Finding feasible timetable solutions for the Stockholm area

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Abstract

MTR (Mass Transit Railway) is contracted by Stockholm Public Transport (SLL) to operate the Stockholm commuter trains. The number of passengers is increasing and traffic is expected to increase by 50 % in ten years. This will therefore require further investigations to enable investments in additional infrastructure and rolling stock.

A generic model has been developed in order to screen future timetable situations and find resource efficient timetable alternatives and investments needed to enable the expected traffic increase.

Short turning traffic lines is one way to reach high efficiency for a commuter system. However, the sequence of short turning and full route lines will affect congestion heavily. Consequently different permutations of a termination pattern results in different passenger distributions on the traffic lines. The core idea of the timetabling model is to combine congestion efficient permutations for the four branches into network timetables.

A number of important features of the timetable are influenced by the choice of termination patterns, permutations of these patterns, the time rotation of the entire timetable and the requisite of symmetry. The latter is required in order to enable long distance traffic on shared line sections. Examples of important features are: the termination times, the number of train set needed, the need for additional termination tracks and the recovery and punctuality that can be reached.

A brief description of the commuter rail network, the demand and the prerequisites for the timetable are presented and discussed. Similarly the main ideas of the generic model are outlined. The method is elucidated by an illustration of a future traffic increase by 25 %.

Keywords
Planning, scheduling, robust timetables, congestion management

1 Introduction

From December 2016 MTR, Mass Transit Railway, is contracted by Stockholm Public Transport (SLL) to operate the commuter trains in Stockholm. The political ambition is to increase peak hour traffic by 50 % until 2030 (Tillväxt- och regionplaneförvaltningen (2017)). The railway network, owned and administrated by the National Transport Administration (Trafikverket), is however already heavily utilized, resulting into lower punctuality and higher passenger congestion on the services than desirable.

Feasibility studies addressing infrastructure measures are initiated. MTR, as key operator holds extensive knowledge and insights within the operational sector, is actively engaged and involved in these studies. One of MTR´s contributions is a timetable generating model that screens the possibilities to find resource efficient timetable solutions for the future.

This screening approach is useful since parts of the network are shared with long distance and regional traffic, which requires a coordination where the timetable for the commuter trains cannot be optimized independently.

1.1 Network and demand

The network is presented in Figure 1 and consists of four branches. All line sections are double or quadruple lines, except for the southern part of Nynäs line (Hemfosa – Nynäshamn) that is still single line with crossing loops. The commuter traffic is well separated from other rail traffic with quadruple lines on most sections shared by long distance and regional traffic. Two important exceptions are the end section of Mälar line (Kallhäll – Bålsta) and East Coast line (Upplands Väsby – Märsta/Uppsala) where a thorough timetable coordination is required to manage the traffic mix.

The mid-section consists of the new commuter train tunnel, City line, launched in 2017, that separates commuter traffic through central Stockholm. This line however, has a limited capacity (Lindfeldt (2017)).

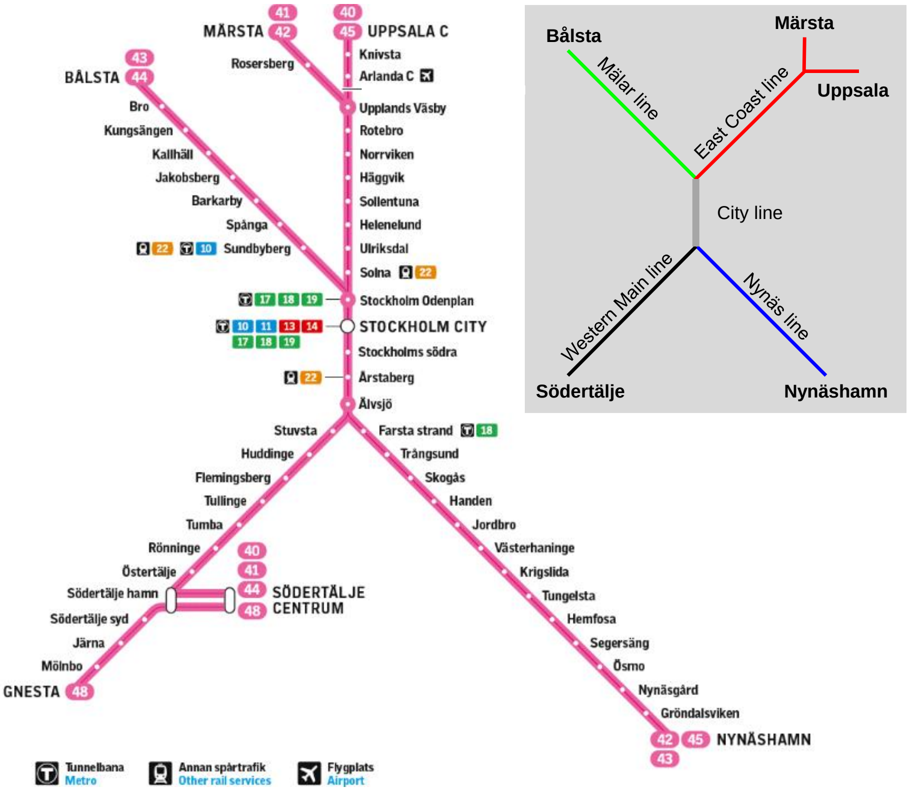

Figure 1 Network. Colour scheme for the branches shown in the small figure. The Gnesta line (48) is not included in the study.

All services on the branches operate City line and the capacity limitation in this line is a major condition for the timetable generation. The color scheme used for the branches in Figure 1 will be used throughout the article in order to increase readability.

The distribution of demand is shown in Figure 2. The average load per timetable cycle (30 minutes) in morning peak period, 07:20 – 08:50, is shown for all four branches. A train set has 750 seats and the diagram gives a first idea of the traffic needed to meet the demand. One important indication is that the demand corresponds to a system where not all traffic lines are full route lines. Hence, a major planning task will be to find feasible solutions for short turning lines.

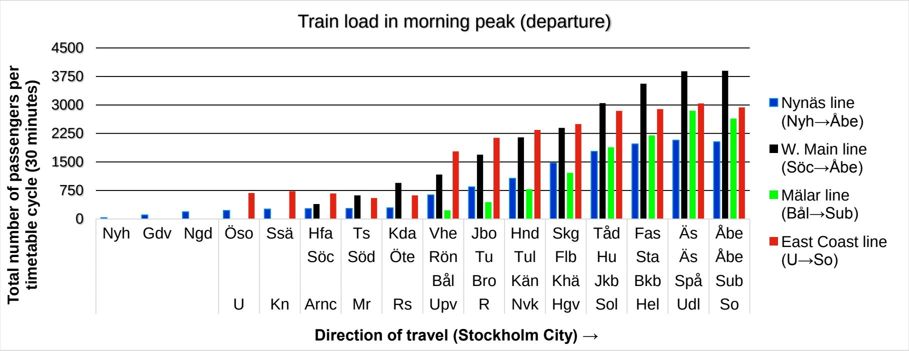

Figure 2 Demand during the morning peak.

1.2 Definitions

In the following section definitions for five concepts that will be frequently used throughout the article are discussed.

Branch: the infrastructure stretch from the separation junction to the farthest located termination station in the actual direction. The East Coast line is divided into two sub branches in Upplands Väsby, but modelled and referred to as one.

City line: is the common line section under Stockholm city. It imposes dependency between traffic lines to the four branches. This calls for a timetable coordination that is a natural starting point in timetable generation.

Timetable period: refers to a period, in minutes, with which the periodic timetable is repeated. The current timetable period is 30 minutes and during peak hour traffic the timetable cycle is repeated six times.

Line: a traffic relation between two termination stations that is operated by a service once per timetable period. Frequency of service between the two stations may be increased by adding more lines and coordinating them in time to get the desired frequency.

Termination pattern: a vector that is defined for each branch and shows the number of terminating lines per station, for example Södertälje C: 4 and Tumba: 2 implying that 4 out of 6 lines terminate in Södertälje C and 2 out of 6 lines in Tumba. The termination pattern gives rise to permutations of line sequences that are of great importance for congestion management.

1.3 Important timetable features

Four operational features of importance have been identified: punctuality, congestion management, timetable symmetry and resource efficiency (high utilisation of vehicles, infrastructure and train staff). It is worth noting that political priorities may also be implemented regarding the distribution of traffic resources in the network, stopping patterns, network extension etc.

Punctuality is highly commended by commuters. A high punctuality can be ensured through a thorough scheduling using balanced and optimized time supplements, buffer times and termination times. Consequently the termination times are in focus in this article, since they also impact the need for additional train sets and infrastructure.

Congestion management might be the most important factor in scheduling of commuter traffic since it has a direct impact on demand, overall customer satisfaction, resource efficiency and even punctuality. Congestion management is closely interconnected to short turning patterns and these two factors form the core when it comes to scheduling of commuter traffic in urban areas.

Symmetry is widely used throughout Europe as a way of achieving coordination between rail services (Liebchen (2004)). In a symmetric timetable the inbound direction is a reflection of the outbound as shown in Figure 3. Each traffic line is represented by a colour and line style (dashed for services on Nynäs line and solid for services on Western Main line). It can be seen that each line crosses itself on the so called symmetry times, i.e. minute 0, 15, 30, etc.

Since almost all other regular rail traffic in Sweden, such as long distance and regional traffic, is scheduled symmetrically it becomes a technical requirement also for the Stockholm commuter traffic in order to manage coordination of traffic on shared line sections. However, the symmetry has at least two major drawbacks for the commuter traffic:

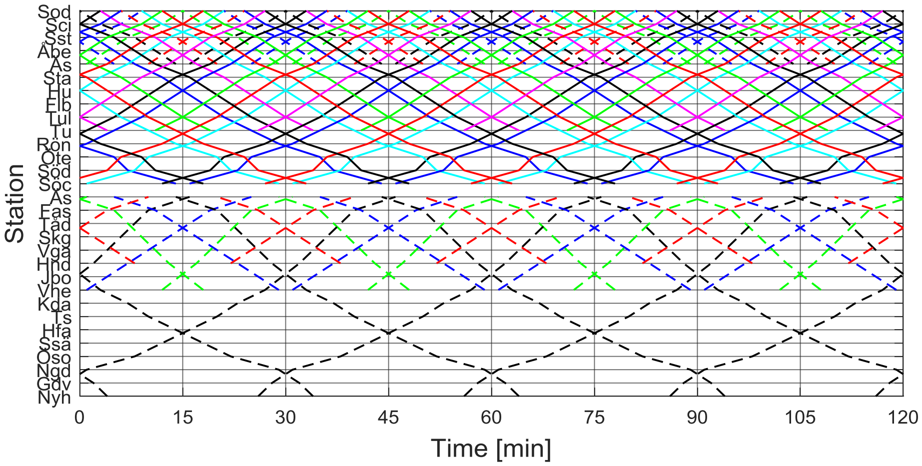

Figure 3 Timetable example showing symmetry. Southern half of the network shown.

- The termination pattern for in- and outbound directions cannot be chosen independently. This have rather severe, limiting effects on congestion management since the demand is different for the in- and outbound direction.
- The termination time, which is important for punctuality as well as resource efficiency, can be chosen less freely since a specific departure time requires a specific arrival time if the timetable is to be symmetric.

This implies that the coordination with other traffic impose a less efficient commuter operation as regards number of train sets and termination tracks (infrastructure) as well as congestion management and punctuality. This is previously shown by (Liebchen (2004)). However, this efficiency decrease might be less costly than a complete separation through additional quadruple line sections.

2 Finding feasible timetable solutions

A feasible timetable might be defined as a timetable that, for a given demand distribution in the network, has a low spread in passengers' loads on the traffic lines, allows enough termination times to reach a reasonable level of punctuality and efficient use of train sets and termination tracks.

As the evaluated system is limited and closed, a generic approach might be applied to find these timetable solutions. The method can be described by the following steps:

1. Establish a slot system with traffic lines in City line, the common link, to define available capacity.
2. Distribute available lines on the four branches, using demand data in Figure 2, and construct alternative branch patterns. These are referred to as line sequences. See Table 1 for two examples.
3. Create a nominal timetable between end stations of the branches according to the defined sequence. This step includes definition of stopping patterns, location of time supplements, buffer times etc.
4. Define termination patterns that are expected to be of interest. Existing as well as investigated termination stations might be listed for evaluation. Table 2 shows two alternative termination patterns for the two sequences.
5. For each branch:
   a. Permute the termination pattern in order to cover all permutations.
   b. For each permutation: adjust the nominal timetable by cutting off short turning lines according to the permuted termination patterns and distribute demand on the lines. Ortúzar and Willumsen (2011) share useful ideas of demand modelling.
   c. Compare load distribution on the traffic lines and select permutations with even passengers' load. One example, based on pattern 1 in sequence 1, is shown in Figure 4.
6. For each branch and selected permutation: calculate termination times and track usage in each termination station. Perform this for all rotation steps within a timetable cycle. The principle of rotation is shown in Figure 5. For a timetable period of 30 minutes the rotation gives 30 timetable variants for each permutation. Data for termination times and track usage are compiled for each permutation and rotation step.
7. Create complete network timetables through combinations of permutations on the four branches including rotation variants. The number of train sets needed,

additional termination tracks needed, expected termination punctuality and data for passenger load distribution is compiled for each timetable variant.

The number of timetables found depends heavily on the complexity in termination patterns and whether only symmetric solutions are accepted. For symmetric solutions a chosen permutation for a branch in one traffic direction defines the permutation also in the opposing direction for the same branch, since they are each other's reflections.

The following tables and figures illustrate the method used. Table 1 shows the slot system on City line with one train path every three minutes. This is followed by two alternative line sequences that divide traffic on the northern branches slightly differently. Table 2 shows two examples of termination patterns for sequence 1 and two for sequence 2. The pattern on Western Main line is simple, with either 4 or 3 out of six lines terminating in Södertälje (Söc), resulting in 15 and 20 permutations respectively for this branch.

Figure 4 shows the unique permutations for the two southern branches. The passengers' load on each line is affected by the line extension and the time distance to the preceding service, shown in the text box in upper left corner. Please note the difference between the most balanced permutation (leftmost) and the least balanced one (rightmost). A train set has 750 seats and a traffic line might be regarded as overloaded from a comfort perspective when the load reaches 1 000 passengers.

Figure 5 shows the principle of symmetry, meaning that a clockwise time shift in departure time imposes an equal counterclockwise shift in arrival time.

Table 1: Line sequences, two examples. ML: Mälar line, NL: Nynäs line, ECL: East Coast line, WML: Western Main line. * Indicates express lines.

Line	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Dep time S bound	00	03	06	09	12	15	18	21	24	27
Seq 1										
North	ML	ECL	ML	ML	ECL	ML	ECL	ECL	ML	ECL
South	NL*	WML	WML	NL	WML	NL*	WML	WML	NL	WML
Seq 2										
North	ML	ECL	ECL	ML	ECL	ML	ECL	ECL	ML	ECL
South	NL*	WML	WML	NL	WML	NL*	WML	WML	NL	WML

Table 2: Termination patterns. Two examples per sequence, 10 lines per timetable period.

		Southern lines					***Northern lines***					
		Western Main line		**Nynäs line**			**Mälar line**			**East Coast line**		
Seq	**Pattern**	Söc	Tu	Nyh	Vhe	Hnd	Khä	Kän	Bål	Upv	Mr	U
1	1	4	2	1	2	1	2	1	2	1	2	2
1	2	3	3	1	3	-	2	2	1	-	3	2
2	1	4	2	1	2	1	2	0	2	2	2	2
2	2	3	3	1	3	-	1	2	1	1	3	2

The procedure discussed above might be applied to screen for feasible timetable solutions. One example is presented in the following section. The procedure has several similarities with the TVEM model that is described in Lindfeldt (2010). Major differences are that demand, congestion, terminations and vehicle rotations are included in the current model.

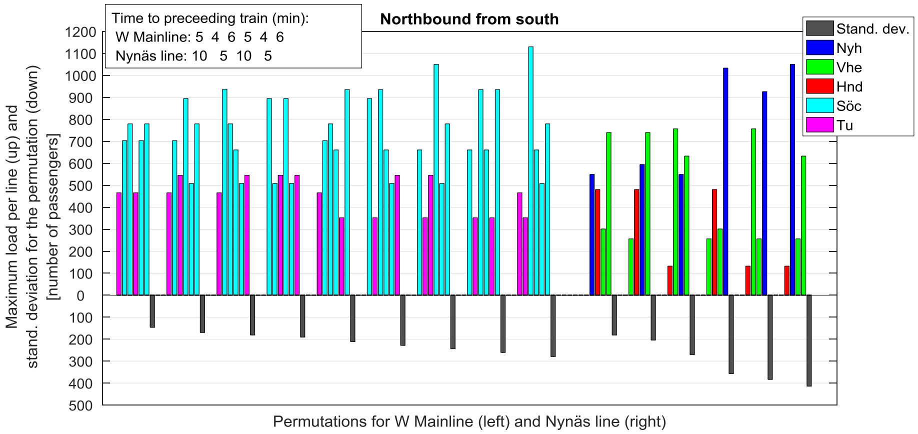

Figure 4 Line permutations and corresponding passenger distributions on lines. Sorted according to ascending standard deviation in passengers' load. Only unique permutations are shown for space reasons.

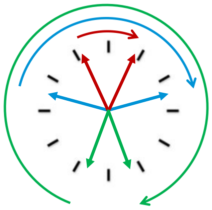

Figure 5 Principle of rotation with symmetry.

3 Application supported by an example

The first pattern in sequence 1 in Table 1 is assumed to meet demand efficiently and serves as a good example. This pattern corresponds to a 25% traffic increase, compared to the operated traffic in 2019. As most permutations have a high variance in passengers' load, (Figure 4) it is feasible to choose only permutations with a load standard deviation lower than 200 passengers. After that selection, only 36 000 timetables remain. All of these constitutes a reasonable passengers' load on all traffic lines.

Despite the fact that the total operated time and distance is exactly the same in all these timetables, termination times differ. This results in different number of train sets needed. Moreover, the existing number of termination tracks might not be sufficient, implying a lack of infrastructure in some locations. Distributions for these resources are shown in Figure 6. The diagrams indicate that a minimum number of 62 train sets is needed for the traffic and at least two additional termination tracks have to be constructed.

Termination punctuality values can be estimated through combination of scheduled termination time, minimum (technical) termination time and historic delay distributions for arrivals at the different stations.

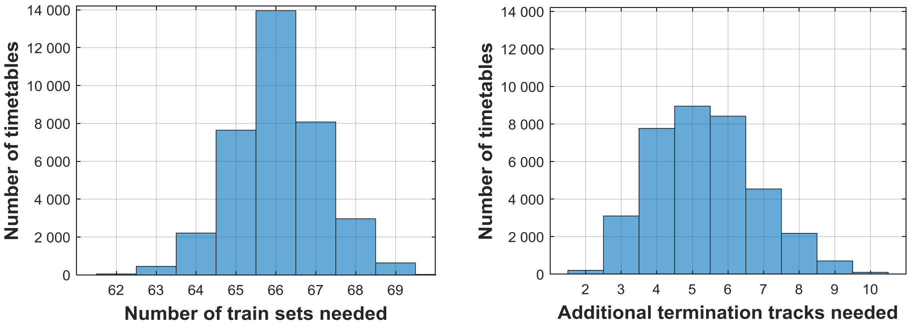

Figure 6 Distribution for number of train sets and additional termination tracks needed.

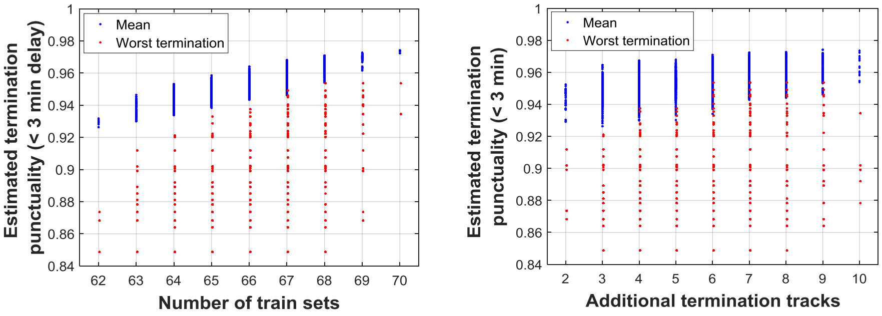

Figure 7 Estimated termination punctuality for different number of train sets and additional termination tracks. Blue: mean for all 20 terminations and red: termination with lowest punctuality.

Figure 7 shows punctuality statistics. All 36 000 timetables are represented by a blue and a red marker, indicating mean termination punctuality and lowest termination punctuality respectively.

As the diagram indicates, additional train sets and/or termination tracks provide a better recovery and higher punctuality through longer termination times. This is a rather unprecise way to estimate punctuality, as the real arrival delays are influenced by the timetable solution and other factors such as recovery in the other end of the line. However, it may be a suitable way to sort out timetable solutions with a distribution of termination time that will ensure an acceptable level of termination recovery.

Further analysis calls for additional filtration, since it is unreasonable to invest in extensive number of train sets and/or termination tracks. Therefore, in the final evaluation only timetables that requires 62-64 train sets are analyzed. These numbers of train sets correspond to 2-5 additional termination tracks.

It is not enough to know the number of lacking termination tracks. It is also important that their locations are specified as well, if the infrastructure is going to be completed in order to meet the analyzed traffic increase.

If the remaining feasible timetables are compiled according to need of additional termination capacity a diagram like the one in Figure 8 can be drawn. As demonstrated in the diagram one additional termination track ought to be constructed in Bålsta and Uppsala respectively. Such an extension would be enough to manage about 15% of the feasible timetables. A further analysis of the corresponding timetables has to be performed in order to assess whether this portion is enough to manage future changes in operation. Complementary flexibility in the choice of timetable requires more termination tracks.

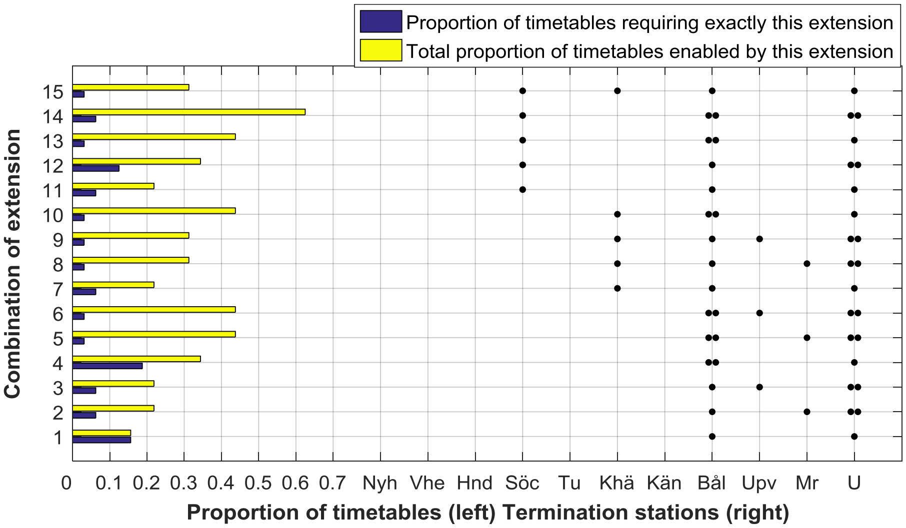

Figure 8 Alternative combinations of additional termination tracks needed to enable the evaluated traffic and the proportion of feasible timetables that they enable. A double dot indicates need for two additional tracks.

4 Conclusions

A generic method for timetable screening of a four branch commuter rail system has been discussed. The method is based on congestion management and combinatorics of short turning traffic lines (termination patterns). The overreaching objective is to explore timetable solutions that are efficient, namely, congestion balanced, that require a limited number of train sets and additional termination tracks, but still have termination times that are long enough and well distributed to reach a reasonable recovery level and punctuality.

The number of available timetable solutions is limited by the common line section, City line, where a slot system has to be applied in order to manage capacity. As in most other public transport systems, short turning is an efficient way to adjust traffic supply to demand. The short turning lines constitute termination patterns and permutations of these.

The permutations influence passenger distribution and congestion and has to be selected with care. A network timetable can be constructed through a combination of permutations for the four branches. Each combination can be rotated through the timetable period, in this case 30 minutes. The choice of permutations and degree of rotation determine the termination times, which in turn define important features such as: recovery/punctuality, number of train sets needed and number of termination tracks needed.

Special attention ought to be paid to the mode of rotation. Coordination with other rail traffic on shared line sections requires the timetable to be symmetric. The symmetry implies that the permutation can only be chosen freely in one direction per branch, since the permutation for the opposing direction has to be a reflection of the first one. This fact strongly limits the number of available timetable solutions, the possibility to reach an efficient congestion management in both traffic directions and to limit the number of train sets and/or termination tracks needed. As such the coordination with other traffic impose a less efficient commuter operation. Nevertheless, it might be less costly than a complete separation through supplementary quadruple line sections.

Further evaluation studies are planned to be carried out to analyse the benefits of asymmetric timetables. It would also be interesting to delve into available capacity for long distance and regional services. The current model can easily be updated to cover timetable solutions for asymmetric timetables as well as other traffic.

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References

Lindfeldt, O., 2017. “Designing the future commuter traffic through central Stockholm”. In: *Proceedings of The 7th International Seminar on Railway Operations Modelling and Analysis (RailLille 2017)*, Lille, France.

Lindfeldt, O., 2010. “Railway operation analysis - Evaluation of quality, infrastructure and timetable on single and double-track lines with analytical models and simulation”. PhD thesis KTH, Stockholm.

Liebchen, C., 2004. “Symmetry for Periodic Railway Timetables”, Electronic Notes in Theoretical Computer Science, vol. 92, pp. 34–51.

Ortúzar, J., and Willumsen, L. G., 2011. “Modelling Transport” (4th ed.), Wiley, Chichester.

Tillväxt- och regionplaneförvaltningen, SLL, 2017. ”Strukturanalyser för Stockholms län och östra Mellansverige år 2050 - konsekvenser av strukturbild år 2030–2050 - Underlag till utställningshandling”, Stockholm. (In Swedish)