Simulation of metro operations on the extended Blue line in Stockholm

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Abstract
The current Blue metro line in Stockholm will be extended and connected to a branch on today's Green line in the future. This paper presents a timetable simulation study which was part of a larger study regarding traffic analyses and design of the future Blue and Yellow line metro conducted in 2015–2016. Two timetable cases were considered, the first one gives 4-minute intervals on the branch lines and the second one 5-minute intervals (peak hours). At that time there was a discussion whether to design a new branch station (Sofia) with two or three tracks. The simulation model could not be set up to model all the features of the signaling system that is used today and is planned to be used when the new extensions open. Therefore, a separate model was developed to study the effects of two or three tracks at the branch station on a more detailed level.

The results from this study shows that the 4-minute timetable case is clearly more sensitive to delays. Although the effects of having two or three tracks on the branch station where northbound trains will merge can be seen locally on that and subsequent stations, there is no significant difference further along the line. There exist other operational benefits of having a 3-track design at a branch station and these were also considered, although not discussed in this paper. Later it was decided that the branch station will be designed with two tracks, mainly due to the significantly higher cost for a 3-track design.

Keywords
Metro operation, Timetable, Simulation, Delay, Buffer time

1 Introduction

Stockholm's Metro is about to be expanded. The current Blue line will be expanded with nine stations, where one replaces an existing surface station and one expands an existing surface station with an underground section. One of the southern branches on today's Green line will be connected to the Blue line. The construction start is planned to 2019.

Earlier in the project a study of the train operations on the expanded Blue line was carried through. This study consisted, among other things, of timetable analyses, trip scheduling from depots and simulations.

A new branch station (Sofia), where the line divides into two branches, is planned a few kilometers south of the current terminal station at Kungsträdgården. The design of this branch station was not decided at the time of this study. In short, this station could consist of either one common platform track or separate platform tracks for northbound inbound trains from the two branches. For outbound trains one platform track was considered in both cases.

The station will lie deep under the street level and the platforms will only be accessible by lifts, no escalators are planned.

This paper aims to describe the simulation setup and presents some results from the simulations. Two timetables are considered. The first one has 5-minute intervals on each branch during peak, giving 2.5-minute intervals on the common section. The other alternative has 4-minute intervals on each branch and 2-minute intervals on the common section. Full weekday timetables are designed with empty train runs from and to depots. However, in this paper presented results correspond to morning and afternoon peak periods only.

In addition, a separate model was developed to be able to model the signaling system behavior in a more realistic way and this model was used to study the difference in inbound train flow for the two considered designs at Sofia station. The results from this analysis are presented as well.

Figure 1 shows a schematic track layout for the new Blue line metro. The new sections reflect the track layout as planned in the fall of 2015 when this study was conducted. Figure 1 shows branch station Sofia with a 3-track design. The existing branch station in Västra skogen (VÄS), the future one in Sofia as well as the connections tracks to the two depots (RI and HÖ) have flyovers (grade separation).

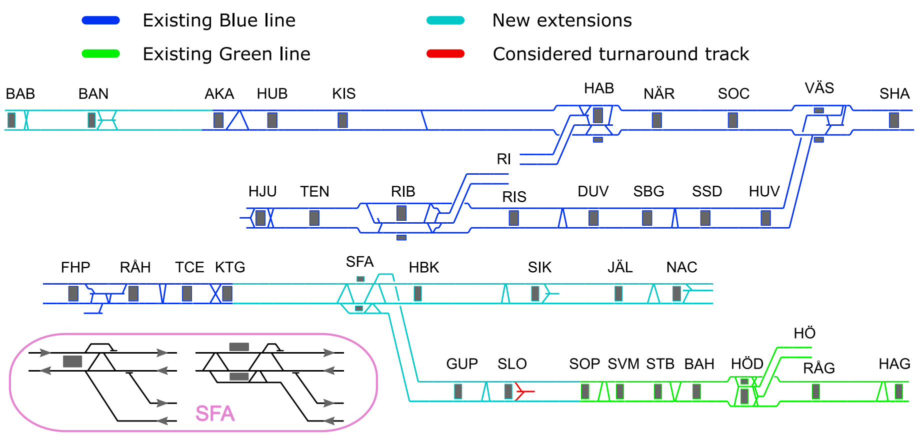

Figure 1: Schematic track layout with station codes for the new Blue line metro as planned in the fall of 2015. The figure shows both station designs for Sofia.

2 Signaling system

There are currently two different signaling systems used in the Stockholm metro. The Red and Blue lines use a relay-based system from Union Switch & Signal, this system was also used on the Green line until replaced with a more modern system by Siemens 20 years ago. The relay-controlled system is planned for installation on the new track sections to avoid different systems when these are opened. However, the section today belonging to the Green line that will be connected to the Blue line will continue to use the Siemens system. Both systems can be handled by the C20 train stock. This is also the plan for the new C30 units delivered in the coming years.

Both systems send information continuously to the train's safety system. In the older system (Union Switch & Signal), the signal is picked up from the rail tracks (Stockholm Public Transport Authority (1964)). Three speed aspects can be transmitted:

- L – Low: 15 km/h
- M – Medium: 50 km/h
- H – High: Line maximum speed, 80 km/h is used on the Red and Blue lines

Speed restriction signs can imply lower speeds than the cab signal speed aspect. If a train exceeds the transmitted speed at any point along the line, the system automatically applies the brakes until the allowed speed is reached. The signal alters successively to Medium and Low when a train approaches another train in front or some other obstruction along the line, e.g. a wayside signal at stop in front of points.

The system allows two trains to come close to each other, the subsequent train has in this case received speed aspect Low at a sufficient distance and can normally continue up to the rear light on the preceding train. If no speed aspect is transmitted the cab signal system interprets this as Low.

The resolution of the system depends on the length of the track circuits, these have been calculated from the braking power of the cars and the interval desired between trains. On straight level track, each track circuit is around 200 meters on central parts of the line. The signal system is designed to give a headway of approximately 90 seconds and 30 second train stops at stations.

In the RailSys-model an ATC system with continuous updating is used since there is no straightforward way to model all the properties of the system used in the Stockholm metro. The block section lengths correspond approximately to the track circuit lengths. This setup is used in the simulations of the Blue line timetables. In the analysis of the effects on train flow if the two branch lines merge before or after Sofia station (i.e. 2-track or 3-track station design), a separate model is developed with the purpose of modeling the signal system properties as closely as possible.

3 Timetable case simulations

The track infrastructure setup for the existing Blue line together with the extensions is created in the simulation software RailSys (see e.g. Bendfeldt et al. (2000)). Management and project data are used. This includes vertical and speed profiles and an approximation of the speed-code signaling system in use today, also planned for the extensions. The vehicle model used is C20, which currently and for years to come most likely represents the largest share in the fleet. Data from the vehicle manufacturer is used for traction diagram, acceleration and braking performance etc. RailSys version 8 is used in this study.

A simplification is that trips are not defined by connecting arriving to departing trains for the whole timetable at terminals. Trains that are late to terminal will not transfer the possible delay for the reversing departure directly (for the same trip). However, crossing conflicts can occur as late arriving and/or departing trains must pass the point area. In metro operations in Stockholm trains can be reversed before the terminal at stations equipped with turnaround tracks. This is done to prevent a delay being passed on in the reverse direction.

Train runs cannot be canceled (in whole or in part) in a RailSys simulation. The advantage of connecting train runs is that delays can be passed on at terminal stations which is realistic. However, the disadvantage is that for larger delays the delay transfer can be unrealistic since a trip could have been reversed before the terminal to counteract the delay transfer. To model a more conservative behavior at terminals, all inbound and outbound trains must change tracks (cross) through the point area. The departing trains are given initial delays from distributions as well.

3.1 Input data for timetable setup and simulation

To verify the infrastructure and the vehicle model, the running times calculated by the model are compared to running time distributions from recorded train data provided by the metro operator. This is done for the existing sections. The median values are normally chosen as the representative values in the timetable setup. For the new sections, scheduled running times are chosen so that the difference between the minimum technical and the scheduled running times are in the same magnitude as the differences between median and 90-percentile running time values for sections of similar lengths in the recorded data.

The variation in dwell times is modeled by using corresponding recorded data provided by the metro operator as distributions and separated to stations, direction and operational period (e.g. morning, morning peak, mid-day etc.). Similarly, distributions for departure deviations at different stations are provided. These are used in modeling initial delays for trains departing from terminal stations. Dwell and departure deviation data is loaded into a Matlab-database from which further handling in assigning perturbation values and writing the perturbation files for the simulations is done. In this process future stations are mapped to existing stations following rough estimates of expected passenger volumes.

3.2 Approach for emulating the bunching effect

Bunching is an effect that is common in congested light rail, metro and commuter train networks. A train (vehicle) that is already delayed will get more people at the next station and the passenger exchange take longer time. This means that the headway to the train in front increases. The following train will therefore accumulate delays. A method for how this effect can be modeled in the OpenTrack software is presented in Krause (2014) in which this method is used in an analysis of the red metro line in Stockholm. The method uses the OpenTrack API to accomplish this.

In a RailSys simulation there is no possibility to dynamically control dwell times once a simulation is running. In this study, the possibility to emulate this effect is instead defined in the setup scripts run in Matlab. The probability of a train getting an extended dwell, the number of consecutive stations the extended dwell is active on, for which stations in the network this can happen and in what time periods are controlled in the setup. The dwell extension value can be a constant or drawn from a distribution. In this way some trains in a simulation cycle will get extended dwells systematically for several consecutive stations, delay is accumulated and the headway to the preceding train increases. This behavior can of course occasionally occur in a simulation cycle without this additional modeling. This can happen if several consecutive higher dwell values are drawn from the normal dwell variation distributions for a train when the values are assigned prior to a simulation. However, the described approach provides a possibility to control this: frequency, levels of the extended passenger exchange times, when, where etc.

3.3 Results from timetable case simulations

The timetable case simulations are evaluated by comparing the average delays (mean values) and standard deviations. In addition, the potential need for short turnarounds is estimated at different stations where some are hypothetical since there are no separate turnaround tracks planned for these and making train turnarounds on main tracks is not realistic in peak periods.

A train run is marked for turnaround at the considered stations if the sum of arrival delay, remaining scheduled time to terminal and a minimum turnaround time exceeds the scheduled departure from terminal with more than one minute. This limit may sound small but with trains running every 2–2.5 minute on the common section the need for precision is high to avoid passing on delays to trains coming from and going to another branch. The minimum turnaround time in these cases is assumed to be 3.5 minutes. Measurements at Kungsträdgården terminal (KTG), where trains turn around every three minutes (in peak), indicated an almost 95 % fulfillment up to this time.

There are ways for shortening this time a little bit by using a second driver that will help activate a train in the reverse direction or by changing drivers at a turnaround, which would lower the time needed for a turnaround even more. This was not considered in the estimations.

Figure 2 shows simulated mean delays in peak periods for the different lines in both directions. Both timetable cases are combined with the two different track designs at Sofia station. There is no difference coming from the station design in the southbound direction which is reasonable since the different designs only affect the northbound trains. There can of course be an indirect effect through crossing conflicts at terminals, but there is no indication of that in these results.

Although the timetable cases have similar scheduled running times there are differences. This is mainly due to that turnaround times and the time differences between inbound and outbound trains differ. Running time allowances are in some parts of the line distributed differently. In general, the recoverability is better in the southbound direction. The mean delays decrease clearly on the common section between Västra skogen (VÄS) and Sofia (SFA). The standard deviation is not shown in any diagram, but it is also lower in this direction compared to the northbound direction. The standard deviation is higher for the relation Hjulsta–Hagsätra and vice versa compared to the other line. The weakest parts of the system seem to be in the northbound direction from stations Sundbybergs centrum (SBG) and Hallonbergen (HAB).

At some stations it can be observed that the mean delay increases during the station stop. The most likely reason is that the passenger exchange time on average take longer time than the scheduled dwell times used.

The difference between the two station designs at Sofia can be seen in the diagrams. The effect is relatively local since the mean delays coincide further ahead. The standard deviation increases locally with 5–10 seconds as well.

Assuming a minimum turnaround time of 3.5 minutes and relating this to the scheduled turnaround times in the 4-minute timetable case, gives that the additional margin is 1:45 in Hjulsta (HJU), 3:00 in Barkarby station (BAB), 2:00 in Hagsätra (HAG) and 2:00 in Nacka centrum (NAC). Checking the simulated arrival delay distributions at these terminals indicates that around 10 % of the arriving trains to Hjulsta will carry on a delay in the reverse direction. Corresponding values for the other terminals are 2–3 %. In the 5-minute case, the scheduled turnaround times are longer and considered to have enough margins based on these results.

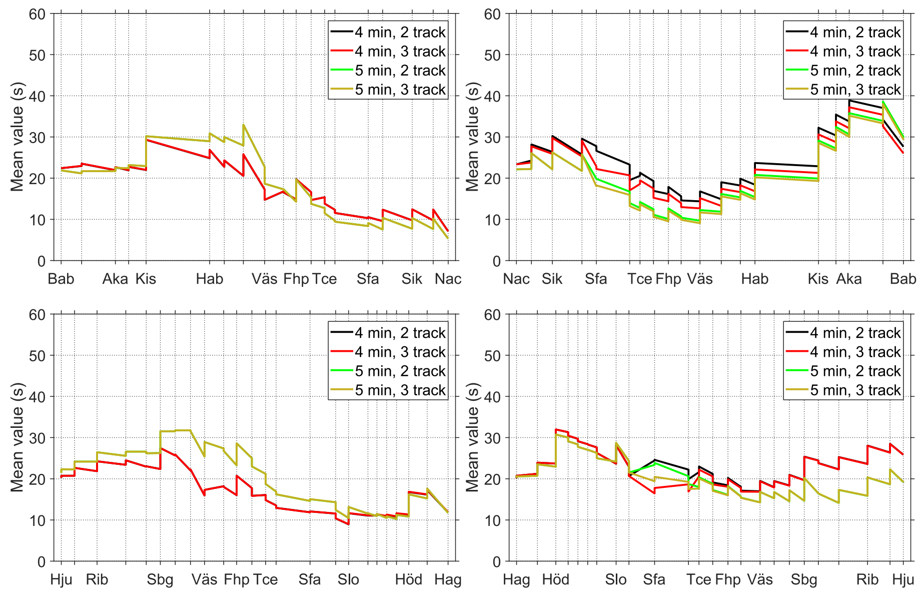

Figure 2: Mean delays in peak periods for the two timetable cases and with different station designs for Sofia station. Trains running from Barkarby station (BAB) to Nacka centrum (NAC) and vice versa on top. Trains running from Hjulsta (HJU) to Hagsätra (HAG) and vice versa on bottom.

Figure 3 shows the estimated number of short turnarounds per day in peak periods at different stations. The relation Hagsätra–Hjulsta and vice versa has in total a higher number of short turnarounds than the other line. It is also clear that the 4-minute timetable case is more sensitive to delays. Akalla (AKA), Rinkeby (RIB) and Högdalen (HÖD) are all situated relatively close to the respective terminals and it makes sense that these would get higher numbers than stations further from the terminals.

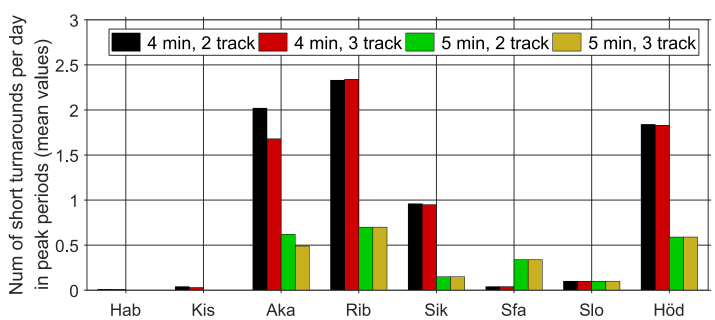

Figure 3: Estimation for short turnarounds per day in peak periods at specific stations. The first four bar groups represent northbound trains (Hab, Kis, Aka and Rib), the remaining four groups represent southbound trains (Sik, Sfa, Slo and Höd).

4 Detailed analysis of train movements through Sofia station

4.1 Method

A new model is developed to determine if it is necessary to have two platform tracks for northbound trains at Sofia station. Northbound traffic from the two different lines merge at Sofia. If the station is built with one platform track for northbound trains, traffic from the two lines must synchronize before arriving at the platform. With two platform tracks, synchronization will occur after the trains depart from the station (see Figure 1).

The reason why the analysis of Sofia station requires a specialized model is that the gradients around Sofia are steep (> 45 ‰, falling for northbound trains) and that the signaling system's characteristics and behavior cannot be fully modeled in RailSys. The steep gradients affect both the braking performance of the trains and the setup of the signaling system. Steep gradients in combination with dense traffic from different branch lines synchronizing at Sofia can mean that the station will become a bottleneck. With two platform tracks for northbound trains, the impact of the steep gradients south of the station will be reduced. However, designing a larger station with one additional platform track implies a more complex construction and a higher cost.

The analysis includes only northbound trains and the infrastructure model includes one stop before Sofia on each branch line (Hammarby kanal/HBK and Gullmarsplan/GUP) and the first stop after Sofia (Kungsträdgården/KTG). The developed model consists of several sub models: infrastructure model, signaling system, driver model and vehicle model. Most of the effort is put into modeling the signaling system's characteristics as accurately as possible.

Modeling the signaling system

As described before, the speed aspect received by a train is transmitted through the track circuits. When a track circuit is occupied by a train, the track circuits behind the occupied track circuit will transmit either one of the three signal aspects (H, M or L). Which speed aspect the track circuits will transmit depends on the location of the track joints and the braking distance calculated from the rear joint of the occupied track circuit. There will always be at least one track circuit transmitting L and one transmitting M. More than one track circuit may be required to transmit the same speed aspects, this depends mostly on the track circuit lengths in combination with gradients. For each track circuit, braking distances are calculated for two different speed aspects, H and M. If a track circuit is occupied, all track circuits behind the occupied track circuit that are located within the braking distance calculated for M will transmit the L-aspect. If the track circuit is within the braking distance of H, it will transmit the M-aspect. Track circuits that are further away than the calculated braking distances, will transmit the H-aspect. Information about which track circuit will transmit which speed aspect is saved and used in the simulation.

The positions and lengths of the track circuits form input to the model. The configuration of the track circuits affects the potential capacity of the system. Hence, the configuration needs to be optimized for each scenario to make results comparable. The adjustments of the track circuit configuration are done manually in several iterations. Each iteration includes recalculation of braking distances and speed aspects as mentioned above. The primary focus for the adjustments is to maximize buffer times at bottlenecks. The bottlenecks of the system are track circuits that are affected when the trains stop for passenger exchange and by the turnout at Sofia station. Several technical limitations, such as for example minimum and maximum permissible length of track circuits, must also be considered in the process.

Braking curves are calculated by means of numerical integration and the effect of varying gradients along the track is considered. The metro train is modeled as a mass band with weight distributed equally along the entire train length. The design guidelines for the signaling system dictates that the calculation of the braking distance shall include a 5.5 second brake reaction time and a 15 % safety margin of the total braking distance.

Deterministic and stochastic simulation

The deterministic simulation aims to analyze the planned situation. The trains in the model run as fast as possible from entry to exit. The trains accelerate, keep constant speed, brakes and stop at stations. No stochastic delays are used in this mode. Trains start with a fixed time interval and station stops (dwell) are performed according to plan. After the simulation, the result is a timetable and stored data about transmitted speed aspects from all track circuits. The information is then used for creating blocking time diagrams and calculate buffer times between trains. The timetable is conflict-free, and the trains will not be affected by other trains (no restrictive speed aspects due to trains in front).

The stochastic simulation is largely a repetition of the procedure in the deterministic simulation. The difference is that the trains are disturbed from their planned timetables by means of stochastic delays (see e.g. Siefer (2008)). The delay distributions determine how often and how much the trains are delayed in different situations. Trains are disturbed when they enter the model by initial/entry delays and when they stop at stations by dwell time extensions. Since the trains are delayed, they will not always run in their planned conflict-free slots. When a conflict occurs with another train, the signaling system will force the train behind to reduce speed according to the speed-code signaling system. The results are delays that are measured relative to the times calculated in the deterministic simulation.

4.2 Results

Buffer times

The distance between trains, buffer time, affects the probability that trains will affect each other in the case of delays. The available buffer time depends on the frequency of the traffic, the minimum headway and the stop times at stations. Minimum headway depends, among other things, on the signaling system (track circuit configuration, reaction times etc.) and the speed and length of the train. Blocking time diagrams (Figure 4) are produced by the deterministic simulation and are used to calculate buffer times. Figure 4 shows the Nacka line. When the turnout at Sofia is not in position for a train coming from the Nacka line (i.e. the optical signal protecting the turnout shows red), the track circuits before the turnout indicate L and M speed aspects. This is the situation when the turnout is either changing from one position to another or when it is in position for trains coming from the Hagsätra line. This is also the reason why some track circuits before Sofia station transmit restrictive speed aspects for long periods of time.

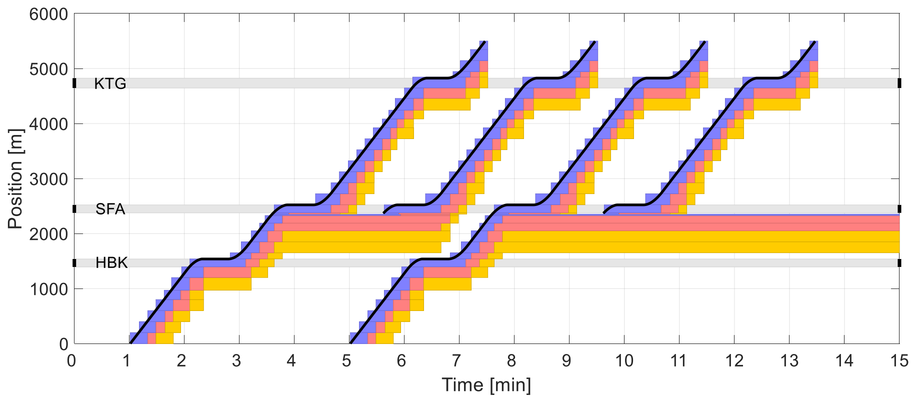

Figure 4: Blocking time diagram with a 2-track station design at Sofia, negative gradients are considered. Red: L-aspect, Yellow: M-aspect, Blue, occupied track-circuit. Station positions for Hammarby kanal (HBK), Sofia (SFA) and Kungsträdgården (KTG) are indicated in the figure.

Figure 5 shows how the buffer time varies along the Nacka line. The figure shows buffer times for each track circuit. Two different buffer times are calculated. The yellow line shows the buffer time to M-aspect and the red line to L-aspect. The reason for why the buffer time to L-aspect is calculated is that the impact on train delays is much higher if a train receives L-aspect (15 km/h) than M-aspect (50 km/h), especially close to stops where trains are not running at full speed.

Figure 5 shows three scenarios. In the first scenario (dashed lines) Sofia station has two tracks in total (one track for northbound trains). The second scenario (dash-dot lines) is the same as the first, but without negative gradients. In the third scenario (solid line) Sofia station has three tracks in total (two tracks for northbound trains). Buffer times to M-aspect are shown in yellow and buffer times to L-aspect in red.

In all scenarios, buffer times clearly decrease between Hammarby kanal and Sofia. The reason is that the traffic frequency doubles at Sofia when trains from the Hagsätra line merge with trains from the Nacka line. In Figure 5, both lines operate trains in 4-minute intervals. Hence, the interval between trains is two minutes from Sofia to Kungsträdgården. The figure shows that buffer times are generally shorter at stations than on the lines. This is due to that trains are standing still at the stations for some time and that they have lower speeds when they decelerate before and accelerate after stops. It is evident from the figure that stops do not only affect buffer times on the platform track circuit(s) but also several track circuits before.

Comparing the dashed end dashed-dotted line reveals the effect of the negative gradients in the scenario where both lines share one platform track at Sofia. Differences are greatest around Sofia station where the negative gradients are located. Without negative gradients, buffer times around Sofia increase from 22 seconds to 27 seconds (M-aspect). For L-aspect, buffer times increase from 38 to 46 seconds. The distance with short buffer times is also about 200 meters longer when negative gradients are considered (M-aspect). It is also worth noticing that the point where the signaling system starts to transmit the M-aspect when a train is at the platform in Sofia, is only about 100 meters after the stop at Hammarby kanal (the preceding station on the Nacka line). If the braking distance had been 100 meters longer, it would not have been possible to operate trains at 4-minute intervals without conflicts at Hammarby kanal. Operating with conflicts means in this case that trains would get restrictive speed aspects due to other train movements also in a scheduled mode. In practice however, the consequences of such a situation would probably be limited since trains stopping at Hammarby kanal will have lower speeds when entering the platform section.

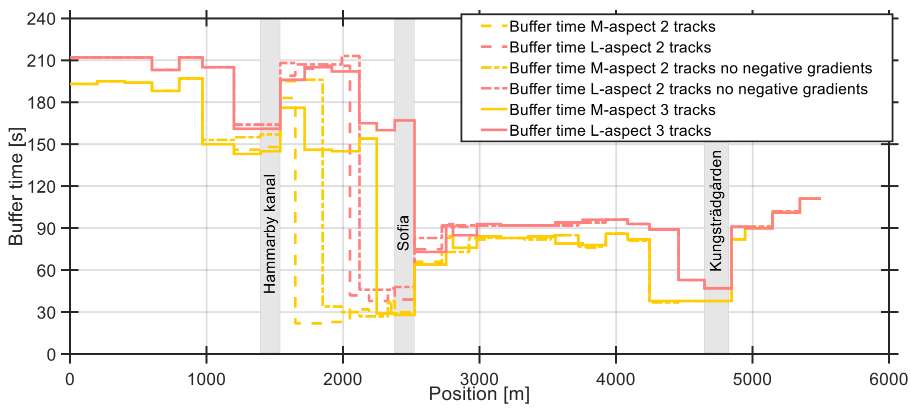

Figure 5: Buffer times for the Nacka line. Station positions for Hammarby kanal, Sofia and Kungsträdgården are indicated in the figure.

In the discussed scenarios, the turnout is located right before the platform in Sofia and both lines share the same platform track. In the third scenario, each line has a separate platform track and the turnout where the tracks merge is located 230 meters after the platform area. Buffer times for scenario 3 are indicated with solid lines in Figure 5. Compared to the scenario with two platform tracks, the buffer time at Sofia increase from 22 to 29 seconds for M-aspect and the distance with short buffer times is reduced with almost 600 meters. The distance between the platform and the turnout is long enough to avoid L-aspect at the platform when the turnout is in the other position (for trains from the Hagsätra line). Hence, the buffer time for L-aspect at the platform is as much as 167 seconds. However, the buffer time between the platform and the turnout is affected by the position of the turnout and it is therefore not independent of the traffic on the other line. It is significantly lower, 73 seconds.

Comparing the buffer times at Sofia with those of the next station, Kungsträdgården, shows that Sofia with a 2-track design (one platform track for northbound trains) have shorter buffer times than Kungsträdgården and might therefore become a bottleneck. Sofia with a 3-track design (separate platform tracks for northbound trains) have longer buffer time to L-aspect but smaller buffer time to M-aspect when compared with Kungsträdgården. How the different scenarios will perform when trains are delayed is not easy to predict based only on the buffer times. For that reason, simulations with delays are performed in the following step.

Delays

Stochastic simulations are performed to determine how the steep gradients and number of platform tracks at Sofia affect the delay sensitivity of the system. Stochastic delay distributions are used to model primary delays and the simulation model is used to determine how the trains will affect each other, secondary (knock-on) delays. Values are drawn stochastically from distributions modeling initial/entry delays and dwell time extensions. The same distributions are used on both lines which are evaluated together. The distributions are compiled from recorded data reflecting years 2011–2015. Distributions used for initial delays have, in this study, relatively high average values and are chosen with the intention to stress the system. Figure 6 shows how the average delay increase from the position where trains are initialized in the model, before Hammarby kanal and Gullmarsplan, until and including departure from Kungsträdgården station.

The average dwell times in the simulation are chosen so that they coincide with the scheduled dwell times. This means that trains, on average, cannot reduce their delays during the station stops. It also means that the delay increase observed in Figure 6 is due to secondary delays only. The figure shows results for the 4- and 5-minute timetable cases. In most cases, the results show a higher increase in delays up to Sofia station, whereas the increase is smaller between Sofia and Kungsträdgården. The difference in delay increase between the 4- and 5-minute cases is significant. In the 5-minute case, delay increases by 3–4 seconds, whereas in the 4-minute case it increases by 9–11 seconds. The impact from the steep down grade (negative gradient) is marginal. In the 4-minute case, the difference when comparing a configuration with and without gradients is around 2 seconds.

Figure 6 shows how the number of northbound platform tracks at Sofia affects the train's average delay. In the scenarios where a 2-track design is used (one northbound platform track) a higher increase is observed in secondary delays up to and including departure from Sofia and less increase thereafter. In the 4-minute case, trains get on average a 10 second delay increase up to and including departure from Sofia and from there up to and including departure from Kungsträdgården a marginal increase. The marginal delay increase on the last section is explained by that trains from the two branch lines have already been synchronized at Sofia which has shorter buffer times than Kungsträdgården. In the simulated scenarios where a 3-track design is assumed (two northbound platform tracks), the increase in secondary delays move from Sofia to Kungsträdgården. The reason is that when Sofia gets larger buffer times, the bottleneck and part of the synchronization effect moves from Sofia to Kungsträdgården.

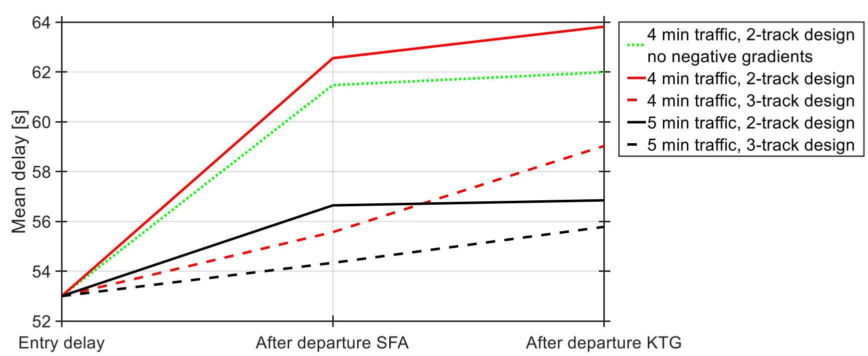

Figure 6: Simulation results (mean delays) for the simulated cases.

The scenarios where Sofia has a 3-track design generate a smaller level of secondary delays in total than in the scenarios where Sofia has a 2-track design. The effect is clearer in the 4-minute timetable. This is expected since the buffer times are smaller. With a 3-track design at Sofia, the delay after Kungsträdgården increases by 3–4 seconds when the train frequency is increased from 5- to 4-minute intervals. The corresponding increase with a 2-track design is 7 seconds.

5 Conclusions

The results from both the timetable case simulations and the detailed analysis shows that the 4-minute timetable case is clearly more sensitive to delays. Although the effects of having a 2 or 3 track design at Sofia where northbound trains will merge can be seen locally on that and subsequent stations, there is no significant difference further along the line. There exist other operational benefits of having a 3-track design at a branch station and these were also considered in other studies, although not discussed in this paper. Later it was decided that the branch station will have a 2-track design, mainly due to a more complex construction and a significantly higher cost for a 3-track station design.

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