Method for an optimized passenger orientated connection management during the planning and the operation process

M. Klemenz, T. Siefer
Institute of Transport, Railway Construction and Operation, Leibniz University of Hanover, Germany

Abstract

The trust of the customers in adherence to their expectation to a transport service determines the modal split of the passenger transport. Therefore it has to be a goal for each public transport operation company to maintain and to improve the customer's trust. An important service criteria by a customer accepted public transport offer is the travel time. The travel time depends on the running time, the dwell time, etc., but also on the number of transfer procedures and the transfer waiting time. One of the essential research problems in the surroundings of the connection planning is the question under which condition it is appropriate for the planning of a connection respectively of the holding of a connection. An important aspect to answer this question is the evaluation of the additional total travel time for all involved passengers in consideration of an achieved (additional travel time for transit passengers in the connecting vehicle) or not achieved (additional travel time for transfer passengers in the feeder vehicle) connection.

The first part of this paper develops a new method of an optimized passenger orientated connection management during the planning process (scheduled timetable). The goal is to minimize the additional travel time in consideration of a planned or not planned connection based on the number of all involved passengers. At first it is necessary to identify all influencing variables (e. g. the interval of the connecting vehicle, the arrival, departure and minimum transfer time of the feeder and the connecting vehicle). After that all boundary conditions will be modelled by using the graph theory. With an adequate shortest path algorithm it is possible to generate connection strategies specific for stations, lines or the whole networks. Particularities of railway operation (e. g. turn around times, operating fleet, timetable interval, conflicts, infrastructure bottlenecks) also can been considered in the model.

The second part of this paper deals with a new method of an optimized passenger orientated connection management during the operation process (including delays). The aim of this model is to calculate in consideration of all influencing factors the waiting time of the connecting vehicle which minimizes the total travel time of all concerned passengers. Influencing factors are for example the interval of the connecting vehicle, the number of involved passengers, the arrival, departure and minimum transfer time of the feeder and the connecting vehicle and the delay distribution of the vehicles.

Finally the feasibility and the benefit of these two models will be verified by using test cases for a generated realistic research area.

The evaluation of the test cases will indicate that the developed methods and models can be used for an optimized passenger orientated connection management during the planning and operation process.

Introduction

In the surroundings of the connection planning there are two essential research questions:

- Under which condition it is appropriate to plan or not to plan a connection?
- Under which condition it is appropriate to hold or not to hold a connection?

An important aspect to answer these two questions is the evaluation of the additional total travel time for all involved passengers in consideration of an achieved or not achieved connection.

If passengers can reach their final destination only by transferring from one train into an other train, the travel time increases according to the transfer time (minimum transfer time and transfer waiting time). The holding of a connection means an extension of the travel time for the passing through passengers (PTP). The no holding of a connection increases the travel time of the transfer passengers (TP). The travel times extension of the PTP in the connecting train and
of the TP in the feeder train are normally anti-proportionally. The amount of the additional travel time for all concerned passengers depends of the difference between the arrival time of the feeder train and the departure time of the connecting train (figure 1). Additional dwell times only appear, if the technical minimum departure time of the connecting train is less than the amount of arrival time of the feeder train and the minimum transfer time (cases 1 and 4).

General influencing factors
The method for an optimized passenger orientated connection management and the influencing additional total travel depends on several influencing factors:
- Number of transfer passengers
- Number of passing through passengers
- Arrival time of the feeder train
- Minimum transfer time of the feeder train to the connecting train
- Departure time of the connecting train
- Departure time of an alternative connecting train (service interval of the connecting train)
- For the operation: delay distribution of the involved trains

Determination of number of passengers
The method for an optimized passenger orientated connection management requires information about the modal split, the demand matrix and the time or date of a travel. For the
determination of these values different resources are applicable (e.g. statistical evaluation of tickets, interview and count of passengers, positioning with handy ticketing, etc.).

**Optimized passenger orientated connection management during the planning process**

To minimize the additional dwell times in the planning process, it is necessary to develop a method in consideration of the difference between the arrival time of the feeder train and the earliest departure time of the connecting train, required transfer times, the frequency of the connecting train (the earliest departure time of an alternative connecting train) and the number of concerned passengers.

**Two train model**

The developed method will be demonstrated at first for a **two train model** (figure 2), with transfer passengers from the feeder train to the connecting train (application: connection station is final destination of the feeder train).

![Figure 2: two train model](image)

**Required data input:**
- Number of passing through passengers (PTP)
- Number of transfer passengers (TP)
- Number of boarding passengers at connection station, without transfer passengers (BP)
- Number of "on the way" boarding passengers (OBP)
- Distance between the amount of the arrival time of the feeder train and the minimum transfer time and the technical minimum departure time of the connecting train
- Technical minimum departure time of an alternative connecting train

This data allows the calculation of the break even point, which defines the time distance between the arrival time of the feeder train (incl. the minimum transfer time) and the departure time of the connecting train. Concerning to a minimized extension of travel times time distance values below the break even point involve a planning of the connection. Time distance values above the break even point entail a no planning of the connection.

The following figure (figure 3) shows a abstract of the break even point calculation in correlation of the proportion of the number of transfer passenger and the sum of number of passing through passengers, boarding passengers and on the way boarding passengers and in correlation of the service interval of the connecting train.
The break even point calculation provides a comprehensive spectrum of applications for the scheduling of timetables:

1. Determination of the maximum allowed time distance between the arrival time of the feeder train (incl. minimum transfer time) and departure time of the connecting train.
2. Determination of the required service interval of the connecting train in cases of no planed connection strategy.
3. Determination of required passing through passengers in cases of a no planed connection strategy.
4. Determination of required transfer passengers in cases of a planed connection strategy.
5. Determination of required minimum transfer time in cases of a planed connection strategy.

The break even point calculation is also adaptive for three or more train models.

Station specific n- train model
In the next step the developed method will be advanced for a station specific n-train model (figure 4), with transfer passengers between all involved trains. The model for a station specific connection management depends on graph algorithms. Each graph represents a station with several train connections. The starting node (source) is the pull into a station and the ending node (sink) is the exit of the station. Each involved train has a connection link between source and the second node. This second node represents the arrival time of this train (tan). A waiting link connects the arrival time with a possible departure time (tab) of this train. The number of different waiting time links depends on the number of involved trains. Each waiting time link includes costs and is representing a certain connection strategy of a train. The costs will be calculated based on the additional travel time of all involved passengers. The last link connects the possible departure time with the exit of the station (sink).

To detect an optimal connection strategy it is necessary to compare all the possible waiting links of a train. The link with the lowest costs and therewith the lowest additional waiting time for the concerned passengers is representing the optimal connection strategy. Each train has only one optimal waiting link. The calculation or selection of a waiting link of one train has no influence of the detection of the waiting links of the other trains. This means that the calculation of the optimal connection strategy is for a station specific n-train model for each train independent. The optimal connection strategy for the whole station is the sum of all calculated optimal waiting time links.
To identify the optimal connection strategy it is necessary to calculate the costs of each waiting link (HK) of a train. Therefore two equations (1 + 2) are necessary:

**Equation 1:** Costs of the waiting link $\rightarrow$ Train $x_0$ without additional waiting time:

$$ HK_{x_0}^{x_0} = \sum_{x=x_0}^{x=n} U_{(x)(x_0)} \times (T_{(x)} - t(x,x_0) + tm(x) - tab(x)) $$

with $x_0 = 1, \ldots, (n-1)$ and with $x > x_0$

if $x_0 = n \rightarrow HK = 0$

**Equation 2:** Costs of the waiting link $\rightarrow$ Train $x_0$ is waiting for train $x$

$$ HK_{x_0}^{x} = $$

1. $D_{(x_0)} \times (t(x) + tm(x) - tab(x_0)) +$

2. $\sum_{y=x_0+1}^{y=x} U_{(y)(x_0)} \times (t(y) + tm(y) - tab(y)) +$

3. $\sum_{z=x_0+1}^{z=x-1} U_{(z)(x_0)} \times ((t(z) + tm(z) - tab(z)) - (t(z) + tm(z) - tab(z))) +$

4. $\sum_{x=4}^{x=n-1} U_{(x+1)(x_0)} \times (T_{(x)} - (t(x+1) + tm(x+1) - tab(x_0)))$

with $x = x_0 + 1, \ldots, n$
Description:
(I): Additional travel time for passing through passengers of train xo
(II): Additional travel time for transfer passengers from train y (which arrives earlier than train xo) into train xo
(III): Additional travel time for transfer passengers from train z (which arrives later than train xo, but earlier than train x) into train xo
(IV): Additional travel time for transfer passengers from train x+1 (which arrives later than train x) into train xo

U(x)(xo): Transfer passengers from train x to train xo
T(xo): Departure time of the next connecting train (service interval)
tan (x): Arrival time of the feeder train
tab (xo): Departure time of the connecting train
tmüz (x)(xo): Minimum transfer time from train x to train xo
D (xo): Passing through passengers of train xo
HK_{xo}^{x}: Waiting link: Train xo is waiting for train x

Equation 3: The link with the minimal costs (K Min Zug xo) is representing the optimal connection strategy per train.

$$K_{Min}^{Zug_{xo}} = \text{Min} \{HK_{xo}^{y}, HK_{xo}^{z} \}$$

Equation 4: The sum of all minimal costs (K Min) is representing the station specific optimal connection strategy:

$$K_{Min} = \sum_{xo=1}^{n} K_{Min}^{Zug_{xo}}$$

N-train model for several stations
In the last step the developed method will be advanced for a n-train model for several stations (figure 5), with transfer passengers between all involved trains. The detection of an optimal connection strategy for several stations is distinctly more complicated and complex than the detection of a station specific optimal connection strategy. The determination of a path with minimal costs can not be done station by station. It must be done simultaneously. The required model also depends on the graph algorithm. To model the connection management for several stations it is useful to use a reference train (yo), which is driving through all involved stations. The graph is representing the whole research area. The source represents the first station of the reference train. The final node represents the destination of the reference train. Links, constrained of the number of possible connection strategies, connect the source with the following nodes. These nodes are representing the new arrival time of the reference train at the following station. The arrival time depends on the chosen connection strategy at the predecessor station. Waiting time links are connecting these nodes with the new arrival times at the next stations. At the last node all possible connection paths are running together. Each waiting link is a possible connection strategy of a train. The costs emerge from the additional travel times of all involved passengers. The detection of the minimum costs overall can not be calculated train by train. Rather the costs have to be calculated for all influenced trains together. Each possible waiting link of a train at a station will be combined with all possible waiting links at the other stations. The link path (per station only one link) with the minimal additional waiting time or travel time for all passengers is representing the optimal connection strategy for the reference train and for all influenced trains. For the calculation it will be used the Dijkstra [2 and 3] algorithm (shortest path or path with minimal costs).
After the detection of an optimal connection strategy follows the verification of the feasibility related to operational aspects. Not conflict free connection strategies must be rejected. Their paths will be blocked and a new calculation will follow.

Figure 5 shows two examples of a abstract of a possible graph model. Example one is a very simple graph model. The connection strategies of the reference train yo and the other trains yo+1(a1), yo+2 (a1) and yo+1 (a2) are independent. They can be calculated by their own. Example two shows that the connection strategy of train yo is directly connected with the connection strategy of train y-1(a2). The detection of an optimal connection strategy for the reference train yo is providing at the same time the connection strategy of train yo-1(a2). The connection strategies of other trains yo+1(a1) and yo+1 (a2) can be calculated by their own.

The connection strategy of a train, which scheduled departure time at a station occurs earlier than the departure time of the reference train, depends on the chosen connection strategy of the reference train at predecessor stations (figure 6 and 7).

Following example illustrates these dependencies: A reference train (train 1) has fixed arrival times at the stations a1 and a2 depending on the chosen connection strategy at the predecessor station. At station a1 train 1 has 3 options: It can continue its journey without holding a connection or it can hold a connection to train 2 or to train 3. Therefore the arrival time of train 1 at station a2 depends on the chosen strategy at station a1. At station a2 train 4 has a scheduled departure time which is located earlier than the possible arrival times of train 1. This means that the waiting time costs of train 4 depend on the chosen connection strategy of train 1 at station a1. If train 4 is not waiting for train 1, the additional travel time of transfer passengers of train 1 increase. This additional time is independent of the chosen connection.
strategy at station a1. If train 4 is waiting for train 1 different additional waiting time costs (depending on the chosen strategy in a1) for the passing through passenger in train 4 occur. This waiting time increase depending on postponed arrival time of train 1. To find the minimal additional waiting time for all involved passengers it is necessary to combine all possible connection strategies.

Following combinations are possible:

- **HKU14 with HKU21,U31**: train 1 and train 4 are not waiting
- **HKU14 with HKD1,U31**: train 1 is waiting for train 2 and train 4 is not waiting
- **HKU14 with HKD1,U21**: train 1 is waiting for train 3 and train 4 is not waiting
- **HKD4(1) with HKU21,U31**: train 1 is not waiting and train 4 is waiting for train 1
- **HKD4(2) with HKD1,U31**: train 1 is waiting for train 2 and train 4 is waiting for train 1
- **HKD4(3) with HKD1,U21**: train 1 is waiting for train 3 and train 4 is waiting for train

The combination with the minimal costs represents the optimal connection strategy for all influenced trains. In this case the optimal results for all passengers can be reached if train 1 leaves station a1 without waiting and train 2 will wait for train 1 at station a2 (figure 7).
Sub Problems

The calculation of the optimal connection strategy for the reference train depends on influences of other trains. The reference train and all influenced trains require only one common graph. If the scheduled departure time of a train occurs before the possible departure time of the reference train, it is possible to solve the connection strategy problem by dividing the whole graph (figure 8) into sub problems [1]. These sub problems can be solved or calculated independently.

Figure 8: Division into sub problems

This method helps to reduce the size of the graph model. Each sub problem supplies one link with the best connection solution for this sub problem (figure 9). This link will be integrated into
the whole graph model for the further calculation of the global connection strategy. At each station $a_i$ and for each sub problem $TP_j$ optimal connection strategies $K_{\text{MinZüge}(<\text{yo})}(TP_j, a_i)$ will be calculated. Each sub problem depends on the arrival time of the reference train and the chosen connection strategy at the predecessor station $a_{i-1}$.

Equation 5: The optimal connection strategies $K_{\text{MinZüge}(<\text{yo})}(TP_j, a_i)$ for train which arrives earlier than the reference train can be calculated with following equation.

$$K_{\text{MinZüge}(<\text{yo})}(TP_j, a_i) = \min \sum_{k=1}^{yo-1} HK_k^x = HK_1^x + ... + HK_{yo-1}^x$$

with $x=1,..,yo-1,yo,yo+1,...,n$

with $k=1,...,yo-1$

$k=1$ Train 1 arrives in station $a_i$ earlier than all other trains

$k=2$ Train 2 arrives in station $a_i$ directly after train 1

$k=yo-1$ Train $yo-1$ arrives earlier than the reference train $yo$

with $j=1,2,...,n$

$j=1$ Connection strategy with earliest arrival time of the reference train at station $a_i$

$j=2$ Connection strategy with 2nd earliest arrival time of the reference train at station $a_i$

$j=n$ Connection strategy with latest arrival time of the reference train at station $a_i$

with $i=1,2,...,m$

$i=1$ Station $a_1$

$i=2$ Station $a_2$

$i=m$ Station $am$

Figure 9: Solution of sub problems
The number of possible sub problems TPj at a station ai depends on the number of possible connection strategies for the reference train at the predecessor station ai-1. And this depends of the number of trains which arrived later than the reference train at all predecessor stations.

In the modelled example of the figures 8 and 9 the reference train arrives at station ai either between train yo-1 and yo+1 (TP 1) or because of waiting strategy at a predecessor station after these two trains (TP 2). Figure 8 shows the complete graph. The two sub problems are highlighted. The optimal connection strategy for each sub problem can be solved independently. The sub problem will be reduced except for one link. This link represents the optimal connection strategy of this sub problem (figure 9) and will be integrated into the further calculation of the connection strategies of the reference train.

The determination of the optimal connection strategy for the reference train yo follows after the dissolving of all sub problems. Therefore it is firstly necessary to calculate all possible waiting links $HK_{yo}^x a_i$ for the reference train for the whole train path (equation 6).

**Equation 6:**

$$HK_{yo}^x a_i = \begin{cases} 
D(a_i)_{(yo)} \ast (\tan(a_i)_{(x)} + tm? (a_i)_{(x)(yo)} - tab(a_i)_{(yo)}) + \\
\sum_{y=yo-1}^{yo-1} U(a_i)_{(y)( yo)} \ast (\tan(a_i)_{(y)} + tm? (a_i)_{(y)(yo)} - tab(a_i)_{(yo)}) + \\
\sum_{z=yo+1}^{zo-1} (\tan(a_i)_{(z)} + tm? (a_i)_{(z)(yo)} - tab(a_i)_{(yo)}) + \\
\sum_{z=yo}^{yo} (T(a_i)_{(yo)} - (\tan(a_i)_{(x+1)(yo)} + tm? (a_i)_{(x+1)(yo)} - tab(a_i)_{(yo)})
\end{cases}$$

Subsequent it is necessary for each station to superpose the optimal result of each sub problem $K_{MinZüg_{(yo)}} (TP_j, ai)$ with the appropriate connection strategies of the reference train yo.

**Equation 7:** The global optimal connection strategy $K_{MinZug_{(yo)}}$ can be calculated with following equation:

$$K_{MinZug_{(yo)}} = \min_i \sum_{i=0}^{m} (HK_{yo}^x a_i + K_{MinZ?e_{(yo)}} (TP_j, a_i))$$

**Optimized passenger orientated connection management during the operation process**

Generally the definition of waiting time rules not considers the number of concerned passengers. Therefore it is essential to improve or to optimize the predefined waiting time rules during normal operational days with average occurred delays (neg. exponential or empirical distribution). The fundamental idea is based on the above mentioned method to minimize the total travel time. The aim is the development of a tool which helps the railway operation companies to define in the correlation of the number of passenger the optimized waiting time for normal operational days.
The calculation of optimized waiting time requires data about the
- Number of concerned passengers (PTP, TP, OBP, BP),
- The scheduled arrival time of the feeder trains,
- The scheduled departure time of the connecting train,
- Minimum transfer time
- And the delay distribution of the feeder and the connecting train (neg. exp. or empirical)

For the calculation of optimized waiting times it will be used the operational simulation [2]. The data of the simulation is necessary to develop an equation of the third degree for the design of functions depending on the service interval of the connecting train, the number of concerned passengers, the distance between the involved trains and the delay distributions.

The developed method will be demonstrated for a three (figure 10) and a five train model (figure 11), with transfer passenger from the feeder trains to the connecting train.

Figure 10 shows the optimized waiting time in case of a two feeder trains with different delay distributions (neg. exp. distribution) in correlation of the proportion of the number of transfer passenger (TP) and of passing through (PTP + OP + OBP) passengers and in correlation of the service interval of the connecting train.

Figure 11 shows the optimized waiting time in case of a four feeder trains with identical delay distributions (neg. exp. distribution) in correlation of the proportion of the number of transfer passenger (TP) and of passing through (PTP + OP + OBP) passengers and in correlation of the service interval of the connecting train. Additionally it will be considered the scheduled arrival time of the feeder trains and the departure time of the connecting train.

Following results can be deflected:
- Large minimum transfer times → increasing of the waiting time
- Large distance (temporal) between feeder and connecting train → reducing of the waiting time
- Large distance (temporal) between connecting and feeder train → increasing of the waiting time
- High service interval of the connecting train → low waiting times
- High number of transfer passengers → increasing of the waiting times
• High number of passing through passengers → low waiting times
• Large delays of the feeder trains → increasing of the waiting time

![Diagram: Calculation of the optimized waiting time](image)

**Figure 11: Calculation of the optimized waiting time**

**Software tool**

For the application of the method of a passenger orientated connection management during the planning and operation process were developed the two software tool **ANPLA** and **AssSi**.

ANPLA calculates for n-trains, n-stations and n-connections depending on the number of concerned passengers, the minimum transfer time, the service interval of the connecting train and the scheduled arrival and departure times the optimized connection strategy of each train. The user has with ANPLA a tool which could answer the question “to plan or not to plan a connection” fast and reliable.

AssSi based on the tabular calculation [MS-Excel]. This tool helps to calculate in consideration of all influencing factors (service interval of the connecting train, delay distribution, proportion of transfer and passing through passengers, minimum transfer time, distance between connecting and feeder train) the optimized waiting time of connecting trains in cases of delayed feeder trains.

**Results and Implementation**

The overall result is the construction of a timetable with optimized total travel times and dwell times at connection stations in correlation of the service interval and the number of concerned passengers. Another result is a passenger concerned orientated new definition of waiting time rules. The potentials for implementation and the impacts for the railway business are for the
timetable construction for train operating companies and for an improvement of the service quality of the transport offer by reducing the total travel time.

The new method of a passenger orientated connection management during the planning process
- reduces the transfer time,
- arises the proportion of direct connections and
- minimizes the travel time of all concerned passengers.

The new method of a passenger orientated connection management during the operation process
- reduces the additional delay according to the waiting times and
- arises the proportion of reached connections.

**Preview**
In further examination it is essential to apply the method for an optimized passenger orientated connection management for larger networks, more involved trains and connection stations.

**References**


[2] Radtke, A. „Software tools to model the railway operation“, Habilitation, at the Institute of Transport Railway Construction and Operation, Leibniz University of Hanover, 2005