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How do Delays Along the Way Influence Delays to Final Destination?

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Abstract:

In daily operation, railway traffic always deviates from the planned schedule to a certain extent. Initial disturbances of trains at some point along the line may cause a whole cascade of delays over the entire network. Average delay analysis approach indicated that the effect of delays along the way to the final destination is random, which is dependent on the traffic conditions. Poor performance up to 7 minutes delay, subsequently higher influence to the final destination were seen from trains 453 and 442 for routes from Trondheim and Steinkjer respectively. The better performance of trains from Trondheim at the final destination, confirmed that the influence of delays along the way to the final destination is affected by the train line or route. Route conflicts or disturbance often occur at busy stations and junctions, which may affect the delays of train arrivals and departures at the intermediate stations and subsequently arrivals at the final destination. The correlation analysis revealed that the influence is highly dependent on the distance of highly utilized (bottleneck station) from the destination. There was a considerable variability associated with train delays during the different time attributes more pronounced in the case heterogeneity. Exaggerated cumulative delays were observed on Tuesday during the third week of the study period. Conflicts, passenger alighting and boarding during morning and afternoon peak hours resulted in relatively larger delays at individual stations and subsequently final destination. Delays at long the way, which are not reported as poor performance according to Norwegian punctuality norm, have greater socio-economic impact. At highly utilized stations typically Stjørdal and Hell the values of delays were found to be up to twice the values at the final destination.

Keywords:

1. Railway
2. Train delays
3. Timetable
4. Punctuality

PREFACE

The punctuality of trains is an important service characteristic of passenger trains. Trains that suffer from frequent and severe delays cause substantial trouble to their passengers, reduce the perceived utility of the system and cost a lot. Therefore, railway system authorities and train operators look at ways in which they can improve punctuality. In order to appraise the benefits of such measures in relation to the costs associated with them, perceived values of delay are needed. This thesis investigates delays of local passenger trains from Trondheim to Steinkjer a long the way to study their influence on the delays at the final destination. It is a great opportunity for me, I have learnt a lot about the railway system while I was working on my thesis. First of all, I would like to thank my advisor professor Nils Olsson for his continuous constructive, pleasant collaboration and advise. Furthermore, I appreciate the engagement and all the valuable suggestions of Hegglund per Magnus, who significantly contributed to the success of this thesis providing all the data. Last but not least I would like to thank all my family and friends for being there.

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1. INTRODUCTION

1.1. Background

Rail traffic is the most important form of public traffic in Europe as the density of the railway network is very high compared to the other parts of the globe. Passenger train plays an important role in the European mobility, since it transport a significant percentage of passengers per unit time compared to other modes of transport. According to Morgan (2010), it is preferred over bus transportation because of comfort, high speed, safety and reliability. Especially during peak hours and for distances between 20 and 800 kilometers, passengers often choose to travel by train. To be in competition with other modes of transportation, railway traffic must be quick, comfortable, cheap and primarily safe.

Delivering train performance is an essential aspect of modern passenger train services. The success of railways is greatly dependent on their ability to deliver reliable service to the customers. When passenger and freight trains are scheduled on a rail corridor the objective is to achieve a given level of customer service whilst minimizing overall operating costs. Customer service in this context is made up of several attributes, which include overall journey time of trains and the degree to which those journey times are achieved on a regular basis (Vromans, 2005). They demand that the railway delivers on its timetable commitments and it must therefore continue to consistently deliver on time journeys wherever and whenever people travel. However, maintaining scheduled departure times of the trains is a tedious task, due to variation in passenger boarding and alighting times at the different stations, adverse weather conditions, poor planning and operations (Hansen, 2001). The situation can become critical when trains operate at higher frequencies; the impact of a proceeding train on following trains affects operations. The existence of competitive modes of transport, cancelled and late running trains cost money through lost customers and diminished reputations. As a result of the increased mobility of people, globalization of trade, competition with other transport modes, saturation of infrastructure capacities, and deregulation of the transport sector, punctuality of transport services has become a major issue during the last decade. Facing continuous growth of traffic demand punctual train services.

A robust railway system can function fairly well under difficult circumstances. When a railway system is not robust, small external influences cause large delays, which propagate quickly throughout the system in place and time. Road congestion, air and railway traffic delays are daily phenomena and seem to increase continuously. Most railway infrastructure managers are not only extending and upgrading the track network and improving the signaling system to create additional transport capacity, but are striving to utilize the existing capacity more efficiently. Train and network operators require systems to measure performance and collect data on train running. In many studies punctuality is mentioned as one of the performance measures for railway traffic systems, and it is one that largely affects passengers. Punctuality plays a role in almost every contract, and in most countries it is considered as the number one factor determining railway service quality. But most of the studies merely focused on arrival delays at the final destination in reporting the punctuality. In a real life scenario, a set of railway junction points or railway stations are connected together with various types of railway lines. The nature of this relationship is determined by the timetable and the structure of the railway network. Trains are driven by timetables and these timetables implicitly define relations amongst the associated trains. Timetables may suffer from inaccuracies and delay due to the unforeseen change in the weather or other external effects. This delay has an effect on every connecting train along the railway network as result passengers may miss their transfer train or bus. The delay is propagated along the railway network and small delays are gradually aggregated into a much bigger one, which might render the timetable useless.

Therefore, this thesis is intended to study the influence of delays along the way to the final destination. Such analysis of train delays and delay propagations enables the prediction of punctuality and reliability of scheduled trains and optimization of variety of rescheduling strategies. It also helps to identify the bottleneck stations, critical lines and hence the sources of delays (Yuan, 2006). Therefore, Delay is rather a critical quality measure of scheduled train operations and is important to operators and passengers. Many Researchers stated that the delay of scheduled train operations are often perceived to be worse than it actually is, since passengers have a selective memory tending to remember poor performances at the expense of good ones. To keep the existing customers and attract new passengers, scheduled train operations must assure acceptable level of delays.

1.2. Research Questions

Delay of trains, or the unpunctuality, becomes a topic of public attention when passengers or cargo suffer many and lengthy delays. This thesis is aimed at finding out the likely effect of delays along the line on the delays at final destination. This effect is likely to vary along the line, between different trains, in different direction, on different weekdays etc. One reason we are interested in this analysis is to be able to show the socio economic effect of delays along the line. There are values for how much delays to final destination cost the society. There are presently no available values for delays along the line. Based on the results from the proposed study, it will be able to show the cost for delays along the line as well. We can then point to certain parts of the line, or certain times of the week, and say that this is where the most costly delays occur. The resources can be allocated based on this information. To this end, the following research questions are derived:

- Which are the bottleneck stations and critical train lines?
- On which days of the week and part of the day will the effect be worst?
- What are the socio-economic effects of these delays?

1.3. Methodology

Delay Assessment, calculating delay severity is a significantly more complex process than a mere consideration of the number of trains involved and the aggregation of the time delayed. A small delay might be acceptable if one is subject to a wait regardless of the delay for any subsequent connection. It should be pointed out that a punctuality measure for passenger trains should relate to passengers, not trains. This section provides the components involved in the overall process of data collection, classification, and analysis.

In order to support the research strategies dealing with empirical evidence, a literature study was applied. It was performed focusing on investigating different perspectives and dimensions of delays and has covered different aspects of the studied phenomenon (for example timetabling, punctuality, reliability and delay). The literature study was performed with a number of search engines, mainly Google Scholar, springer link, Elsevier Science Direct and journals of transportation and annual reports of various railway companies. The searches were triggered by relevant keywords identified through the project description. In order to reduce the vast number of hits, a reduction process was performed. This reduction consisted of three main steps, where the first step was related to the reference titles, the second to their abstracts, and the third step to the whole or parts of the references. The literature search identified over 70 articles and reports dealing with delay, punctuality and related issues, which were reviewed for potential relevance. Out of these, 45 articles were selected as relevant and were summarized. This included a review of international literature on key elements associated with rail transport delays, a qualitative study of delays and their consequences of delayed trains on rail passengers. The result of the literature study can partly be found in the theoretical framework of this thesis and its reference list.

Data Analysis was the primary method used to answer the research questions. To quantify the delays of local trains associated with stations as perceived by the passengers empirical data was collected by documentation. The data used in the study has been taken from Jernbaneverket. The requested data has been supplied as excel files and much effort had to be spent on importing and saving the large amounts of data to a format useable. The analysis presented in the thesis is based on data pertinent to train delays, which are retrieved, classified and analyzed in close cooperation with personnel from Jernbaneverket. This is expected to provide a more relevant and reliable feedback. The focal point of the analysis is identifying train delays at individual stations along the way. These are subsequently compared to the delay at the final destination. Thereafter, the results from the analysis and literature studies were compiled.

1.4 Limitations

In order to study the socio-economic impact of delays along the way in depth, more detailed data such as the total number of passengers, repartitioned into groups of lines, number of delayed passengers and station of the arrival of delayed passengers are required. Such view demonstrates how to provide great amount of data in such a way to help decision: in a glance, bad/good lines or bad/good days can be identified, once interesting parts are identified, zooming into data allows to get more details when it is needed. The average arrival delay of the trains is one of the most important reliability measures. When passenger counts are known, both punctuality and average delay can be weighted for them, but usually a plain average is taken. However, an ideal but almost impossible to compute reliability measure is the average delay of the complete journey (including transfers) of each individual passenger, therefore, it is difficult to draw conclusions on such stations.

1.5. Relevance

Analysis of train delays and delay propagation in stations is an important research topic in the field of railway operations research. The study enables prediction of critical sections and trains linked with knock on delays (i.e. it helps in the identification of platform tracks and junctions in complex stations and interlocking areas and the resulting departure and arrival delays at the stations). This thesis contributes to the understanding of railway operations and actual traffic aspects that are important to construct robust timetables for reliable railway operations. The empirical analysis of train delay and delay propagation can help railway managers, timetable designers and train operators to adopt appropriate strategies to reduce delays and increase the punctuality level. It enables the maximization of capacity utilization for critical track sections with in a complex station network. It also supports traffic controllers to make appropriate rescheduling decisions in case of big operational disturbances.

1.6 Thesis Outline

The structure of the report is as follows: Part I is an introduction to the problem including the present chapter with a general introduction. Followed by Literature review, the second and slightly broader part, presents a concise overview of the important concepts. It briefly explains some of the relevant keywords used in the over all study. First the existing timetabling principles, timetabling characteristics and timetable optimization parameters are described. Further more, performance measures and perception are discussed. Classification of delays, disturbances and delay propagation are elaborated in a relatively detailed extent. This contributes to provision of a broader understanding of the issue. Part III is concerned with the main research stream corresponding detailed delay analysis. It provides a summary of the main findings. This includes the results of a literature review, a statistical analysis of delay data. Finally, the last part summarizes the main conclusions based on the own research contributions and remaining issues for further research.

2. LITERATURE REVIEW

In this section a few theoretical concepts are discussed, which are important for understanding the thesis. Most of the thesis is built around these concepts. The first concept is timetabling.

2.1. Timetabling

Performance of a rail traffic network depends on many aspects. Railway schedules are necessary for the coordination of resources in different planning stages in order to match transport demand and capacity, at the same time to inform stakeholders and customers (Ingo, 2009). Effective timetable design and real-time traffic management strategies play a key role in improving the level of railway service due to the complexity of rail operations, the expected growth of traffic and the limited possibilities of enhancing the infrastructure. To provide high quality train services to the customers, it is necessary to evaluate the quality of planned timetables (Yuan, 2006). Issues related to planning and operational processes are therefore areas rich in interesting optimization problems.

The operational traffic conditions are completely summarized in the timetable. A timetable implicitly includes the set of train lines, train characteristics, and rail infrastructure (Goverde & Odijk, 2002). The main task of timetable design is to determine the arrival and departure times of trains at successive stations and the routes of trains through the network. It is a promise of the operator to the passengers, telling them when and where trains are planned to run. The travelers use the timetable to plan their trips. For operators the timetable forms the basis for further planning, such as rolling stock planning and crew planning (Yuan, 2006). Timetables must assure that the expected transport demand can be realized according to the requirements of passengers, shippers, train operating companies, infrastructure managers and public authorities effectively and efficiently. Effectively means a high quantity and quality of available infrastructure, rolling stock, personnel, transport and traffic services, while efficiently requires a maximum output with the least possible input. For high frequency services, such as metros, timetables are sometimes not published externally, but they do exist internally at the operator for planning purposes.

Busy complex railway stations having dozens of platforms and sub-platforms with more than several hundred trains per day arriving and departing are common in Europe. Trains of different types and speeds arrive and depart on multiple conflicting lines and are subject to restrictions or preferences concerning which lines and platforms they can use. They also have various dwell time and headway requirements, typically have desired or preferred arrival and departure times, and have various costs or penalties for deviating from these times. To ensure that all of these constraints are met, detailed schedules are usually constructed months in advance, and the timetable is usually published. It is important to generate good feasible schedules for such busy stations (Carey, 2000). Constructing timetables with fewer dependencies between the train services can play a great role in minimizing problems associated with train delays. However, this must not disturb other important timetable characteristics such as planned travel times. Moreover, it has been mentioned that constructing timetables with fewer dependencies is not at all straightforward. Due to random disturbance at the nodes and links of railway networks, running time supplements and buffer times are added respectively (Hansen, 2004). The effectiveness of such timetable can be expressed by indicators such as: Number of trains, passengers and per time period, Amount of passenger per kilometer, Operating and circulating speed of trains, Headways and buffer times, Scheduled waiting times, Time and effort for modification and rescheduling.

For a railway to operate efficiently, trains must operate according to the published timetable. This is constructed to avoid conflicts by choosing compatible train paths, departure times, and, where necessary, holding trains briefly at junctions. A train delayed for whatever reason can directly result in passengers arriving late at their destinations and missing connections, and can also cause knock-on delays to other trains. Very minor delays can often be absorbed by the recovery margins built into the timetable with little or no disruption to other services. As train delays increase, however, the knock-on effects become more serious and it may be advantageous to modify the usual dispatching order of trains to minimize the subsequent delay. The key for high-quality timetables is a precise estimation of blocking times according to practical operations. The blocking time graph of a train represents the time instances that a train needs to run safely without hinder at design speed over a sequence of track sections. The critical track sections are situated at a location where the time gap between the blocking time graphs of two trains following each other on a route is minimal. The available time margins (buffer times) between the end and the begin of a sequence of two blocking time graphs at the critical block sections as well as the running time supplements are a measure of timetable slack (Yuan, 2006). In case of absence of buffer time, the time gap between two consecutive blocking time graphs represents the minimal time headway. The buffer times are aimed to reduce knock-on delays in order to maintain a certain quality of operations in case of disturbances but, generally, cannot limit initial delays. Running time reserves (recovery times) and dwell time margins are adopted to compensate the initial delays of each train (Nie & Hansen, 2005). Moreover, any timetable comprises scheduled waiting times and generates non-scheduled waiting times. Scheduled waiting times are the times needed for a scheduled passing and overtaking and to synchronize the transfer times for connected train services of a fixed interval timetable. In general, these times cause an increase of dwell times (i.e., longer stopping times) or an extension of running times, except in some cases when an entire train path is moved (Wendler, 2007). For this reason, scheduled waiting times are used as indicator of timetable quality, whereas non-scheduled waiting times are experienced as train delays during operations.

Larger time reserves allow increasing train punctuality, but reduce the capacity usage of the lines, i.e., the maximum number of trains, which may be operated through a line at a specified period. Large running time supplements and buffer results in longer planned time travel of passengers, lower operating speed, higher operation cost and less efficient infrastructure capacity utilization. Therefore the desired level of service may affect the expected operation cost, revenues and the efficiency of capacity utilization. Moreover, the railway infrastructure is becoming more and more saturated by which local delays are more difficult to manage and easily generate many knock-on delays (due to hinder between consecutive trains). In congested areas, the amount of time reserves that can be inserted in the timetable is limited. In fact, despite the big effort spent in the offline development of timetables, in congested areas deviations from the timetable frequently happen, thus often requiring the restoration of a feasible schedule. Since disruptive events are unpredictable, appropriate running time reserves and other time margins are distributed over the network and in the timetable.

In complex railway networks, the main performance factors to assess the quality of a railway system are its ability to perform well under disturbances, i.e., robustness, and reliability. Precisely, robust and reliable timetables should be able to deal with small delays, whereas larger disturbances and their propagation may be prevented or reduced significantly by suitable dispatching actions. An optimal timetable design contributes to improving the performance of railway operations while increasing the quality of passenger service and decreasing costs due to delays. A robust timetable must be able to deal with a certain amount of delay without traffic control intervention (Vromans et al., 2006). Timetable robustness therefore determines the effectiveness of schedule adherence after disruptions. Analysis of real-world operations data and train performance enables structural feedback between operations and timetabling. Evaluating a train network timetable on stability and robustness is an important part of the timetable design process. The line-planning problem considers how to choose a set of operating lines in a network of tracks, such that the provided transportation capacity is sufficient to meet the passenger demand. Typical objectives are maximizing the passenger service while minimizing the operating costs. Timetabling mainly consists of designing a robust schedule, which enables a reduced propagation of delays that has to be faced periodically. Train services are planned in detail, defining several months in advance the train order and timing at crossings, junctions and platform tracks. A robust timetable is able to deal with minor perturbations (i.e., few minutes of delays) occurring in real-time by using smart planning rules. However, no reasonable railway plan is robust or reliable enough in case of large delays or the blocking of some tracks.

The timetable plays an important role in managing the risk of unpunctuality (Revisorer, 2002). This is because one might construct a sparser timetable by allowing more travel time for the trains and allow more time on the track for maintenance and investments. However, this allows less traffic to fit in the railway network and might also lower the ambitions. The same reasoning goes for infrastructure maintenance, where recurrent faults that take only a short time to repair are considered ‘normal’. Conversely, a denser timetable makes it more likely that the delay of one train hinders other trains; that is, the delay multiplies. These phenomena make planning of train traffic, infrastructure maintenance and train traffic control important areas of research (Bente et al., 2003). If appropriate stability measures are not taken during the construction of the timetable, then there is a risk that the minor delay of a train may propagate to other trains in the network mainly due to connections at a given station thus creating a snow-ball effect. Every new timetable needs to be evaluated for stability especially for cyclic timetables in a highly interconnected network before putting it into service. The stability of timetables is very important to provide high quality train services to customers

A relevant aspect of delay management, that has recently drawn attention of researchers, is how to reduce or increase delays of trains in such a way that the inconvenience for passengers is minimized. An optimal coordination of connected train services is thus important to improve punctuality whereas at the same time reliability of connections is obtained. For each possible connection one has to decide if a connecting train should wait for a delayed feeder train or if it is better to depart on time. Schobel (2001) also considered the problem of which connected train ¨services at railway station should be maintained and which can be dropped in case of small disturbances. The goal is to minimize the inconvenience for all affected passengers and her approach is considered for practical instances of the German railways. In Vromans (2005) and Vromans et al. (2006), a procedure to create more homogeneous timetables has been proposed by reducing the running time differences and imposing a similar number of train stops per track section. This is done to decrease the propagation of delays caused by interdependencies between trains. Despite the big effort spent, technical failures and disturbances, such as delayed trains or temporary unavailability of some routes, may influence the running times, dwelling and departing events, thus causing initial delays. Due to the interaction between trains, these delays may be propagated as knock-on delays to other trains in the network. In fact, trains may be required to stop in front of crossings or junctions, causing non-scheduled waiting times and longer running times due to slowing down and subsequent re-acceleration. Hence, managing railway traffic in real-time requires modifying the timetable, minimizing delays between consecutive trains and ensuring the feasibility of the resulting plan of operations. This short-term process requires effective solutions within minutes and is called real-time traffic management.

Nie el al (2005) has described the cyclic process of train scheduling and operation as shown in Figure 1. According to them the basic periodic schedules prepared for a long time period will need some modifications in daily use due to daily and hourly traffic fluctuations. If necessary and possible, the operations of delayed and/or hindered trains are re-scheduled in order to recover at least partly from delays. However, random variations still affect train operations and use of track infrastructure. Actually recorded train delays may lead to an adjustment of the current schedule by re-timing, re-ordering and re-routing of train paths.

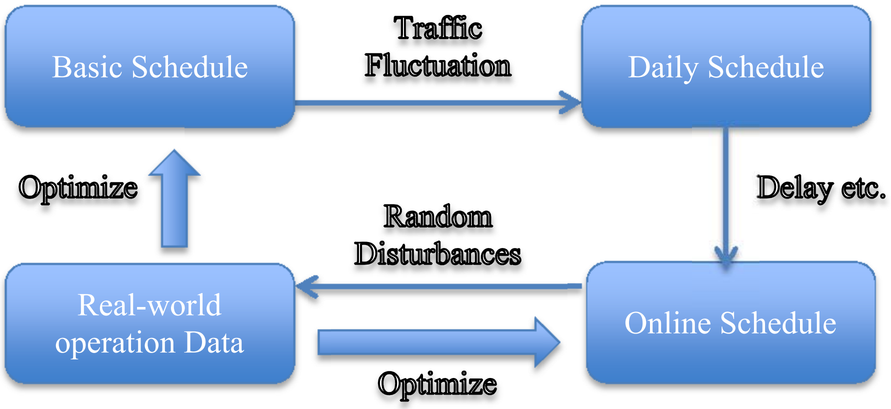


Figure 1 The cyclic process of train scheduling and operation (Nie, 2005)

2.2 Aspects of timetable optimization

Since train operations are not perfect random minor disturbances and failures occur in the real management of trains during the railway operation of certain lines reducing the theoretical capacity. Some buffer times must be taken into account in order to design a robust timetable. This stochastic effect is often difficult to take into account in line capacity evaluations. However, a balance between service reliability and maximum physical capacity is needed to find the economically optimal level of capacity. Capacity utilization and stability of timetables are closely related. It is intuitively clear that robustness will suffer when available capacity is fully utilized. On the other hand, leaving generous buffer times in a timetable prevents delay propagation, but also forfeits high network utilization. The relation between these two subjects is discussed here. The principal goal of railway transport is to attract a maximum number of customers and load on planned or existing lines with a minimum of investment cost, personnel, equipment, energy consumption, operating and maintenance costs. The acceptance by passengers, shippers and public authorities depends in a competitive market on performance criteria as speed, frequency, comfort, reliability, punctuality, safety and price of services (Ingo, 2009). The quality and effectiveness of timetable design for a given traffic demand, rail infrastructure and train mix depends mainly on: Frequency, Regularity Precise and realistic running and dwell times Sufficient but not too large recovery times, exact minimal headway times between different pairs of trains, Estimated waiting time.

Capacity Utilization

An efficient utilization of the existing railway infrastructure is an essential component of a high-quality transportation system and has become a central task for railway infrastructure managers. Line capacity is, in essence, what the infrastructure managers have to sell as their final product. Although capacity seems to be a self-explanatory term in common language, its scientific use may lead to substantial difficulties when it is associated with objective and quantifiable measures The capacity conditions in railway traffic are fundamentally characterized by the very limited overtaking possibilities of the individual trains. This property implies that the travel time for one train may influence the travel time of other trains, and that the travel times will therefore depend on the actual timetable. This lack of continuous overtaking possibilities gives rise to many dependencies between the individual train departures. The dependencies are partly seen during the planning phase, where they have a great influence on the design of the timetable, i. e. the establishment of the departure and travel times of trains, and partly during the operation process as delays spread to the other trains. Therefore, railway infrastructure capacity is limited and has therefore to be used carefully. Due to the increased utilization of the railway infrastructure, the railway system has become quite vulnerable to disruptions. This resulted in a lower punctuality and many customer complaints. Many interconnected relations characterize the railway system; Passenger transfers, rolling stock circulations and crew schedules all play their role in the relations between trains (Vromans et al, 2006). However, the shared use of the same infrastructure by different railway services, with different origins and destinations, different speeds, and different halting patterns, is probably the main reason for the propagation of delays throughout the network.

It is relatively easy to determine the capacity on roads; the capacity is normally just determined as vehicles per hour. Capacity on railways is, however, more difficult to determine since the capacity depends on both the infrastructure and the timetable. Over the years railway capacity has been defined in different ways; generally, the capacity of an infrastructure facility is the ability to operate the trains with an acceptable punctuality or the capability of the infrastructure to handle one or several timetables. Some argue that Railway infrastructure capacity depends on the way it is utilized. The reason that it is difficult to define railway capacity is that there are several parameters that can be measured. The parameters (number of trains, stability, heterogeneity and average speed) are dependent on each other.

Operations quality and capacity are two basic characteristics of public transport. Reliability and punctuality are critical measures of quality of scheduled train operations and are being paid much attention at the present by customers and public authorities. But railway infrastructure capacity and capacity utilization affect the volume of train service and the reliability/punctuality of real operations, respectively. The study of Railway capacity validates the feasibility of scheduled timetables in an existing railway network. The utilization of railway capacity has a considerable impact on the reliability and punctuality of train operations. Running and dwell time supplements, which reduce the impact of primary delays of individual trains, decrease capacity use. Buffer times between scheduled train paths reduce the propagation of delays from one train to the next, but lead to a lower use of capacity (Goverde and Hansen, 2001). Facing a continuous growth of traffic demand and consequently the needed additional train services, most railway infrastructure managers strive to utilize the existing capacity as much as possible. However if the utilization rate of railway capacity is designed too high, the train traffic becomes easily perturbed, leading to lower level of reliability and punctuality of operations. A compromise must be found for more efficient utilization of the existing capacity of railways networks on the one hand and improve the level of reliability and punctuality of operations on the other hand.

Yuan (2006) described a number of conditions to obtain a high capacity; for particularly long distance between the crossing stations, increasing the lining speed reduces the running time between the crossing stations. Establishing many crossing stations is proposed in minimizing the chance that traffic flows in opposite direction will meet at the crossing stations, which in turn reduce the traffic disturbance. The utilization of railway capacity has a considerable impact on the reliability and punctuality of train operations. Running and dwell time supplements, which reduce the impact of primary delays of trains, decrease capacity use. Buffer times between scheduled train paths reduce the propagation of delays from one train to the next, but lead to a lower capacity.

Stability

In literatures a distinction is made between non-periodic and periodic timetables. The latter are more and more international standard, because cyclic timetables are easy to remember for passengers and easier to handle for railway personnel. The scheduled intervals between the trains of the same line of a cyclic timetable are regular over the service period, but may be increased to an integer multiple of the base interval or decreased by an integer divisor e.g. during peak periods. European railways are typically operated according to a predetermined (master) timetable, which represents a conflict-free coordination of train paths and includes slack time to manage train delays. From a system point of view the timetable can be understood as a steady state for the train traffic. The stability of timetable is very important to provide high quality train services to customers (Yuan, 2006). The stability of railway systems then refers to the possibility and effort necessary to return to normal (a steady state) operations after disruptions. When unexpected events appear in the operating conditions, the railway traffic will be irregular for a transitional period of time, a railway system is instable if the train traffic is irregular for too long. The issue of railway traffic stability is rapidly gaining attention in Europe because of the increasingly saturated railway infrastructure where a slightly delayed train may cause secondary delays over the entire network. That is, delays propagate quickly throughout the railway network in time and space, possibly causing a domino effect of increasing train delays. The system response to disruptions is highly complicated due to complex cyclic train interdependencies generated by infrastructure restrictions (e.g. conflicting routes or a fast train getting stuck behind a leading slow train on an open track), timetable constraints (passenger connections at transfer stations), and logistics (rolling stock circulations and train personnel schedules). A railway timetable must therefore contain sufficient time supplements and buffer times to be self-regulating with respect to minor daily disruptions and to grant control space that dispatchers can utilize for managing larger delays. Since the timetable must accommodate disruptions it must have been tested a priori for recovery times and delay reduction capabilities to avoid a collapse of the entire timetable structure.

The stability of a railway system is interpreted broader here, because it is required that the system's ability to return to normal circumstances. Therefore, stability is a measure for the time and effort, which are needed to return to normal operations after a disturbance. A disturbed situation can, in a stable environment, return to normal operations quickly. When a system is instable, traffic will be irregular for a long time. The stability of a timetable is strongly dependent on the utilization of available capacity. Imagine a very extreme timetable in which all trains are scheduled to run at maximum velocity and the shortest possible distance of succession, i.e. the safety distance. There would be no possibility for a train to recover from a delay should it get behind schedule. Additionally, the delay would spread among the other trains since they are running at minimum distance. Therefore, buffers are needed in a timetable. The larger they are the more stable railway operations become. However, the buffers use up capacity that could be otherwise used for additional track slots and should, therefore, be no larger than needed (Yuan, 2006). For a given schedule timetable and routing for trains the buffers can be measured. The planned route of each train has a certain length of time, during which it can be used without coming into conflict with some other train.

Frequency

Ingo (2009) stated that the higher the train frequency the more attractive it is for the customers, but the higher are the operating costs. According to the author, depending on the trip distance, transport demand and competition with other modes in the area served, an average frequency of 6(12) times/(peak) hour and direction can be considered as excellent for heavily loaded national (regional) passenger railway lines. Only in densely populated metropolitan areas higher frequencies than 12 times per hour per track might be needed. A passenger train frequency of less than once per hour frequency per direction must be considered as poor.

Regularity

A high level of regularity of scheduled services is very important for high frequent passenger lines in order to avoid hinder due to overloaded platforms and trains (Ingo, 2009). Irregularity of a timetable can be easily computed through the standard deviation of the scheduled intervals between trains at stations in a network. The smaller the standard deviation, the higher is the regularity of the planned train services. The regularity of lines or certain stations in a network may be weighted differently according to their importance. Regularity of train operations is generally more critical than that of schedules.

Running and recovery times

To attain an acceptable level of punctuality of the train services, technically minimal running times are increased with running time supplements in the published timetables. These supplements are used to decrease, or even eliminate, incurred delays. For the operation of the timetable, it is both important to have sufficient running time supplements, and to have the supplements at the right location and at the right moment. Deterministic running times at a scale of minutes are standard in most railway timetables. A major reason is the inability of train drivers to perform better without more precise on-board information and advanced support. Another reason is the common practice to add certain running time supplements to the nominal technical running times in order to enable easy recovery from small delays without hinder for other trains. Many railways apply a standard running time supplement of 7%, as recommended (Ingo, 2009). In fact, the scheduled running times and required supplements can be estimated much more accurate, provided detailed statistical analysis is made of empirical track occupation and release data. Empirical distributions of exact running times can be easily derived from track occupation and release data. The running times depend on the alignment, number of train and dwell times at intermediate stops, type, length and weight of rolling stock operated as on the behavior of the train drivers and weather conditions. The running time distributions per train line can be used for estimation of the amount of recovery time instead of using a standard supplement.

Minimal headway and buffer times

Headway is the time between two consecutive trains traversing a point in the network. Minimum headway is the minimum time between consecutive trains, which must be observed according to safety. Minimum headways are sometimes referred to as safe headways. Planned headways are the times between the departures for the different lines in the timetable. In practice, timetable designers mostly apply standard mean minimal headway times (2 to 5 min) between train paths depending on the type of conflict and train sequence. The existing buffer times in a conventional graphical timetable which indicate only the train paths and headway times at a scale of minutes cannot be determined sufficiently, because these do not indicate the precise start and end of the capacity consumption according to the prevailing signaling an safety system. Buffer time, also referred to as slack time, is the extra time, which can be incorporated into the timetable to be able to maintain scheduled departure and arrival times when delays occur (Mads, 2005). The minimal time headway between two trains on a railway route is governed by blocking times of trains and its speed differences. The blocking time diagram of a train represents the time instances that a train needs to run safely without hinder at design speed over a sequence of track sections (Ingo, 2009). Furthermore, the scheduled dwell times are often exceeded during operations, which lead to an increase of the blocking time of the routes serving the platform tracks. The quality of timetable design would be enhanced considerably if the estimated blocking times reflect well the variation of train speed and dwell times in practical operations. The arrival and departure times of trains and the headway times between trains in most railway timetables, however, are determined currently with a precision of minutes due to rounding-up of the estimated running times and easy comprehension by the passengers. For capacity estimation of heavily occupied routes in bottlenecks the track infrastructure needs to be subdivided in individual route nodes: the smallest track elements that can be used by one train at a time.

Waiting times

Every timetable comprises scheduled waiting times and generates, in practical operations, non-scheduled waiting times (delays). Scheduled waiting times result from differences between the scheduled and desired running, headway, departure/arrival times by train operating companies, as well as timetable constraints. The scheduled waiting times depend on the market demand, track possession times due to maintenance and synchronization conflicts between train graphs at railway nodes and bottlenecks, whereas non-scheduled waiting times can emerge from technical failures of track infrastructure or rolling stock, accidents, and train delays (Ingo, 2009). The amount of scheduled waiting times can be used as indicator of timetable quality.

2.3 Performance Measurements

Train operators and network rail are all committed to improve timetable performance because they recognize that a reliable train service is a prime requirement for passengers. The performance challenge is two fold, first in real time, to record the progress of every train that operates and where the train performance deviates from the plan to understand the reasons why and put in place robust mitigation measures to eradicate delays. Secondly, timetable changes are necessary in modern railway system to match supply to demand. The use of tools to predict the performance of a new timetable can avoid costly delays and compensation on the introduction of a new timetable. The tools allow operators to measure the effectiveness of planned changes and perform robustness tests during operations to define contingency plans.

2.3.1 Reliability

When trains are scheduled the objective is to achieve a given level of customer service whilst minimizing overall operating costs. Customer service in this context is made up of several attributes, which include overall journey time of trains and the degree to which those journey times are achieved on a daily basis. The ability of rail systems to compete effectively relies to a large extent on consistent transit time reliability, which is expressed as the probability that the planned arrival time will be achieved for each train (Fowkes et al., 1991). Overall timetable reliability is a measure of the likely performance of the timetable as a whole, in terms of schedule adherence. For railway services, “reliability refers to the ability to perform its required functions under stated conditions for a specified period of time” (IEEE 1994). Many characteristics and details of a railway timetable have a direct or indirect influence on the reliability (Vromans et al, 2006). For instance according to some studies speed differences play an important role in railway services, speed differences often lead to an increased delay propagation. Homogenization of train traffic increases the capacity of the system. Furthermore, there are probably less peaks in the capacity utilization of the platforms at large stations.

The concept is important for both urban and non-urban rail passenger services, as well as rail freight transportation. In regards to the importance of reliability in public transport services, Bates et al., (2001), proposed two explanations: (1) travelers are sensitive to the consequences associated with travel time variability, such as prolonged waiting times, missed connections and arrival times before or after the desired time; and (2) travelers place a level of value on the uncertainty induced by variability that is independent of its outcome, perhaps as a result of anxiety or stress, or the added cognitive burden involved with planning activities and travel in uncertain conditions. Also, reliability impacts total trip time, as most passengers must plan to arrive prior to the scheduled departure time to ensure that they do not miss their bus or train, (Transit Cooperative Research Program, 4 2003). Delays are also likely to extend waiting time and in some cases generate uncertainty for the overall trip.

Rail service reliability can be seen differently from carriers or shippers perspective. A carrier responsible for a particular rail service may be interested in the likelihood that the trains belonging to the service can be operated according to a preplanned schedule, which can be termed as train schedule reliability. Some of the primary sources of train schedule reliability problems are unexpected events, such as long border station delays, unavailability of crew, rolling stock or locomotives. In a highly interconnected rail traffic network, trains share infrastructure with several other trains and so a delayed train may cause a domino effect of secondary delays over the entire network. A shipper, on the other hand, may be interested in the likelihood that a shipment reaches its destination at the desired time. The shipper may then choose rail transport depending on shipment connection reliability, which is the likelihood that the shipment makes all the scheduled train connections required to reach its destination at the desired time. Shipments may miss their scheduled train connections due to train delays or variability in yard operating times. Railway operators responsible for a particular rail service may be interested in the likelihood that the trains belonging to the service can be operated according to a preplanned schedule, which can be termed as train schedule reliability. Customers, on the other hand, may be interested in the likelihood that they reach at destination at the desired time.

The most common measure for reliability is the percentage of the planned operations that are completed in time. However, a wide range of definitions can be found, mainly depending on the system or application (Vromans, 2005). It is highly correlated to events in railway systems, namely a departure, an arrival or a passing time. The reliability of arrivals is a critical performance measure for all rail markets. When a railway system is reliable, the trains run properly most of the time (Keyhani et al, 1998). This means that most of the passengers and goods are transported at the scheduled time. Only a small portion of the trains has delays or is not operated at all. Both the average delay and the variation in the delays are low. Reliability of railway operations is often expressed through measurement of punctuality and regularity. Punctuality and regularity are two of the most important quality factors for railway customers, and improvement of punctuality and regularity are part of the strategy for all the examined companies. Rudnicki (1997) stated that improvement of punctuality and regularity is the main task in improvement programs of public transport system, due to the fact that both are measures of unreliability and therefore “take very high place in opinions of passengers”. From passengers’ point of view, reliability can be seen as two closely related concepts: namely, regularity and punctuality (van Oort 2005). Regularity is the variation in headways while punctuality relates to the deviation from the scheduled arrival and departure times. Reliability largely affects traveler’s time, as it is often related to the possibility of lateness, longer time spent waiting, as well as with the stress associated with uncertainty itself (Bates et al, 2001). Therefore, attention to transit quality and efficiency in general and reliability in particular is increasing (Landex, 2012).

Vromans, et al (2005), explain that an effective way to increase the reliability of timetables is to reduce the propagation of delays generated by the correlations and mutual relations of trains and also heterogeneity of trains. There are relatively vast literatures looking at reliability of railway services (Vromans, Dekker et al., 2006). Their emphasis lies mainly on punctuality and the associate concept, which is one of the key performance measures of a railway system. However, many more measures for reliability exist, minimize the positive difference between the arrival times in operations and the scheduled arrival times. Minimizing this aspect has in many cases beneficial effects on all others. Two other concepts are highly correlated to reliability and need to be introduced as well, viz. robustness and stability.

2.3.2 Robustness

The robustness of a railway system indicates the influence ability of the system by disturbances. A robust railway system can function fairly well under difficult circumstances. When a railway system is not robust, small external influences cause large delays, which propagate quickly throughout the system in place and time. In the planning of time schedules for lines, many factors need to be considered. There is a high degree of interdependency since trains are sharing tracks, so schedules for different lines might depend on each other. A schedule for a line also depends on security regulations and speed restrictions etc. Naturally cost is a very important factor in the planning of line schedules; therefore timetables are often optimized according to a minimal use of train sets, since the number of trains used is one of the largest cost terms for running trains. On the other hand it is not necessarily recommendable to have an optimal plan with regards to cost and minimal number of trains necessary, since a small disturbance might affect the robustness of the whole schedule, and adjustments need to be performed all the time.

A way of creating robust timetables is to incorporate time buffers (slack). Robust means that the performance of the system is less sensitive to deviations from the assumed timetable. Large time margins will increase the robustness, but at the expense of longer travel times for passengers and the need of more trains. Another way of creating more robust timetables is to run fewer trains on a particular series. This will create larger time margins and hence less probability of cascading delays.

Again the expected travel time will increase, which is a drawback for passengers. Scheduled headways between trains on shared stations should also be allocated as evenly as possible to ensure the largest buffer time between all trains.
Often the timetables are constructed to be cyclic. This means that passenger services are repeated every cycle time, usually every hour. Also in the planning of timetables it can be considered how good the connections between the trains are, such that train services at large stations fulfill that a passenger can change between trains with maximum waiting time at the station. A timetable is designed to be feasible, in the sense that if no disturbances occur then there will be no delays. On the other hand if it is not possible to run all trains at the assumed speed, then delays will occur.

2.3.3 Punctuality

Punctuality is one of the most used performance measures in railway systems. In railway systems this is the percentage of trains arriving within a certain margin from the scheduled arrival time. The optimization of timetable is often based on several different and opposing considerations, as one criterion is not enough to make a good one. Quality parameters, such as; direct connections, good transfer conditions, regular departure schedule, short travel time, high departure frequency are part of a timetable evaluation. Particularly during high travel intensities, it preferred to have a limited number of transfers, as they are considered a nuisance. When transfers cannot be avoided, the transfer time to connecting trains must be strictly adapted. In case of transfer it is furthermore desirable if the connecting trains can be caught from the opposite side of the platform in order to reduce the walking distance and thereby also the transfer time. Regular interval timetables and constant use of the same platform track also makes it easier for the passengers to remember the timetable. The passengers wish a high travel speed and a limited number of stops during the trip. Therefore, it is necessary with several train systems on the lines where this is possible, so that certain trains do not stop at the less used stations. Several of the issues will be directly conflicting. Thus, many direct connections and a high departure frequency mean a high utilization ratio of the infrastructure, but an intensive utilization of the infrastructure increases the risk of poor punctuality. Short transfer times means that in many situations the planned connection will not be possible, or the passengers have to wait for the connection. In the latter, the travel time is extended “unnecessarily” for all the travellers who have not made transfers. However, if you do not have to wait for the delayed train, all the trans boarding passengers suffer a substantial travel time extension equivalent to the frequency on the route to which they make the transfer. With a high departure frequency the operation speeds of the trains must adapt to each other, provided the traffic intensity is close to the capacity level. This will therefore increase the travel time for trains that under free conditions could run at higher speeds, and the risk of poor punctuality is also increased.

The punctuality analysis represents the most important measure of rail operation performance and is often used as standard performance indicator. Mostly it estimated on the basis of train detection data from measuring devices in the vicinity of large stations. This corresponds to ex-post delay estimations with regard to daily and hourly patterns in the variations of the arrival and departure-scheduled times at stations. Furthermore, train delays are considered only if larger than a certain value, usually three minutes. However, smaller train delays, which are due to non-technical reasons, in general, are representing a vast majority of all delays (Hansen, 2001). Punctuality is the quality parameters that travellers generally appreciate most [6]. With the railway liberalization, the punctuality has been brought into focus as it is a measurable quality parameter that can be observed at the individual train operators. When the actual

Many studies of travel choice behavior have found that reliability, punctuality and dependability of a transportation system are very important for passengers. These factors affect riders' perceptions and their level of use of the different transportation modes. In some cases, passengers place higher value in having consistent and predictable services than in the average time spend traveling. Bates et al. (2001), found that punctuality is indeed highly valued by rail passengers. In practice punctuality is probably the most widely used reliability measure. Besides, it is one of the most commonly used performance measures in railway systems. In railway systems punctuality is expressed as the percentage of trains arriving within a certain margin from the scheduled arrival time. Therefore, Railway punctuality describes the accuracy and reliability of train traffic. It is a well-known indicator among actors of the field and passengers, and is often easily measurable. Olsson & Haugland (2004) stated that in the railway industry, punctuality is a key performance indicator affected by several factors. It is described as an important success factor for railway traffic systems, which largely affects passengers. For passengers, punctuality is an indicator of the quality of a journey. Railway traffic punctuality is often discussed in public, and high requirements are placed on the reliability of train schedules. Passengers tend to associate punctuate so strongly with quality. Measuring punctuality in railways has many different applications (Salkonen, 2010).. It can provide a measurement of quality, and can be used for example in individual investment projects or in scheduling. In practice a three-five minute margin is used

In order to calculate the punctuality figures, measuring points have to be chosen, usually a set of large stations. An improved punctuality measure would be the weighted punctuality, where each train is weighted according to its number of passengers (Schittendelm, 2011). In general, Reliable and punctual trains make passenger trains more attractive towards potential customers and just-in-time delivery for production companies has become more usual within the freight transportation business.

A train might suffer a number of delays along its route; yet arrive punctually to the final destination, due to a higher speed attained than planned for on certain parts of the journey (Veiseth & Bititci, 2003). Another aspect is that punctuality at the final destination does not always "tell the full story", because the under-way punctuality is not necessarily equal the punctuality at the end point. Studies showed that the punctuality over the lines often is shaped as a "bath tub". An example of this can be seen in Figure 2.

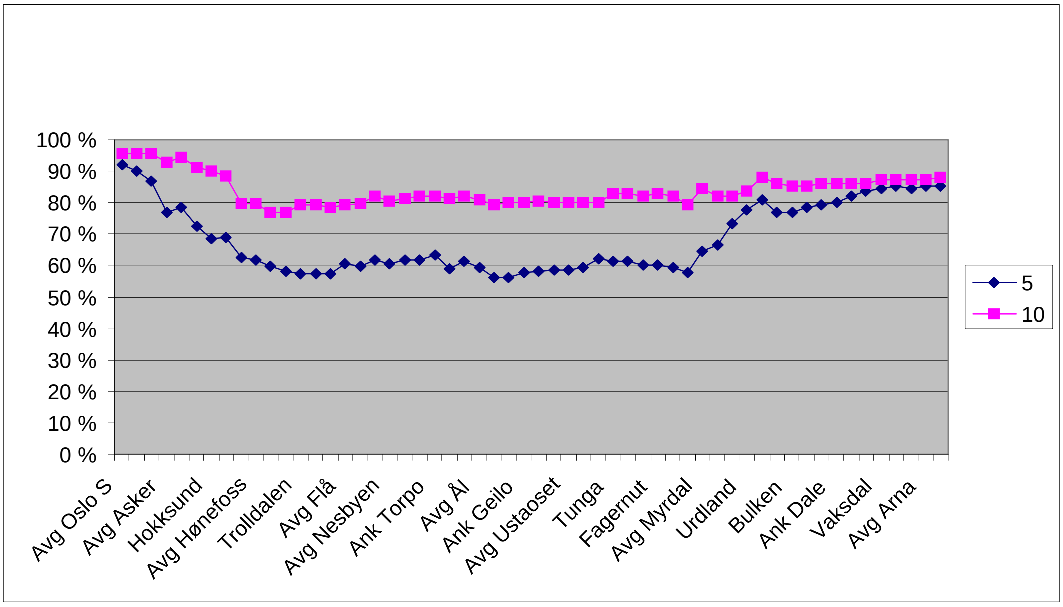


Figure 2 Punctuality profile for 5 and 10 minutes time limit for the Oslo-Bergen line, Norway (Veiseth and Bititci, 2003)

It can be seen that the punctuality, for the 5 minutes time limit, lies between 80 and 90 % at the final destination, but are below 60% at other stations. A large part of the Norwegian railway systems consists of single-track lines.

Skagestad (2003) discusses performance indicators used in the improvement of punctuality in the Norwegian railways. She claims there is a need for different "levels" of punctuality information and indicators, because the need of information varies between the different users. She points at three different groups with different needs: Customers, decision makers and improvement teams. The first groups only need a rough overview of the punctuality where as both he latter groups need more detailed information about the punctuality and what causes the delays than the indicators used today can provide.

Methods of measuring punctuality in most countries are simple, concentrating solely on measuring the deviation of scheduled stops and counting the percentage value of punctual trains. Also, threshold values of punctuality vary between countries and common uniform measurement methods are missing. Measurement of punctuality and regularity are indicators developed from the stakeholders' needs and from the companies' strategies, which correspond to best practices identified in the performance measurement literature. Percentage punctuality and regularity seem to be good indicators when it comes to communicate with external stakeholders. They are easy to understand and compare between different lines and operators, although they are difficult to use in international benchmarking. On the other hand, percentage punctually and regularity do not seem so good for the improvement work, to monitor trends and to control the operation. This is because they are too aggregated and only measured at the final destination, which makes it difficult to track the effect from specific improvement measures. Delay minutes combined with registration of "delay-causes" seems to be a better indicator. There is also a need to focus more on under-way punctuality, especially for single-track lines. Due to the limitations in the use of the percentage punctuality measure, there has been a development towards more focus on delay minutes and under-way punctuality.

2.3.4 Train Delays

A delay is the positive difference between the planned time of an event and its actual realization time. Train delays form the basis of punctuality, which is an important measurement of the trustworthiness of railway operations. Although punctuality and reliability measures are important, they give only limited information about train delays. According to public reports on punctuality, the large number of smaller delays for trains that are not actually considered as delays have a considerable impact on the quality of operations (Yuan, 2006). This is because trains are not registered as being delayed before a certain threshold of delay is reached, even though passengers may miss a connecting train due to this smaller delay. The threshold of delay varies by country as a train is considered as either delayed or not delayed (Yuan, 2008). Delays smaller than 5 minutes are usually not considered as delays by the European railway companies because of limited precision of the applied modes of measurement, tolerances of the timetable and insufficient means of control of operations in practice (Goverde et al, 2001). As there are no standard definitions and the mode of measurement of delays is varying, the punctuality rates of the railways differ a lot.

The word delay was used as being the antonym of punctual by most informants, but this is not necessarily so from Jernbaneverket's definitions. Today, the length of delay to the end station is somewhat indicated by measuring average end station delays. This particular example considers only delays due to infrastructure.

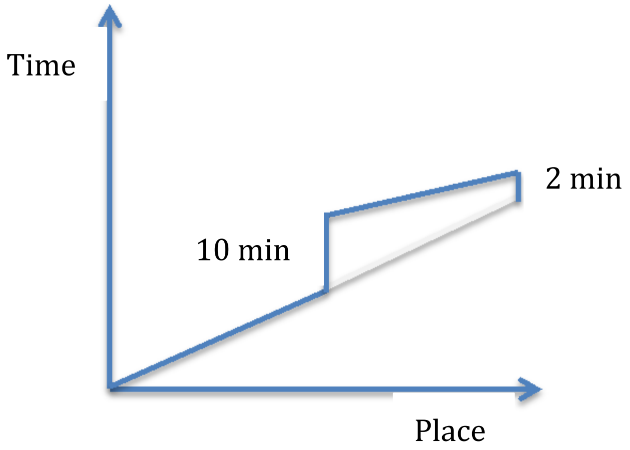


Figure 3 A train suffering a 10 minutes delay underway, but ending up punctual at end station (Nystrom, 2004)

Figure 3 shows a train path (light line is the scheduled path). Underway the train has a 10 min delay, but arrives at end station only 2 min after its scheduled time, and is therefore considered punctual thanks to timetable slack. This phenomenon as well as when a train departs before the scheduled time counts as punctual if it arrives punctually to the end station, though it might have created problems underway.

It is relatively easy to apply punctuality as a measure of operational quality. However, there are significant differences when using punctuality as an evaluation parameter. Nowadays, customer management is increasingly important in all fields. Railway actors have to be able to follow how railway customers' punctuality evolves from the customers' point of view (Salkonen, 2010). Punctuality can be related to trains or passengers. If a train is on schedule, this does not mean that all passengers inside the train are punctual. A passenger is delayed inside a punctual train if he/she has missed the previous connection due to a delayed feeder train. However, it is also possible that a passenger is punctual, or even ahead of time, when using a previously delayed train instead of the originally scheduled one (Martin, 2008). Therefore, passenger delays could be another measurement of reliability. In this way, the measurement would reflect how passengers actually experience the railway service. Even though punctuality is a commonly used measure of reliability of railway operations, it gives only limited information about train delays. Delay analysis helps railway infrastructure managers in the optimization of capacity utilization and operators to minimize the operating cost while simultaneously assuring a desirable level of reliability and punctuality of train operations (Yuan, 2006).

Train delay is one of the most important performance indicators of railway operations. It is the result of many factors, such as the layout of the infrastructure, the occupancy of the infrastructure, the variation of running times, arrivals and departures, and the traffic control (Nie, 2005). First, the infrastructure must provide enough capacity and smooth routes. The timetable is the basic plan for train operation; therefore, it should ensure efficient and balanced use of the infrastructure. In addition, it should be flexible enough to cope with stochastic disturbances during operations. The real operation of trains will hardly ever be in complete accordance with the timetable due to unavoidable small disturbances like technical failures, construction sites along the tracks or delays at stations during boarding. Suitable recovery times in a timetable are very important to reduce train delays, and also buffer times can decrease delay propagation (Engelhardt et al, 2004). Stochastic disturbance of operations cannot be eliminated and will always occur, but its statistical distribution can be grasped by analyzing historic and actual train operation data. To some extent, this will help to forecast and prevent train delays. Traffic control is another means to supervise and improve the train punctuality. The effectiveness of traffic control, however, depends on the quality of the actual schedule, the time and precision of conflict detection and the available means for disposition.

For the prediction of the reliability and punctuality of the train operations according to a certain timetable, it is necessary to distinguish two types of delays, primary and secondary/knock-on delays (Vromans, 2005). A railway line might be single-track, with the line merely consisting of one track. To permit trains to meet (or overtake), stations are built. A delay to the leading train might inflict a further delay on the second train. This situation illustrates that a delay of one train can spread to other trains. Therefore, it is beneficial to define two kinds of delays. An arrival delay of the arriving train might then impose a delay on the departing train.

Primary Delay

Primary delays, also called initial or source delays, are the direct outcomes of the causes of delay, which are not caused by other delayed trains (Vromans, 2005). A Primary delay is a delay to a train that results from an incident that directly delays the train concerned, irrespective of whether the train was running to its schedule at the time the incident occurred, i.e. the delay is not the result of another delay to the same or other train. Therefore, primary delays have a direct impact on the train service. They are caused by disturbances: mistakes, malfunctions or deviating conditions within a railway system or its environment, which can influence the railway traffic. Disturbances have many different causes, for which many different railway organizations are responsible (Mads, 2005). Moreover, a sizable portion of the disturbances has an external cause. For these external causes it is difficult and expensive to reduce their occurrence. Fore instance, technical failures, running at lower than scheduled speed, prolonged alighting and boarding times of passengers, and bad weather conditions. The reasons for initial delays that can be related to the infrastructure or the rolling stock will generally be regarded as technical errors. The duration of the technical errors plays an important role with respect to the consequences. Note that slack in the timetable can reduce the size of a disturbance before it is measured as primary delay. To improve punctuality and efficiency in the traffic flow, the link between disturbances and their impacts on train delays needs to be analyzed and understood more precisely. Accordingly some of the sources of disturbances that result in primary delays are discussed below.

Sources of Disturbances

- Failures of the infrastructure are a reason for large delays. Infrastructural disturbances include malfunctioning switches, broken catenary, failing signals and non-working automatic barriers. These failures have their effect on all trains, which are planned to pass the infrastructure in question. A separate reason for disturbances and canceled trains are maintenance works, which take longer than planned.

- Accidents with other traffic: Accidents happen quite regularly at level rail-road crossings, both at guarded and unguarded crossings. Also vandalism has to be included in this list. Regularly stones, trash or bikes are found on the tracks. Too often these items are not found until a collision is unavoidable, damaging both the tracks and the rolling stock. Additionally, coins on rail joints can cause signaling problems.

- When rolling stock breaks down it can block a trajectory or part of a station. Still, many small rolling stock malfunctions only have a minor influence on the railway traffic. Rolling stock problems include engine break-downs, leaks in the hydraulic system, problems with closing the doors, problems with splitting and combining train sets, and so on.

- Human factors: Operating the trains is still mainly a human process and therefore it cannot be flawless. For instance, driving a train is a process with a stochastic nature. Each train driver has its own driving behavior, and even the same driver does not realize the same running time for the same track every time. Although passengers should not be blamed for delays, they can sometimes be seen as a disturbing factor. A passenger arriving on the platform just at the moment the crew wants to close the doors often causes the conductor to wait a little longer. Also dwell times are sometimes extended because of pushing and pulling at the train doors, or even blocking the people trying to get off the train. In addition aggressive passengers can cause delays. Sometimes it is even necessary for the conductor to call for police assistance. Furthermore, emergency breaks are sometimes pulled for fun.

- Weather conditions: Weather conditions are another source of disturbance. An extremely fast temperature increase can cause the track to bend or cause signaling failures. An extremely fast decrease in temperature can cause the tracks to crack. The most problematic weather conditions usually occur during the fall, when a combination of leafs and moist causes the tracks to be very slippery. This causes breaking distances to increase and acceleration rates to go down. Although the resulting delays are usually small, under bad conditions they occur frequently and over large areas.

Primary delays cannot be eliminated and are independent of the design of the timetable. Primary delays are also in theory independent of capacity utilization, but analysis of the causes and locations of primary delays can be used to generate a reliable schedule, where primary delays cause the least secondary delays. This is possible since the occurrence of secondary delays is affected by the schedule design. It has been pointed out that slack in the timetable can reduce the size of a disturbance before it is measured as primary delay. When slack time in the timetable is too small a cause of delay on a train may create a conflict with another train. These delays are called secondary delays.

Secondary Delays

A railway system is a complex system with many interacting processes that depend on technical devices, human behavior, and the external environment, and therefore contains many risks of disturbances (Nyström & Kumar, 2004). Once a delayed train deviates from its original time-distance path, it may hinder subsequent trains that are scheduled over the same railway infrastructure or it may conflict in passings or meetings with other trains (Mads, 2005). Hence, a delayed train may propagate its delay to other trains due to infrastructure, signaling or timing conflicts. In practice, major disturbances may influence the off-line plan of operations, thus causing primary (initial) delays, such as train delays or temporary unavailability of some routes, that propagate as secondary (consecutive or knock-on) delays to other trains in the network. In such situations, the timetable no longer provides an optimal use of infrastructure capacity, and short-term adjustments are worthwhile in order to minimize the negative effects of the disturbances.

Therefore, secondary delays are delays caused by earlier delays due to the interdependencies in railway systems (Vromans, 2005). They are also known as reactionary delays and expressed as delays that result from an incident that indirectly delays the train concerned, i.e. the delay is the result of a prior delay to the same or any other train. A secondary delay is a delay caused by another train’s deviation from the timetable (Dahl, 1997). Often, other terms are used synonymously to secondary delay, front mostly knock-on delay (Carey & KwieciĚski, 1995) and cascade delay (Nelson & O’Neil, 2000). The crowdedness of railway network induces strong dependencies between train services. The dependencies are created by the timetable and other logistic plans, such as the rolling stock circulation.

Route conflicts and the resulting knock-on delays often occur at busy stations and junctions, which may affect the punctuality of train arrivals and departures at the stations and the use of network capacity. The knock on delays of a train is determined by the buffer time between the scheduled path of this train and that of the preceding train as well as the delays of the two successive trains. The buffer time is defined as the time added to the minimum line headway to avoid the transmission of smaller delays and it is the smallest slot between the blocking time stairways of trains (Yuan, 2006). Railway experts believe that there are more secondary than primary delays. Costs to reduce the disturbances and primary delays are usually high. Normally passengers do not see the difference between primary and secondary delays, for them a delay is a delay (Murali, 2009). A primary delay to the train on station might impose secondary delays on the other trains. Primary delays occurring due to signaling and engine problems might cause a secondary delay. However, it is not clear whether to blame the secondary delay on the faulty signaling or the faulty engine. From this, it can be understood that it is not true in principle that removing a cause of primary delay nullifies the secondary delay. In addition arriving and departing trains often suffer from knock-on delays due to the late release of platform track or junctions by other trains. Ready to depart trains at stations wait for late arriving feeder trains to secure the scheduled transfer connections.

Delays can also be categorized as arrival and departure delays (Goverde and Hansen, 2001). Arrival and departure delays A delay is the positive difference between the planned time of an event and its actual realization time. Arrival delays are usually the result of a late departure at the preceding station, too large running time, or route conflicts between trains. The running time of a train between two particular stations (slightly) varies for each trip depending on a wide range of factors from within the railway system and from exogenous sources. Internal sources are technical failures (of signals, switches, tracks, power supply and distribution, superstructure, and rolling stock), operations personnel behavior (driver, conductor, dispatcher), and passenger flows (fluctuating alighting and boarding times depending on the amount of involved passengers). Exogenous sources are for example weather conditions. These sources of random variations are difficult to forecast and constitute a fundamental part of the practice of railway operations. Therefore there will always be a certain amount of trips that exceed a scheduled process time leading to primary delays, although scheduled running times and dwell times usually contain some margin or slack time to compensate for small variations.

Also hinder by other trains via the signaling system such as a slow train upstream a single track or a conflicting train movement at a junction or crossing, influence the train running time. Departure delays even increase the probability of mutual hinder of trains as the delayed trains deviate from the scheduled train paths. Analysis of realized train running times is therefore a crucial step in punctuality management, regardless of the used method in the planning process for the running time calculations. The variation in running times should be small in a well-designed railway system. Buffer times between conflicting train movements decrease the possibility of secondary delays. Analysis of realization data reveals tight headway times or the actual amount of buffer times at infrastructure bottlenecks. Statistics of arrival delays at a station may help to identify unstable timetable designs and give directions to further analysis of train interactions. It has been said that the major causes of a (large) departure delay are a late arrival, a prolonged dwell time due to boarding/alighting passengers or logistic reasons, waiting to secure connections, and a delayed outbound route setting due to conflicting train movements. Recall that a train is not allowed to depart early, i.e., before its scheduled departure time, and hence practically always departs late.

Interdependencies and delay propagation

Delays may accumulate during a train journey and may also be propagated to connecting trains of other lines. Analysis of the propagation of delays is a most complex task as the propagation of train delays is a dynamic process. The propagation of train delays depends, among others, on the utilization of railway network capacity and timetable design (yuan, 2006). Complicated dependencies between train delays exist due to crossing routes of trains, train routes merging to the same track, etc. A railway line might be single-track, with the line merely consisting of one track. The amount of delay propagation reflects the stability of timetables and the reliability of train operations in networks (Yuan, 2008). According to (Vromans, Dekker et al., 2006) one way to increase the reliability is to reduce the propagation of delays due to the interdependencies between trains for example by decreasing the interdependencies by reducing the running time differences per track section and by thus creating more homogeneous timetables. When investigating railway reliability, it is important to make a distinction between primary and secondary delays.

(Meer et al., 2009) mentioned that in busy railway networks the delay propagation has a great impact on train operations in case of delays. Stations are the bottlenecks in a railway network as here trains of various lines meet and interact. Delayed and/or early trains result in potential conflicting train paths controlled by the interlocking system causing mutual hinder at conflict points. Delays measured at stations represent a mixture of primary and secondary delays. Arrival delays are input delays to a station area summarizing the train operations upstream to the station including the inbound routes. They are a mixture of primary running time disruptions on the preceding open track and e.g. a provoked low speed by following a slow train on the open track, and hinder at merging and crossing inbound routes. Disruptions in the dwelling process, such as extensive alighting and boarding time and a prolonged departure process, are a source of primary delays (Yuan, 2006). The measured departure delays are the result of arrival delays, disruption in the dwelling process, and secondary delays at departure resulting from conflicting outbound routes or waiting for delayed feeder trains. The actual departure of a train at a station is determined by a number of factors. The most important factor is the free dwell time introduced. The free dwell time of the train is the necessary dwell time in the absence of hindrance due to route conflicts and late transfer connections. In case of short scheduled headway, a departing train may be hindered due to the occupancy of on-route junctions by preceding trains that are approaching or have departed from the station (jianxin yuan, 2006). Likewise, train arrivals at main stations initiate several concurrent activities: alighting and boarding of passengers, passenger transfers to connecting trains departing in different directions, and exiting passengers walking to their final destination or continuing their journey in another transport mode. Likewise, train departures synchronize activities of through, starting and transferring passengers. Rolling stock connections show similar structures: trains from different directions may be coupled to continue as one combined train or a train may be decoupled after which the front and back continue in different directions. The railway infrastructure and safety and signaling systems cause a different kind of synchronization between trains on conflicting routes which must run in sequence over the shared infrastructure in some decided order.

Many disturbing factors and causes for primary delays were mentioned in the previous section and these have a direct impact on the train services. However, studies have shown that the total number of delays is much larger due to delay propagation. Delay propagation is the spread of delays in the railway system, both in time and space. Delays spread around due to dependencies between train services. The main reasons for delay propagation are discussed in this section.

- If a train incurs a delay early on, and it is not possible to recover this delay, this delay will be carried up to its endpoint. In case of long distance trains, delays may be carried along several measuring points. This means that one primary delay can easily be propagated to the other side of the network. However, it still about a single train: there is no ‘real’ secondary delay, but the primary delay is measured more than once.

- The limited capacity of the railway infrastructure: The high utilization of the infrastructure implies a short headway between the trains. Still, because of safety, there is minimal time headway between trains. Depending on the situation and location, the minimal planning distance from several seconds to ten minutes. Especially at and around large stations and on the busy tracks, planned headways between trains are often not much larger than the minimal headways. This is true for the open tracks, platforms at stations and level crossings. The positive difference between the planned headway and the minimal headway is called buffer. When two trains are planned at a minimal headway, with no buffer time between them, and the first one is just slightly delayed, it will already cause the second train to be late: it incurs a secondary delay. When buffer is included in the planned headway, small delays do not directly lead to secondary delays. In many cases a train is scheduled very close to many other trains. This means that a small delay can already cause many other trains to be late. These other trains can then cause further propagation of delays through the network.

- When a train reaches its terminal station, its rolling stock will be used for a subsequent train. When this layover time is shorter than the delay of the arrival train, the second train will be delayed as well. When the rolling stock of one arriving train is used for more than one departing train, delay propagation may even go faster. When delays are large, and spare rolling stock is available, the rolling stock dependency between consecutive trains can be broken.

- Both train drivers and conductors change trains several times in their duties. When a crewmember arrives late with a train early on in his duty, he may transfer this delay to later trains. Note that both the driver and conductor must be in time to have a punctual departure. When additional spare crewmembers are available, they can be used when other personnel is late because of delays. Crew schedule dependencies can be reduced in this way.

- The positive difference between the planned headway and the minimal headway is called buffer. When two trains are planned at a minimal headway, with no buffer time between them, and the first one is just slightly delayed, it will already cause the second train to be late: it incurs a secondary delay. When buffer is included in the planned headway, small delays do not directly lead to secondary delays. In many cases a train is scheduled very close to many other trains. This means that a small delay can already cause many other trains to be late. These other trains can then cause further propagation of delays through the network.

The distribution of delays and its parameters may depend on the types and routes of trains differ from location to location and vary over time. It appears difficult to find a standard distribution type to be applicable everywhere. To analyze the robustness of timetables and the reliability and punctuality of train operations in railway network, the distribution of input delays at the network boundaries should be known.

The impacts of train Delay

Train delays can generate different levels of customer dissatisfaction, based on the degree of severity of negative incidents. Delays and incidents have a significant negative impact on passengers' satisfaction motivating users to discontinue the use of public transportation after having reached a certain point of frustration. Passengers may respond to incidents by changing their perceptions about the reliability of the service, or by changing their location and/or travel behavior on either a permanent or a temporary basis. As Friman et al. (2001) noted negative critical incidents could have a higher impact on customers' cumulative satisfaction with the service than positive experiences, because negative encounters tend to be more significant and stay longer in memory. Their research revealed that a negative relationship exists between the frequency of negative critical incidents and attribute-specific cumulative satisfaction (e.g., travel time, cost, and frequency of service). Edvardsson's (1998) study in public transportation, revealed that the dominant types of negative critical incidents include punctuality, treatment or conduct by front-line personnel, and poorly designed information. Friman et al. (2001) found that, “avoiding dissatisfaction is likely to be the users’ goal in using public transport services.”

Regarding the source of some of the aforementioned punctuality related incidents; the main challenge for public transport service providers lies in preventing defects in the coordination of services (Edvardsson, 1998). Trains may arrive too early, too late, not frequently enough during peak hours, or may not arrive at all. Trains that suffer from frequent and severe delays cause substantial annoyance to their users and reduce the perceived utility of the system. Such poor punctuality, whether through trains being delayed or cancelled, has a direct impact for the passenger: their journey will take more time than expected, leading to extra “cost” and may become uncertain about their arrival time. If they then miss a connecting train or bus with a low frequency service, their journey time will increase further (Kroes, 2006). Most regular train passengers will recognize the frustration of missing a connecting train when their feeder train arrives at the transfer station with a small delay. In low frequency railway systems, missing a connection can have a severe impact on the travel time of the passengers, even if the delay of the incoming train is only small (Dollevoet, 2012). In such cases, an alternative would be to delay the departure of the connecting train, so that passengers from the delayed train can transfer to the connecting one. If a train waits for passengers from a delayed feeder train, the punctuality will be reduced; if it does not wait, passengers need to wait for the next service connecting to their destination. Passenger journey times are less affected in the case of high-frequency services than in low-frequency ones. In other words, delays are less for high-frequency services. Only the delay at the final destination matters to passengers. A small delay can be very annoying if it results in the user missing a connecting rail or bus service.

Indirectly, poor punctuality during peak periods can have a negative effect on other aspects of the quality of train services as well: passengers accumulate on the station platforms, and density may exceed comfort and even security standards (Hironori Kato, 2010). The delayed train is likely to be more crowded than usual so that passenger comfort on the journey will be poorer than usual, and stop times at stations will increase. In extreme cases, trains may be so overloaded that travellers cannot board at all, and will have to wait for the next train. Such degrading of service quality will increase the perceived cost of poor punctuality further. It is highly expected that frequent delays in rail services influence passengers’ perceptions of service reliability. In addition, the delays may also affect their behaviors including their choice of departure time.

The costs associated with delay are incurred by the suburban train users themselves and by society. The actual cost of delays is not always borne by the passenger; part of it is sometimes transferred to a third party. When an employee’s trip to work is affected by a delayed train, this may be presented as force majeure, and the costs may be borne by the employer. The summation of these costs makes up the social cost of unpunctuality. The value of this cost is currently not well known, as there has been little interest in valuation of punctuality effects up until a few years ago. The perceived cost of a delay affecting a trip made for personal purposes (travelling home, visiting a doctor, etc.) may be valued higher by the traveller. Passengers who rarely suffer from train delays tend to view a delay as less acceptable than passengers who frequently face irregular services. Passengers with more flexible working time schedules view irregularity as less of a problem than passengers with rigid office hours. Men and women with children give a higher importance to delays occurring in the evening; the younger the children, the more burdensome is the perceived delay. Passengers indicate that information about delays greatly reduces the cost associated with them, insofar as the information allows them to decide to change their mode of transport (Kroes, 2006). The value of delay increases with decreasing comfort in trains and on platforms. When trains run ahead of their schedule, they always have to wait their scheduled departure time at station stops. Therefore, delays have a large influence on dwell times of trains at stations. (Nyström, 2008) noted that train delays in railway affects its competitiveness relative to other transport modes, that is, road, sea and air transport, not only due to the inconveniences it causes to the customers, but also due to the costs imposed on other stakeholders.

Identification of causes of delays

Train series have different operation histories upstream and distinct routes in the station area. The corresponding trains may also have different dynamic characteristics. These factors eventually lead to different statistics of train delays. Knowing the source of delays is crucial information to railway infrastructure managers and train operators, but assigning a given delay to its causes is very difficult (Nyström and Kumar 2003). Actual delays at stations are monitored online using train describer systems and timetable databases, but it is unknown whether for instance a delay has been caused by a slow running train or by a route conflict where a driver had to slow down due to a restricted signal. In particular, delays due to route conflicts are hard to recognize afterwards, although their identification is crucial to assess and optimize the quality of infrastructure capacity allocation (Goverde et al, 2008). There is great diversity in the availability and quality of information on causes of delay, since the breakdown used by railways is not standardized. It is agreed that the best measure was one of “train delay minutes” in order to weight the differing effects of the various delay causes, using a limited number of categories as the lowest common denominator. A further unresolved problem concerns the allocation of delays to “primary” or “secondary” causes. The greater the train frequency or utilization level of track capacity, the greater the share of secondary delays in the total, and the more difficult it is to allocate delays by cause accurately.

Train delays occur for various reasons: the causes might be related to a technical system in the railway or related to organization. The railway sector consists of many business areas managed by different independent organizations and companies. Therefore, the assumption of a single rational stakeholder does not apply to the railway (Zoeteman, 2004). That each stakeholder sees to its best might generate sub-optimizations. This creates many problems related to effective management of the railway sector. It also creates difficulties in assuring high punctuality. Disruptions in the operations flow, accidents, malfunctioning equipment, construction work, repair work and extreme weather conditions like snow and ice, floods, and landslides, to name just a few (Berger A, 2011). Initial delays of these types are called primary delays. They usually induce a whole cascade. The technical causes of delay of trains are diverse. Examples are non-functioning of wagon doors, faulty turnouts and contact wire failures (Granström, 2005). Another cause of unpunctuality is overweight trains leading to trains getting stuck on slopes. The physical interfaces between rolling stock and infrastructure are wheel-rail (makes the propulsion possible), pantograph-contact wire (collects the power needed for propulsion) and signaling (ensures safety), including ATC (Automatic Train Control). Also, the interface to road traffic, level crossings, might be places of interference with train traffic. When problems occur in the interfaces, it might be hard for the involved stakeholders to agree on a suitable action. Naohiko at al (2006) stated that train delay is caused by the passenger factor and later on extends to the train operation factor. Therefore, management of passenger flow offers a basic measure for controlling the increase in the train dwell time and thus becoming one of the effective measures to the problem of train delays (Hibino & Naohiko, 2010). Transfer connections are one of the major sources of secondary delays. Especially in the highly urbanized cities, where intensive train services are coordinated in an integrated periodic timetable offering good connections between any pair of stations with (cross-platform) transfer opportunities between main lines when direct connections are not available. These transfer times are crucial as the connecting train may wait or the connection might be cancelled. One would expect that if a train waits for transferring passengers of a late feeder train it would depart as soon as these passengers get on the train. However, they found that the mean transfer times from late feeder trains exceed the scheduled transfer time. Several explanations are possible, such as conflicting train movements (route settings) or headway constraints.

3. DATA ANALYSIS

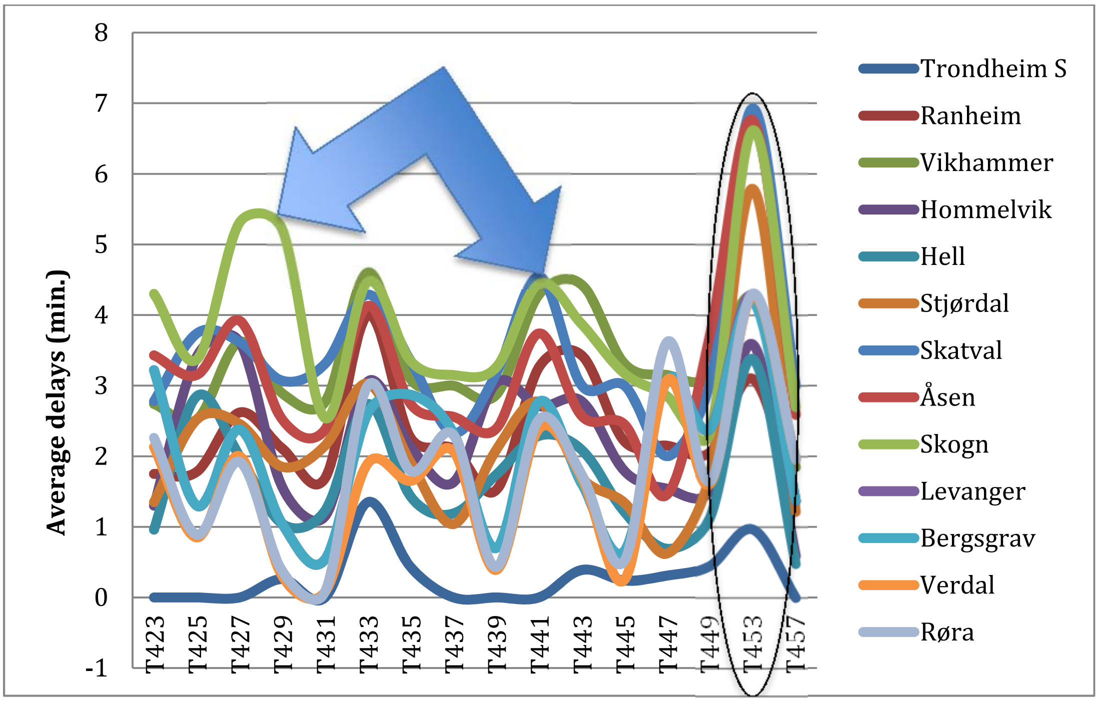
Punctuality reflects only the over all performance of train operations, to get a more comprehensive impression of the quality of train services, it is necessary to know other statistics of train delays, at least the mean and standard deviation. One should make clear which unpunctuality is described. It might be the punctuality of the passengers, the part of the journey travelled by train, or one of the trains in the journey etc. In the case of measuring the punctuality of passengers, the punctuality of the passenger's whole journey, for example train plus bus, should be considered. Even a small train arrival delays might result in the passenger missing the bus connection and hence the passenger will suffer from larger delays. The next section provides a discussion about the components involved in the overall process of data analysis to study the effects of delays along the way on delays to the final destination.

For the study, timetable analysis of local passenger trains between Trondheim and Steinkjer section of Norwegian railway were chosen as case study. However, the research method can be applied analogously to any other railway station. Delay data of 35 trains collected from 14 stations during August 2011 was obtained from Jernbaneverket. The number of observations for some trains was relatively small as these trains travelled only few days during the month. These trains were specifically assigned for school; therefore they usually start being used after August 15. The analysis was decomposed into three parts; including train operation (train delay) analysis, network analysis and timetable analysis. First the average delays for all the trains were computed at each station to analyze the distribution of individual train delays along the way. Then in the network analysis, delays at individual stations were studied in order to identify the conflicting routes and nodes in the network. In train operation or delays investigation, the analyses were often restricted to a single railway line or section of the network. However, a change in one part of the network can influence other parts of the network. This influence can even be far away from where the original change was made. These influences were denoted as network effects and are supposed to dependent on the given infrastructure as well as timetable and can result in longer travel times for trains and passengers. The timetable analysis comprises time-distance graphs between the stations, in order to describe the role of time attributes such as weeks, days or parts of the day on the effect of delays along the way to the final destination. Finally the socio-economic impact of delays on the bottleneck stations for the worst performances was analyzed. Jernbaneverket's punctuality threshold of 4 minutes was used throughout the analysis and discussion. Detailed timetable information and main train data are listed in appendix.

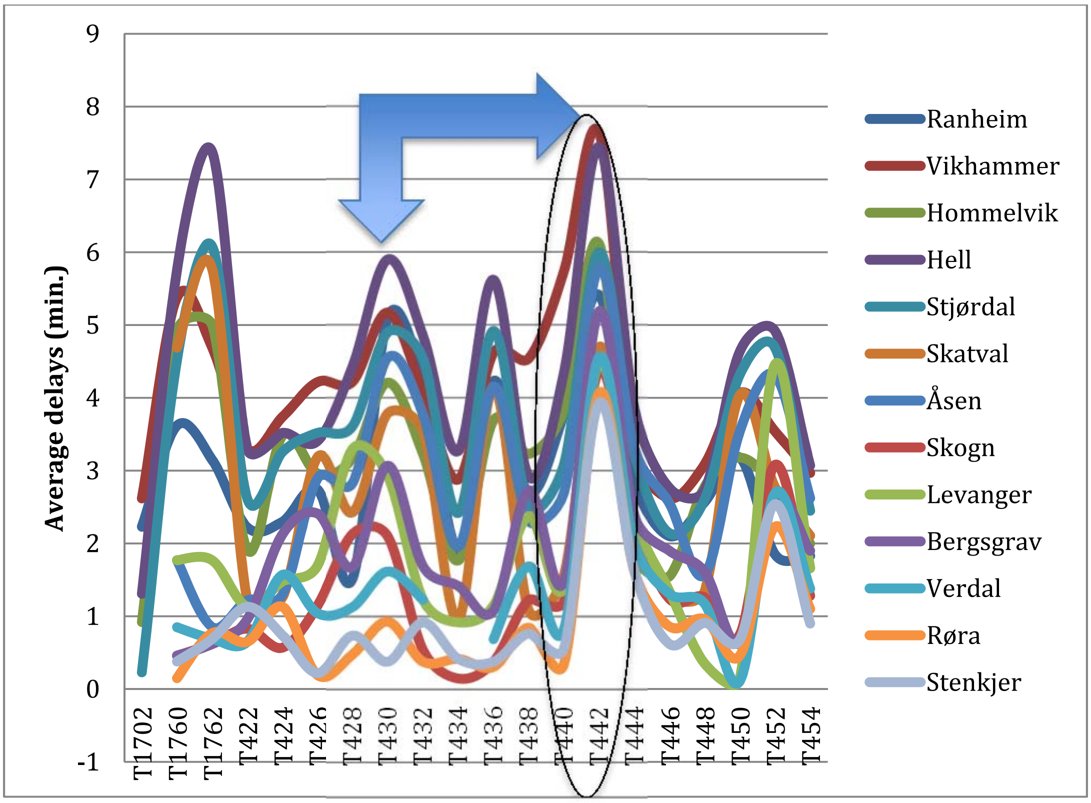
3.1 Train delay (operation) analysis

Departure Delays

Despite the time supplements added in the process of timetabling, the variation in actual train departure times is inevitable due to many circumstances such as arrival delays and fluctuations in alighting and boarding time. Moreover, a departure may be delayed by waiting for a feeder train to secure a connection and by conflicting train. Figures 4 and 5 show the average departure delays of all local passenger trains between Trondheim and Steinkjer during the observation period. Most of the trains traveling from Trondheim to Steinkjer have average departure delays less than 4 minutes with the exceptions of trains during the rush hours (indicated by the arrows) and 453. The largest average departure delay corresponds to train 453, which is almost 7 minutes. From this category, the average departure delays of trains 431 are relatively smaller and range between 0 and 3.5 minutes. Looking at the fraction of stations where departure delays did not exceed 4 minutes, train 453 has the worst performance (i. e. only from 31 % of the stations or from 4 of the 13 stations the train departed within the threshold). The fraction for the other trains ranges between 62% and 100%. In the case of the other category of trains, traveling from Steinkjer to Trondheim, the worst performance was observed from train 442. This train has departed from all stations after 4 minutes of the scheduled time. For the other trains in this category the share of stations where the trains were punctual ranges between 54 % and 100%. Comparing the two categories of trains, trains from Trondheim have relatively better performance. This indicates that the influence of delays along the way to the final destination is definitely affected by the train route. Trains from Steinkjer experience relatively large delays closer to the destination station; therefore relatively large residual delays will remain at the final destination.

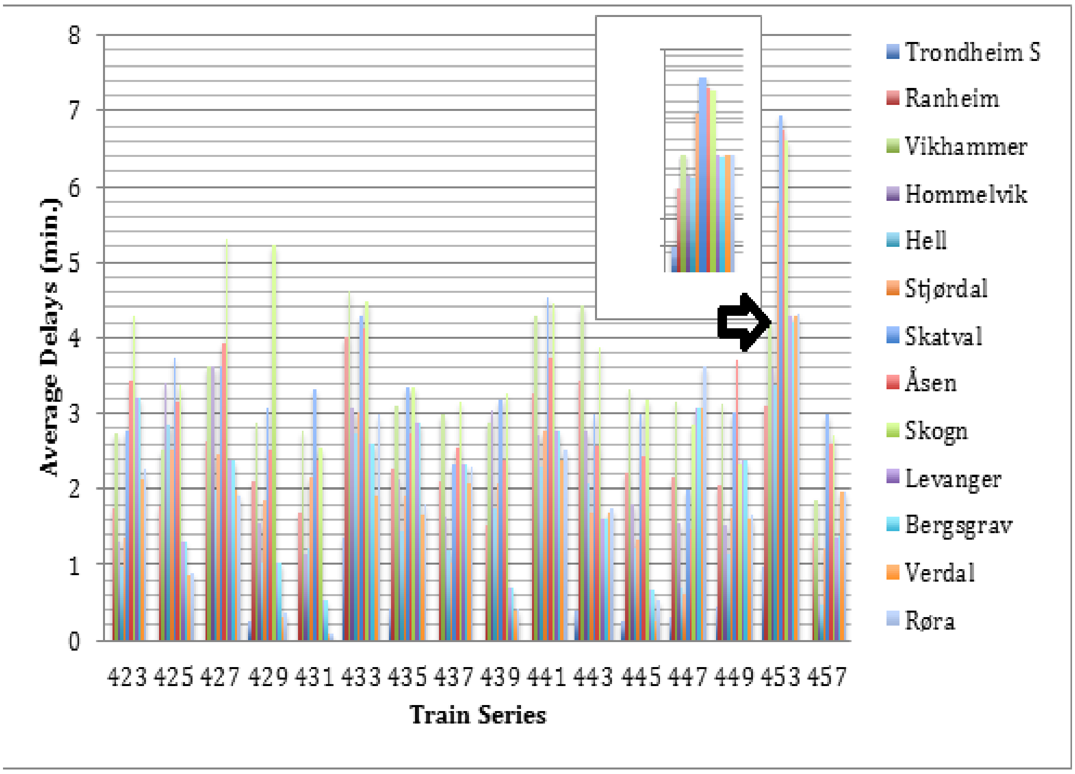


a) Train from Trondheim to Steinkjer

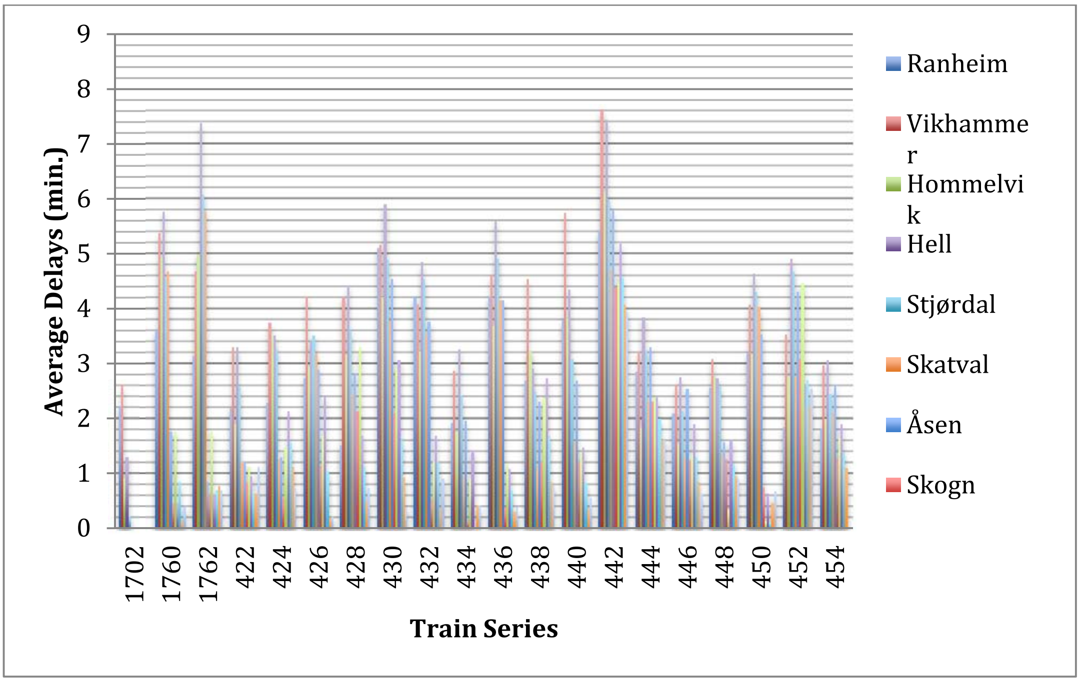


b) Train from Steinkjer to Trondheim

Figure 4 Average departure delays of train series at the different stations



a)Trains from Tronezidheim to Steinkjer



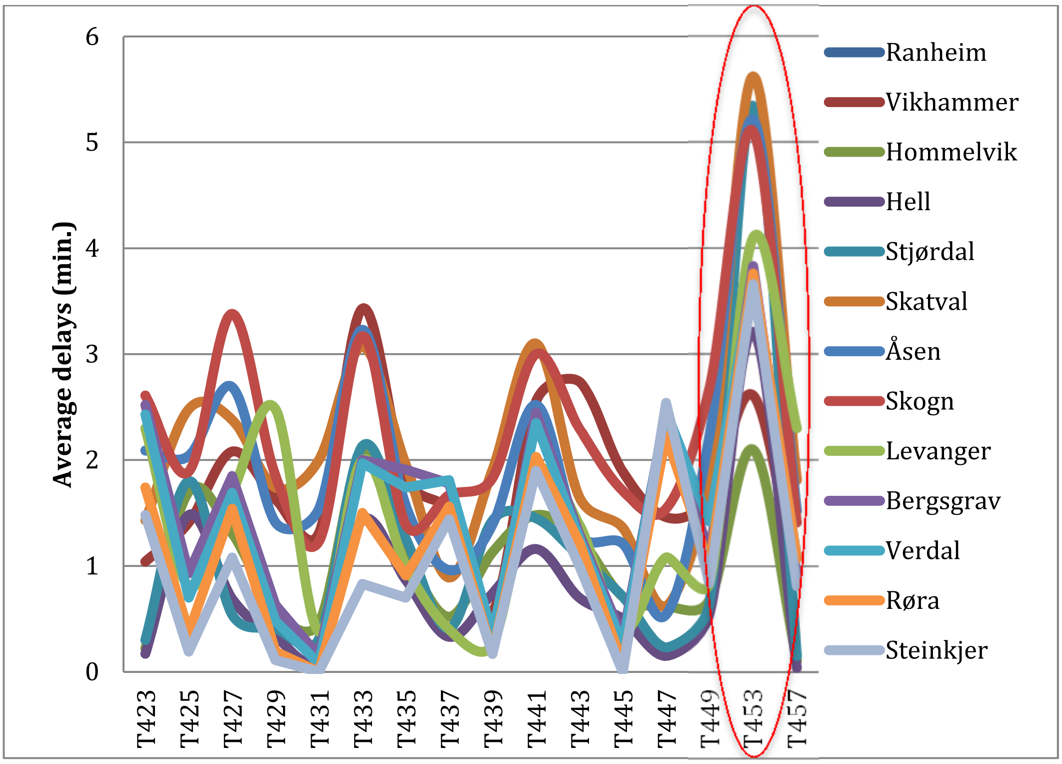
b) Trains from Steinkjer to Trondheim

Figure 5 Average departure delay histograms

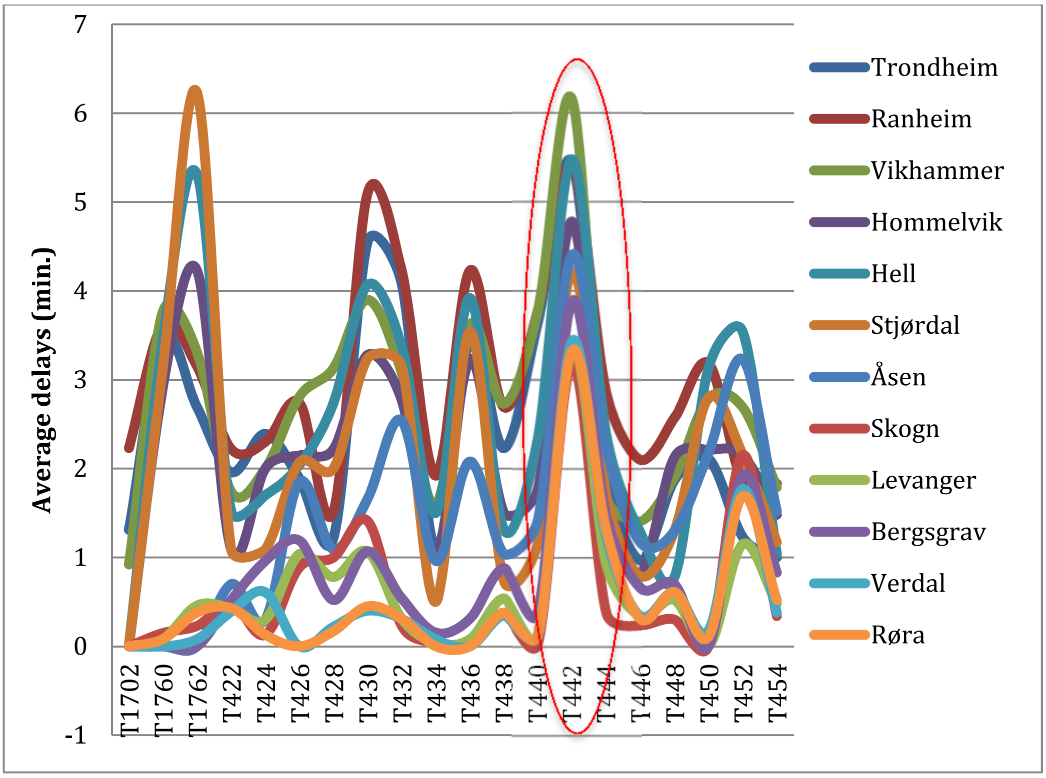
Arrival Delay

It is assumed that the late departure at the preceding station, too large running time, or route conflicts between trains will usually result in arrival delays. For an individual passenger the reliability is a measure of his or her own experience of delays. For the evaluation of railway systems, more aggregate and objective measures are necessary besides the delays of individual trains; this also includes the number of cancelled trains and the number of realized connections between trains. Additionally, the number of passengers on a train and the number of passengers for certain connections are necessary to determine the average arrival delay. And last but not least, the perception of passengers is a subjective issue, which needs additional attention. Even though these issues are not the scope of this thesis they raised during the discussion. For all trains the arrival times at stations have been obtained from the data. The resulting arrival delays are computed as the difference between the actual arrival times and the scheduled arrival times according to the published passenger train timetable. Hence, positive arrival delays correspond to late arrivals and negative values to early arrivals, as experienced by the passengers.

Figures 6 and 7 display a summary of the average values of the arrival delays for each train at the different stations. The average values for most trains from Trondheim are less than 4 minutes for each case, this indicates that the scheduled timetable has been designed reasonably well with out resulting in large structural delays, but there exist big variations of train operations.



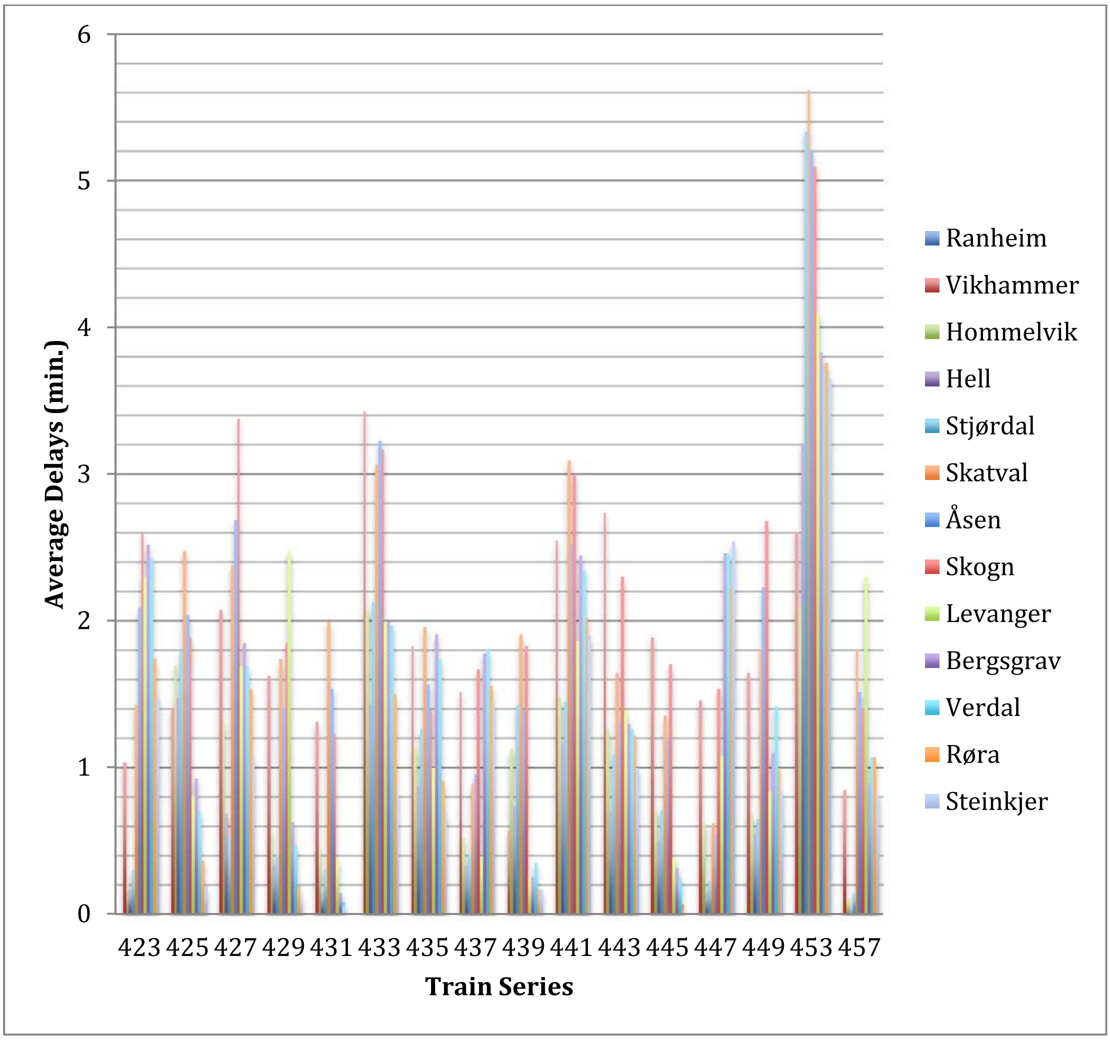
a) Train from Trondheim to Steinkjer



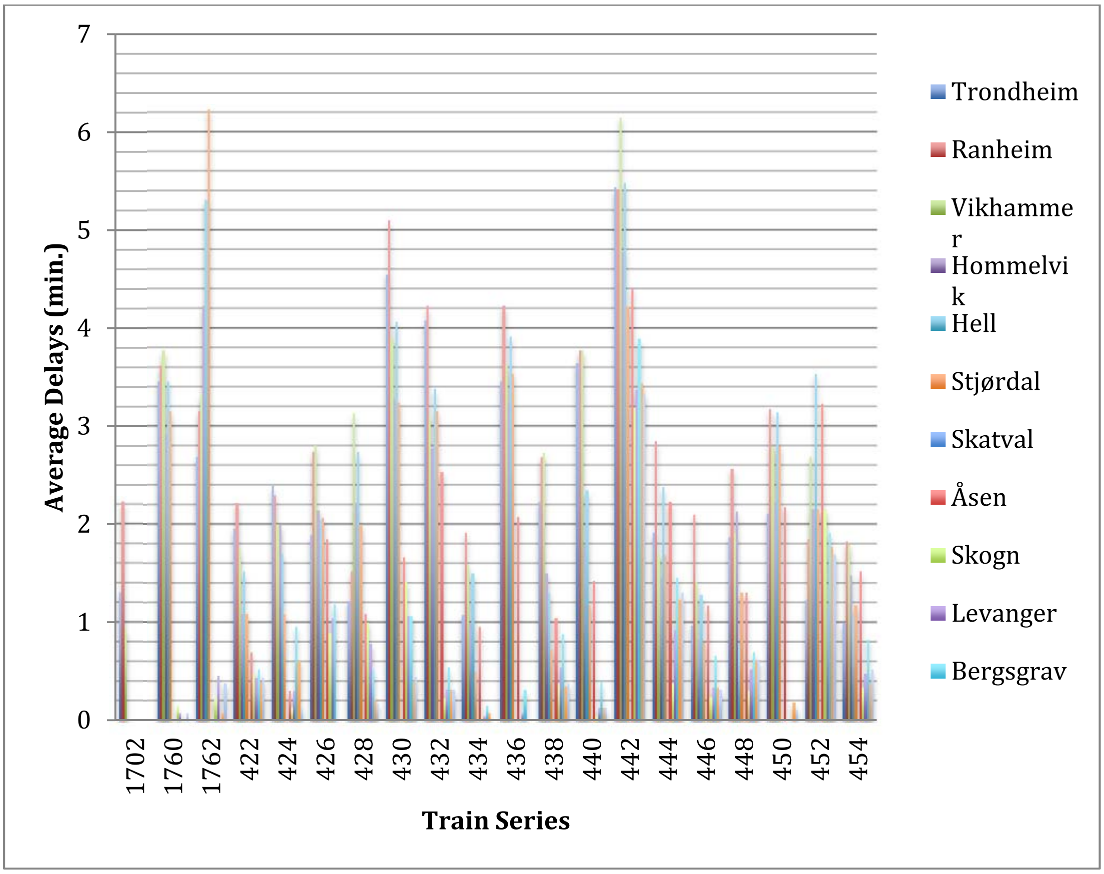
b) Train from Steinkjer to Trondheim

Figure 6 Average arrival delays of train series at the different stations

Few exceptional large arrival delays have been observed that deviated relatively from the bulk of the data as it can be seen from Figure 6a. The result coincides with that of the departure delays, the general view is that train 453 performed worse than other trains travelling from Trondheim to Steinkjer. The average arrival delay for this particular train varies between 0 and 6 minutes. It has arrived within the threshold only at 58% of the stations. From this category, train number 431 has a considerably smaller mean arrival delay ranging basically from around 0 to 3.5 minutes. This train arrived within the threshold at all the stations. As it is illustrated in Figure 6b the performance of trains from Steinkjer is worse than those from Trondheim. The worst performer from this category is train 442; it was not punctual at most of the stations including the final destination. All other trains arrive within 4 minutes after the scheduled arrival time at 88% to 100% of the stations. For the other category of trains, the worst performer was train number 442. Only at 42% of the stations (5 of 12), it has arrived within 4 minutes after the schedule; furthermore it was not punctual at the final distinction.



a)Trains from Trondheim to Steinkjer



b) Trains from Steinkjer to Trondheim

Figure 7 Average arrival delay histograms

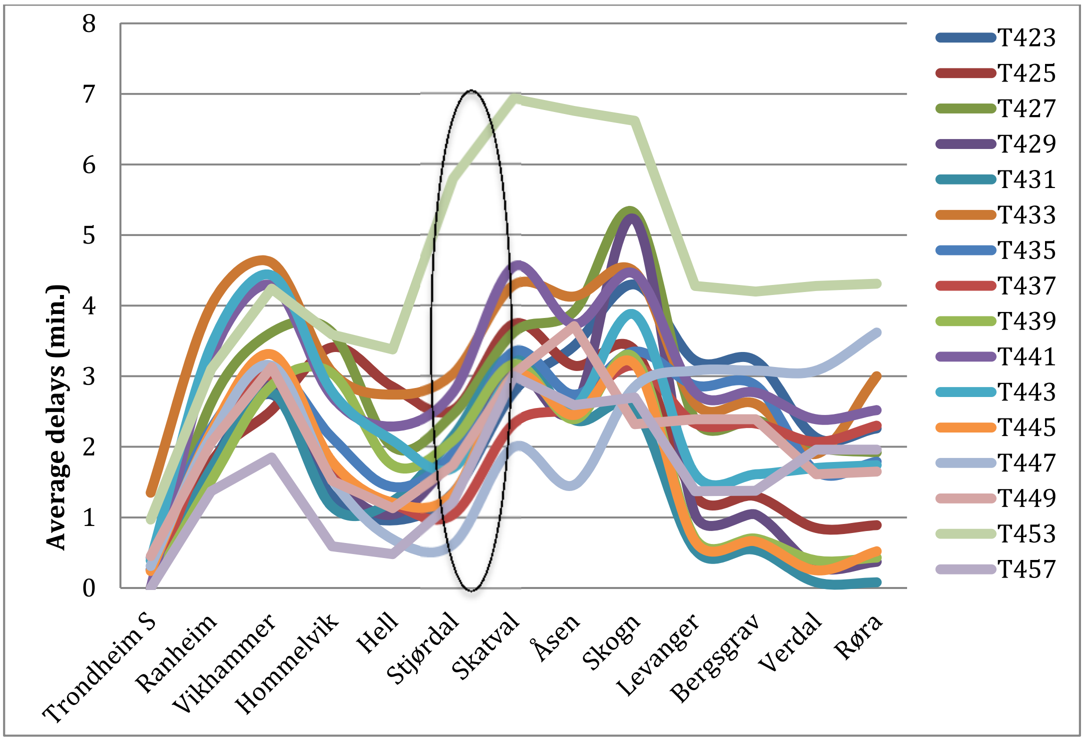
Traditionally, punctuality of the railroad system has been measured as delays of trains arriving within a certain threshold. These measurements do not take the passengers/customers experiences of the punctuality into account. In the railway the traffic control priority is "based on delivering the timetable passenger delay to be minimized. Once a passenger has decided to use the train to travel from Trondheim to Steinkjer, the railway system should provide the advertised service, which means delivering passengers at their destinations on time. There are two important aspects here; the first is the arrival time at the destination station compared to the scheduled time of arrival. The second aspect that has to be considered is the success or failure of a passenger connection or arrival at intermediate destinations. The lateness of arrival at the connecting station, school or work some place along the way, contributes to the cost function and also a passenger may reasonably feel stress if making all these looks doubtful. From the analysis, train 453 arrived within the threshold only at 7 of the 12 stations. But yet it has arrived within 4 minutes at the final destination. Even though the fractions are less in case of other trains the same is true. Such delays are not reported as poor performances because of the fact that in most cases arrival delays at destination are considered important. Although the contribution of such delays along the way to the punctuality at the final destination is reactively low, they will have a great impact on the passengers, as there is a high probability that the passengers will miss their next train or bus.

3.2 Network analysis

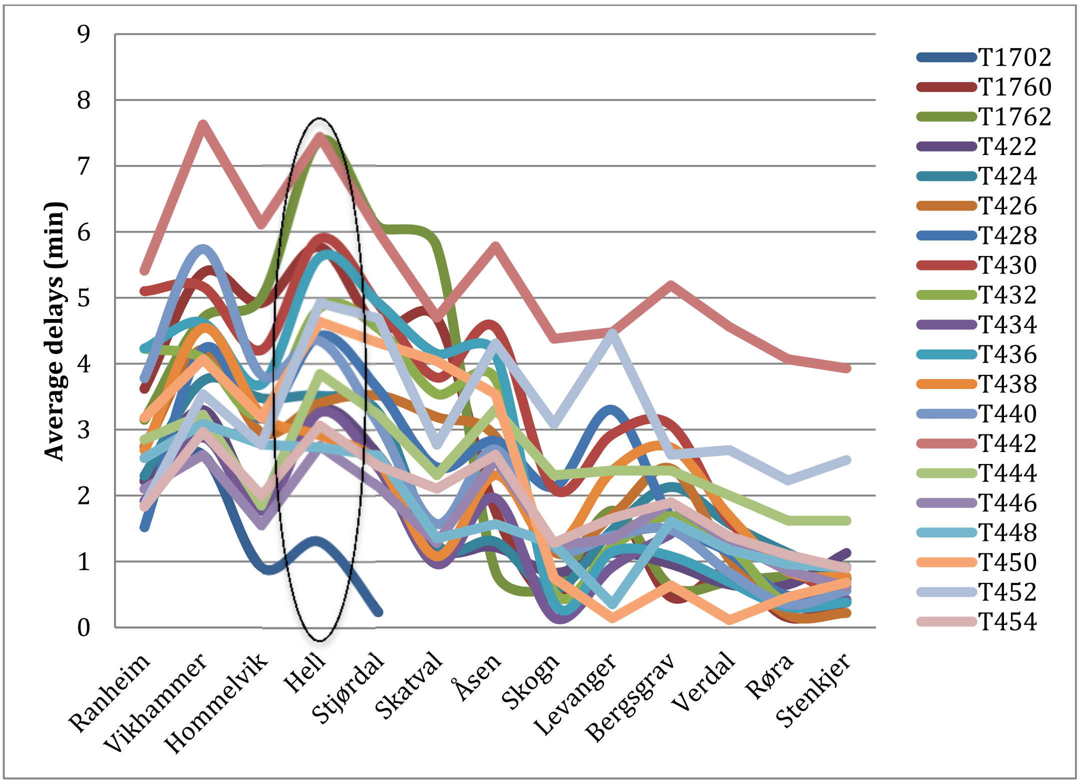
Trains cannot cross/overtake each other everywhere in the network. The network effects are expected to occur because train routes are normally long and the railway system has a high degree of interdependencies. Train traffic has to deal with a large amount of network dependencies. Some of these dependencies are caused by the railway timetable and logistics, such as passenger rolling stock circulations, alighting and boarding. Other dependencies relate to the shared railway infrastructure, such as following trains on open tracks, conflicting routes at station layouts between in and outbound trains. Trains may have to wait for trains with a conflicting inbound or outbound route before the route from the platform to the open track becomes available.

It has been studied that only 5% of the Norwegian network consists of double tracks and all double tracks are located close to Oslo. All long distance, regional and freight trains mainly run on single tracks including the local passenger trains between Trondheim and Steinkjer. In such tracks various types of perturbations to the timetable occur during operations. A potential conflict is when two or more trains claim the same available block section simultaneously, and a decision on the train ordering has to be taken. In that case the movement authority is given to only one of the trains involved at a time. In case of short headway distances, the other trains are forced to decrease their speed or even completely stop on the open track or within the interlocking area. The conflict resolution may therefore cause some train delays. A set of trains cause a deadlock when each train in the set claims a block section ahead which is not available and cannot be made available, due the occupation by another train in the set.

This situation can be seen from the result of the analysis; Figure 8 illustrates the distribution of average departure delays at the different stations. From the illustration it is visible that each train has its own delay distribution, but relatively larger deviation in delays was observed at Stjørdal for all the trains from Trondheim. The large deviations of actual running times from the scheduled ones at this station are the results of random disturbances. According to the informant respective trains from both directions will meet at this station; therefore, trains from Trondheim have to wait and/or slow till the trains from Steinkjer leave the route for them. A train may depart to a single-track route only if all opposite trains have left the open track. In addition to this a train is ready-to-depart if it has arrived and the minimum dwell time has been respected to guarantee alighting and boarding of passengers; if the train has a transfer connection with a feeder train then it also has to wait for the arrival of this feeder train plus a minimum transfer time to allow transferring passengers to board the train. In addition to the conflicting train movements, late arrival, prolonged dwell time due to boarding/alighting passengers or logistic reasons are possibly the major causes of the large departure delay at Stjørdal. For the other category of trains, from Steinkjer to Trondheim, relatively large deviations were observed at Hell, right after they have passed Stjørdal. Even as compared to trains from Trondheim the contribution of delays along the way to the final destination is larger. Hell is located at a distance 2 minute from the airport; therefore, passengers alighting and boarding cause the large deviation at this station.



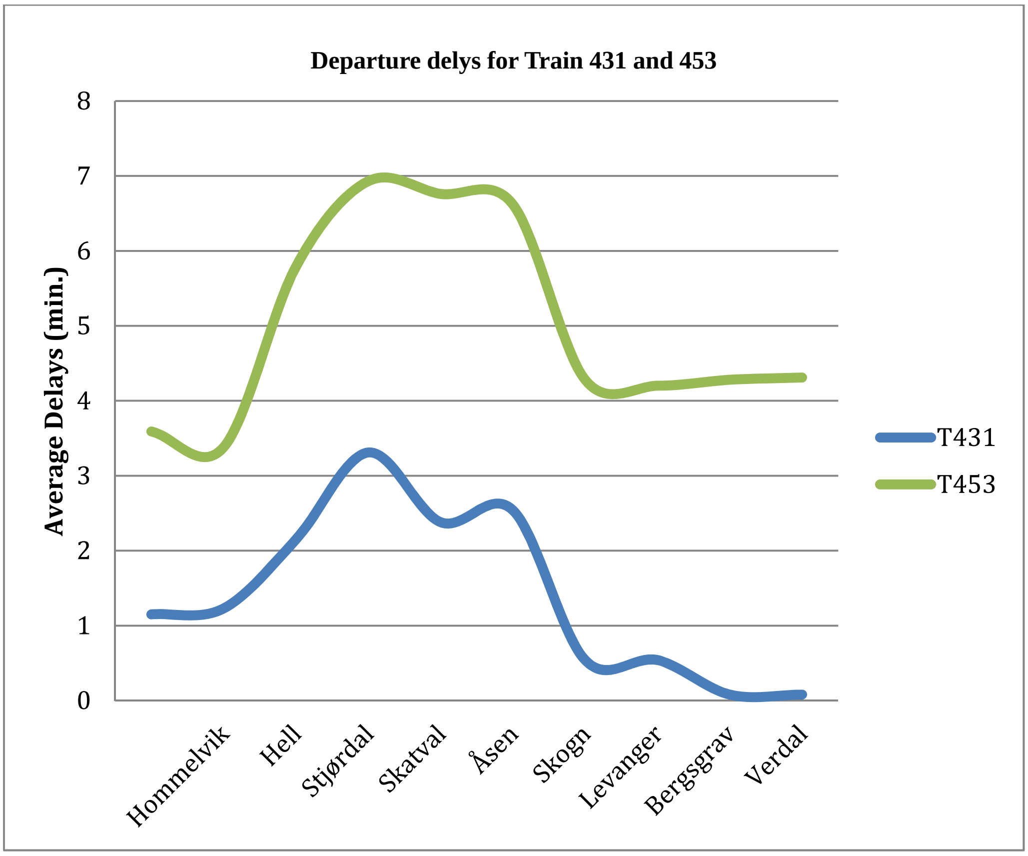
a)From Trondheim to Steinkjer



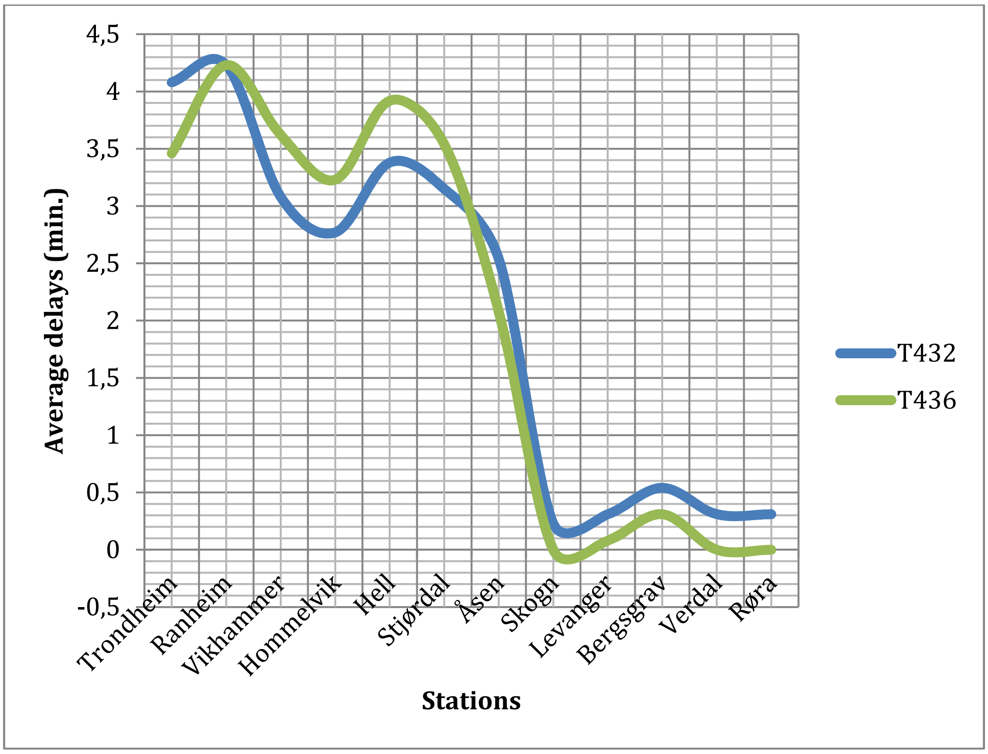
b)From Steinkjer to Trondheim

Figure 8 Departure delay distributions

Departure delays are generally non-negative since passenger trains are not allowed to depart from the station earlier than scheduled departure time. Owing to this fact delays are expected to follow an exponential distribution, which is a train departs after the scheduled departure time with a random delay whose probability decreases as time elapses. In order to study this behavior the departure delays for selected trains are illustrated in Figure 9, there is a random behavior of departure delays along the line. The behavior of the delays also fluctuates significantly over the stations. For the trains from Trondheim there is some evidence that the arrival delay follows a kind of normal distribution with respect to the station, although the empirical distributions have some peak points at highly utilized stations. Where as the distributions seems to coincide with the standard hypothesis of exponential distribution of train delays in case of trains from Steinkjer. The proven fit of most of the delay times to normal and exponential distributions respectively will allow an improved design of the timetable and more reliable forecasts of train delays during operations based on historic empirical data. The distribution of departure delays can also be used to predict the distribution of outbound track release times and the distribution of train arrival times at the following station. The dwell time of an early train is larger than scheduled since an early departure is not allowed. On the other hand, late trains may have a dwell time smaller than scheduled owing to the fact that the composite process of alighting, boarding, and departing takes less time than scheduled.

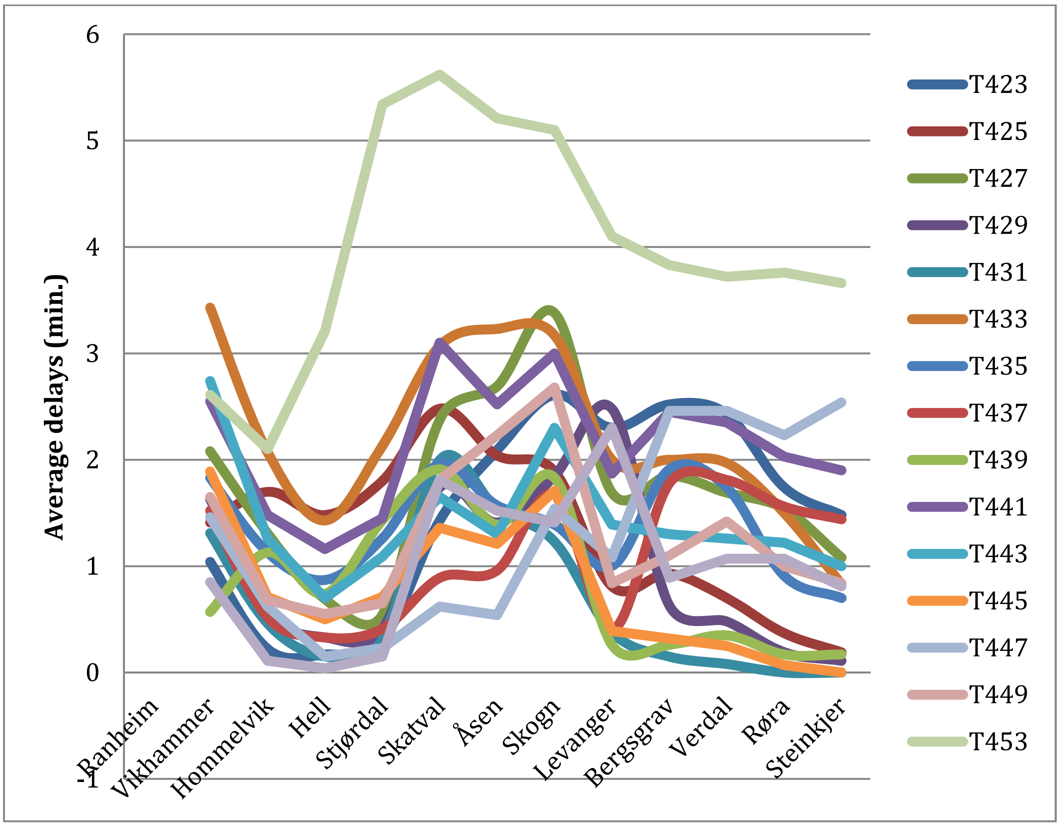


a) Trains from Trondheim

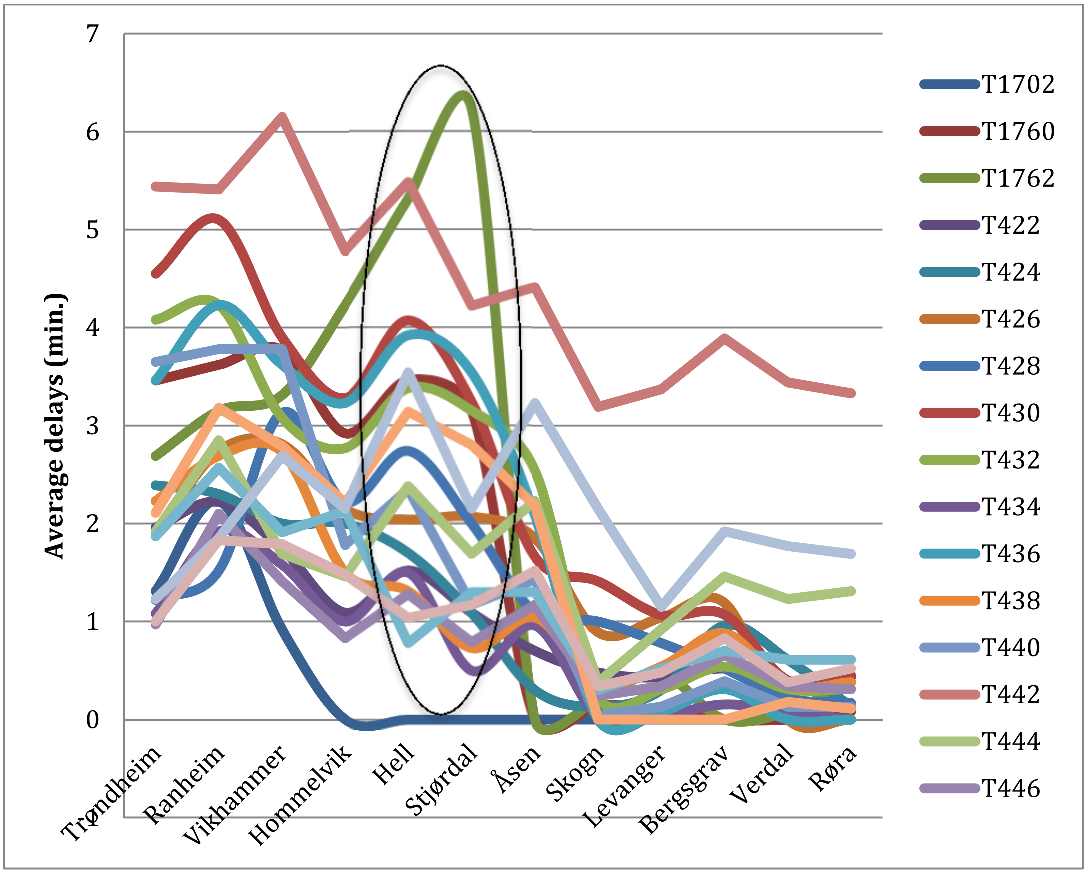


b) Train from Steinkjer

Figure 9 Departure delay distributions for selected trains



a)From Trondheim to Steinkjer
b)

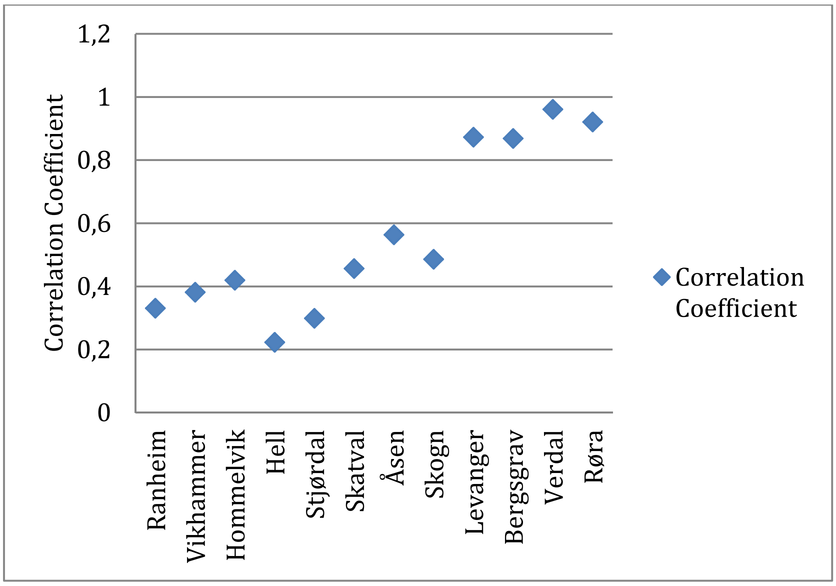


b) From Steinkjer to Trondheim

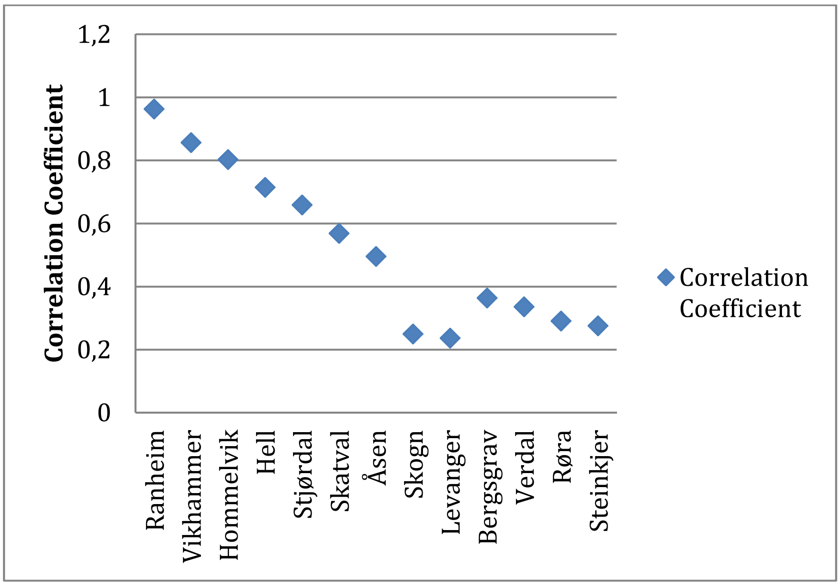
Figure 10 Average arrival delay distributions

Similarly the arrival delay distributions are illustrated in Figure 10, these can affect passengers because not all the wanted correspondences to/from other connections can be kept due to too many interdependencies or network effects. Furthermore, the network effects can result in reduced capacity as some trains or train routes can make it impossible to operate other planned/desired trains or train routes.

Further analysis on the effect of delays at individual stations on the delays at the final destination was carried out using the correlation analysis between the average delays at the intermediate stations and that of destination station. As it can be seen from Figure 11 there is a strong correlation between the delays at the last three or four stations and that of the destination station. This shows that part of the large delays due to random disturbances along the way seems recovered at subsequent stations. Incase of the trains from Trondheim almost all has a departure delay less than the punctuality threshold before the destination station, which was not possible in case of trains from Steinkjer. This is possibly because of the fact that large deviations from the scheduled time in case of trains from Trondheim has occurred early on, as a result they have sufficient slot for recovery. On the other had for the trains from Steinkjer the large deviations has occurred at stations closer to the destination station which makes it difficult to recovery from a large amount of delays.



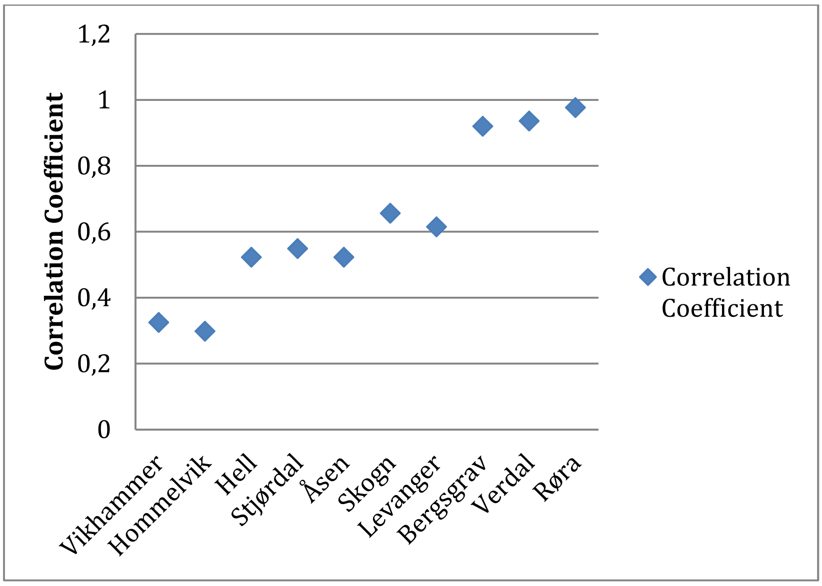
a) Trains from Trondheim to Steinkjer



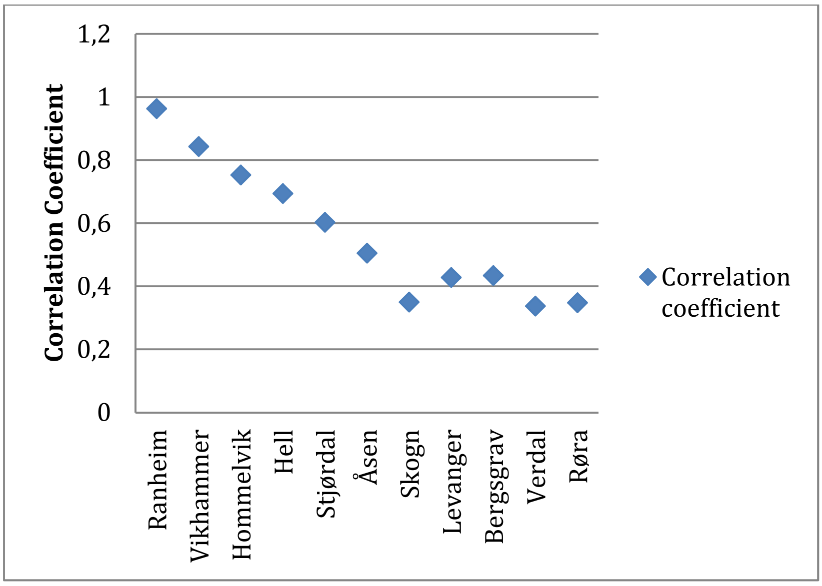
b) Trains from Steinkjer to Trondheim

Figure 11 The correlation coefficients between average arrival delays at intermediate stations and destination station

Similarly as it can be seen from Figure 12 there is a strong correlation between the arrival delays at the last three stations and that of the destination station. Part of the large delays due to random disturbances along the way seems recovered at subsequent stations. It seems that incase of the trains from Trondheim almost all have arrived punctual at destination, which was not possible in case of trains from Steinkjer. From this one can say that railway performance between the initial and destination station is hampered by frequent delays at intermediate stations. These delays influence the delay at the final destination. The influence of delays along the way to the final destination varies with the distance of highly utilized stations from the final destination. Depending on the available slot between these two stations part of the delay are recovered. From this one can say that delay along the way closer to the final destination point have a high probability of being carried out till the final destination.



a)For trains from Trondheim to Steinkjer



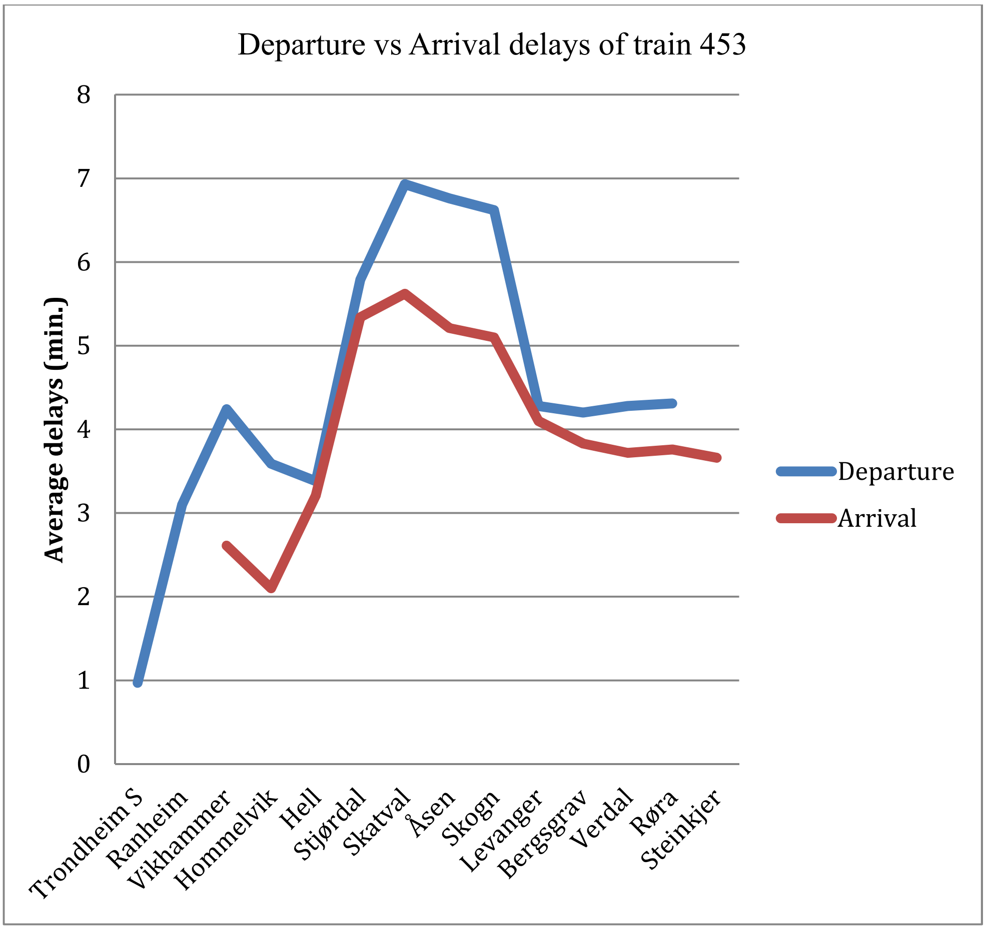
c)For trains fro Steinkjer to Trondheim

Figure 12 The correlation coefficients between average arrival delays at intermediate stations and destination station

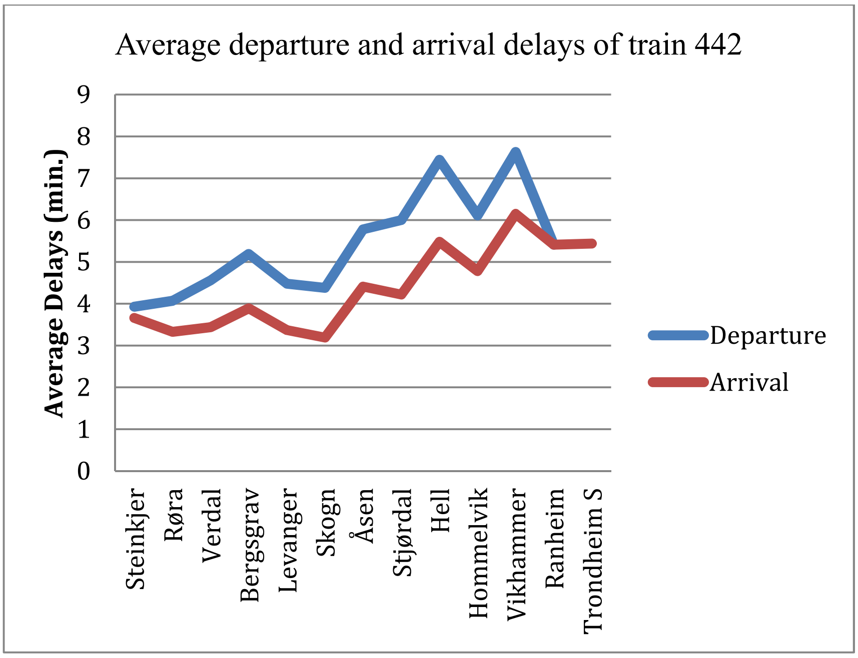
The usual method of punctuality estimation is neglecting the big share of smaller delays in scheduled services. The hinder of approaching trains at railway junctions and in stations due to conflicting movement from the opposite direction of the route definitely has an impact on the delay at the final destination. The delay at the destination is the result of disturbances at some point along the way carried on through out intermediate stations.

Comparison of arrival and departure delays

Figure 13 shows the comparison of the arrival and departure delays. The average arrival and departure delays of the worse performing trains have been analyzed during august 2011. From the illustration it is visible that mean delay consequently performance at departure is generally worse than at arrival. Possible causes of this performance drop are too tight dwell times or transfer times, and conflicting train movements. A small arrival delay thus results in an increased departure delay, whereas for a large arrival delay the (departure) delay is reduced although the delay will never settle to zero. The latter behavior corresponds to the practice that trains with large arrival delays are given priority and stop only for a minimum necessary time.



a)From Trondheim to Steinkjer



b) From Steinkjer to Trondheim

Figure 13 Arrival and departure delays of trains 453 and 442

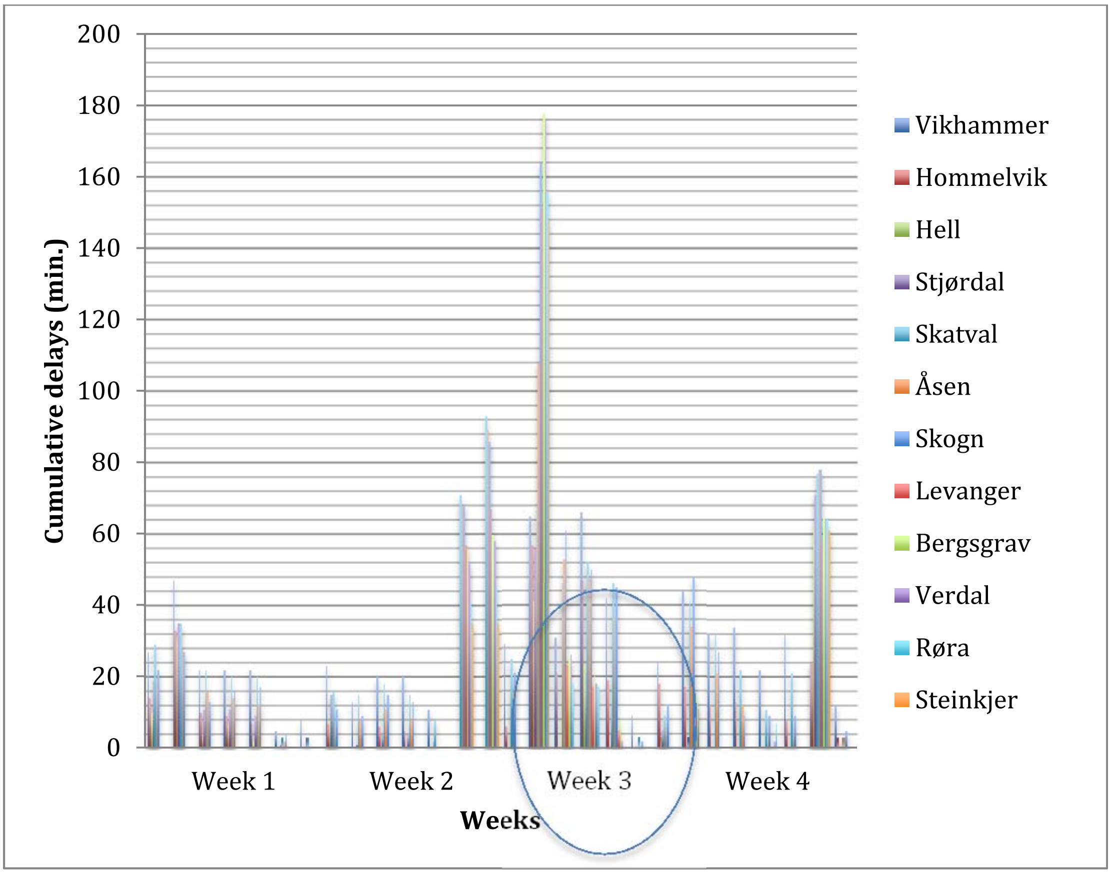
Generally, from the above results it can be said that delays along the way has definitely an influence on the delay at the final destination. But the effect is random, depending on the traffic conditions on route the extent of unrecoverable delays will vary. A single line cannot be considered as a fully independent part of the whole network due to crossing and overlapping lines, which can be true bottlenecks. As a consequence, the capacity of a line cannot be defined without considering what happens on the interfering lines. The variations of time headway and train speed at heavily occupied junctions may lead to knock-on delays and queuing of trains before network bottlenecks. On the routes approaching to level crossings close to main stations, a significant drop of performance is observed. Route conflicts and the resulting knock-on delays often occur at busy stations and junctions, which may affect the delays of train arrivals and departures at stations and the use of network capacity. In fact, the blocking times are stochastic and not deterministic, and so are the resulting delays. Most of the trains arrived generally punctual, the mean arrival and departure delays at the final destination are thus less than 4 minutes for each train line and the trains are therefore not delayed according to the Norwegian railway's norm. However, looking at the fraction of intermediate station where trains are less than 4 minutes late, one can also see a significant punctuality drop for some of the trains.

3.3. Timetable analysis

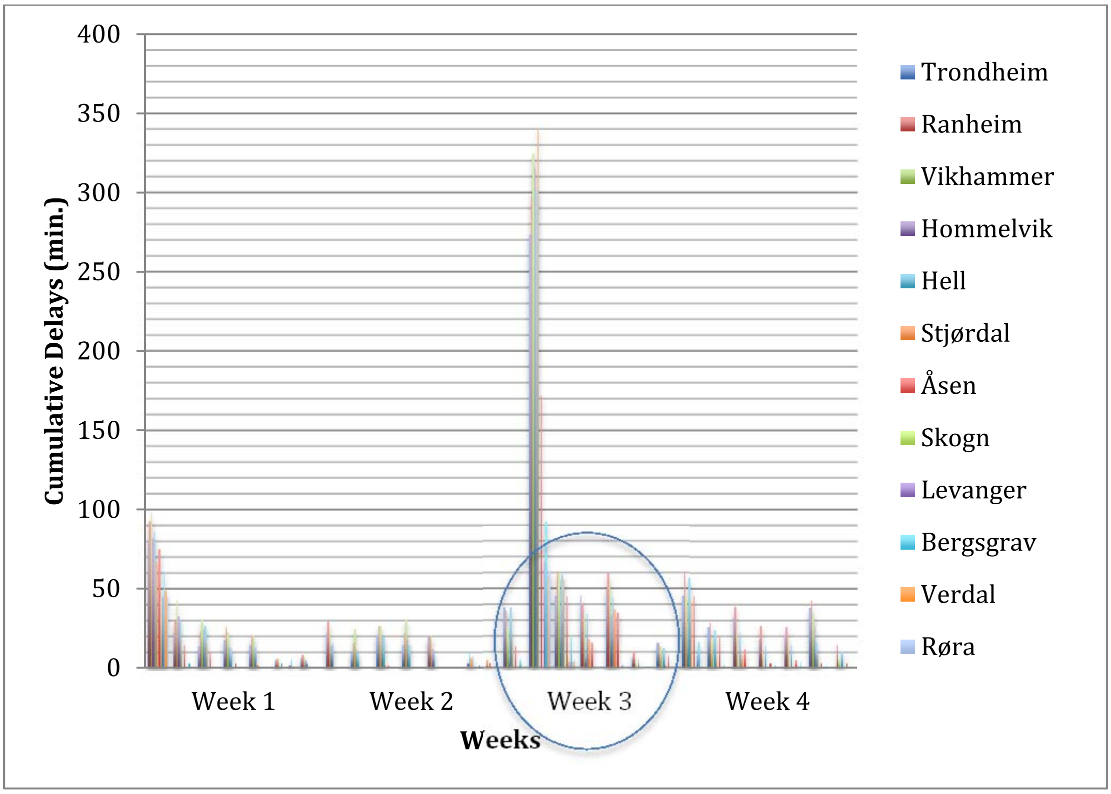
Though the time element might seem to be a fairly one-dimensional variable, there are a few classifications to be considered. Time Elements for Consideration: Time of day, day of week, week of the month, month of the year and year-by-year trend. Due to the limitations of both this study and the data from Jernbaneverket, this analysis only accounts for a few of these time elements. However, in an expanded study, they could all be incorporated more extensively. For travel time, the Travel Time Data Collection Handbook suggests three time elements for consideration: month, day of week, and time of day. The delays of trains may vary among different weeks of a month, days of a week and between peak and off-peak periods in a day because of differences in traffic flows and an uneven distribution of passengers alighting and boarding. The impact of week, type and period of day on the delays of trains is studied for local passenger trains from Trondheim to Steinkjer in the following section.

Train delays by weeks

The arrival delays in minutes are added up for each train number, day of week and weeks of the month during the study period. Figure 14 corresponds to the cumulative arrival delays at the different stations during different days of the weeks. When results are compared between weeks, it is quite visible that there is substantial variation in the cumulative delays. The values at all the stations are relatively higher during the third week of the month. One possible reason for this is the start of school after August 15, but still compared with the 4th week the values are quite large.



a) Trains from Trondheim to Steinkjer

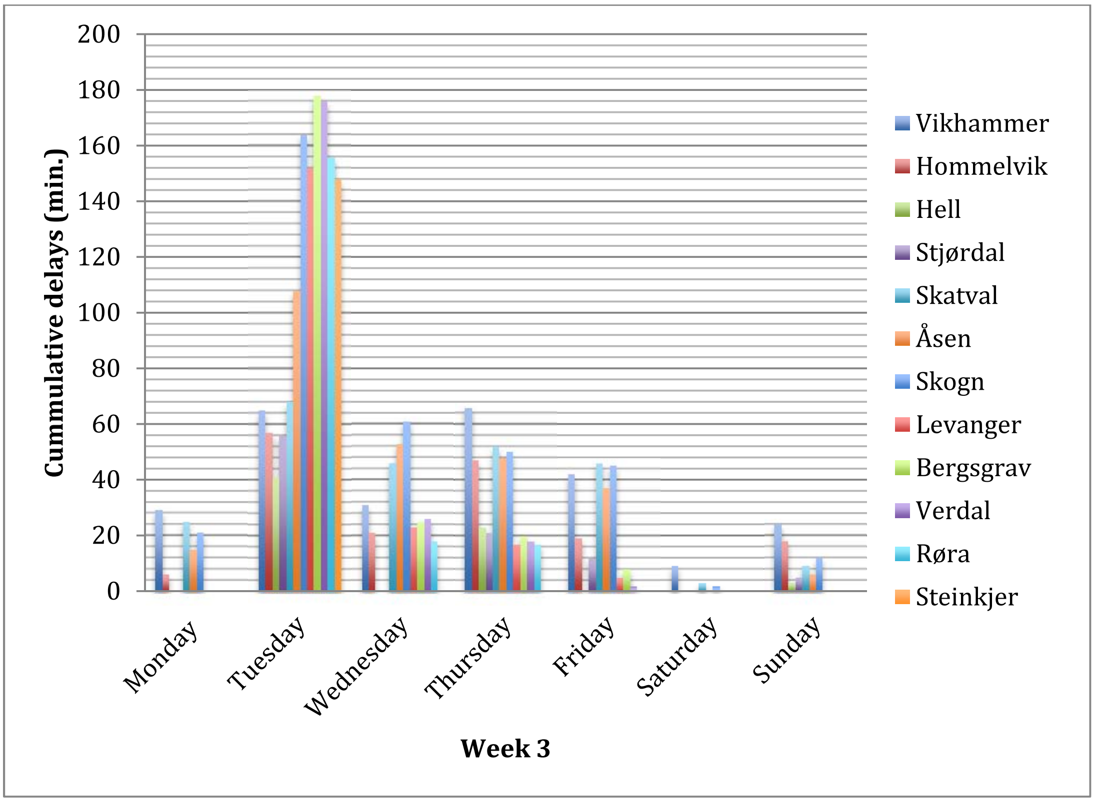


b) Trains from Steinkjer to Trondheim

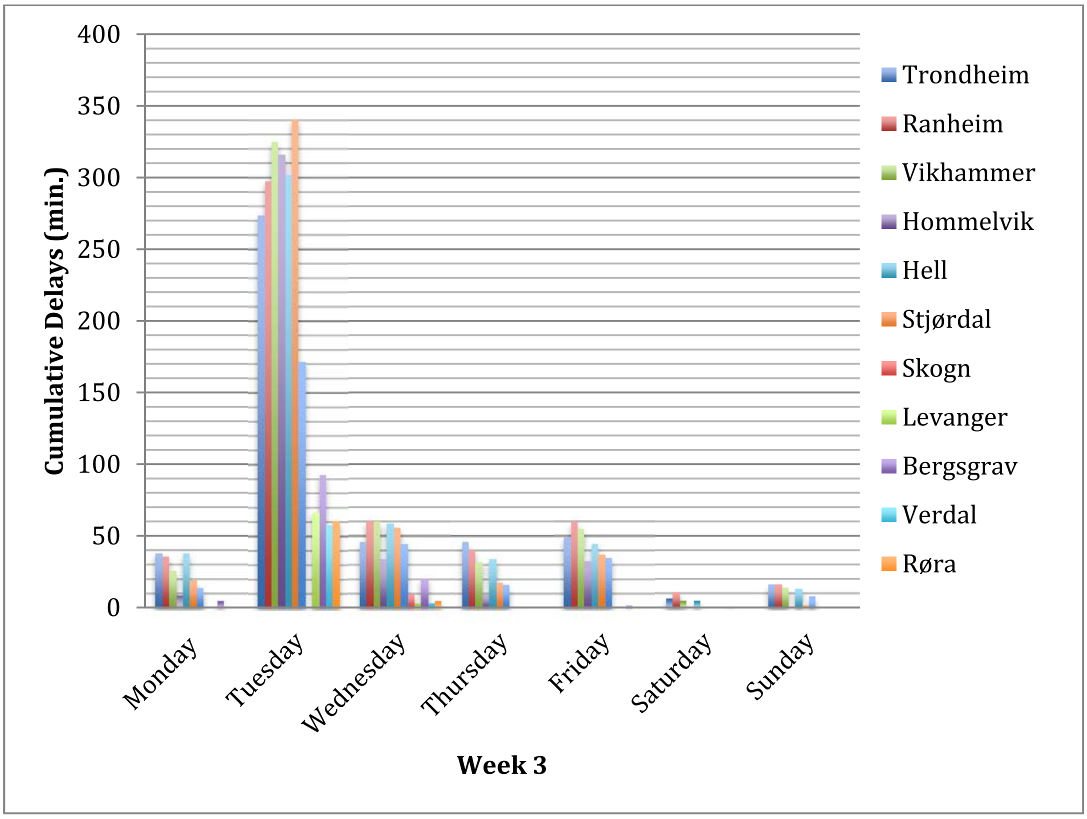
Figure 14 Cumulative arrival delays at stations during the different weeks

Train delay by day

The arrival delays of the trains are separated by type of the day: Saturday, Sunday, weekdays (Monday, Tuesday, Wednesday, Thursday and Friday) for week 3. There is a significant difference between the average arrivals delays of the train series at the different stations, the average arrival delays on weekends differs from that on weekdays significantly. Many factors are identified in the literature to increase delays. When two trains in opposite directions of travel encounter one another on the same track, resulting in one train stopping for another. As a result, train headway, which is the distance maintained between trains running in the same direction is reduced. This reduction in headway can have a cascading effect of propagating delay as trains may be slowed to maintain minimum headway distances. The delay-volume relationship is also dependent on the traffic mix of a particular track segment. Lai et al. (2010) discussed the relationship between train volume and delay with respect to single-track segments. Apart from volume, train type heterogeneity also impacts delay (Dingler et al., 2009). Different train types have significantly different operating characteristics, generally represented via train velocity, reflecting the varying business needs of each cargo type. Generally with all things being equal, heterogeneous traffic results in greater delays as compared to homogenous traffic. Homogenous networks generally eliminate passes which helps in reducing the network variability. These are the possible reasons for the relatively larger cumulative delays during working days.



a) Trains from Trondheim to Steinkjer



b) Trains from Steinkjer to Trondheim

Figure 15 Cumulative arrival delays at stations during different days of week 3

Figure 15 shows the cumulative arrival delays at the stations on the different days of week 3. The analysis of delays for different days of the week also shows visible differences between working days (Monday–Friday) and weekends (Saturday, Sunday). The effects of variations in traffic and operations that occur in reality can be clearly seen from the result. On a single-track line the effect of additional trains on delay is not linear. Instead the relationship between train volume and delay is different with each train type and train mix having its own particular functional relationship. The informant described that particularly on Tuesday during the 3rd week of the month a freight train will also share the line with passenger trains. Owing to this fact the delays are typically maximum for all trains on this particular day during week 3. This particular train had a significant impact on the amount of delay created by their interaction. This result coincides with Dingler et al (2009) work, in which they found that the percentage of different train types affects delay, with the greatest delay occurring when heterogeneity is highest. This was expected because there are more opportunities for conflicts. This requires estimating the travel times and delays in the network, and assigning trains to routes based on the expected running times in order to balance the railroad traffic and to reject or defer the train(s) that would overload the network and result in unacceptable delays in traveling through the network.

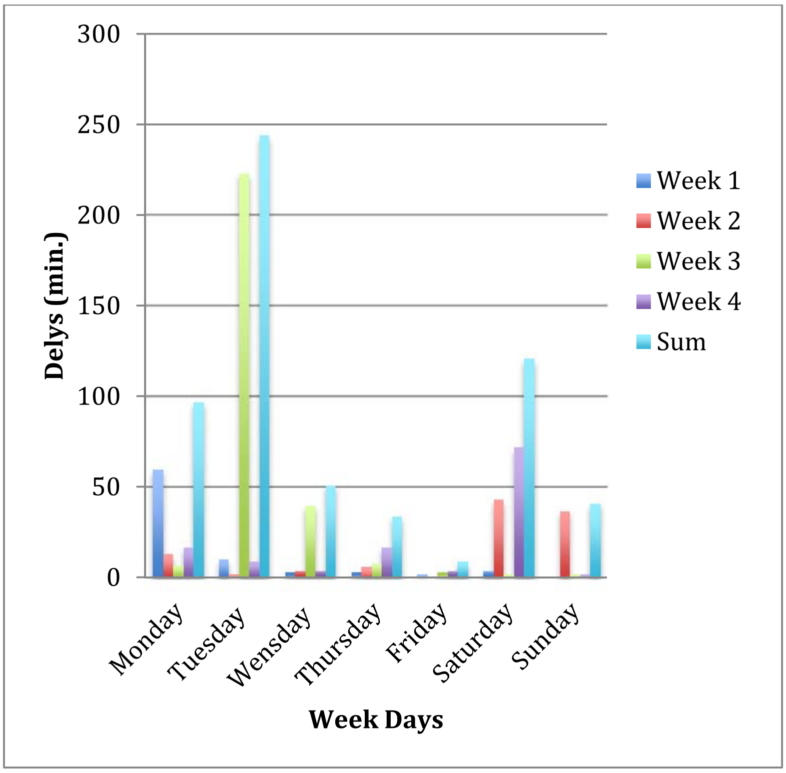


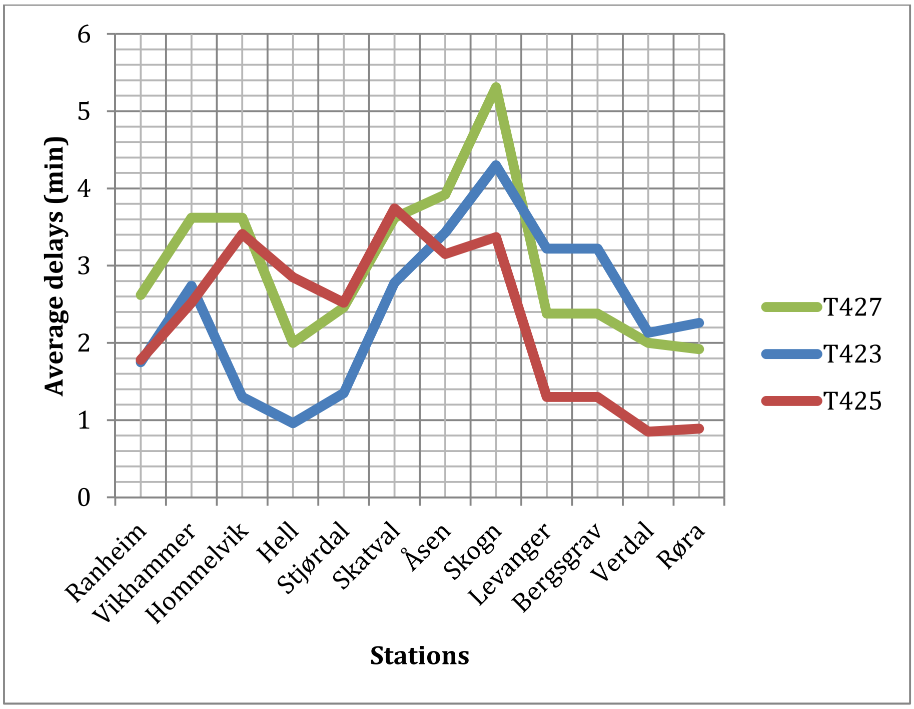
Figure 16 Cumulative arrival delays at Steinkjer

Considering the cumulative arrival delays at the final destinations during the entire study period (august, 2011), Figure 16, It can be seen that there is a difference between arrival delays at the destination station, assuming the same shape of the delay distribution by the type and period of the day. This assumption can be partially justified by the fact that a train series runs on the same route and has the same stopping patterns in different days of the week during different periods of the day. The analysis has shown that there was significantly high cumulative delay during the third week specifically on Tuesdays.

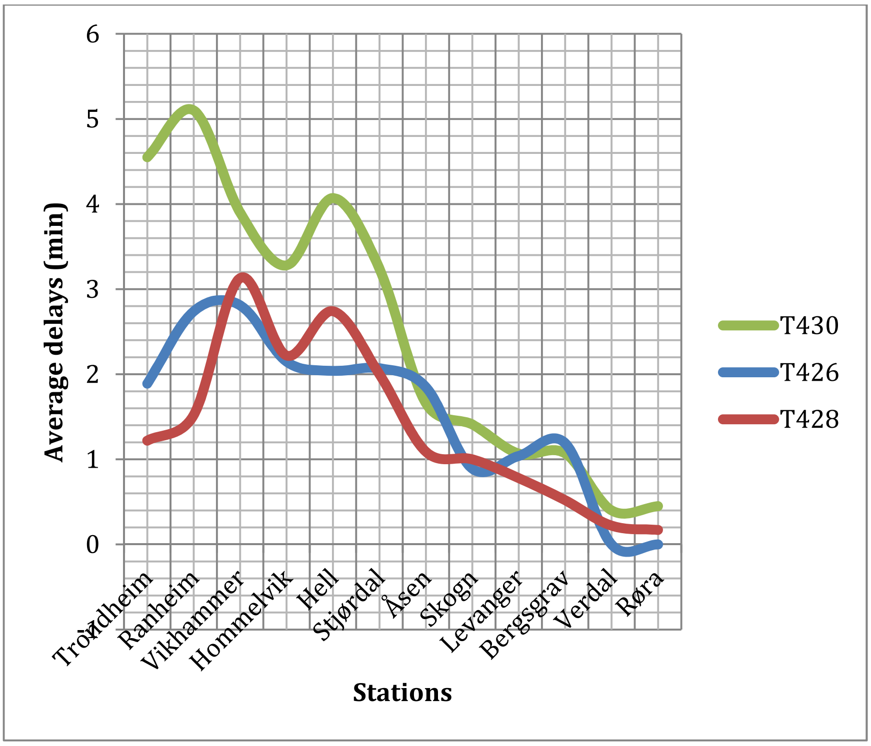
Delays by the time of the day

As with road traffic, many people use the local trains to commute to work in a morning and back home at the end of the working day. During these times trains will have a shorter time interval between them, have more carriages and trains as well as platforms will be more congested. These peak-hour effects should be detrimental to the service; as commuters complain about how unreliable the train service is and yet the train companies fulfill their tight quotas. Such analysis will help in determining whether the commuters are correct and the trains are performing badly at important times.

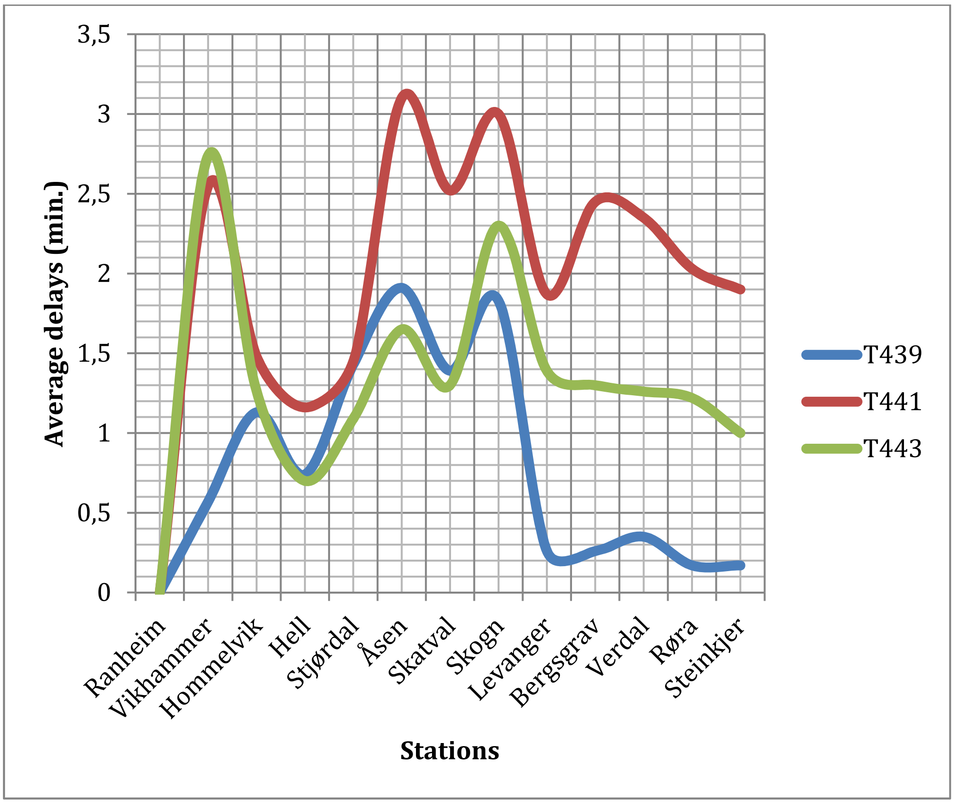
The scheduled train paths as well as the track occupancy times are represented in a time-distance diagram and indicate clearly the remaining buffer times. It is visible that relatively more number of trains are assigned during rush hours. Because of largely standardized working hours, there is a sharply peaked demand at times associated with the trip to and from work. Figure 17 shows the average delays of trains during the different parts of the day, for about four hours a day, between 7:00 am and 9:00 am and again between 4:00 pm and 6:00 pm, traffic congestion causes stress on commuters. However, this level of traffic demand drops drastically during other parts of the day.



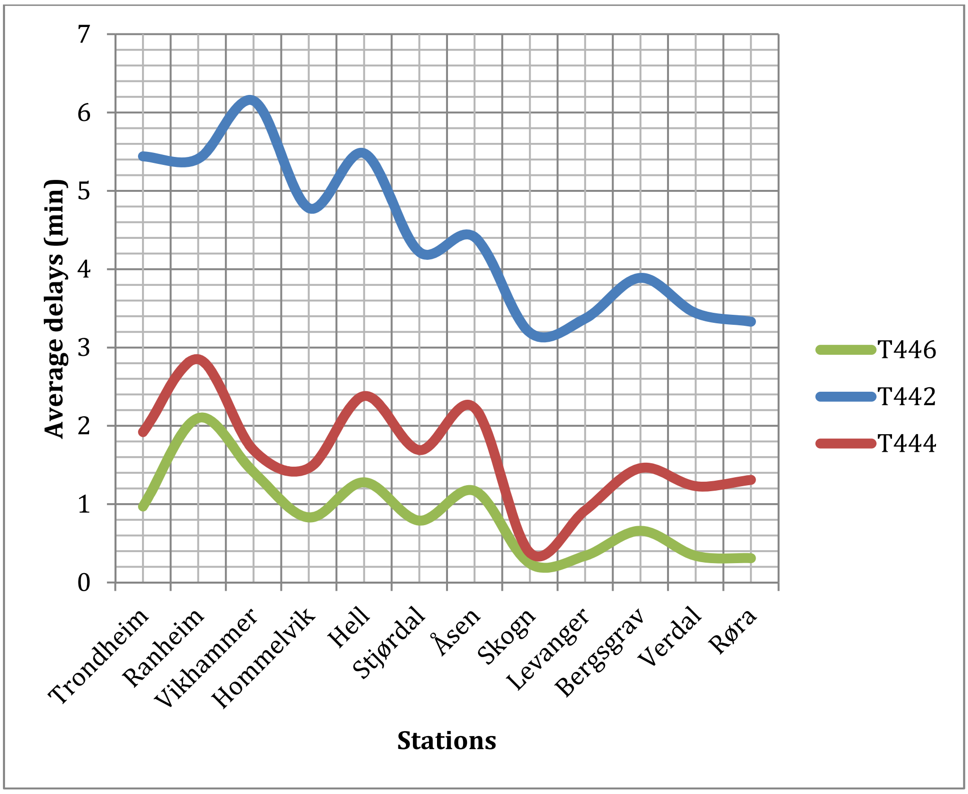
a) Morning peak hours for trains from Trondheim to Steinkjer



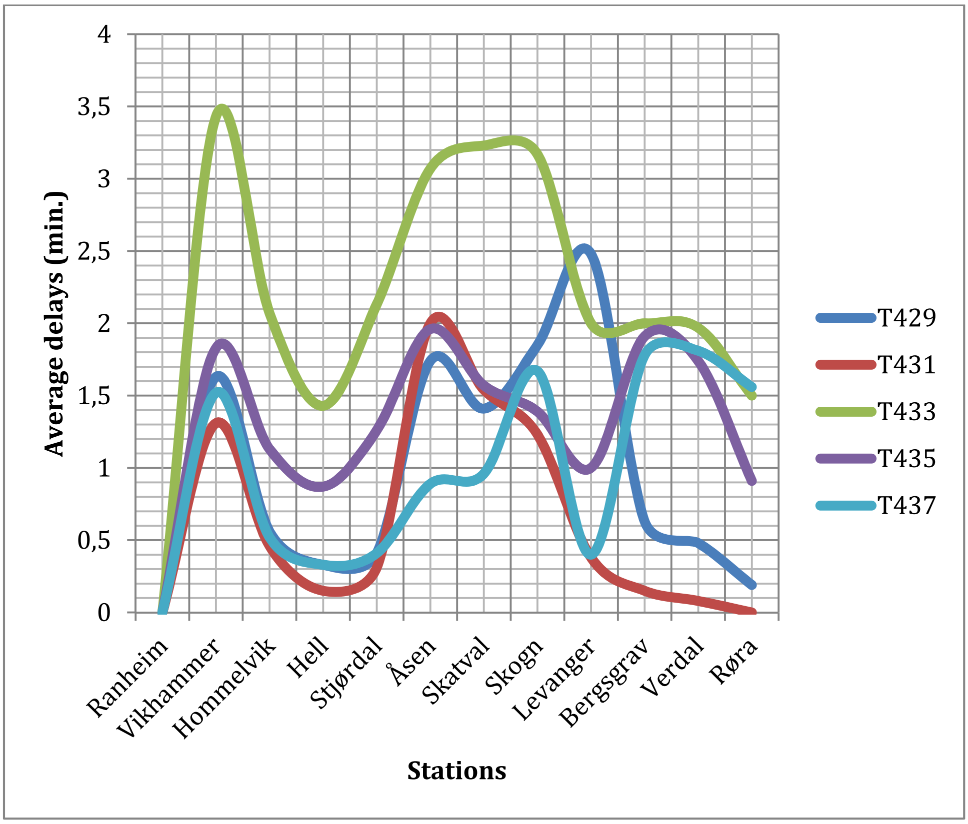
b) Morning peak hours for trains from Steinkjer to Trondheim



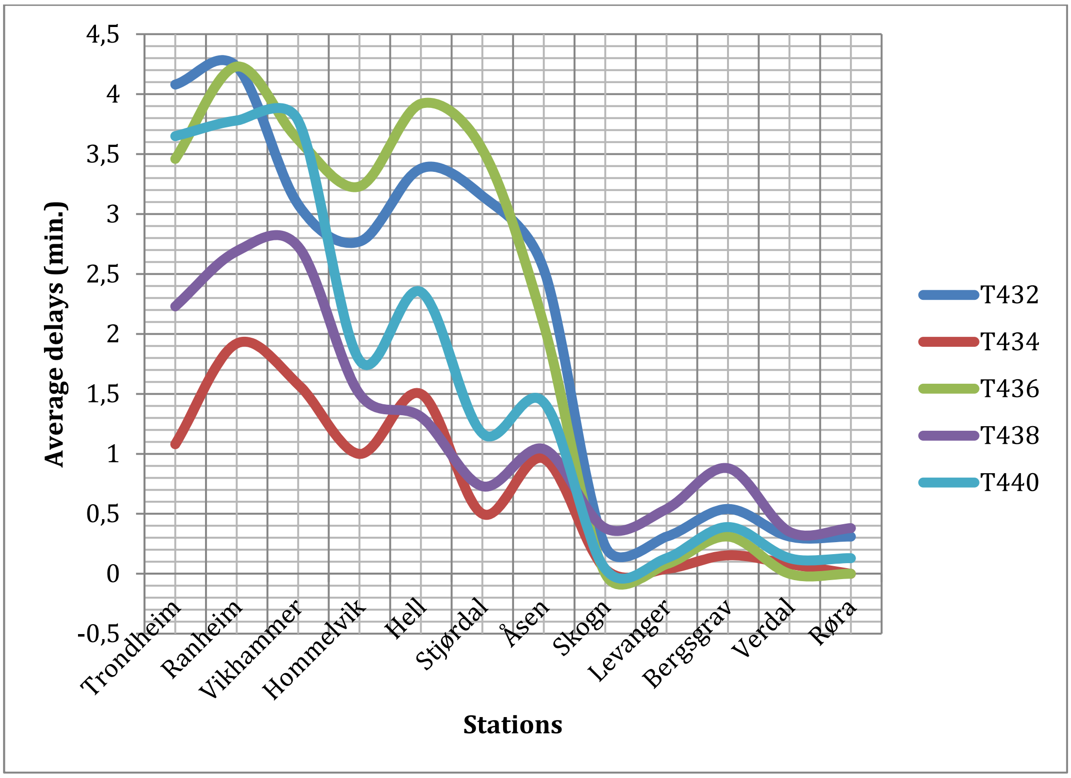
c) Afternoon peak hours for trains from Trondheim to Steinkjer



d) Afternoon peak hours for trains from Steinkjer to Trondheim



e) Off peak hours from train delays from Trondheim to Steinkjer



f) Off peak hours from train delays from Steinkjer to Trondheim

Figure 17 Average delays of trains during different parts of the day

During peak hours more passengers use the railway network, causing an increase in the amount of boarding and alighting passengers at stops, which may lead to longer minimal dwell times. This effect only becomes visible for trains with short scheduled stops, or for trains with an arrival delay such that the minimum dwell time can be measured. The number of trains running in the peak hours will also influence the statistics of arrival delays. This makes it difficult to draw statistical conclusions about the influence of peak hours. When delays during compared morning and evening peaks it seems that during evening peaks the delays are systematically more frequent than during morning peaks.

3.4 Socio-economic impact of delays

The cost of delay is a key issue when discussing different actions to improve punctuality. Delays affect a specific resource (track, train, station, team, etc.). In order to manage the socio-economic effect of these delays it is important to consider delays along the way, because of the fact that customers in these trains may be delayed at any point along the way, if the train arrived with delay in their stop station. Basically, there are two approaches of economic analysis of delays stated in literatures; namely, an operator approach and customer approach. An operator approach considers delayed trains and delay minutes, the cost for delays includes overtime payments and other expenses related to the personnel, fixed costs for keeping staffing and to handle the average delays; and lost business due to the punctuality history and reputation.

A customer approach deals with delayed customers and economic impacts. In order to help management and adopt more actual indicators, it is important to include travelers and economical points of view when dealing with punctuality. The economic consequences taken into account in this case are the compensation of customers, but this approach can easily be extended to other economic aspects. A better responsible and customer oriented management of train delays can be provided once data regarding the following three indicators are obtained: the spatial dimension (a train, a specific line, group of lines), the temporal dimension (a specific day, a month, a year) and the variable of interest (number of delayed customers, compensated euros). Indicators can be provided from several points of views: very synthetic such as monthly evolution, intermediate views such as consequence for a given incident or to a very detailed view: station stop for a specific train for a specific date. The interface helps to easily navigate between these points of views from very synthetic view to very detailed one. It can be quite difficult to have a detailed view of the delays along the way and their socio-economic impacts, because numerous data are involved and these data are quite complex to analyze under all their dimensions: time, space, economics, etc.

Even though the data set limits detailed analysis of economic aspects of delays, an attempt has been made to study the general socio-economic impacts of delays along the way based on some previous studies from Jernbaneverket and other authors. Several studies have been made on the value of travel time, and some of them also include value of delay time. In Table 3, a summary is made of some values of delay time for delays of passenger trains. Value of time (including delays, but usually focusing on travel-time savings) is a key element in cost-benefit analysis. This is illustrated by the project evaluation methodologies used by Jernbaneverket (Jernbaneverket, 2001). To determine the delay cost incurred by a single passenger at the bottleneck stations, arrival delays at that station is multiplied by a constant delay cost figure obtained from literature. A recent estimation of average total train delay cost was approximately 2.15 per passenger-minute for commuting travellers of distance less than 50 km. Therefore, for a single passenger of train 453 during the study period whose stop station was Stjørdal, the delay cost was found to be 34.45 NOK, which is almost twice that of a passenger whose stop is the final destination. AS illustrated in Table there the socio economic impact of delays along the way is worse than the final destination. The values given the table are only for the worse performing train at a bottleneck station.

Table 1 Estimates of values of delays for railway transportation (The estimates are made as the value per minute and passenger.

Source	**Type of travel**	**Value of delays** (NOK)	**Values for train 453** (NOK)		**Values for train 442** (NOK)	
			Stjørdal	**Steinkjer**	**Hell**	**Trondheim**
Jernbaneverket (2001)	Business travellers (<50 km),	5,95	34.45			
	(>50 km)	3,35		12.26	18.36	18.22
	Commuting travellers, (<50 km),	2,15	12.45			
	(>50 km)	1,13		4.14	6.19	6.15
	Other travellers, (<50 km),	1,35	7.82			
	(>50 km)	1,75		6.41	9.59	9.52

For passenger satisfaction, one intuitively has to weigh the arrival delays with respect to the number of arriving passengers. Still, official performance measures are usually based on the arrivals at certain large stations only, and they are not weighted for the number of passengers and stations along the way. Timetable optimization with respect to the passengers is in this case quite different from optimization with respect to the official performance measure.

4. CONCLUSIONS

The effect of delays along the way to the final destination is random, which is dependent on the traffic conditions along the line. Route conflicts or disturbance often occur at busy stations and junctions, which may affect the delays of train arrivals and departures at the stations and subsequently arrivals at the final destination. The analysis also revealed that a single line can not be considered as a fully independent part of the whole network due to crossing and overlapping lines, which can be true bottlenecks. On the routes approaching to highly utilized stations, in this case Stjørdal and Hell, a significant drop of performance was observed.

Trains from Trondheim have better performance at the final destination. This indicates that the influence of delays along the way to the final destination is definitely affected by the train line or route. Trains from Steinkjer start to experience relatively large delays closer to the final destination (i. e. at Hell which is close to Trondheim). As a result they will not get sufficient slot to recover fully from the relatively larger delays acquired at this station. It can be said that the influence is dependent on the distance of the large disturbances from the destination.

The worst performance subsequently higher influence to the final destination was seen from trains 453 and 442 from Trondheim and Steinkjer routes respectively. For these trains route conflicts, passenger alighting and boarding have resulted in larger deviation (up to 7 minutes) of actual running time from the schedule.

There was considerable variability associated with train delays during the different time attributes due to the variation in traffic conditions. However, the variability was more pronounced in the case of heterogeneity. Exaggerated cumulative delays were observed on Tuesday during the third week of the study period, because freight trains shared the network during this day. The percentage of different train types affected delay, with the greatest delay occurring when heterogeneity was highest. Conflicts, passenger alighting and boarding during morning and afternoon peak hours resulted in relatively larger delays at individual stations and subsequently final destination.

Delays at intermediate stations, which are not basically reported as poor performance according to Norwegian punctuality norm, have greater socio-economic impact. At highly utilized stations (Stjørdal) the values of delays were found to be twice the values at the final destination. The lateness of arrival at the connecting station, school or work some place along the way, contributes to the cost function and also a passenger may reasonably feel stressed if making all these looks doubtful. These facts indicate that the large number of smaller train delays has an important impact on the quality of service and regular more detailed investigation is worthwhile in order to increase the level of punctuality of the Norwegian Railways.

5. FUTURE SCOPE

Calculating delay severity is a significantly more complex process than a mere consideration of the number of trains involved and the aggregation of the time delayed. Delay assessment is a complex issue that merits further independent and protracted discussion, which is beyond the scope of this thesis. It should be pointed out that a punctuality measure for passenger trains should relate to passengers, not merely trains. Therefore, a better responsible and customer oriented management of train delays can be provided if a detailed passenger approach economic analysis is carried out based on the spatial dimension (a train, a specific line, group of lines), the temporal dimension (a specific day, a month, a year) and the variable of interest (number of delayed customers, compensated NOK). These Indicators can be provided from several points of views: very synthetic such as monthly evolution, intermediate views such as consequence for a given incident or to a very detailed view: station stop for a specific train for a specific date. Such analysis could be a potential area of research as a future scope.

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Appendix

A. Some of the departure delay statistics of train from Trondheim to Steinkjer

Train series	TRD	RAN	VIK	HEL	**STD**	SKT	Åsen	SKO	LEV	Røra
423	0	1.75	2.74	0.96	**1.35**	2.78	3.43	4.3	3.22	2.26
425	0	1.78	2.52	2.85	**2.52**	3.74	3.15	3.37	1.3	0.89
427	0	2.62	3.62	2	**2.46**	3.62	3.92	5.31	2.38	1.92
429	0.26	2.11	2.89	1.04	**1.85**	3.07	2.52	5.22	1.04	0.37
431	0	1.69	2.77	1.23	**2.15**	3.31	2.38	2.54	0.54	0.08
433	1.35	4	4.61	2.74	**3.03**	4.29	4.13	4.48	2.61	3
435	0.43	2.26	3.09	1.43	**1.91**	3.35	2.74	3.35	2.87	1.79
437	0	2.11	3	1.19	**1.04**	2.33	2.56	3.15	2.33	2.3
439	0	1.52	2.87	1.74	**2.09**	3.17	2.39	3.26	0.7	0.43
441	0	3.26	4.29	2.29	**2.77**	4.55	3.74	4.45	2.77	2.52
443	0.39	3.43	4.43	2.09	**1.7**	3	2.57	3.87	1.61	1.74
445	0.24	2.21	3.31	1.21	**1.34**	3	2.45	3.17	0.66	0.52
447	0.31	2.15	3.15	0.69	**0.62**	2	1.46	2.85	3.08	3.62
449	0.45	2.06	3.13	1.13	**1.74**	3.03	3.71	2.32	2.39	1.65
453	**0.97**	**3.1**	**4.24**	**3.38**	*5.79*	**6.93**	**6.76**	**6.62**	**4.28**	**4.31**
457	0	1.37	1.85	0.48	**1.22**	3	2.59	2.7	1.37	1.96

B. Some of the departure delay statistics for the trains from Steinkjer to Trondheim

Train series	**Average Departure Delays**									
	RAN	VIK	HOM	**Hell**	STD	Åsen	SKO	LEV	Røra	STN
1702	2.23	2.62	0.92	**1.31**	0.23					
1760	3.62	5.38	4.92	**5.77**	4.54	1.77	0.46	1.77	0.15	0.38
1762	3.15	4.69	5	**7.38**	6.08	0.85	0.62	1.77	0.77	0.69
422	2.22	3.3	1.91	**3.3**	2.61	1.22	0.83	1.13	0.65	1.13
424	2.3	3.74	3.48	**3.52**	3.26	1.3	0.57	1.48	1.13	0.74
426	2.74	4.22	2.96	**3.41**	3.52	2.90	1.15	1.7	0.19	0.22
428	1.52	4.22	3.17	**4.43**	3.61	2.83	2.13	3.3	0.48	0.74
430	5.1	5.17	4.21	**5.9**	4.9	4.55	2.1	2.93	0.93	0.38
432	4.23	4.08	3.23	**4.85**	4.54	3.77	0.54	1.23	0.38	0.92
434	1.92	2.88	1.77	**3.27**	2.42	1.96	0.15	0.92	0.42	0.42
436	4.23	4.62	3.69	**5.62**	4.92	4.15	0.38	1.15	0.31	0.38
438	2.69	4.54	3.23	**2.92**	2.5	2.31	1.23	2.38	0.85	0.77
440	3.78	5.74	3.83	**4.35**	3.09	2.7	1.22	1.39	0.35	0.56
442	**5.41**	**7.63**	**6.11**	*7.44*	**6**	**5.78**	**4.38**	**4.48**	**4.07**	**3.93**
444	2.85	3.23	1.85	**3.85**	3.23	3.31	2.31	2.38	1.62	1.62
446	2.1	2.62	1.55	**2.76**	2.14	2.55	1.24	1.34	0.86	0.62
448	2.57	3.09	2.78	**2.74**	2.61	1.57	1.26	0.35	0.96	0.91
450	3.18	4.07	3.18	**4.64**	4.32	3.54	0.75	0.14	0.46	0.68
452	1.85	3.54	2.77	**4.92**	4.69	4.31	3.08	4.46	2.23	2.54
454	1.83	2.97	2	**3.07**	2.45	2.62	1.28	1.66	1.1	0.90

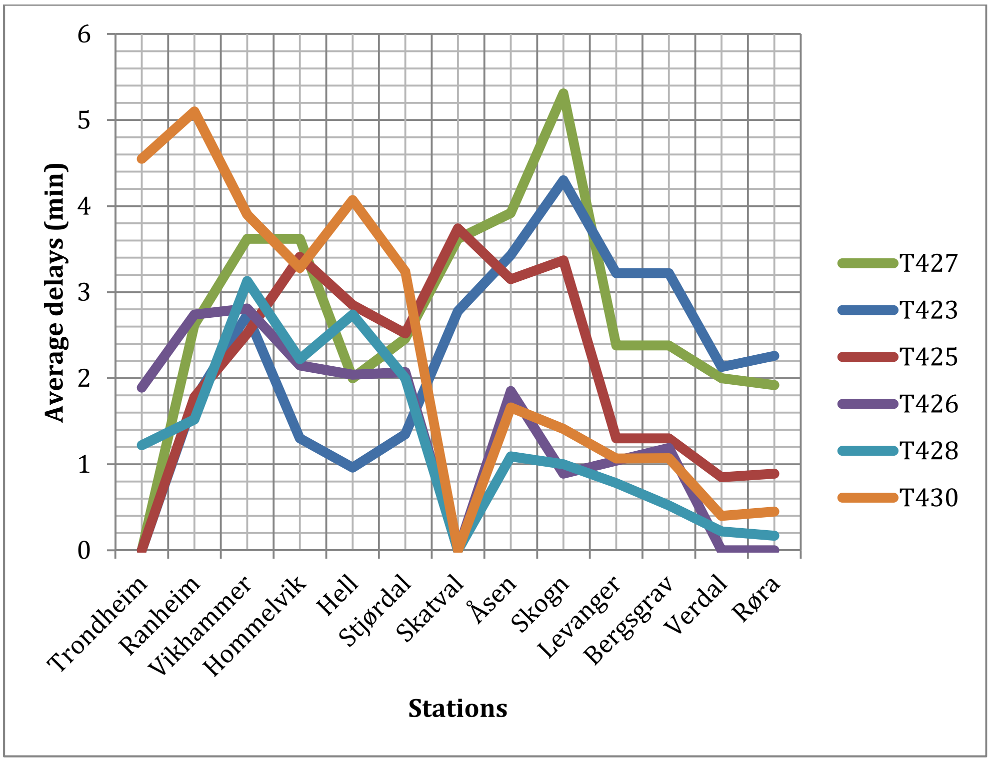
C. Some of the arrival delay statistics from Trondheim to Steinkjer

Train series	VIK	HOM	HEL	**STD**	SKT	Åsen	SKO	LEV	Røra	STE
423	1.04	0.22	0.17	**0.30**	1.43	2.09	2.61	2.30	1.74	1.48
425	1.41	1.70	1.48	**1.8**	2.48	2.04	1.89	0.81	0.37	0.19
427	2.08	1.31	0.69	**0.54**	2.38	2.69	3.38	1.69	1.54	1.08
429	1.63	0.56	0.33	**0.41**	1.74	1.41	1.85	2.48	0.19	0.11
431	1.31	0.46	0.15	**0.31**	2	1.54	1.23	0.38	0	0
433	3.43	2.07	1.43	**2.13**	3.07	3.23	3.17	2	1.5	0.83
435	1.83	1.13	0.87	**1.26**	1.96	1.57	1.39	1	0.91	0.70
437	1.52	0.52	0.33	**0.41**	0.89	0.96	1.67	0.40	1.56	1.44
439	0.57	1.13	0.74	**1.43**	1.91	1.39	1.83	0.26	0.17	0.17
441	2.55	1.48	1.16	**1.45**	3.10	2.52	3	1.87	2.03	1.90
443	2.74	1.26	0.70	**1.09**	1.65	1.30	2.30	1.39	1.22	1
445	1.89	0.71	0.5	**0.71**	1.36	1.21	1.71	0.39	0.07	0
447	1.46	0.62	0.15	**0.23**	0.62	0.54	1.54	1.08	2.23	2.54
449	1.65	0.68	0.55	**0.65**	1.81	2.23	2.68	0.84	1	0.84
453	**2.61**	**2.10**	**3.21**	***5.34***	**5.62**	**5.21**	**5.10**	**4.10**	**3.76**	**3.66**
457	0.85	0.11	0.04	**0.15**	1.81	1.52	1.41	2.30	1.07	0.81

D. Some of the arrival delay statistics trains from Steinkjer to Trondheim

Train series	**Average arrival delays**										
	TRD	RAN	VIK	HOM	**Hell**	STD	Åsen	SKO	LEV	VER	Røra
1702	1.31	2.23	0.92	0	**0**	0					
1760	3.46	3.62	3.77	2.92	**3.462**	3.15		0.15	0.08	0	0.08
1762	2.69	3.15	3.31	4.23	**5.31**	6.23		0.23	0.46	0.08	0.38
422	1.96	2.22	1.74	1.09	**1.52**	1.09	0.7	0.48	0.43	0.39	0.43
424	2.39	2.3	2	2	**1.7**	1.09	0.3	0.13	0.3	0.61	0.13
426	1.89	2.74	2.81	2.148	**2.04**	2.07	1.85	0.89	1.04	0	0
428	1.22	1.52	3.13	2.22	**2.74**	2	1.09	1	0.78	0.22	0.17
430	4.55	5.1	3.9	3.28	**4.07**	3.24	1.66	1.41	1.067	0.4	0.45
432	4.08	4.23	3.08	2.77	**3.38**	3.15	2.54	0.23	0.31	0.31	0.31
434	1.08	1.92	1.58	1	**1.5**	0.5	0.96	0.04	0.04	0.08	0
436	3.46	4.23	3.62	3.23	**3.92**	3.54	2.08	0	0.08	0	0
438	2.23	2.69	2.73	1.5	**1.31**	0.73	1.04	0.38	0.54	0.35	0.38
440	3.65	3.78	3.78	1.78	**2.35**	1.17	1.43	0.04	0.13	0.13	0.13
442	**5.44**	**5.41**	**6.15**	**4.78**	***5.48***	**4.22**	**4.41**	**3.19**	**3.37**	**3.44**	**3.33**
444	1.92	2.85	1.69	1.46	**2.38**	1.69	2.23	0.38	0.92	1.23	1.31
446	0.97	2.1	1.41	0.83	**1.28**	0.79	1.17	0.241	0.34	0.34	0.31
448	1.87	2.57	1.91	2.13	**0.78**	1.3	1.3	0.3	0.52	0.61	0.61
450	2.11	3.18	2.79	2.21	**3.14**	2.8	2.18	0	0	0.18	0.11
452	1.23	1.85	2.69	2.15	**3.54**	2.15	3.23	2.15	1.15	1.77	1.69
454	1	1.83	1.79	1.48	**1.039**	1.17J	1.52	0.34	0.48	0.38	0.52

E. Arrival delays during morning rush hours



F. Correlation Coefficients

Departure delays from Trondheim to Steinkjer

Stations	Ran	Vik	Hom	Hell	Std	Åsen	Sko	Lev	Ber	Ver	Røra
Correlation Coefficient	0.382	0.42	0.223	0.299	0.457	0.564	0.486	0.873	0.869	0.961	0.921

Departure delays from Steinkjer to Trondheim

Stations	Ran	Vik	Hom	Hell	Std	Åsen	Sko	Lev	Ber	Ver
Correlation Coefficient	0.963	0.857	0.803	0.715	0.659	0.496	0.25	0.237	0.364	0.336

Arrival delays from Trondheim to Steinkjer

Stations	Vik	Hom	Hell	Std	Åsen	Skogn	Lev	Ber	Verd	Røra
Correlation Coefficient	0.325	0.298	0.523	0.549	0.523	0.656	0.615	0.920	0.936	0.977

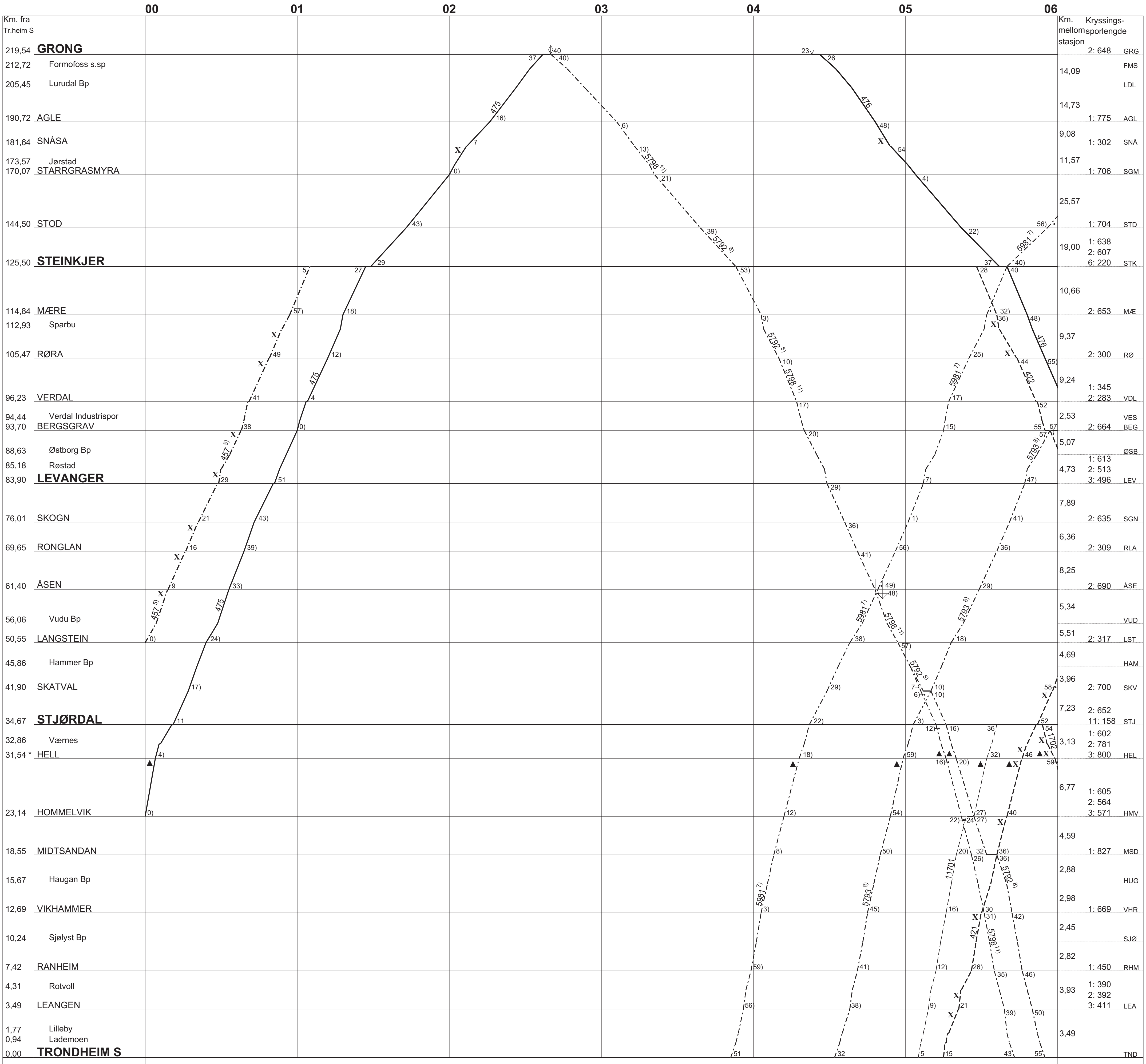
Arrival delays from Steinkjer to Trondheim

Stations	Ran	Vik	Hom	Hell	Std	Åsen	Sko	Lev	Ber
Correlation Coefficient	0.963	0.843	0.753	0.694	0.603	0.505	0.35	0.428	0.434

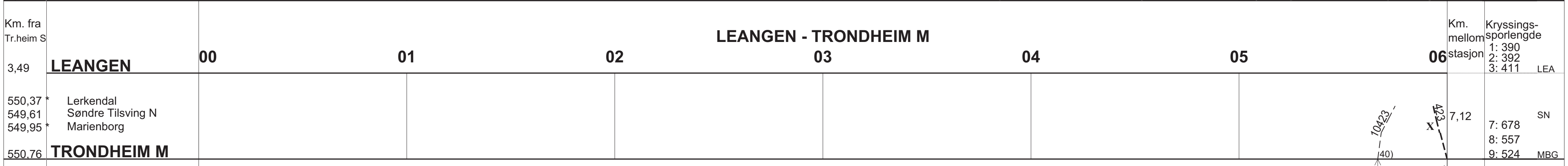
Jernbaneverket

BLAD NR. 14	RUTEORD. NR.	GJELDER FRA OG MED:
GRONG - TRONDHEIM S	**162.1**	**Søndag 09. desember 2012**

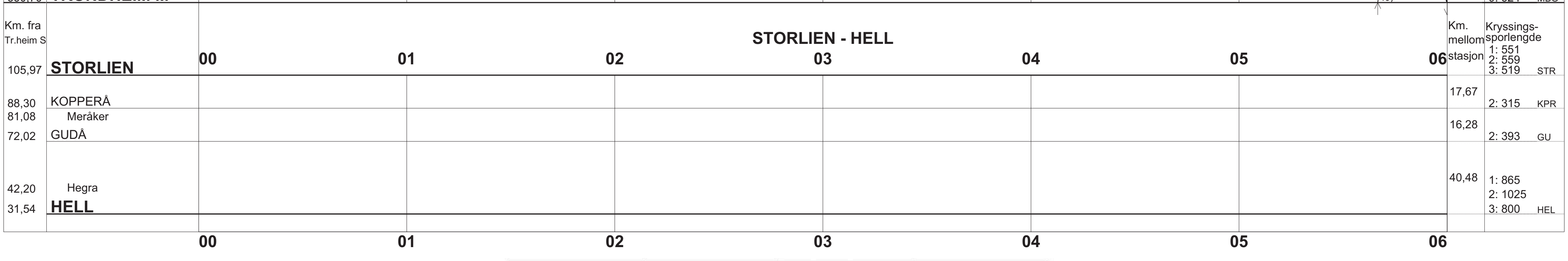
1) 425 Lerkendal hp. - Trondheim S mandager - fredager unntatt helligdager, Trondheim S - Steinkjer mandager - lørdager unntatt helligdager.
2) 426, 430, 434, 438, 442 Steinkjer - Trondheim S alle dager, Trondheim S - Lerkendal hp. mandager - fredager unntatt helligdager.
3) 429, 433, 437, 441, 445, 449, 453 Lerkendal hp. - Trondheim S mandager - fredager unntatt helligdager, Trondheim S - Steinkjer alle dager.
4) 446, 450, 454 Steinkjer - Trondheim S alle dager, Trondheim S - Lerkendal hp. søndager - fredager.
5) 457 Lerkendal hp. - Trondheim S mandager - fredager unntatt helligdager, Trondheim S - Langstein søndager - fredager, Langstein - Steinkjer mandager - lørdager.
6) 477, 10446, 10450, 10454 Søndager - fredager.
7) 5788, 5981 Lørdager unntatt dag etter helligdag.
8) 5792, 5793 Tirsdager - lørdager unntatt dag etter helligdag.
9) 5794 Onsdager, torsdager og fredager unntatt dag etter helligdag.
10) 5795 Tirsdager - fredager unntatt dag etter helligdag.
11) 5797, 5798 Søndager unntatt dag etter helligdag.
12) 5982 Søndager.
13) 5990, 5991, 6791 Mandager og torsdager.
14) 5992, 5993, 6792, 6795, 25994, 25995 Tirsdager og fredager.
15) 5996, 6796 Onsdager.
16) 5997 Onsdager og lørdager.
17) 5998, 6798 Lørdager.
18) 11764 Fredager unntatt helligdager.



LEANGEN - TRONDHEIM M



STORLIEN - HELL



Tegnforklaring:

Togbetegnelser	Alle dager	Mandager - fredager unntatt helligdager	Andre kjøredagsmønster
Persontog	━━━━	━ ━ ━	━·━·━
Godstog	────	— — —	—·—·—
Løslok, Tomtog	────	— — —	–·–·–
Behovstog	- - - - - - - -		

▲ - Ubetjent alle dager △ - Ubetjent helligdager ▼ - Ubetjent hverdager ▽ - Ubetjent lørdager unntatt helligdager ◇ - Ubetjent lørdager og helligdager ⊗ - Om betjening, se rutebroken
* - Kjedebrudd

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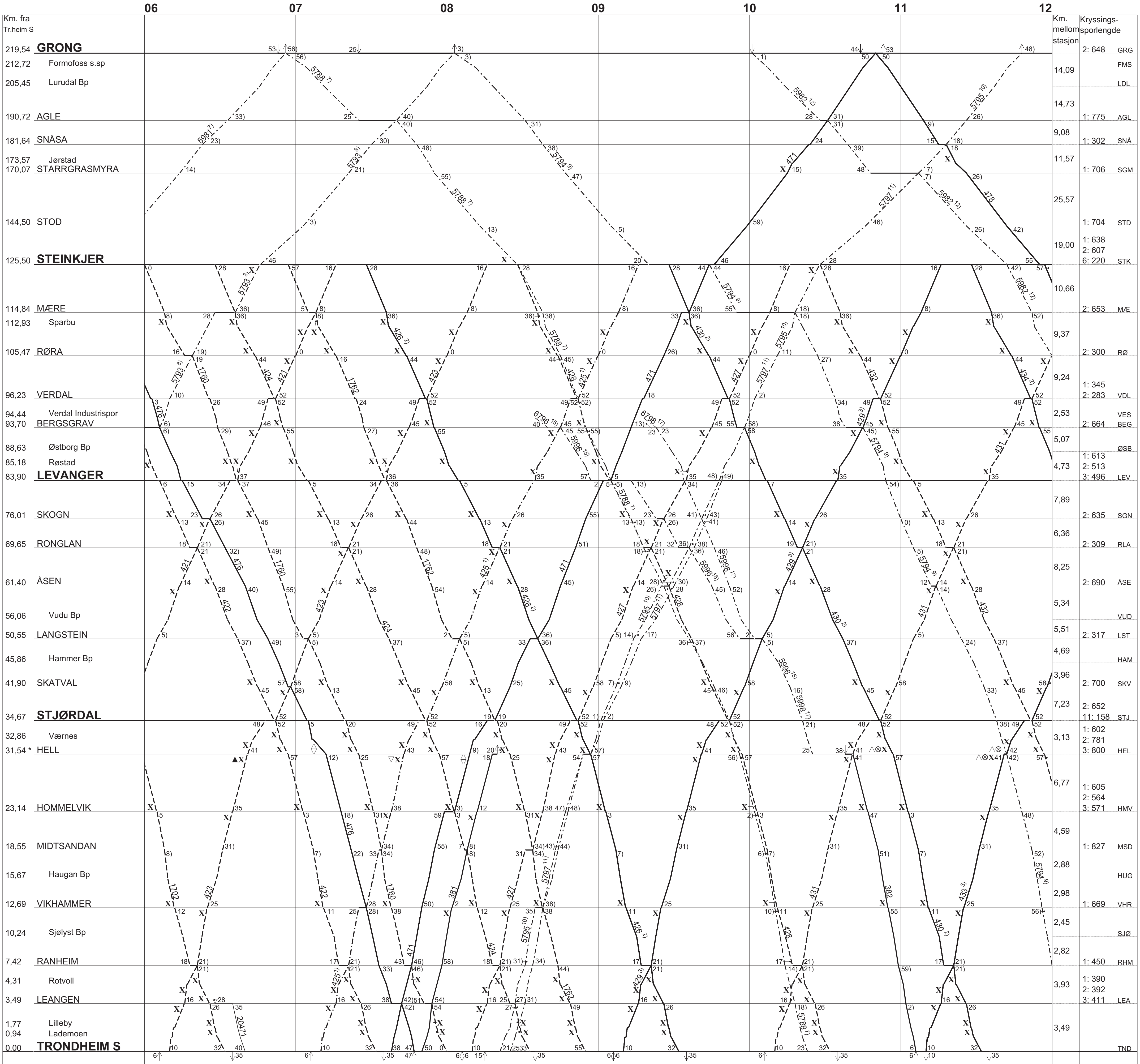
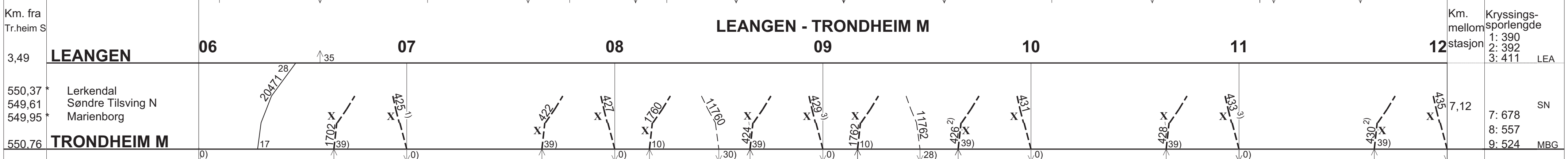
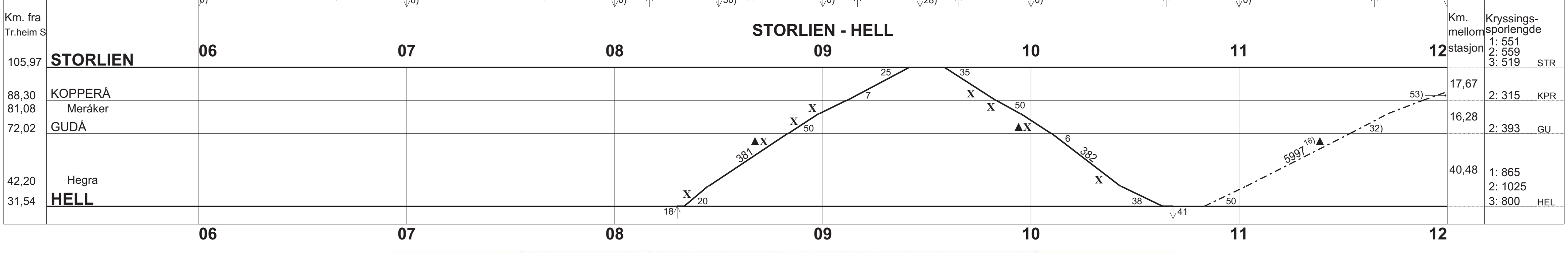


LEANGEN - TRONDHEIM M



STORLIEN - HELL



Tegnforklaring:

Togbetegnelser	Alle dager	Mandager - fredager unntatt helligdager	Andre kjøredagsmønster
Persontog	━━━━━	━ ━ ━ ━	━·━·━
Godstog	─────	─ ─ ─ ─	─·─·─
Loslok, Tomtog	─────	─ ─ ─ ─	─·─·─
Behovstog	- - - - - - - - -		

▲ - Ubetjent alle dager △ - Ubetjent helligdager ▼ - Ubetjent hverdager ▽ - Ubetjent lørdager unntatt helligdager ◇ - Ubetjent lørdager og helligdager ⊗ - Om betjening, se rutebroken
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BLAD NR. 14

GRONG - TRONDHEIM S

RUTEORD. NR.

162.1

GJELDER FRA OG MED:

Søndag 09. desember 2012

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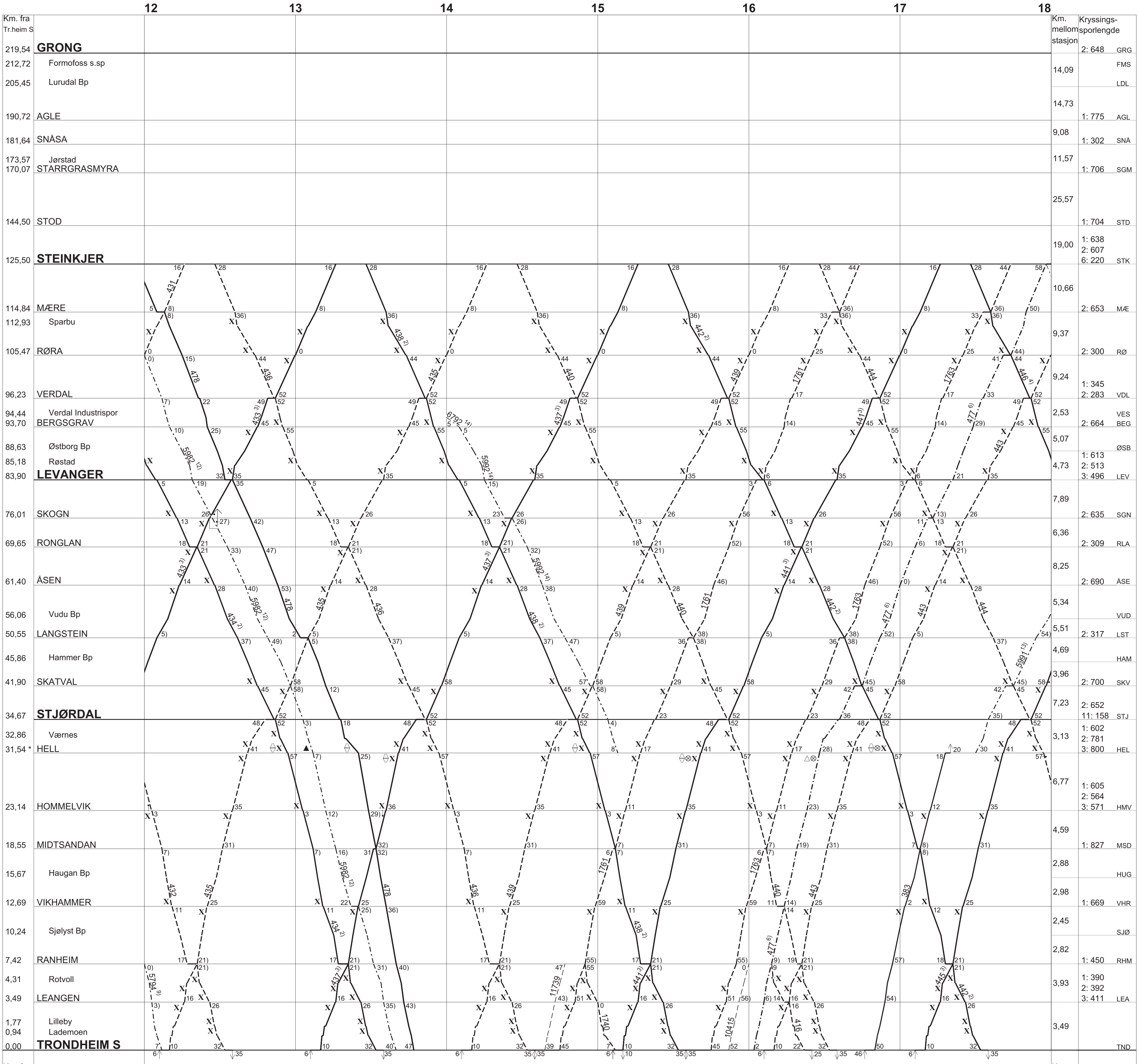

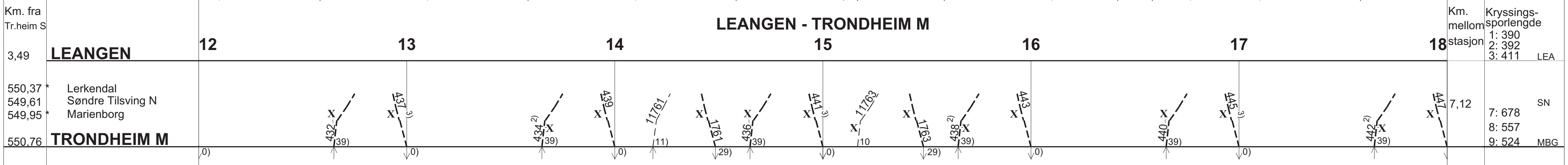

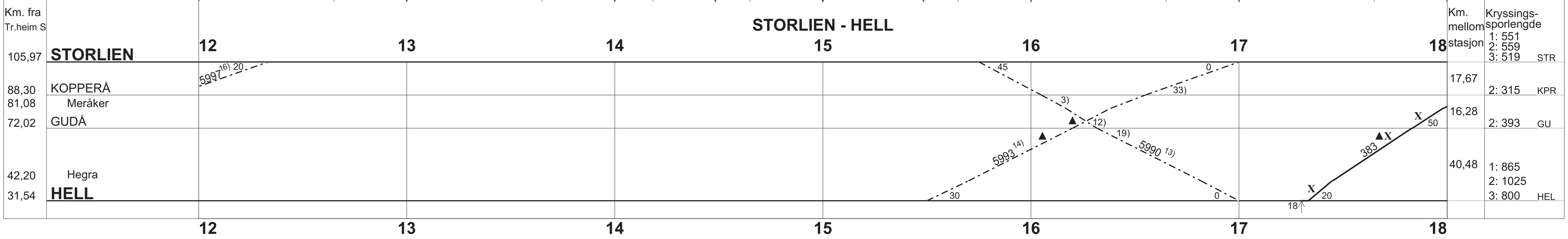

Tegnforklaring:

Togbetegnelser	Alle dager	Mandager - fredager unntatt helligdager	Andre kjøredagsmønster
Persontog	━━━━━━	━ ━ ━ ━ ━	━ · ━ · ━ ·
Godstog	──────	— — — — —	— · — · — ·
Løslok, Tomtog	──────	— — — — —	— · — · — ·
Behovstog	- - - - - - - - - - -		

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BLAD NR. 14
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RUTEORD. NR.
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GJELDER FRA OG MED:
Søndag 09. desember 2012

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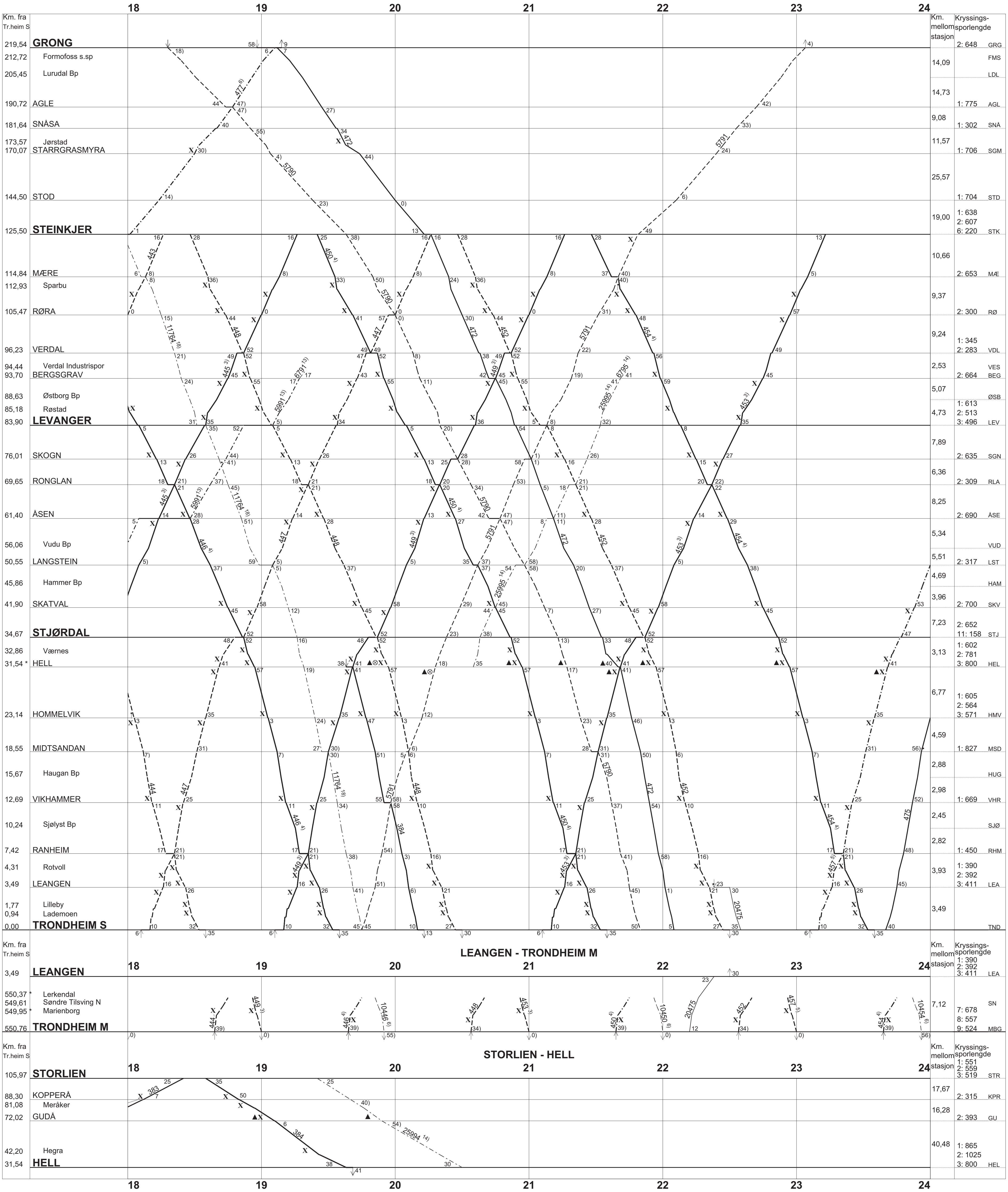

Tegnforklaring:

Togbetegnelser	Alle dager	Mandager - fredager unntatt helligdager	Andre kjøredagsmønster
Persontog	━━━━━━	━ ━ ━ ━ ━	━ · ━ · ━ ·
Godstog	──────	─ ─ ─ ─ ─	─ · ─ · ─ ·
Løslok, Tomtog	──────	─ ─ ─ ─ ─	─ · ─ · ─ ·
Behovstog	- - - - - - - - - - -		

▲ - Ubetjent alle dager △ - Ubetjent helligdager ▼ - Ubetjent hverdager ▽ - Ubetjent lørdager unntatt helligdager ◇ - Ubetjent lørdager og helligdager ⊗ - Om betjening, se rutebroken
* - Kjedebrudd