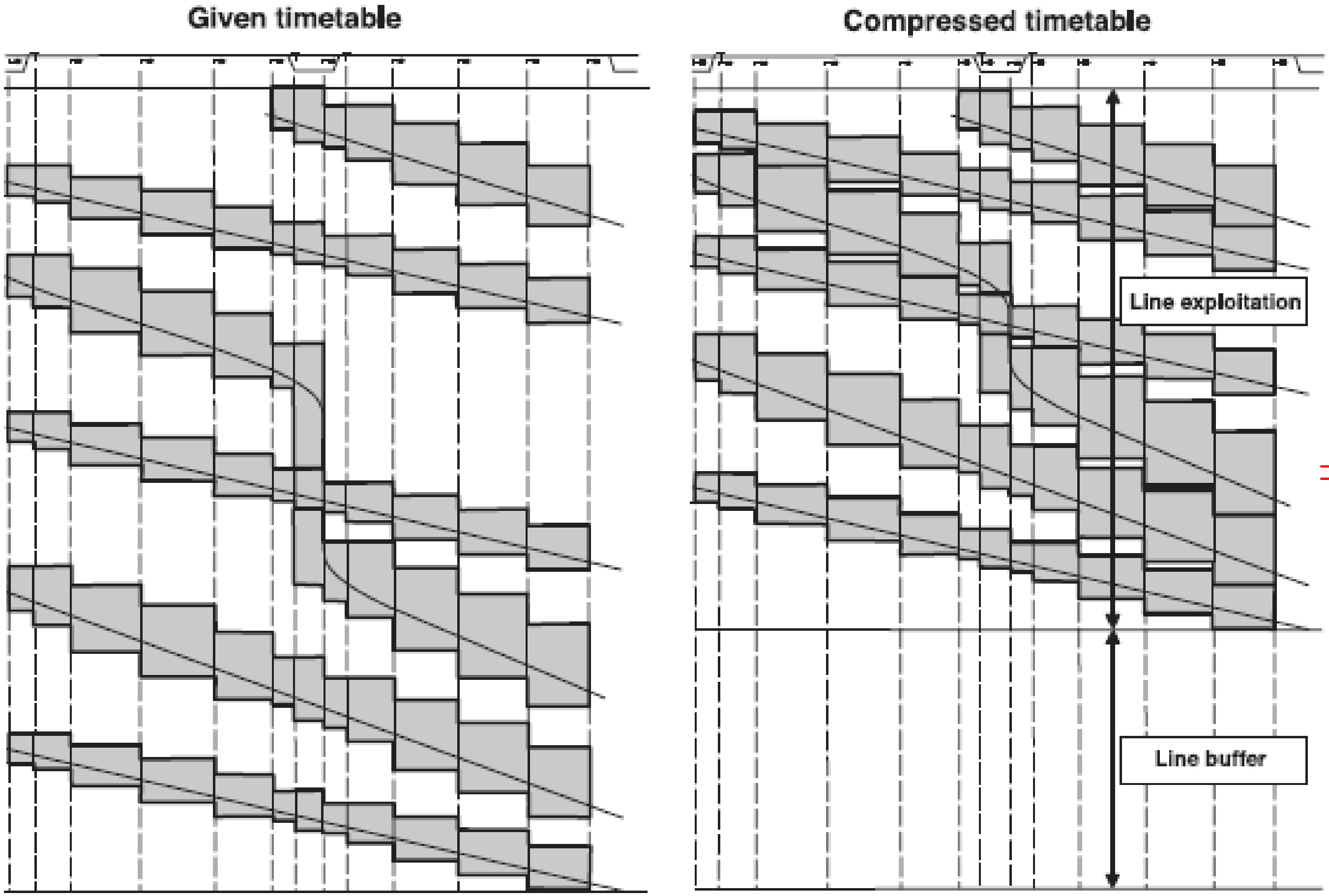
Input

- Graph modelling of track infrastructure
  - Track section and platform lengths, radii, gradients and max. speed
  - Location and distance between signals, switches, crossings, insulation joints, overhead contact line separators,
- Specification of signalling and safety systems
  - Blocking and clearance, signal aspects, overlaps
  - Train detection, location of track circuits/axle counters/fouling points
  - Interlocking, set-up and (partial) release of routes
  - Train protection, train control
  - Train regulation
- Train length, weight, resistance, tractive effort-speed diagram

Calculation of (scheduled) blocking time overlap



Capacity consumption: ‘compression’ of blocking time diagrams



⇒Drawbacks:
timetable
dependency,
transferability

Microscopic capacity estimation

1. Estimation of blocking times $t_{bl\,i}$ of trains per line
2. Determination of minimal headway time $t_{h\,ij}$ between trains
   - at departure (according to different train sequences)
   - at arrival (stations)
   - at conflict points (merging/crossing of lines, long block, speed limit)
3. Determination of prevailing minimal headway times;
   mean minimal headway $t_{hm} = \Sigma\,(t_{hij} \cdot p_{ij})$; $p_{ij} = n_i \cdot n_j / n^2$
4. Estimation of (scheduled/feasible) number of train path n/n_{max}
5. Estimation of total track occupation time of compressed (scheduled) train graph $T_{toc} = n \cdot t_{hm}$
6. Estimation of scheduled track occupation $\rho_s = T_{toc}/T$ [%]
7. Estimation of maximal track occupancy $\rho_{max} = T_{toc\,max}/T$ [%]

Impact of block length and speed on blocking time

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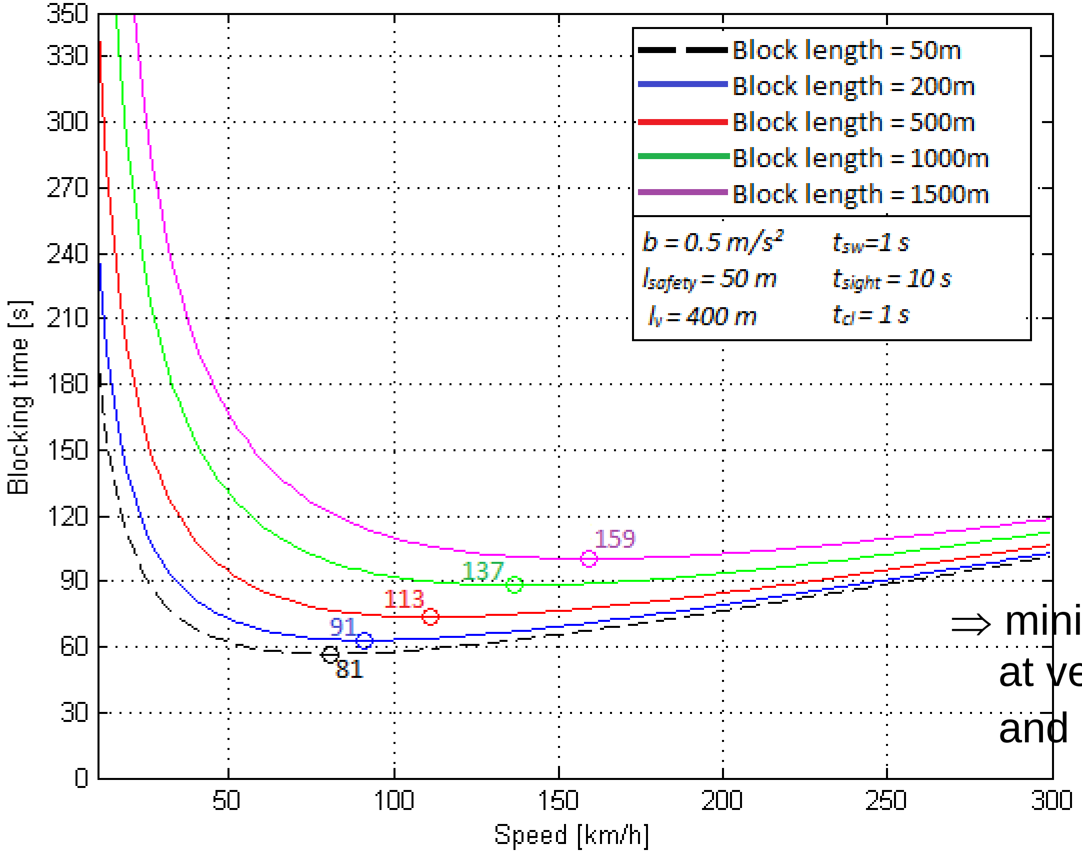
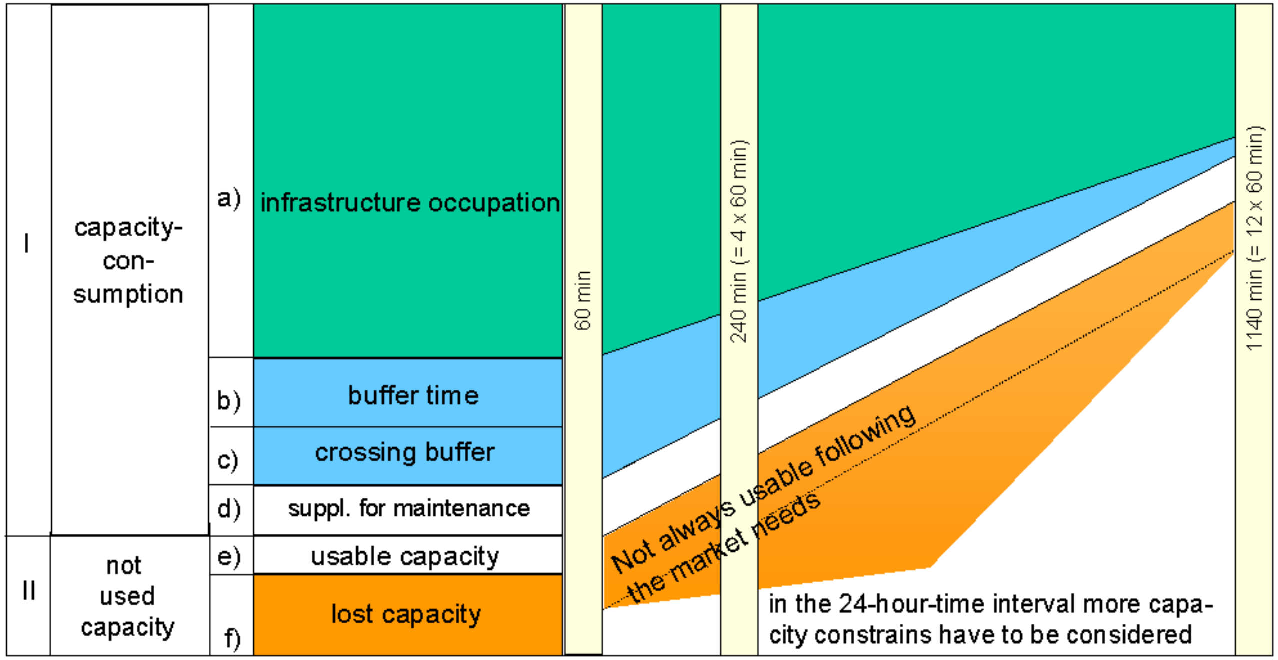


⇒ minimum blocking time at very short block length and low speed ≈ 80 km/h!

$$T_{block} = t_{sw} + t_{sight} + (l_{br}+l_{block}+l_{safety}+l_v)/v + t_{cl}$$

Capacity consumption levels recommended by UIC leaflet 406



Type of line	Peak hour	Daily period
Dedicated suburban passenger traffic	85 %	70 %
Dedicated high speed lines	75 %	60 %
Mixed traffic lines	75 %	60 %

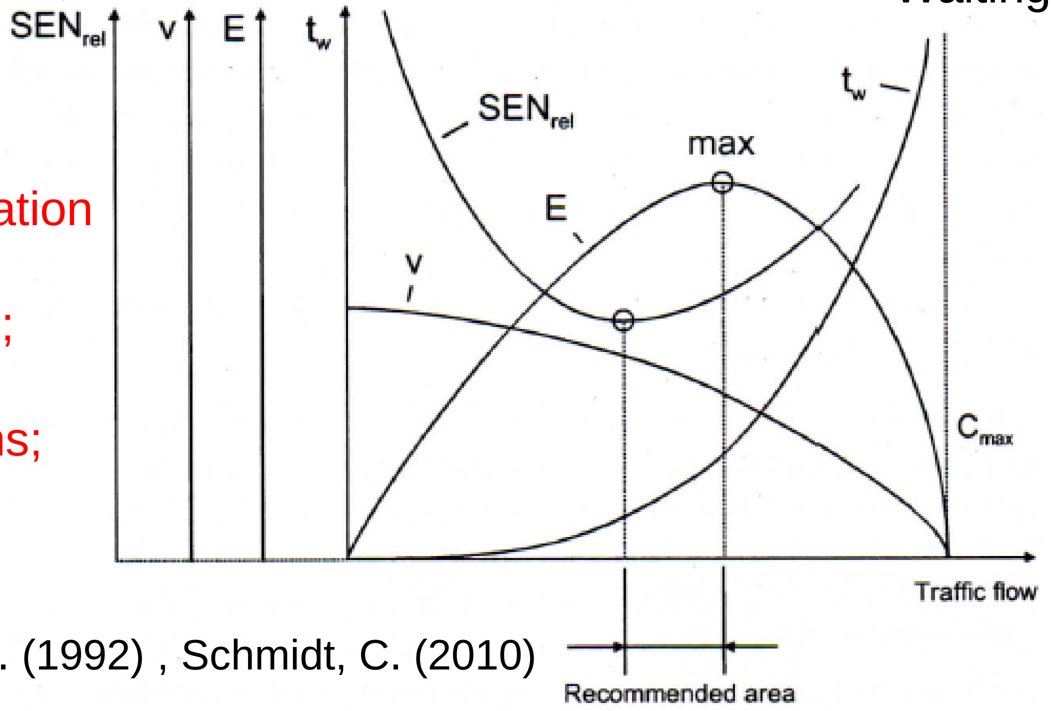
Recommended area of traffic flow

Traffic energy E = N·v^2 $[\frac{km^2}{h^2}]$

Relative sensitivity of waiting time

Speed v

Waiting time t_w [min]

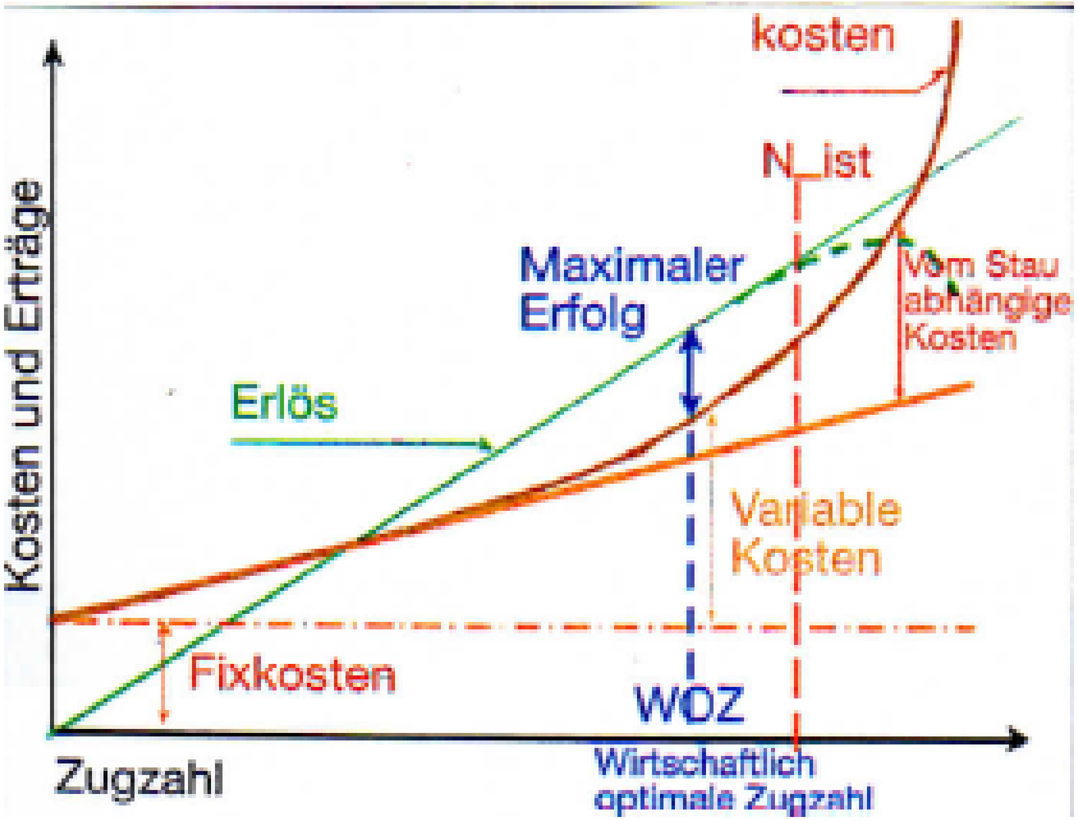


Capacity [1/*T*]

⇒ Problems: validation of waiting time and speed distributions; combination of different dimensions; transferability

Sources: Hertel, G. (1992) , Schmidt, C. (2010)

‘Optimal’ analytical route capacity and cost-benefit model

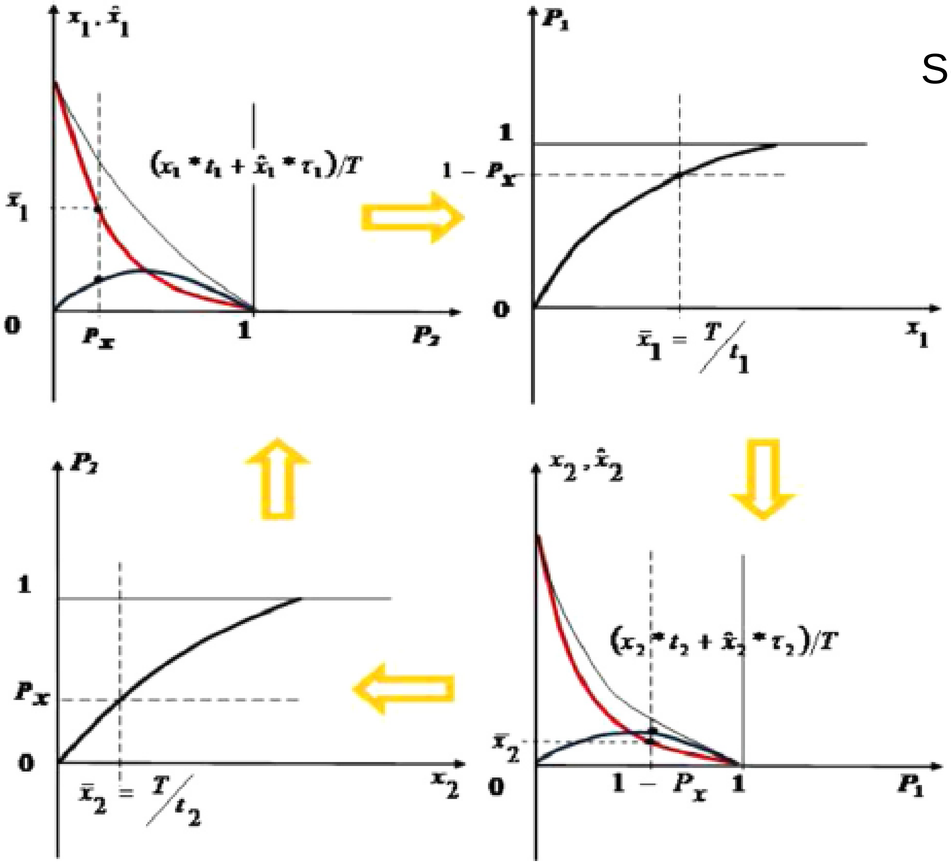


Source: Schwanhäußer, 2009

⇒Shortcomings:

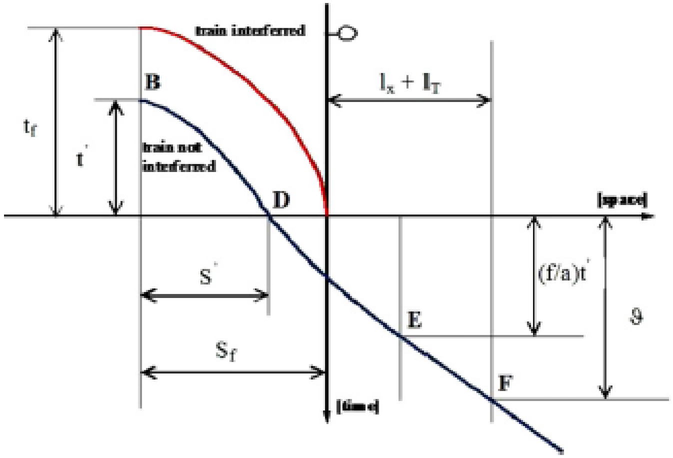
- complicated parameter calibration;
- validation?
- optimality gap unknown

Analytical junction occupation model



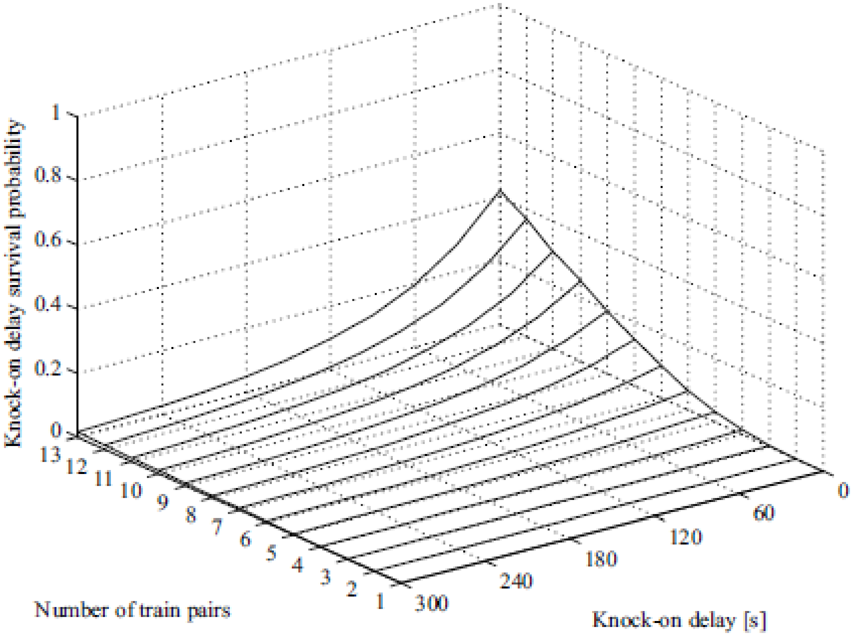
Source: Mussone & Wolfler Calvo, 2013

⇒Shortcoming: Switch, sight and approach time neglected

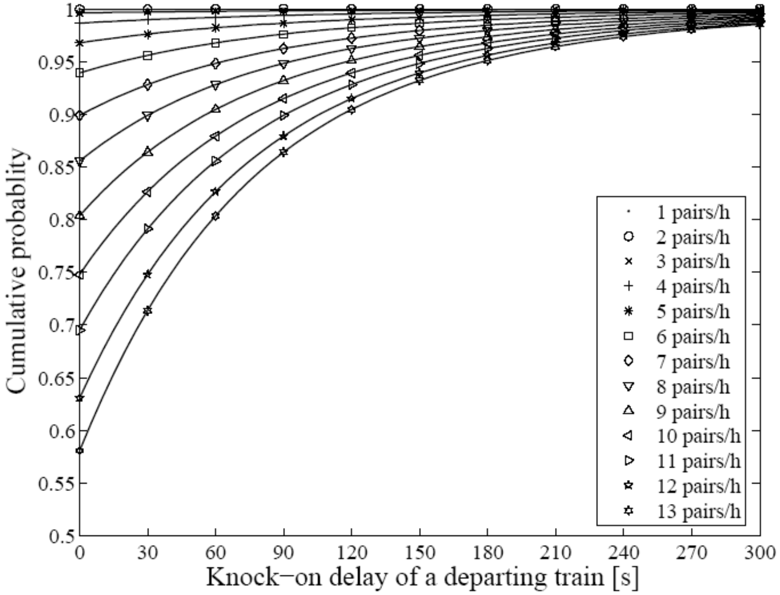


Conditional probability junction capacity estimation model

Consecutive delay survival probability for northbound departing trains as function of number of trains passing at level crossing



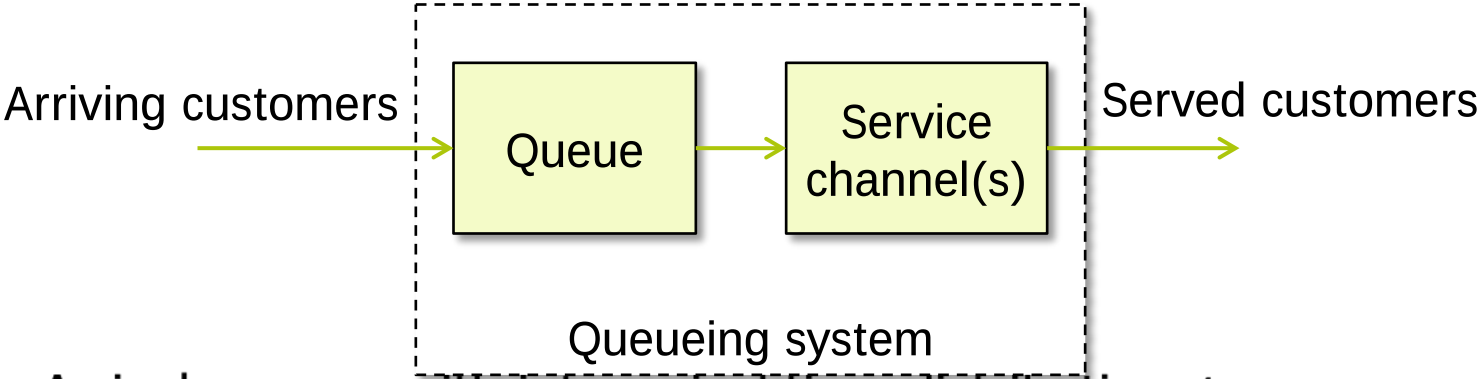
Consecutive delay survival probability for a northbound departing train as function of train frequency passing at level crossing



Source: Yuan, 2006

⇒ Shortcomings:…

Queuing models to estimate train delays and capacity



Arriving customers

Queue

Service channel(s)

Served customers

Queueing system

- A: Arrival process with interarrival time distribution A
    - Arrival time t_k, interarrival time $a_k = t_{k+1} - t_k$ of customer k
- B: Service process with service distribution B
    - Service time b_k
- n: Number of service channels
- Queue discipline: First Come First Served (FCFS), Priority (PR)

Notation:

- $A/B/n$ are systems with queue capacity $m = \infty$ (general $A/B/n/m$)

Classification of queuing models

Variation coefficients

$k = 1/V_A^2 = (\sigma^2 A / E^2 A)^{-1}$, V_A: variance of arrival headway times

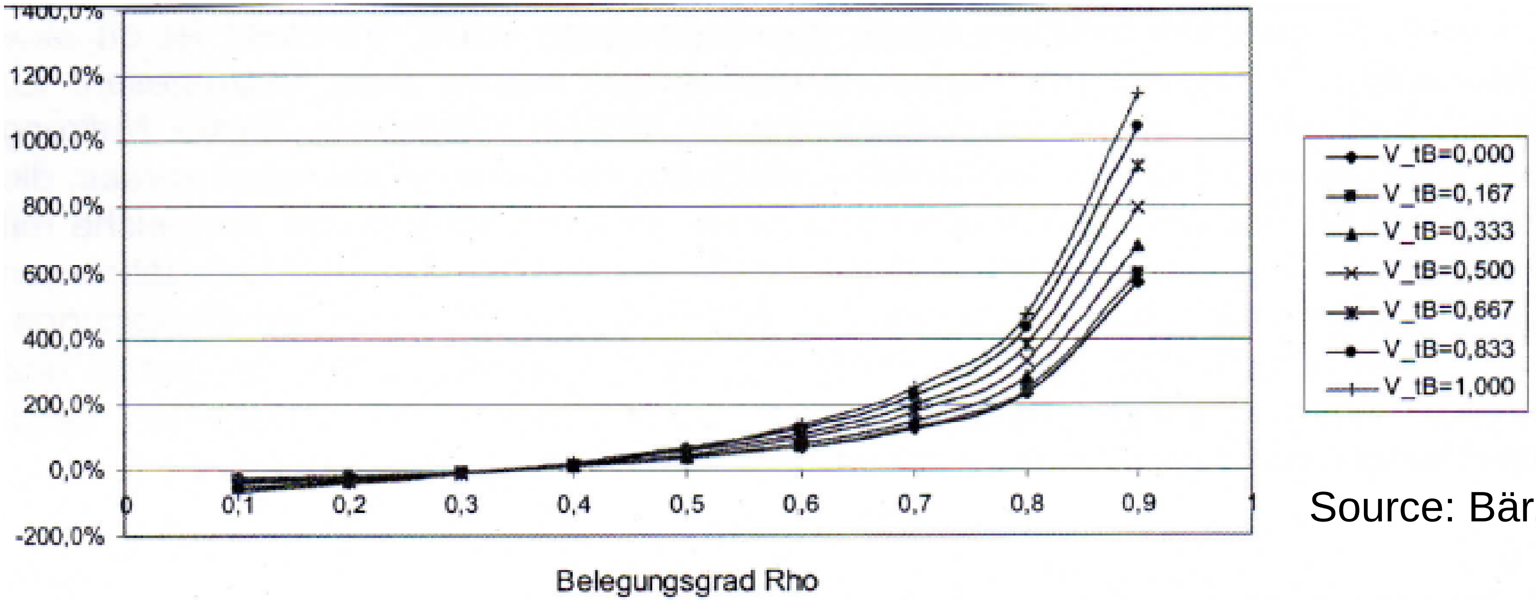
$l = 1/V_B^2 = (\sigma^2 B / E^2 B)^{-1}$, V_B : variance of service times (minimal headway)

Arrival distribution	Service distribution			
	big variance $0< l <1$	Markov $l = 1$	small variance $1 < l < \infty$	deterministic $l = \infty$
big variance $0<k<1$				
Markov $k = 1$		M/M/1	M/GI/1	M/D/1
small variance $1<k<\infty$		GI/M/1	GI/GI/1	
deterministic $k = \infty$		D/M/1		D/D/1

M: Markovian process (exponential)
GI: General independent process (iid)
D: Dirac process (deterministic, variance = 0)

⇒ Drawbacks: iid assumption invalid for periodic timetable and heavy traffic; service distributions unknown

Comparison with estimated waiting time of clockface timetable



Source: Bär, 2009

Relative deviation between *GI/GI/1* queuing system and 2-train clockface timetable

⇒ Modelling of clockface process by estimated waiting time and variation coefficient of interarrival time must be rejected!

Combinatorial optimisation models

1. Integer Linear Programming (ILP)
   (Review see Cacciani & Toth, 2012)

2. Genetic Algorithms (GA) }

3. Simulated Annealing (SA) } Disregarded here

4. Constraint Programming (CP) }

5. Job-Shop Scheduling
   (Mascis & Pacciarelli, 2002; D'Ariano et al. 2007, 2008, 2009...
   Burdett & Kozan, 2004, 2006, 2009, 2010; Liu & Kozan, 2011)

Integer Linear Programming (ILP)

- Objective functions
  - Maximize customer satisfaction (minimize travel times, waiting times, number of transfers)
  - Maximize infrastructure use (train throughput)
  - Minimize changes w.r.t. requested arrival & departure times
  - Minimize costs of train operation
  - Increase robustness (avoid/minimize delay propagation)
- Constraints
  - Periodicity (regularity, running, dwell and transfer times)
  - Safety (minimal headway times)
  - Infrastructure discontinuities (number of tracks, terminals, switches, crossings, platform length)
  - Rolling stock composition, performance and assignment
  - etc.

Integer Linear Programming (ILP)

Cyclic train timetabling

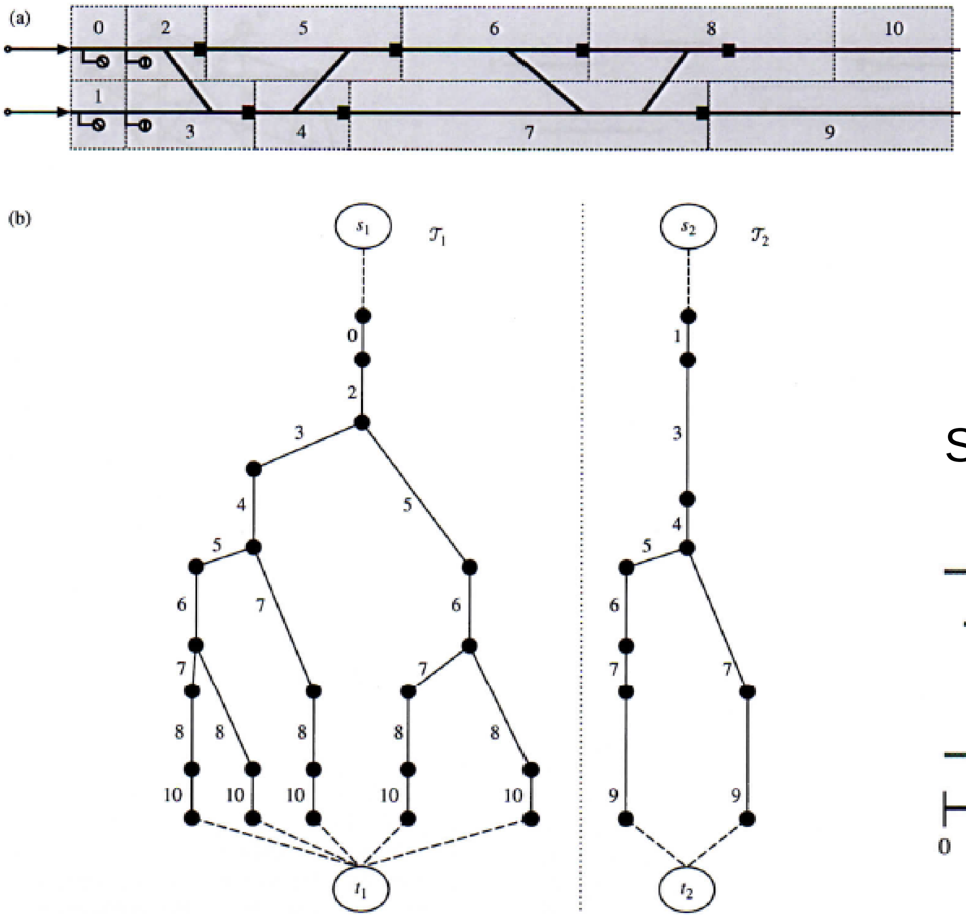
- Periodic Event Scheduling Problem (PESP)
  - Constraint Graph (directed graph with node set N and arc set A)
  - Constraint propagation algorithm
- Given timetable of train operator assumed to be *feasible,* i.e. route conflicts within stations (interlocking areas) neglected
- Timetable consists of fixed running times between stations that may be altered within certain bounds (time windows)
- Solving PESP of larger networks and complex nodes is *NP hard*
- Relaxation of (some) constraints in order to find a near-optimal solution and/or speed-up computation time
- Mixed Integer Linear Programming (MILP) tolerates mix of non- and integer constraints

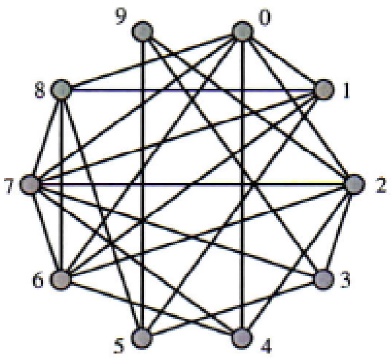
Integer Linear Programming (ILP)

Non-cyclic train timetabling

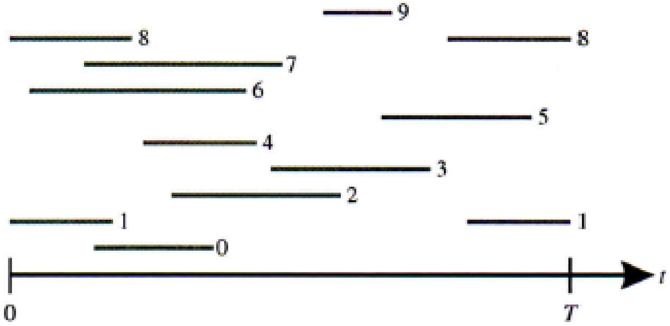
- More appropriate in competitive market with generally conflicting train path requests
- Arrival and departure times represented by continuous variables (MILP)
- Binary variables expressing the train order at departures
- Discretising the time (each node corresponding a time instant, arcs representing train travel or stop at station)
- Costs associated e.g. with the deviation from preferred departure time, travel times and dwell times
- Set of arcs representing assumed *feasible* travel times between and dwell times per train at each station (time-space graph equals train path)
- Trains may be cancelled
- Easier to solve than PESP of periodic timetable (more flexible)

Resource-Tree Conflict Graph





Source: Caimi et al, 2011



Drawbacks of (M)ILP

Exeption: ILP relaxation of Resource-Tree Conflict Graph by Caimi et al, 2011

- Possible headway conflicts on open and station tracks due to speed limitations and/or longer approach and block signal distances neglected
- Route conflicts in interlocking areas neglected (*feasibility* assumption)
- Shunting movements generally neglected
- Availability of sufficient parking/stabling tracks not guaranteed

⇒ Validity of given timetable and used safety constraints not proven!

⇒ Lack of accuracy compared to analytical, queuing and microscopic simulation models that may endanger timetable feasibility!

⇒ Optimality claim may lead to misunderstanding

⇒ Stochastic Programming and Robust MILP train timetabling models cannot provide optimal allocation of timetable margins due to inherent restrictions of macroscopic models!

Conclusion

- Track capacity is influenced by the timetable, infrastructure, signalling and safety systems, rolling stock, weather and human behaviour
- Macroscopic capacity estimation models simplify infrastructure, route and signalling constraints but can support strategic network and timetable planning
- Microscopic capacity models can accurately estimate minimum headways, capacity consumption and timetable margins for different signalling and safety systems
- (M)ILP cannot substitute more accurate analytical capacity analysis and microscopic timetable simulation
- Micro-macroscopic (meso-scopic) models can bridge the gap between accurate analytical and efficient combinatorial optimisation

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