Simulation of dynamic station dwell time delays on high frequency rail transport systems

Representing dynamic station delays with OpenTrack

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Abstract

The railway simulation software solutions available today are increasingly used for other purposes than they initially have been created for. These software products aimed at first to recreate the operations on a normal railroad network, with often a schedule allowing for minor delays. However, nowadays light rail as well as underground railway networks, which are highly congested and have high passenger exchange within the cities, are also simulated. Although these systems do have the same basic functionality as the full railway, there are effects that sometimes can’t be represented easily with the existing software solutions.

One of these effects is the dynamic delay build up at the stations during peak-hour traffic: a vehicle that is already delayed will get more people at the next station, making the passenger exchange longer, and therefore accumulating delays. This often leads to the widely known effect of bunching, where several vehicles follow each other closely. This master thesis will show a method to implement the effect of dynamic dwell time delays on high frequency, high passenger frequentation systems in an existing microscopic railway simulation. The application of this effect is based on the analysis of the red lines of the Stockholm Tunnelbana system simulated with the OpenTrack software during a case study. There, the results show clearly that the effect of a dynamically growing delay can be achieved with the implemented method.

Sammanfattning

De tågtrafiksimuleringsverktyg som finns idag används i högre grad till andra tillämpningar än de ursprungligen skapades för. Syftet med dessa simulatorer är att avbilda tågtrafiken på ett normalt järnvägsnät, oftast med en trafikering som har små förseningar. Dagens spårvagns- och tunnelbanetrafik har ofta ett högt resenärsutnyttjande, ofta med stor trängsel och stort resenärsutbyte vid stationerna. Även om dessa simulatorer har samma grundläggande funktionalitet som för den normala järnvägen så finns det effekter som inte kan representeras i de befintliga simulatorerna.

En av dessa effekter är den dynamiska stationsuppehållsförseningar som byggs upp i trafiken för spårvagnar och tunnelbana under högtrafik. Ett tåg/spårvagn som redan är försenat kommer att få fler resenärer vid nästa station, vilket gör att resandeutbyte tar längre tid, därmed ökar förseningarna ytterligare. Detta leder ofta till effekten av hopklumpning (bunching på engelska), där flera tåg samlas och följer tätt efter varandra. Detta examensarbete kommer att visa en metod för att ta hänsyn till denna effekt av dynamiska stationsuppehållsförseningar vid högtrafikerade mikrosimuleringar av trafiken. Studien av denna effekt är baserad på en analys av den röda tunnelbanelinjen i Stockholm som är simulerad under en fallstudie med simuleringsprogramvaran OpenTrack. Där visar resultaten tydligt att effekten av en förändring växande försening kan uppnås med den föreslagna metoden.
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1. Introduction

a. Background

When setting up a model for the railway traffic, it is merely possible to set up delay functions and occurrences that lower the performance of a vehicle. However, every day operations on high-frequency rail transport systems such as subway, light-rail or tramway systems show that these kinds of performance settings are simplified too much. Especially during times of high frequentation of the transport systems during peak hours, any minor delay of any vehicle can set up a severe chain reaction.

From previous conducted studies, it has been shown that for transportation systems with high frequency (with around 7.5 minutes headway\(^1\) between the vehicles (DJOKO & KRAUSE, 2013)) the passenger arrival at the station is random: therefore, a vehicle having a minor delay will take more passengers on the stop after the initial delay, which very likely will increase the delay as the passengers need more time to board and alight. The following vehicles however will then have fewer passengers on this station, leading to slightly faster station stop times and therefore catching up (after a certain time) with the delayed vehicle in front: the effect of bunching occurs. However, as these existing studies focused on bus and light rail traffic, this effect has not been described for metro systems and it will be shown in this master thesis that this effect also occurs on subway lines.

As of now, the microscopic railway software solutions such as OpenTrack are not able to fully depict this effect. However, as operators as well as planners would like to have more accurate models of their public transport systems, the models should be able to account for this effect.

b. Aim of the Master thesis and expected contributions

- Investigate through field work and analysis of existing track-circuit data (1-second-accuracy) the delays which lead to the rail bunching effect

- Elaborate a way to implement the dynamic delay function into OpenTrack, using the OpenTrack API

- Implementing the dynamic delay calculation model in an OpenTrack simulation

- Give options for solving rail bunching occurrences in real operation as well as further modeling approaches to calibrate the model to real operations

\(^1\) Words that are underlined with a dashed line are explained in the glossary.
c. Delimitations

This master thesis will focus on the search for a better representation of dynamic dwell time delays within the OpenTrack microscopic simulation program and their applicability in general simulation models. Therefore, an analysis of the different delay types will be included to have a good base line for understanding the processes and the causes of these type of delays; it will also be checked whether the passenger arrival rate at the station is randomly distributed (i.e. no significant peaks at repeated points in time) between two vehicles. As the analyzed effect only is shown with a high to very high passenger frequenceation, the study will focus on the analysis of the most crowded times of a day, namely the morning peak hours. Also, the effects of the dynamic delays, like the vehicle bunching, will be described and analyzed.

Further, the elaboration of the dynamic delay function will result in a small algorithm and code that can be adjusted to any other transportation model, provided that the users of the model have enough data. However, it is not the aim to write commercial software. It is more thought as giving a general approach to the way this problem could be solved and how to make use of it when working in planning and/or consulting companies.

d. Methodology

The methodology used for gaining insight in the underlying processes and developing the project follows the five steps below:

1. Search for information and key factor assessment

   - At first, a comprehensive search among the existing literature is carried out in order to find information about the effect of dynamic delays as well as studies and works that have been carried out earlier.

   - Interviews with modeling and planning experts at consultant companies and university researchers then complement the preliminary information about the causes and influences the dynamic delays may have.

   - A field examination in the Stockholm Tunnelbana during the morning rush hour is also carried out with the help of Tunnelbana drivers. It allows for a detailed understanding of passenger movement exiting and entering a railway vehicle as well as the repartition of the passengers on the platform and in the vehicles.

   - An analysis of the obtained documents and information then forms the basis for determining the key factors for having dynamic delays on high frequency railway lines.
2. Determining the necessary data and model in order to carry out the project

– The data that can be obtained from the different sources (infrastructure / vehicle based) is screened for then creating an overview of the data that is generally available when analyzing a transportation network.

– Extensive data samples of the Tunnelbana Red Line in Stockholm are taken as an example. These samples are subsequently mined, potentially identifying additional key delay factors. The so established mined data is then checked for evidence of the key delay factors determined in the first step. After confirming the influence of the key delay factors, the data is checked for recurring patterns in order to be able to establish the basic principles that govern the dynamic delay effect.

– Eventually, the analyzed and mined data allows for an examination of the effects that the dynamic delays have on the traffic.

– After having collected all the data, a general algorithm is devised stating how the dynamic dwell time effect should be calculated.

3. Case Study: Modeling of the Tunnelbana Red Line without the dynamic delay effect

– Through discussions with planning and modeling experts as well as by analyzing the data samples above, the state that the OpenTrack simulation model should be in (time of day, vehicles and signalization for example) is determined.

– The data necessary for building the simulation model is collected from the different responsible parties. With this data, a complete model of the Red Line of the Stockholm Tunnelbana is set up in OpenTrack, including the dwell time delay distributions; these distributions do however not represent the dynamic dwell time effect by themselves, as they are not related one to another.

– After completing the debugging and the test runs, the model is calibrated with a normal traffic situation during which the operation is not affected by the dynamic delay effect (non-peak hour traffic, for example).

– Eventually, the simulation model is validated with another set of operational data which then enables the simulation of the traffic during peak hours with the calibrated and validated running time model and the usual dwell time delay distributions. However, the simulation of the peak hour traffic with the calibrated model not using the dynamic dwell time adjustment should show significant differences between the simulation and the real-world data.
4. **Modeling, coding and implementation of the dynamic delay model**

   - A simulation model that is based on a non-congested situation is set up in OpenTrack. This model does not use the dynamic delay calculation. The technical features and the software for building and implementing such a calculation model are reviewed and the knowledge of using this software is acquired.

   - According to the technical features of the available, the general algorithm established in step 2 is adapted for the implementation. This forms the basis for the development of the code for the dynamic delay model.

   - This dynamic delay model is then implemented into the validated simulation model that was established in step 3. The simulation with the dynamic delay model during the peak hours should show that the dynamic delay model fits the real-world data better than in step 3.

5. **Simulations with the dynamic delay model and results**

   - This new simulation model with the dynamic delay model is consequently used for a few scenario runs in order to show that the delay model is a viable.

   - In order to be able to use the dynamic delay model conveniently and in other contexts than this work, recommendations for the usage of the model are made.

   - The results obtained from the delay model implementation eventually will lead to suggestions for actions on how to minimize the effects of the dynamic delays.
2. Dynamic delays – Causes and effects: Preliminary analysis

a. Dynamic delays vs. normal delays

Dynamic delays are a very common effect in heavily frequented rail networks in an urban environment. The dynamic delay is the most apparent for buses, as buses are often said to come in bunches; this effect is known as bus bunching and has already been analyzed thoroughly (Cats, et al., 2010; Cats, et al., 2012 and Daganzo, et al., 2011).

There, initial minor delays on the line, such as badly timed traffic lights or a longer dwell time at a station, make the following bus stops get an additional amount of people which corresponds to the delay of the vehicle. This additional frequentation makes the dwell time at the station increase in comparison to the normal conditions, and therefore the bus is being more and more delayed. As the delay of the vehicle depends on the previous stops and the dwell time at the station is itself influencing the dwell time the bus needs at the next station (more people have to get on or off), this kind of growing delay over the line is called dynamic delay in this master thesis.

The effect that has been already well analyzed with buses; on subway systems however, this effect is less apparent to the user, as the trains are often not visible from the surface and bunching is less visible. On light rail systems which mostly have a dedicated track, this effect is commonly seen as well as for bus lines, but there are differences between the dynamic delays that occur on railway bound systems and those occurring on a bus system.

The dynamic delays for buses can be caused by traffic jams, weather conditions, traffic lights and other occurrences on the road network (Wahlstedt, 2014), as well as the variable dwell times. For the light rail systems and especially for subways, the dynamic delays are in a great extent caused by the extended dwell time at the stations, as the distance between the stations are designed as a completely own infrastructure; the vehicles can therefore drive there in nearly the same conditions all over the day. Further, the trains don’t have the possibility to overtake each other like buses would sometimes do in order to ease the load and the delay.

When using the notion of delay in a railway based case, the most common association is a delay caused by an interruption or another punctual occurrence in traffic. This type of “common” delay is mainly felt on railway systems that do not have a high frequency, as the passengers cannot take any train they want to get to their destination.

The trains may have special access conditions or the passengers may have only tickets valid for one certain train. The incapability to “jump on the next train” in order to reach the destination increases the frustration further for the passengers, especially when the frequency is low. (Passenger Focus UK, 2014)

However, these “common-sense” delays, although they are also seen in high-frequency operation urban railway networks, their effects are less frustrating for the passengers as all the trains in the same direction can be used in order to reach the destination. However, it may be that even without any punctual occurrence in traffic, the trains that should come every 5 minutes arrive with 2 minutes interval at a station, leaving an interval of 7 minutes to the following trains.
It is very probable that the train that arrives at the station 2 minutes after the train of the same destination is less crowded, and so its station dwell time being lower than the following train, which comes 7 minutes after. That means that the train driving with 2 minutes interval will be faster along the line, probably even catching up the train that left before; the train coming after the 7 minutes interval will collect all the passengers that have come to the platform during this time, making the dwell times longer (on average).

It is also very probable that as the dwell time is longer than other trains, this train will be more and more delayed along the line as it catches more and more people. As the dwell time at one station is directly related to the dwell times that occurred previously on the stations, the dynamic delay effect results; this will be the effect that will be focused on.

However, also other kinds of dynamic delay exist, for example considering drivers’ behavior or problems with the rolling stock, factors that will be explained in the next section. The important feature of the dynamic delay is that it develops along the line and being related to past delays.

The effect of the dynamic dwell time delay also is apparent on national railroads, especially on peak hour traffic in Friday and Sunday afternoons. However, as the trains travel longer distances, the schedule is not as tightly knit as in urban railway systems, having more relief time between the stations (Weidmann, 1994). The train might be able to make up for the delay between stops with better acceleration or braking.
b. Causes for Dynamic delays

In order to be able to simulate and model the dynamic delays correctly, it is important to know what the causes are that create the dynamic delays. As seen in Figure 1, the way passengers arrive at a station is one of the first factors. This, as well as the other factors, is described in the following sections.

Figure 1: Chart of the influences of the dwell time and journey time of a vehicle. The greyed-out factors are not taken into account in this project. – Adapted from Boyd (1983)
i. Passenger arrival rates at the station

The effect of the dynamic dwell time delays is most common during periods of high train frequency and high occupancy rates of the trains. The dynamic dwell time delay is usually the effect that takes over as soon as there is a minor delay on the line and the line is highly utilized by passengers. Dynamic dwell time delays are based on the fact that no system is perfect, and that there are variabilities in exploitation of the system. These variabilities can range from a driver starting a little late at the end station to some higher punctual loads at one station (and taking more time for the passengers to get on and off the vehicle), with punctual delays because of infrastructure or rolling stock problems or congestion on the line. During this minor delay, more and more people are entering the station, and as the train is for example 1 minute late, it will pick up 1 minute worth of extra passengers at the station. These additional passengers increase the passenger exchange time.

The morning rush hour between usually 6:30 and 9:00 a.m. (depending on the city that is analyzed) is the period where the highest extent of the dynamic delay effect is often seen (as the trains are bunching). The morning rush hour is also the period that has the highest train frequencies on urban rail networks (SL, 2013), as these systems are often designed to bear a high commuter passenger load. The afternoon rush hour, as seen in Figure 2, is more spread along the afternoon, leading to less people on the urban network at the same time; therefore the trains are less crowded, even though the frequency is lesser than in the morning peak hour (Cats, 2013). The effect of the dynamic delay is not that clearly visible there, and it may be that the passenger arrival rate at the station is not totally random at certain stations in for example industrial areas where shift-workers do finish their shift at the same time. There is no reason for irregularities as seen during the rush hour to occur during the off-peak hours.

A random arrival at a station is characterized with a constant flow of passengers into the station. The normal frequency of the trains departing from the station is so high that the waiting time for the passengers at the station is not a factor in the decision for the choice of the transportation mode, nor for choosing a specific departure time.
The passengers do come into the station often without caring how much they have to wait, knowing that the waiting time is normally short. In the Stockholm Tunnelbana for example, the frequency during rush hour on one line is usually 5 minutes, with in case of the red lines two lines overlapping in the central areas. The randomness criterion is a crucial part in order to determine what the relationship is between the occupancy and delay made by a train. Therefore, the randomness of the arrival rates will be analyzed in chapter III.

In Stockholm, the schedule is made public by the transport authorities, but receives usually little interest during rush hour traffic. However, on some urban railway networks, on the Strasbourg light rail for example, the exact schedule is not even shown at the stations, only the usual frequency of trains on the stretch of line are detailed. There, trains on one line depart for example every 6 to 8 minutes, as seen in Figure 3. This increases even the effect of a random arrival at the station, as the exact time is simply not known.

The real time passenger information system is also a good information source for the passengers, which makes the arrival less random, as the systems shows the time until the next departure of the vehicle; the departure times are known by the passengers so that the time staying on the platform is connected to less uncertainty about the train arrival. The passengers can also plan their arrival at the platform when they enter a station.

The location of the exits as well as differences in the frequentation of these exits can also affect the later occupancy of a train. This effect is even more pronounced if the station platforms are long, as the passengers will wait for the train to arrive more or less close to the entry on to the platform and not spread along the platform.

Some other passengers, that are familiar with the situation of the station and their exits, do also consider on which side of the platform they wait in order to minimize later walking time when having to exit the station.

As seen during the field examination in the Stockholm Tunnelbana, the passengers waiting for example for the Red Line to the north during rush hour at the station T-Centralen are mostly waiting in the back of the platform creating therefore a high occupancy in the rear vehicles whereas the front vehicles are less crowded. The implications of this behavior are later important in chapter III for approximating the dwell time.
ii. Problems on the vehicles/infrastructure

Problems on the vehicles or the infrastructure are also capable to directly cause dynamic delay. For example, a vehicle can lose up to 50% of the normal motor power due to technical problems and therefore needs more time for accelerating, thus increasing the delay along the line. Other causes for failures, which lead to a reduced vehicle performance in maximum speed, acceleration or braking, are vectors for a dynamically transmitted delay. Luckily, these effects do occur quite rarely, and it usually leads to the withdrawal of the vehicle as soon as possible (Anes Viseu, 2013). Therefore this kind of dynamic delay will not be treated further. Newer vehicles have also a feature that allows them to weigh the current passenger load. If this passenger load exceeds a certain limit (over 300% of the seated capacity), these newer vehicles can decrease the maximum operating speed in order to avoid an overuse of the brakes. (SL, 2013) This in return also creates a dynamically growing delay.

iii. Driver behavior

A dynamic delay can also be caused by the behavior of the train driver. As most of the rail bound vehicles are still driven by humans, there is variability in the way people drive their vehicles. Not all drivers will drive the train as fast as possible and will brake as much as possible when entering a station. The drivers will more or less take the appropriate measures that are needed for the passengers to have a nice smooth ride. Furthermore the behavior is also depending on the mood and on the type of driver that is driving the rail car. For automatic operations, this point does not apply; there no variation is introduced by the human factor. The rolling times between the stations, i.e. the time between doors close and the doors open up again at the next station, follow also a distribution that looks very much alike at dwell time distribution. However, by averaging out all the runs throughout a big sample at always the same time of day with such a difference in drivers and different occupancy rates in the vehicles, this effect can be minimized (Boyd, 1983). This however is not relevant for the study and will therefore not be analyzed.

iv. Planning of the timetable

The planning of the timetable may also have an effect that can be seen as a dynamic delay. As in most cases, the timetable is rounded to the minute, the driving times between the stations as well as the dwell time is not exact; In some cases, the planning of the timetable is also made with very little relief time when running on the line (Olsson, 2013). This, as well as the rounded minutes, makes that the driver is usually a little late (up to 45sec-1min) at the station compared to the original schedule. By doing so, it gives the drivers an incentive to drive as fast as possible in order not to be late, especially during rush hour traffic. The whole relief time is instead usually planned when arriving at the end station.
Through this procedure it is also much easier to compare the driving times between the stations, as the drivers try to always adhere to the very tight schedule.

In figure 1, it can be seen that the driver performance has an influence in many ways on the final dwell time at the station. However, as the driver behavior between the station and therefore the acceleration and braking process is pushed to the limits due to the very tight schedule, it can be assumed that the drivers do have approximately the same performance. For the sake of clarity of the results, this work will only take a fixed average value for the running times between the stations.

c. Effects of the Dynamic delays: bunching on railway lines

Bunching is an effect that causes great troubles in an urban railway network. As the arrivals of vehicles to a station are getting irregular, the service that is given to the passengers is not constant. This increased headway variance implies an increase in average passenger waiting time and increased waiting time variance (as, with a random arrival at the station, the average waiting time at a station is equal to half of the headway). (Boyd, 1983)

As explained before, the effect of bunching is a well-known effect in transportation systems, especially for bus lines. This effect is created as one vehicle is delaying more and more at each station and other vehicles will catch up the first, delayed vehicle.

For tramway systems as seen in Germany or France, that have no automatic train control systems and are not totally grade separated from the individual traffic, the effect of bunching just looks like the effect that can be seen analyzing bus traffic (Ullrich, et al., April 2014). Figure 5 is a good example for that, showing severe tram bunching on the Kaiserstraße in Karlsruhe.

For railway systems, bunching is quite difficult to discern, and it is even more so on subway systems, most of the subway system is underground and cannot be seen directly. An important feature is the role of the signaling system, which is set to give to vehicles on a railway line (subway or light rail in this case) a safety distance between vehicles.
A buffer zone between vehicles is therefore created, which in the case of the Stockholm Tunnelbana are track sections insulated from each other, but can be any sort of block-section system (or the safety distance in ETCS). In this sense, bunching can be seen as the fact that the one train that is delayed causes the subsequent train to catch up to this safety distance that is set up by the signaling system. The train consequently has to wait until the train that is delayed frees the section that precedes the safety distance.

The headway between two trains following each other is therefore set as the running time that is allowed by the signaling system and the station stop time. Still, the safety distance makes the trains follow each other with an interval that is about 90 to 120 seconds (Städje, 2009). This effect however only applies to conventional signaling systems as the one in Stockholm or to the fixed-block systems, where the trains still have to respect a safety distance. With the arrival of the moving block system, or even by using driving on-sight as seen with the conventional light rail systems, the trains can drive up to the end of the previous vehicle.

As the vehicles bunch together, by for example an increase in average dwell time, the overall measured average passenger travel speed will be lower than the overall average vehicle speed as there are more passengers travelling on the slower vehicles than on the faster vehicles (Pilachowski, 2009).

3. Modeling and implementation of the dynamic delays

   a. Preliminary data requirements and technical requirements
      
      i. Consistency of the vehicles on the line and means of comparison

In order to analyze the data in a correct way and to be able to compare the vehicles with each other, the line operations that are analyzed should be as consistent as it can be. Especially when looking into the vehicles, they should be comparable in terms of capacity, seat arrangement, number and widths of doors.

This is necessary in order to ensure that the data collected later on in a second step are not influenced by any of these variables and that the distributions are not biased from the fact that the vehicles are different to each other.

This is for example important when looking at the dwell times, as these times depend on the speed of boarding and alighting of the passengers; if one vehicle is completely different than the others it might have a much better performance when boarding or inversely could have a much worse performance, so that these vehicles should be excluded from the study.
ii. Randomness of passenger arrival at a station

Randomness of passenger arrival at the station is a central feature of the methodology. As the passengers are coming randomly, the stream of passengers does not present a pattern with spikes and lows, meaning that passengers arrive at a constant rate at the station. The usual belief tells that passengers are very likely to come randomly to a subway stop, especially when the headway is relatively short.

On many subway systems it is not possible to determine how many passengers are boarding and alighting at a certain stop, as most of the stations do have barriers for the two directions and sometimes have other high-frequency lines getting into the station that make a direct change possible without being counted in the systems. It is also difficult to find evidence about this fact in the literature.

Only a few studies have been carried out about the random passenger arrival at the stations. Studies also show that cities do differ from one another depending on the organization and operation of the urban transportation network, and that results that were found in one city can only be used with caution for another city.

A good example for this are the studies of Luethi, et al. (2006) made in Zürich and Krause, et al. (2013) which was analyzing stations in Stockholm. The study carried out in Zürich analyzed the influence of headway on the passengers who either knew the tram/bus timetable (the "schedule-dependent passengers") or did not know it (the "schedule-independent passengers"). The results of this study can be seen in Figure 6.

Luethi, Weidmann and Nash also dealt with the influence of other factors that can affect the waiting time and the share of schedule-dependent and schedule-independent passengers; they pointed out that the arrival rates and the headways were quite correlated with mostly schedule-independent passengers for headways less than 6 or 7 minutes and a clear proportion of schedule-dependent passengers for headways up to 30 minutes.
However, even at small headways (around 5 minutes), a large amount of schedule-dependent passengers could be observed in Zürich. This is maybe due to the very high familiarization with the public transportation system observed throughout Switzerland. In Stockholm however, indications were found that for a headway approaching 5 minutes the average waiting time being half the headway is a good approximation.

Also other papers, as for example O’Flaherty et al. (1974), suggest that with a 5 minute headway the passengers are not interested in knowing the exact timetable, more about how long they would have to wait on average until the next train would come. However, as shown in Figure 7, the average waiting time is not evolving linearly, but merely logarithmically. The half of headway is generally quite accurate until a headway service of 5 minutes, but gets a lot less accurate when considering headways of 10 or more minutes.

The two studies by Luethi et al. (2006) and Krause et al. (2013) were carried out on tramway and bus systems, and it can be seen that light rail services have (at same headway) significantly reduced waiting times as opposed to the bus services. The fitting curve for the tram flattens out earlier than the one for the buses, even considering the few minutes delay. As the average waiting time is smaller for the light rail, it can be said that passengers arrive more randomly at bus stops than at light rail stations (the fitting curve is nearer the half of headway line indicating randomness).

This is maybe due to the bigger number of timetable-dependent passengers of the light rail lines, as the service there is more reliable and therefore more attractive than buses. The subway being even more attractive to passengers than the light-rail (faster transportation and more frequent), the results can also be transposed to heavier transportation systems.

![Figure 7: Average passenger waiting time (WT) versus headway in Stockholm for Bus and Tram – Source: Krause et al. (2013)](image-url)
These studies also pointed out caveats, as for example the studies were carried out on relatively small samples and on stops that did not have a very high passenger frequenceation.

It is therefore necessary to look into the random passenger arrival at stops in a city when analyzing the rail bunching effects in this city, in order to get even more precise results and eventually a better simulation.

iii. Data requirements

In order to be able to apply this method to a real world analysis, certain requirements should be given: The operation of the vehicles should not be influenced significantly from other sources of delay (as for example street lights or traffic jam for light rail systems, systematic connections on grade separated systems) at a station; these features would make an analysis very difficult and the resulting data probably biased. However, at some stations minor timetabling issues exist (relief points, driver change etc.) and should also be taken into the analysis.

As stated above, the main focus point in this study will be the dwell times at the stations for each vehicle. Also, the dwell times are in form of a histogram distribution, from which the simulation will eventually draw randomly one dwell time for the actual station. The dwell time is connected to the headways, and therefore an analysis of the headways and the dwell times is needed.

It is proposed that at first the dwell times in relation to the occupancy are looked into, with for example the 100% occupancy mark corresponding to the seating capacity on the vehicles. This also may lead to a unification of the vehicle types, as it is crucial for further analysis that the vehicles can be compared to each other.

In a second step, the headways are analyzed in relation to the occupancy. There, a cloud of points should appear, with a trend that is showing upwards.

When looking at the technical features, the occupancy on the vehicles can be measured by many different methods; however, the timestamp for the measures, unless it is directly synchronized, may differ from the effective time. It is therefore not possible to study the headways directly from the dataset of the trains, and the synchronized, infrastructure-based data have to be taken in order to get the right time stamp. However, this may be difficult, as the data may often be corrupted. A detailed description of an example of how to connect the two databases will be given in the case study.

For systems where vehicles are coupled together (and thus not giving the possibility to adjust the passenger occupancy easily within the vehicles), the data used in the analysis is the maximum value of the occupancy of a vehicle, as it can be seen that the vehicles that are the fullest take the most time to clear the doorways.
iv. Software

The simulation will be carried out with OpenTrack, which is a simulation software developed at the ETH Zürich and initially conceived for use on heavy rail systems. Throughout the years, the software was adapted for simulations of urban railway eventually for light rail traffic. It allows the implementation of realistic operational behavior and as the simulation is dynamic, the delays that are observed are not always the same.

Further, OpenTrack gives the opportunity to include dwell time distributions from which the simulation then draws randomly the dwell time the train should have at this precise station. A visualization of the operational activities allows the simple assessment of existing problems and solutions. The simulations can be implemented in OpenTrack with relatively little effort and can be very detailed. The tasks can then be carried out incrementally and iteratively. All this gives a good overview on the system from the operator’s perspective.

The analysis will also make use of the OpenTrack API, which is a new web-server based SOAP communication tool, which sends out commands to and receives status messages from the OpenTrack simulation. Figure 8 shows the functionality of the API, which is that the messages the API sends out are directly read into the simulation and can therefore act as an external controller of the simulation, much like line control centers that exists in the real world.

The messages that can be exchanged with the simulation are of many different kinds, as for example starting the simulator or reserving certain stretches of the line. The most useful tool will however be the timetabling messages that the API can send, as for example setting the departure time at a station or looking at the priorities at a junction.

This tool will be the central exchange interface between the dynamically calculated dwell times and the running simulator, as the calculation of the different occupancies depending on the headways are made by a model written in VB.net language in Visual Studio and then applied to Windows Excel.
b. Algorithm

The algorithm for being able to model the effect of dynamic delay in a simulation program comprises several steps.

At first, when a train comes into a station, the simulation sends an arrival message to the external dwell time model. This arrival message is then analyzed with the previous departure of a train from the same station; from these two time values, the headway between the two vehicles is determined.

The dwell time model does have access to a database which combines the values of the headways for each station with corresponding distributions of occupancies. A discrete distribution for exactly this value of headway is obtained from this database, and the model draws randomly a value from this distribution.

This procedure results in having a value of occupancy in the vehicle itself at the time it comes to a halt in the station. This frequentation is tested against an average occupancy value that was determined beforehand for the station, and the calculated frequentation should lie within the first and the third quartile. In a second step, the occupancy is used to determine the average dwell time on the station that is taken from a second database which combines the dwell times at this station and the occupancy that is in the vehicle as it enters the station.

From this database, the occupancy that was obtained from the Headway analysis is translated into an average dwell time. This average dwell time is then used as basis for re-centering an existing distribution onto this average. Finally, the model draws randomly a value from this re-centered distribution and the actual dwell time for the train in the station is set and communicated via the API to the simulation which assigns the determined dwell time to the train.

The different steps in calculating are explained in Figure 9 below, and the flow chart in Figure 10 shows further intermediate steps as well as the intermediate data that were obtained.
Program(Determine_DwellTimes_at_station)

Get Train1.DepartureTime = Depttime
Get Train2.Arrival = Artime
Set Headway = Depttime - Artime

Lookup(Headway) in Headway-Occ_Database = Occdistribution

FrequentationBoundaries = 1st and 3rd Quart. Of observ. values
RandomDraw from Occdistribution = Frequentation Until
Frequentation is between FrequentationBoundaries

Lookup(Frequentation) in DwellTime-Occ_Database = AvgDwellTime
Set Avg_Usualdistribution = AvgDwellTime
RandomDraw from Usualdistribution = DwellTime

Set Depttime_Train2 = DwellTime + Artime
Send (Depttime_Train2) to Train2

End Program

Figure 9: Algorithm in code form
c. General implementation

As explained above, the new model will be implemented through the OpenTrack API.

This API feeds the necessary data directly from the simulation to the model. As the API is independent of which programming language is used, the model can be written in any language that is convenient. OpenTrack as well as its API are being installed on the same PC for this project, but might also be installed on different computers as the web-based API can send the messages over the internet.

As the model is based on a customized Excel workbook, the software solutions needed for the calculation model are Microsoft Excel and .Net Framework 4.0 or higher, which should normally both be already installed on any PC which is used for office applications. Further, the PC either needs OpenTrack installed locally or a connection to another PC which has OpenTrack installed.

The model is thought to be a complement to the normal OpenTrack features, and it therefore can be used together with other functions. The implementation is very much dependent on the system and on the expected results of the study that is carried out. However, it can be said that the implementation presented here should function for most cases that show a tendency to develop dynamic delay.

In the course of this study, it became apparent that OpenTrack did not yet have the functionality that was necessary to the adjustment of the departure time. As a train entered a station, OpenTrack calculated a preliminary dwell time based on the information that was entered in the timetable beforehand.

The message that was sent from the calculation model to the simulation was acknowledged, but the new departure time that was supposed to be a factual departure at the station was misinterpreted as a schedule value, meaning the simulation orientated itself to it. The simulation therefore kept the old, unrevised departure time and calculated the difference to the newly calculated time as delay to the “scheduled” time.
d. Functionalities of the Dynamic Delay calculation model

The model is based on a self-calculating Excel workbook, which can be adapted to other transportation networks. This Excel workbook is fed beforehand with a database of the usual occupancy distributions, the usual dwell time distributions, the formulas upon which the average of the distributions is adjusted as well as the boundaries of the difference in passenger frequentation, for each station. This database is then used for calculating the values that are needed in a separate sheet for each station.

i. Communication OpenTrack - calculation model

In order to use the Dynamic Delay calculation in an OpenTrack simulation, OpenTrack has to be started in the API-mode, which enables the sending and receiving of status messages and commands. The messages that are emitted by OpenTrack are sent to a port on a specified IP-Address of the computer (which usually is the localhost / 127.0.0.1 if the delay calculator and OpenTrack are used locally).

The Excel sheet, which has been fitted with a TCP-Listener, can listen to this port and retrieve the incoming messages using the TCP protocol. These messages are SOAP XML-style messages, which contain several different relevant pieces of information, as for example information about the time, the train identification, the station name or the delay that the train has.

The sample message of Figure 11 shows a few of these bits of information within the SOAP framework. The messages, which are sort of responses of the simulation, are therefore then parsed and the pieces of information prepared for analysis.

```xml
POST /otd HTTP/1.1
Host: localhost
SOAPAction:
Connection: close
Accept: application/dime
Content-Type: application/dime; charset=us-ascii
Content-Length: 311

<?xml version="1.0" encoding="UTF-8"?>
<SOAP-ENV:Envelope
xmlns:SOAPENV="http://schemas.xmlsoap.org/soap/envelope/"
<SOAP-ENV:Body>
<trainDeparture trainID="09-14N" stationID="FRÄ" time="36520" />
</SOAP-ENV:Body>
</SOAP-ENV:Envelope>
```

Figure 11: Example of a SOAP message used during the communication with the OpenTrack API

The outgoing communication from the delay calculation to OpenTrack follows the same pattern as above, as the pieces of information are composed in the specific pattern that is used for OpenTrack and then sent to the OpenTrack API.
ii. Starting, time-stepping and stopping the simulation

In OpenTrack, the simulation parameters can be set up beforehand as shown in Figure 12 (for example which simulation start time would be used, or what the time for ending the simulation is); All the data needed for running a normal simulation (infrastructure model, timetable, vehicles etc) are contained in one database, which has to be opened prior to simulation.

As the Excel workbook contains all the databases, the data and the calculations, some cells have to be initialized before each simulation run in order to not inadvertently using wrong values. Furthermore, the TCP Listener and the analysis of the SOAP-messages received from OpenTrack are running on their own threads in the CPU; it is therefore simpler that the whole simulation is controlled over the Excel workbook. In this case, the simulation starts automatically with the predefined parameters after the necessary initializations have been made in the Excel workbook.

As mentioned before, OpenTrack is a microscopic simulation model with synchronous calculation, meaning that it models the operation of each individual train during a time step and then repeating the process for the entire simulation period.

As the analysis of the message sent by the simulation, especially when having to calculate the right dwell time, the Excel workbook calculation takes longer than it takes OpenTrack to advance by one time step, the simulation has to be paused in order for Excel to complete the calculation. The simulation has therefore to be paused every time step to be able to analyze the responses from the simulation.

As soon as the response of the simulation indicates that there are no further operations that need further calculation, the simulation is continued for the next time step and the returned messages analyzed again.

At the end of the simulation, the message indicating the end of the process is sent by the simulation, which then ends also the analysis and the TCP listening routine.

iii. Filtering and analysis of the simulation responses

The messages that are received by the Excel workbook are caught in a filtering routine, which depending on what actions triggered the message, sends the information forward to other routines in order to be evaluated. If the messages were send as a status notification (pause of the simulation or time-ping), the simulation is directly restarted for simulating the next time-step.

In order to accelerate this process, the filtering routine uses an own thread; however, as the calculation time can vary considerably (especially for the calculation of the dynamic dwell time), the other processes are halted until the filtering has finished.

The analysis routine that is eventually triggered by the filtering executes the calculations necessary for the problem-free course of the simulation. This analysis routine is not only for the calculation of the dynamic dwell times, but also to sort the incoming data in a way that the data is ready and available when the dynamic dwell time calculation begins; this includes for example the check for the train status (if running or not) or the logging of the departure times.
iv. Calculation of the dynamic dwell time

When the analysis routine detected that a train stopped at a station, the algorithm described before is triggered in order to change the departure time that was calculated beforehand by OpenTrack with the time that is calculated using the algorithm.

For each station, the patterns of the distributions of the occupancies and of the dwell times are adjusted to match the average value for this headway or occupancy. The average value is computed using the linear formulas that were established by the analysis of the raw data.

The adjusted patterns are eventually returning a value that was randomly drawn following the distribution, which is the difference to the average value that was determined earlier.

When looking at the vehicle occupancies, this value is subsequently added to the previous vehicle occupancy (before it made the stop in the station) and it returns an actualized occupancy (that the train will have when it will exit the station). This actualized value is then tested against the boundaries of the difference of the occupancy to the previous station, and if successful the occupancy value is further used for computing the dwell time at the station, using the same method but without testing against boundaries.

e. General drawbacks of the calculation model

The first drawback of this approach becomes apparent when looking into the time of simulation. As the simulation has to pause after each simulation step (usually 1 simulation second), the simulation is very time consuming. It takes for example seven hours in order to simulate two and a half hours on a modern, up-to-date computer with both the simulation and the calculation running locally. This can however be solved by changing the way OpenTrack is calculating the dwell times.

OpenTrack predefines the dwell time beforehand, so that the dynamic delay calculator as of now has to be active all the time listening to the simulation and waiting for the information that it can calculate and send a new departure time. It is however possible that OpenTrack genuinely asks for the new dwell time information and pauses until the calculator sent a message back with the new dwell time. That would decrease dramatically the time, but also the (calculating) resources needed for running the simulation with the dynamic dwell time model.

Another drawback can be seen in the data that is taken for the calculation. It is based on the distributions and the formulas which merely give empirical averaged values of the available raw data for both the occupancies and the dwell times, the calculations are random approximation of the average behavior of the passengers in the tunnelbana. This however is a drawback that is consciously taken into account, as the methodology aims for an approach that can relatively easily be understood and replicated by others, for example for consultant work.

Further, the analysis of this empirical data is very time consuming, and often also very complex. It might also happen that the access of the data is very difficult or not made available by the company operating the public transportation system (Meister, 2013), especially regarding the data of the frequentation in the vehicles.
f. Advantages of the usage of the calculation model

The major advantage of this general approach as well as the calculation model can easily be adapted and applied to other transportation networks. Further, the data that is necessary for the setup of the calculation model is rather accessible from the real-world data, and not based on previously established reference values as it is for example the case for the value of time.

As mentioned before, the data of the frequentation in the vehicles is not yet often used for analysis in consulting works. However, the data gets more and more attention in the last years (Nilsson, et al., 2013), and new methods are applied in order to get more accurate readings of this data. The frequentation data will therefore get easier to use, especially with the introduction of new vehicle types, probably even allowing automatization of the data collection (Pendelkollen, 2014).

It is also possible to add or to adjust certain functions that are needed to correspond with the local requirements, as the calculation model is modular. Through the use of the API as a communication tool, it is further possible to implement the calculation model in another third-party software that can remotely control the OpenTrack simulation. This third party software can for example be also made interactive with feeding the actual real time data into the simulation model in order to get an even more precise simulation result.

When looking at planning for new lines or for line extensions, the model can be adapted as existing stations can be taken as reference. The necessary data of the station can be approximated by for example looking at the occupancy distributions and the formulas of already existing stations that have approximately the same features (number of passengers, location of exits etc.) as the new stations.
4. Case Study: Stockholm Tunnelbanans Red Line

The Case Study for testing the method described above will be carried out on the Red line of the Stockholm Tunnelbana system. Especially in the morning rush hour, the effect of the dynamically growing delay is very visible. As more and more people are boarding the Tunnelbana during the rush hour, small initial delays may lead to an increasing delay during the course of the line.

The Red Line of the Stockholm Tunnelbana is the common name for two underground metro lines in the Stockholm Tunnelbana system, lines 13 and 14 as marked on the map in Figure 13. As the two lines are running together on the stretch between Liljeholmen and Östermalmstorg, they are usually called the red line. Together, the two lines have 36 stations, of which 19 are under ground.

The line 13 starts south-west from Stockholm in Norsborg. From there, the line runs north-east through the southern suburbs, and reaches the station Liljeholmen after 14 stops. There, it joins line 14 on the inner-city stretch passing Slussen, T-Centralen onto Östermalmstorg. In Östermalmstorg, line 13 splits in a north-eastern direction towards Ropsten, serving two more stops on the branch.

Line 14 starts at Fruängen in the south, and reaches Liljeholmen after four stops. From there it passes through the city center until the line branches out at Östermalmstorg to the north, stopping at 6 stops on the way to Mörby Centrum.

Figure 13: Maps of the Stockholm Tunnelbana network – Source: SL.se
The analysis has been made on the north-bound rush hour traffic between 7 am and 9 am, as it is the
time of the day where both lines are running at a 5 minutes interval (resulting in a planned frequency of
2.5 minutes on the central stretch) and the effect of a dynamic delay can be well observed.

a. Identification of problems

On the Stockholm Tunnelbana, the analysis of the delays is rendered difficult as there are two different
types of vehicles running on the lines, but only the newer models are equipped with weighing sensors
that enable to know the occupancy of the vehicles. This is crucial, as the occupancy is a central point in
the analysis as shown above. The older vehicles (Cx trains) do have an important difference in
performance with the newer trains (C20), as seen in the table of
Figure 14.

<table>
<thead>
<tr>
<th></th>
<th>Cx</th>
<th>C20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seats</td>
<td>384</td>
<td>378</td>
</tr>
<tr>
<td>Length of Train set</td>
<td>138,56 meter</td>
<td>139,50 meter</td>
</tr>
<tr>
<td>Weight</td>
<td>232 tons</td>
<td>201 tons</td>
</tr>
<tr>
<td>Usual Formation</td>
<td>8 cars</td>
<td>3 cars</td>
</tr>
<tr>
<td>Max. Power</td>
<td>2,59 MW</td>
<td>3,0 MW</td>
</tr>
<tr>
<td>Width</td>
<td>280 cm</td>
<td>290 cm</td>
</tr>
<tr>
<td>Max. Speed</td>
<td>80 km/h</td>
<td>90 km/h</td>
</tr>
<tr>
<td>Entry into Service</td>
<td>1982</td>
<td>1996</td>
</tr>
</tbody>
</table>

Figure 14: Comparative table for the Cx and C20 trains
Source: Spårvägs Sällskap (Cx) & SL, 2013(C20)
Pictures: Wikimedia Commons

The C20 train is a more recent type of vehicle and the most frequent used vehicle in the Purchasers
operation. The C20 traction equipment comprises converters fitted with IGBTs (Insulated gate bipolar
transistors) and three-phase asynchronous machines. All axles in the vehicle are powered. The C20 can
return energy to the third-rail system by means of electro-dynamic braking.
With these indications it becomes apparent that the older Cx trains do have completely different specifications to the newer ones. Especially when looking at the weight and the maximum power that each train set has, the C20 trains do have a serious advantage to hold the schedule as the acceleration and breaking are much better. Therefore, a problem is that the older trains are more likely to be delayed, as they probably cannot make up for lost time at stations as much as the C20 trains can. According to discussions with planning experts at MTR the increased maximum speed of the C20 trains does however not make any difference in this case, as the maximum operational speed is set to 80 km/h on the whole red line.

The Cx trains can however be faster at the dwell times, due to the opening and closing of the doors. As observed during the field work, the doors of the Cx trains are opened directly after the arrival in the station, whether the C20 trains have a few seconds until the doors open. There, sensors in the train have to make sure that the door is indeed located at the platform for letting the door open. Further, the Cx trains have doors directly integrated in the car body, only requiring a lateral opening motion. The C20 trains have doors that first have to be lifted out of the car body to then be able to open laterally, which takes a little more time.

These two effects result, according to Olsson (2013), in a tiny advantage to the Cx at the stations, but the lower acceleration may devour this tiny advantage again. The timetable itself is planned independently of the type of train that is used. The Case Study will be made with the assumption that all the trains are C20 trains, so that the small differences between the two train types are not another variable that has to be accounted for in the analysis.

The timetable is planned with fixed tours, which are the complete journeys a vehicle is operating during the day. Usually, one tour is assigned to one vehicle per day; however, it may happen that due to severe delays or incidents with a vehicle another vehicle takes over the tour and therefore is assigned the same tour number.

The analysis cannot be carried out using the passengers boarding and alighting the vehicles, as the vehicles are not equipped with this kind of measuring system. Further, the arrangements of the platforms in the Stockholm Tunnelbana network are mostly central quays with common access points to the platforms so that the data collected during the ticket control cannot be used. Furthermore, the electronic ticketing system records the passenger flows from and to the station only on an hourly level. This problem was solved by using the data of the passengers that are in the vehicles before and after a station, as explained in section 4.b.ii).
b. Data Analysis

The data used for this work has been carefully selected for not having any influences of exceptional occurrences, as for example the breakdown of a vehicle, track works, accidents or other disruptions in normal traffic. The days selected are several days in September as well most of the weekdays in November 2013. As only the C20 has weighing equipment, only this data of this train type is analyzed. Further, the description below applies to the data used only for the dynamic delay calculation model as the data is filtered to the morning rush hour between 7 am and 9 am; the data for the calibration has however been extracted to a similar way but over the time-period of 10 am to 2 pm.

i. Preparing the data for further analysis

For each day, two main databases were read out. The first one is an infrastructure-based database, which gives out a standardized timestamp of the readouts of the track circuits which indicate the entry and the exit of a station. The other vehicle-based database contains, among others, the weighing data with the exact timestamp of when the vehicle started and stopped moving.

The weighing and the delay data however cannot be read out from one and the same data base from the beginning. The timestamp recording each weighing process on each vehicle is different; the vehicle clocks are not set to the same time, and a manipulation has to be made in order to connect the weight database with the infrastructure database which has accurate timings. In the case of Stockholm, the weighing database has only the number of the leading vehicle, but not the number of the tour that the vehicle is following. The timestamps being different from vehicle to vehicle, the timestamp could also not be used to assign a certain exact (infrastructure-based) timestamp on the features in the weighing database, in order to link these to the headways of the trains.

The solution to this problem was to use a third database which had both the tour number and the vehicle number. After having combined the three databases, the sequence of the passages through the stations were compared. The infrastructure and the vehicle (weighing) data have both the same sequence of the passages through the station: There is always a certain succession of vehicles/tour numbers going through stations, when starting in the morning with the first train (usually around 4:30). This allowed finding for both entry in the vehicle and the infrastructure database a unique identifier which was then used as a mean of linkage.

The combination of the three databases was made using a large Microsoft Excel macro with around 950 lines of code; the process is unfortunately not fully automatized as the databases (especially the vehicle one) presented a series of wrong entries due to human error when setting up the vehicle for the next tour, through which the data gathering gets corrupted. A good example for this fact is that the direction stored in the vehicle database depends on the driver changing the destination on the vehicle computer; at turnovers, the drivers do sometimes only change to the right destination in the computer after the train already has left the station. This leads to a wrong entry in the database.
When planning the traffic, the planners at MTR make use of the time between the opening and the closing of the doors at a station. However, in order to be able to use the dwell time in OpenTrack, the time between the arrival (stopping of the train) and the departure has to be used. As explained before, the time that the vehicle needs to control the position of all the doors while opening as well as the time that the driver takes to get into his cabin, closing the door and pressing on to the “fast start” button make the dwell time longer than for example looking at tramways (although newer tramway models also have a certain delay, see the new Bombardier Tram-train in Karlsruhe). This additional time appears to be around 10 seconds of dwell time throughout the stations. Therefore, the dwell time at stations was read out from the database of the vehicle data.

ii. Linking of the occupancy data with the headway data

The weighing equipment on each vehicle has different calibration, so that the weighing had to be initialized for each day of service for each vehicle. This was made by taking the minimum weight value of each vehicle that was recorded during the day as the calibration value. After having calibrated the weighing equipment and subsequently linked the weighing data to the different courses, the weight of each of the vehicles was translated to the actual occupancy according to the table in Figure 15 below, which gives out an average value of 77kg per passenger:

<table>
<thead>
<tr>
<th>Occupancy level</th>
<th>Weight (kg)</th>
<th>Passengers</th>
<th>Seat occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>AW 1</td>
<td>9700</td>
<td>126</td>
<td>100 %</td>
</tr>
<tr>
<td>AW 2</td>
<td>19400</td>
<td>252</td>
<td>200 %</td>
</tr>
<tr>
<td>AW 3</td>
<td>31300</td>
<td>406</td>
<td>322 %</td>
</tr>
<tr>
<td>AW 3++</td>
<td>41840</td>
<td>543</td>
<td>430 %</td>
</tr>
</tbody>
</table>

Figure 15: Occupancy level table for the C20 vehicle – Source: SL (2013)

The AW 3 occupancy level was only reached once in the data used in this Case Study, and only on the stretch T-Centralen – Östermalmstorg. There were however sometimes occupancies over 275% of seated capacity on the same stretch. Nevertheless, as these occurrences are quite rare the reduction of the performance at these high occupancies was not taken into account in the simulation model. For each headway that was determined with the value returned from the track circuit which is recording the arrival of a train in the station, the corresponding maximum occupancy of the three vehicles that form a C20 train was extracted from the database.
Around 150 data points in total are obtained for each station during rush hour traffic. Plotting both these values against each other yields a point cloud into which a linear trend is fitted, as shown in Reference source not found.. The values of the vehicle occupancies are then used as the reference distribution seen in Figure 17, which average value is modified according to the formula of the linear trend.

Figure 16: Occupancy plotted against the headway for the station Gamla Stan, on the Red line 14 northbound during rush hour

Figure 17: Frequency distribution of the occupancies (smoothed) in Gamla Stan during the morning rush hour on the red line 14 northbound
iii. Determining the boundaries of the vehicle occupancy

The third set of necessary data is the boundary values, which indicates the limits within which the random drawn occupancy value can be positioned. This is done to avoid having an unnatural fluctuation of the occupancy from one station to another. These boundaries are calculated with the whole occupancy data set obtained before. The first and the third quartile values of this set have been taken as the boundaries, which values can be seen in Figure 18; simulation test runs have shown that these boundaries depict the desired effect well. However, further analysis can be carried out in finding an optimal boundary set.

<table>
<thead>
<tr>
<th>Line 13</th>
<th>Difference of the maximum occupancy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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Figure 18: Summary table of the occupancy boundaries that were used in the calculation model.
iv. Linking the dwell time data to the occupancy data

Now that the occupancy data is known, the dwell time data had to be extracted from the databases. The dwell time could, for that matter, not be extracted from the infrastructure-bound database, as the track circuits that indicate a start or a stop in a station are located not in the station itself, but a little distance away from the station platform. This small difference in placement accounts for a calculation error of up to 10 seconds when only taking the infrastructure-based data, depending on which station is analyzed. The dwell time therefore were calculated from the times given in the vehicle based database.

The dwell times are calculated as the difference of the start time and the stop time at a same station, so that the different clock settings on each vehicle were no problem. The dwell times include the time that it takes for the driver to open and to close the doors explained before, this time considered to be constant.

The two data are then modified similarly to the occupancy/headways data. Exactly as before, the resulting point clouds lead to obtaining a reference distribution and a formula of a linear trend, seen in Figure 19. As the boundaries established in section iii) are sometimes quite small (+1% to +3 % of occupancy at some stations), these data-sets had first to be classed into 10 seconds intervals to then being interpolated again back to a single second interval to smooth out random irregularities in the data collection.

The resulting datasets of the three operations mentioned before constitute the necessary data of the dynamic delay calculation model.
v. Distribution of delays at the starting station

As explained in chapter 2, the simulation model controlled by the dynamic delay model only takes the dwell time as variable into account. Further, no incident has been implemented, so that the whole system would only be varying according to the randomly drawn occupancies and dwell times. However, the dwell time delays form whenever a punctual initial delay exists; therefore, some simulation runs were conducted using a distribution of delays at the starting station as a variable. OpenTrack has a built-in function to directly use a distribution at the start station; however, this function does not allow for the entry of negative initial delays, which depict a train starting from the station too early. This however sometimes happens, with ahead-of-schedule departures of up to 30 seconds approximately. The data was extracted from the infrastructure-based data and adjusted to the effective values taken from the vehicle-based data. The distribution of the delays was subsequently used as a discrete distribution with a direct modification of the departure time of a train at a departure station, as can be seen in Figure 20.

![Initial Delay distribution in Fruängen](image)

*Figure 20: Distribution of the initial delays at the starting station, in this case in Fruängen (line 14 northbound) during the rush hour traffic*
c. Implementation of the dynamic delay model of the Red Line

i. Building of the simulation model in OpenTrack

In order to test the method with the data that were collected before, the whole red line of the Stockholm Tunnelbana was built as a simulation model in OpenTrack. The data necessary for the model was retrieved mostly from MTR and from the Stockholm Trafikförvaltnings (known as SL) for the data about the signalization system.

The first data used was the mileage of the platforms and tunnel sections. As the Tunnelbana in Stockholm has first been built starting from the Slussen station, the points of origin of the lines are at the northern end of the platform. From there, the mileage increases in both directions until reaching the end station. The tunnel sections were also included in the model as they may have an effect on the air resistance exerted on the train, making it a little less performant than on open sections.

In a second step, the gradients were inserted in order to have accurate acceleration and deceleration values. Some stations have specially designed tunnels that descend just after a station and climb again before entering a station. This allows for a faster acceleration and braking and for less wear and tear on the brakes of the vehicles (Merlaku, 2007)

The infrastructure model was then complemented with the signalization system. This signalization system is a system which is based on track circuits with isolated track sections. These sections are evenly spread every 200m, and these work as a sort of blocks so that only a train can enter the space between two circuits.

The available data however showed distance readings which were quite inaccurate, as the resolution was in 10m intervals at best. Also, some consistency errors appeared so that the position of the signals cannot be very accurate. In OpenTrack however, this problem was mended by establishing a security distance behind a train of 75 m with a driving operation that is based on the ETCS system.

Eventually, the speed information was inserted on each stretch of the line. The maximum speed is 80km/h, with speed reductions to 50 km/h in station areas (at the platforms). An example of the final infrastructure model can be seen in Figure 21.

Additionally to the infrastructure model, the behavior of the vehicles themselves was also modeled. The technical data of the C20 trains, taken from the manufacturer's technical sheet, included the acceleration and braking curves and modeled in OpenTrack. As a last step, the timetable was implemented for determining the start time of the trains.
The calibration process for the OpenTrack model was done in a two-step process. As the simulation had to include the right dwell time for calibration in non-congested situations, the dwell time distributions of the off-peak hours for each station were put into the model. These distributions were obtained in the same way as the distributions for the rush hour explained before. The second step of calibration was to calibrate the driving times between the stations. Therefore, the average of the difference between two consecutive stations was extracted from the vehicle based database. The un-calibrated model appears to use the full performance of the train, with maximum acceleration when driving and maximum exploitation of the maximum speed. However, these performance figures are not used in reality, as it would lead to a quite uncomfortable ride. The real operation data show that a performance of about 80% train performance is used in normal traffic, with some stretches in the central part only using about 70%. This information was transferred into the model by using performance signals after each station, which determine at which performance the train will be supposed to be driving.

The driving time between the stations would usually be a variable, as every driver is handling the vehicle differently. As the purpose of this study was however to focus on the dwell times, the driving time between the stations was taken as a fixed time; it corresponds to the average driving time between starting and stopping the stretch between two stations.
The model was therefore calibrated to a set of non-congested dwell times and average driving times; a data set of non-peak hour full-line riding times that were not taken for calibration was averaged and compared to the results of the simulation. The comparison in Figure 22 showed that the simulation only had a difference of a few seconds at some points of the lines, which indicates a good representation. The visual calibration method was used in this case study, as this corresponds to the usual procedure when calibrating a simulation model in a consulting company.

iii. Setting up the OpenTrack API communication

The OpenTrack API enables a communication between the simulation and the dynamic delay calculation model. This communication, as explained above, is based on the use of a TCP-Listener routine which checks every 75 milliseconds if the simulation sent a message to a specified port of the IP-Address of the Localhost. As the message was transmitted by the simulation in bits, the messages were caught one line at a time, put together and then inserted into the Excel sheet in order to be parsed further. This routine continues until no bits of the message are left for transmission on the specified port. When inserted into the excel sheet, these messages are not yet parsed, and all the information used for the transmission itself are still attached to the actual message. The parsing is done by formulas in Excel that automatically sorts out the unnecessary bits of information of the message and writes each bit of information into cells. The information obtained there are the actual messages that are analyzed further. The outgoing bits of information are assembled and fitted with the necessary data for the transmission, and then sent to the OpenTrack API which functions in a very similar manner as explained above.
iv. Constructing the automatized calculation framework

The calculation framework is the entity of the calculation model which contains all the formulas. This framework only needs a few inputs that are automatically inserted by the filtration routine mentioned in chapter 3. The first input data that this framework needs is the arrival time of the train in the station.

There, the difference with the arrival of the previous train determines the headway in seconds. This headway is then used with the linear formula established from the point cloud to calculate an average occupancy for this headway. This average occupancy value is then taken as the zero-point, and for each other occupancy value the difference with this average value is made. This yields a list of numbers that constantly grows and which is centered with the value 0 to the calculated average value.

The frequencies that were established before by the distribution are then taken to determine the frequency of the differences to the calculated average value. A random number is drawn from this distribution, and the difference to the calculated average value is added to the previous occupancy of that vehicle to form its occupancy value after the stop in the station.

This occupancy value is then tested if it lies within the boundaries that were established before, and if this test was successful, the calculated occupancy is used for drawing a dwell time for the station in the same way as the occupancy value was drawn before.

This procedure is initiated as soon as the simulation shows that a train has stopped in a station.

v. Creating the User-Interface for entering the data

In order to be able to use the formulas and the distributions which were established earlier, the data has to be copied into the right fields of the framework. A simple user-interface was created in order to make the import of the data easier and faster for the user. All the data only has to be imported once, and an initialization routine checks for each station which data is available and where this data would have to be inserted.

It generates further a list which creates an amount (determined by the frequency in the distribution) of cells which have a direct link to the value of the corresponding occupancy value. It is therefore easier to determine a random value from the discrete distributions given.

The User-interface eventually returns a table in which the different vehicles with their maximum frequency can be seen during the simulation, as well as an indication whether these vehicles are being simulated or not used in the simulation any more.
vi. Possible improvements of the calculation model

The calculation model can be improved by taking a wider time range of data for the determination of the base data; the data used for this study is only based on 20 days’ worth of data yielding around 150 data points in the rush hour. The sample size is enough to obtain satisfactory results, but as the analysis routines are already in place, it should not be difficult to analyze further datasets.

Further, the calculation model could contain a list of all the messages that were transmitted and received for better traceability. This could be achieved by modifying the code of the calculation model which operates behind Microsoft Excel.

As mentioned before, the calculation procedure could be significantly sped up by not having to halt the simulation in order to give the model to proceed with some calculations. This could be done by integrating the model into the OpenTrack simulation directly, but is complicated to implement and the developer Mr. Hürlimann himself would have to do it as OpenTrack is not OpenSource.

As the calculation model calculated simultaneously with the simulation running, several threads have to be used within the CPU. Using these threads (for the simulation, calculating the cells in Excel, listening to the IP-address’ port with the TCP listener, analyzing the results) makes the whole calculation model rather unstable. When running the calculation model, any user input (key stroke or mouse click) makes the model crash. It also sometimes happens that the calculation model gets new input before the existing information was completely analyzed, and therefore the program fails to execute further. Unfortunately, no satisfying solutions were found for these problems.

d. Determination of occupancy boundaries and real-world Simulation scenario

As explained before, the boundaries for the occupancy figures can be quite important when drawing randomly from an occupancy distribution. Several tests have been executed to be able to discern whether the quartile boundaries are yielding a graphical timetable showing a comparable pattern to the patterns seen with the graphical timetables established from the real data. Tests were performed taking the 95th and the 90th percentile and compared to the boundaries at the quartile values; the quartile boundaries were however yielding better dynamic delay figures than the other boundary values. This is due to the narrower field in which the random number is drawn from the occupancy distribution, as the number cannot jump that often between high and small numbers drawn.

Other boundaries can be also used for an even more optimized result; this however is not part of this thesis.

Having found a good value for the boundaries of the occupation distribution, the simulation was run with the actual timetable. The characteristics of the real timetable are a same start time at the end stations and a planned headway of 5 minutes on both lines.
e. Analysis of Results

i. Simulations runs without delay at the start station

The first simulation runs were carried out without using a delay at the start station, in order to know how random the effect of the dynamic delay calculation can be. According to Figure 23, it appears that a calculation without a start station does not show a very significant impact of the dynamic delay, as the headway between the vehicles is more or less always constant and does not vary that much. However, small effects can already be detected, as the calculation is a totally random process.

The effect of the dynamic delay can be seen whenever the distances between the trains are diminishing gradually along the line. In Figure 23 several vehicles are getting more and more delayed, and consequently the following vehicles are either faster than or as fast as normal, so that the non-delayed vehicle bunches with the delayed vehicle. The areas that are marked in the graphical timetable are the areas where this effect can be seen the most. Certainly, the central area is the most affected by the effect, as the trains run in a very short interval.

ii. Simulation runs with delay at the start station

The simulation runs that include a delay distribution at the start station are thought as close representations of the real situation. The results that are obtained from these runs are clearly showing the effect of the dynamic delays, as some trains that are late from the beginning (and therefore have a large headway to the train in front of them) are more bound for getting more and more delayed. Further, the trains that follow the ones that are dynamically delayed, are sometimes having shorter dwell times in the stations and therefore tend to bunch to the previous trains. The patterns observed in Figure 24 indicate that there are very similar to the results obtained from the actual data. These results show that simulating the effect of dynamic delays is possible in OpenTrack to the same extent that is seen in the real traffic operations.
Simulation of dynamic station dwell time delays on high frequency rail transport systems

Figure 22: Graphical timetable as result of the simulation without delay at the beginning station. Examples of the dynamic delay effect are given in the marked areas.
Simulation of dynamic station dwell time delays on high frequency rail transport systems

Figure 24: Graphical timetable as result of the simulation with delays at the beginning station. Examples of the dynamic delay effect are given in the marked areas.
f. Suggested actions to minimize the effects of dynamic delays

i. Infrastructure-bound measures

In order to counter the effect that increased dwell times have on the traffic, one idea can be to directly influence the boarding of the passengers at the stations. As it was seen in the data analysis, the passengers are not evenly spread along the platform, but tend to crowd the areas around the entries to the platform. As many of the highly frequented platforms in Stockholm have their exits at the back or at the front of the trains, the usual maximum frequentation is seen in the last or the first vehicle. As the dwell time is directly influenced by the maximum frequentation in one of the vehicles (it takes the most time to alight and board there), one of the possibilities is to redirect the passengers even more to the center of the trains where there is more space. Spreading the passengers more evenly along the platform will eventually lead to decreased passenger exchange times, a more consistent boarding and alighting process and eventually a decreased dwell time. This can be done by small infrastructure adjustments on the platforms or better passenger guidance, along with good passenger information in the stations.

The other method for countering this effect is to make sure that the delays are transmitted back onto other trains as less as possible. This could be done by introducing a new signaling system which would operate with a moving block operation, much like the ETCS system level 3.

This moving block system is already set to be implemented into the Stockholm Tunnelbana system in the next years, therefore diminishing the safety buffer distance that still exists with the current system. This will allow the trains to run even closer together and to have less “lost time” on the line.

In order to durably solve the problem of the high frequentation causing the dynamic delay on the stretch between Liljeholmen and Östermalmstorg, only a new infrastructure creating a bypass of this critical section can provide relief. One of the ideas that would lead to a diminished capacity saturation on the red line would be the idea to connect the north and the south of the city without having to pass through the stretch T-Centralen – Slussen. The Thesis of Emeric Djoko (2014) shows that a line connecting directly Danderyds Sjukhus/Roslagsbanan, Odenplan, Friedhemsplan, Hornstull and Älvsjö could diminish the overall occupancy rate on the subway trains from a value of 0.98 (near complete congestion) to 0.85. This alternative is helping quite well for the problem solution, it is however also the most expensive.
ii. Timetabling measures

When looking at the graphical timetable, it can be seen that the trains coming from the Norsborg branch (line 13) sometimes arrive in Liljeholmen (the point where both branches join) just before the trains from Fruängen enter there. As the station can accommodate the two trains simultaneously, the exit of the trains from Liljeholmen creates conflicts between the two branches. The trains that create conflict coming from the Norsborg branch are trains that are often 1 to 2 minutes delayed, so that the departure time in Norsborg could be adjusted to one minute before with keeping the departure time in Liljeholmen the same. This measure would have a longer travel time on the one hand for the passengers from Norsborg, but a more regular traffic on the whole line on the other.

Generally, the effect of dynamic delays can be greatly reduced by adding relief points along the line, where trains that run on time can wait until the set departure time has come, and trains that are already a little late can make up time in these stations. However, in the case of the Stockholm Tunnelbana, having relief time in the central stretch is quasi impossible as the trains are following each other so closely and the stations do not provide any possibility to overtake a waiting train.

The effect of bunching can also be greatly reduced through the implementation of a dynamic headway system on board of the trains, where the trains would not follow a fixed timetable but would merely try to keep an even spacing between the trains. This can be done by either directly feeding the current headway into the drivers’ cabin, or having stopwatches at the end of a platform indicating the train’s deviation to the normal headway. This method was tested with success, amongst others, on some of the trunk bus lines in Stockholm. It shows a much more regular schedule and therefore a smaller tendency for the vehicles to bunch as the amount of the passengers that wait in a station is more or less the same. However, this method applied to the Tunnelbana system would lead to a revised way of how Trafikförvaltningen (SL) accounts for the delays, as it is based on the actual delay the trains has according to the timetable.
g. Possible applications for the dynamic delay model

The dynamic delay model that was developed in this thesis can be applied in many different cases. As the simulation software like OpenTrack and Railsys are today enlarging their activities to inner-city rail bound networks, the effects that can be seen in reality have to be recreated in the simulation. As these simulations until now do not take the interdependent effects that are caused by passenger frequentation into account. The effect of dynamic delay for example could until now only be recreated by an approach resembling a trial-and-error procedure. Now that the dynamic delay effect can be recreated, the usage of the simulation in congested railway bound networks having a big passenger frequentation can be represented by using the method based on empirical data described before.

The dynamic delay calculation effect can be used for example when simulating the network in order to know how the passenger frequentation in the stations influences the timetabling. As discussed in the previous section, the differences in headways seen in the simulation are not due to conflicts created by delays occurring from mechanical problems or significantly different driver’s behaviors, but simply from the increasing number of passengers waiting at a station. Therefore, it can be discussed which sections of the track should have an adjusted timetable, either with extended driving times in the timetable or modified departure times at the initial stations.  

Another timetabling issue is to make sure that the timetable can be held in the congested conditions, as many of the public transportation operators such as MTR Stockholm are very time-critical and have to comply with the timetable that they self-created in order not to pay any delay fee.

A capacity analysis can also make use of the dynamic delay calculation model. The passenger frequentation being most probably also a factor in the capacity of the line, the simulations do not have to approximate this effect anymore by complicated punctual incident-type dwell time extension. The passenger frequentation is directly plugged into the simulation, so that the capacity analysis yields a more complete picture.

Another possible application for the dynamic delay model is for analyzing the effects that an extended line might have. This is due to the headway which might not be totally constant as the passenger boarding and alighting time differences are having a cascading the longer the line is and the more passengers are frequenting the line. The necessary data for establishing the dynamic delay calculation model for the newly planned stations can be taken by transferring known data from the existing stations and approximating the data according to the parameters the new stations have.
5. Conclusion

Discussions with railway planning experts and university researchers indicated that the microscopic railway simulation software solutions that are available on the market today are not able to render the effect of dynamically growing delays on a line, an effect which can lead to bunching without having a punctual source of delays. The method developed in this project aims to remedy to this problem, through having established a dynamic delay calculation model on the basis of an extensive analysis of empirical data that was collected from the Red Line of the Stockholm Tunnelbana.

This calculation model works as an add-on to the simulation software OpenTrack, which is a well-known and widely used simulation software in the field of rail-bound traffic planning and consulting. It was developed using the Microsoft Excel platform, which was modified to enable the automatized assessment of the status of the simulation. The communication between OpenTrack and the calculation model was carried out by the OpenTrack API.

In a case study, a simulation model that was calibrated by using a non-congested situation was used in order to calibrate the OpenTrack model, after which the dynamic delay model was implemented for representing a morning rush-hour scenario. The graphical timetables that resulted from the simulation runs were compared with the graphical timetables that are determined on the basis of the data collected directly from the vehicles and the track, and the patterns that were visible in the simulation were similar to the real ones.

It can be therefore said that the methodology for calculating the dynamic delays determined in this project yields promising results for being able to recreate a more realistic simulation output for the Stockholm Tunnelbana. These results were then used to make recommendations for the operation on the Tunnelbana line.

The method tested will most probably also yield good results in other simulations of networks. However, as only one set of data was accessible, the methodology was not yet tested with other rail bound transportation networks.
6. Glossary

**ATC: Automatic Train Control;** train protection system for railways which involves automatic speed control and driver cabin signalization in conjunction with railway trackside equipment.

**Bunching:** the effect that occurs when a group of two (or more) transit vehicles running in the same location at the same time instead of running evenly spaced along the same route as they were scheduled.

**Dynamic Delay:** Delay that is a positive feedback loop regarding the number of passengers; The more a vehicle is delayed (from the ideal headway), the more passengers are waiting at a station which in turn takes longer for the passenger exchange. In this way, the delay increases in relation to the previous occurrences on the line.

**ETCS: European Train Control System;** signaling element of the system that, amongst others, provides automatic train protection. It brings track side signaling into the driver cabin, allows for permanent train control and provides the possibility of a moving block system with ETCS Level3. (UIC, 2013)

**Headway:** measurement of the time between two consecutive vehicles in a transit system. (Ceder, 2007)

**Light rail:** urban form of public transport using similar rolling stock as a tramway but operate primarily on grade separated tracks and have vehicles that are capable of operating as multiple units coupled together when needed. The operation of the light rail is mostly controlled by a block signaling system.

**Microscopic /macroscopic simulation:** A microscopic simulation models the behavior of each individual vehicle whereas a macroscopic simulation returns the features on the whole traffic system.

**MTR: Mass Transit Railway;** company operating the subways in Hong-Kong and in Stockholm

**OpenTrack API: Application Programming Interface;** the interface enables to connect other applications with OpenTrack, by sending standardized commands to OpenTrack and getting defined status messages back from OpenTrack. Technically, SOAP-Messages are exchanged via HTTP. (Hürlimann, 2014)

**Relief time:** time that is given in the schedule at a station in order to be able to catch up time if delays occur.

**SL: Storstockholms Localtrafik (Trafikförvaltning);** public transportation organization authority in Stockholm

TCP-Listener: Transmission Control Protocol; one of the core protocols of the internet protocol suite (IP), and provides reliable delivery of a stream of information between local programs and web servers. The listener is a routine that checks in a certain interval whether messages have been received on a specified port and sends the incoming messages on to be analyzed. (Network Sorcery, Inc, 2012)

Track-circuit data: data that is collected from a track circuit, which is an electric device to detect the absence/presence of a train on rail tracks

Tramway: rail vehicle systems that operates on tracks that are laid mostly along public urban streets, but can run on grade separated tracks as well. Through the operation within the streets, tramways are usually not having a block signaling system, and are running on sight.

Tunnelbana: Subway system in Stockholm
7. References


8. Appendix

Appendix 1: User interface for the Delay calculation model (the blue areas are updated automatically)
### Occupancy on Line 14N

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### Appendix 4: Occupancy data of the stations on the line 14 northbound that was used in the delay calculation model
## Appendix E: Headway and Dwell time linear formula coefficients that were used in the delay calculation model

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Simulation of dynamic station dwell time delays on high frequency rail transport systems
Appendix 6: Graphical timetable of Norsborg–Ropsten as result of the simulation with delays at the beginning station and occupancy boundaries at the 90th percentile.
Appendix 7: Graphical timetable of Fruängen - Mörby Centrum as result of the simulation with delays at the beginning station and occupancy boundaries at the 90th percentile.
Appendix B: Graphical timetable of Norsborg-Ropsten as result of the simulation with delays at the beginning station and occupancy boundaries at the 95th percentile.
Appendix 9: Graphical timetable of Fruängen-Mörby Centrum as result of the simulation with delays at the beginning station and occupancy boundaries at the 95\textsuperscript{th} percentile.