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Timetable evaluation with focus on quality for travellers

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Timetable evaluation with focus on quality for travellers

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Abstract

Punctuality and reliability are important for travellers. Railway lines with heterogeneous and dense traffic have proved to be prone to generate delays. Faster services and increased traffic have to be counterbalanced with measures for increased reliability. Efficient timetable planning can improve the use of such lines. Usually, that aim is treated from either a capacity or a socio-economic point of view. Because both are important, this thesis aims to combine the fields. A new method to evaluate timetable alternatives is developed. Commonly used methods are combined in a novel way to reveal values for different variables as input for evaluation of alternatives. That enables the comparison of timetable strategies using relevant input data. The idea is to estimate the benefits of a timetable for a traveller by expressing them as a timetable performance index (TTPI). For this purpose, quality indicators and methods to reveal them are identified. In the next step, traditional valuations for relationships between the indicators are used to test different model configurations for evaluation of alternatives, for example alternative departures on the same line or different timetables.

To treat this multidisciplinary task, several case studies were performed on the Swedish Southern and Western Main lines. As part of a study focussing on methods to measure and evaluate capacity based on travellers' valuations, the importance of delays was analysed in a questionnaire study and relationships between several variables describing the timetable were found. The other case studies aimed to identify relevant variables and use them to evaluate alternatives. Static and dynamic variables are distinguished. The static ones describe the timetable before operation, the dynamic ones the result of operation or estimated outcome revealed by means of, for example, simulation. Empirical delay data is used in one study, simulation with the microscopic tool RailSys in the others. In one of the studies, analysis is combined with the macroscopic timetabling tool TVEM (Lindfeldt, 2010). The case studies showed the characteristics of the analysed lines described by the chosen variables and which methods and variables are relevant to use for a comparison of timetable slots or evaluation of effects of changes in the timetable. An evaluation method was developed where simulation and timetable analysis reveal the variables. The idea is to construct an analytical function using traditional weights for relationships between the variables to convert the values of the variables into a performance index (PI). Based on a PI for each train slot (TSPI), the TTPI for the whole timetable is estimated. It describes the quality of a timetable in terms of timetable time, i.e. the resulting value is a time that is comparable to the scheduled travel time of one train departure, but includes additional information. With this method, complex timetables can be evaluated regarding their robustness to perturbations, which is valuable for socio-economic analysis of effects of measures applied on the railway system.

As shown in a one of the case studies, quality in terms of punctuality and reliability is important for travellers, at the same time as the design of the timetable has

significant impact on these aspects. Timetable analysis and simulation are relevant methods to reveal variables that describe these characteristics and evaluation with the presented method is recommended. The configuration of the TTPI is essential for the outcome whereas it is important to choose variables and parameters adequately. If this is taken into account, the approach can be an efficient way to adjust timetables and choose the best alternative, for instance if a train path or timetable change is to be chosen among several.

Sammanfattning

Punktlighet och tillförlitlighet är viktiga för resenärer. Järnvägar med heterogen och tät trafik har visat sig vara benägna att generera förseningar. Snabbare tåg och utökat trafikutbud måste uppvägas mot punktlighetsåtgärder. Effektiv tidtabellsplanering kan förbättra utnyttjandet av sådana linjer. Detta ändamål behandlas oftast utifrån antingen kapacitets eller samhällsekonomisk synvinkel. Eftersom bägge är viktiga syftar den här avhandlingen på att kombinera dessa områden. En metod för utvärdering av tidtabellsalternativ utvecklas. Befintliga metoder kombineras på ett nytt sätt för att ta fram värden för olika variabler som indata för en utvärdering av alternativen. Detta möjliggör en jämförelse av tidtabellsstrategier med relevant indata. Idén bygger på att bedöma en tidtabells nytta för resenären genom att uttrycka denna som ett prestationsindex (TTPI). För detta syfte identifieras kvalitetsindikatorer och metoder för att ta fram dessa. Traditionella valideringar för relationerna mellan indikatorerna används sedan för att testa olika konfigurationer av modellen för att utvärdera alternativ, till exempel alternativa avgångar på samma linje eller olika tidtabeller.

För denna multidisciplinära uppgift har flera fallstudier på svenska Södra och Västra stambanan genomförts. Som del av en studie med fokus på metoder för att mäta och utvärdera kapacitet baserad på resenärers värderingar har förseningens värde analyserats med hjälp av en enkätundersökning och relationer mellan några variabler som beskriver tidtabellen hittats. De övriga fallstudierna syftade på att ta fram relevanta variabler och att använda dem för att utvärdera alternativ. Variablerna delades upp i statiska och dynamiska. De statiska beskriver tidtabellen innan den körs, de dynamiska det verkliga utfallet eller det estimerade resultatet framtaget med hjälp av exempelvis simulering. Empiriska förseningsdata används i en studie, simulering med det mikroskopiska programmet RailSys i de andra. I en av studierna kombineras analysen med det makroskopiska tidtabellsverktyget TVEM (Lindfeldt, 2010). Fallstudierna visade de analyserade linjernas egenskaper beskrivna av de valda variablerna och vilka metoder och variabler som är relevanta för en jämförelse av olika tåglägen eller en utvärdering hur en ändring i tidtabellen påverkar. En utvärderingsmetod där simulering och tidtabellsanalys används för att ta fram variablerna utvecklades. Idén är att skapa en analytisk funktion med hjälp av traditionella vikter som beskriver sambanden mellan variablerna för att räkna om variablernas värden till en prestationsindex (PI). Baserad på en PI för varje tågläge (TSPI) estimeras värdet för hela tidtabellen (TTPI). Detta index beskriver tidtabellens kvalitet som tidtabellstid, dvs. värdet är en tid som är jämförbar med den tidtabellslagda restiden för en avgång, men med ytterligare information inkluderat. Med hjälp av denna metod kan komplexa tidtabeller utvärderas med avseende på robusthet mot störningar vilket är värdefullt för samhällsekonomiska bedömningar av åtgärder i järnvägssystemet.

Som en av fallstudierna visade är kvalitet i form av punktlighet och tillförlitlighet viktig för resenärer samtidigt som tidtabellens utformning har en signifikant påverkan på samma aspekter. Tidtabellsanalys och simulering är relevanta metoder

för att ta fram variabler som beskriver dessa egenskaper och utvärdering med de visade metoderna rekommenderades. Modellens konfiguration är betydelsefull för resultatet vilket gör det viktigt att välja variabler och parametrar som är lämpliga. Om detta respekteras kan metoden vara effektiv för att anpassa tidtabeller och välja det bästa alternativet, till exempel när det gäller att välja mellan olika tåglägen eller justeringar i tidtabellen.

Zusammenfassung

Pünktlichkeit und Zuverlässigkeit sind wichtig für Reisende. Stark belastete Eisenbahnlinien mit heterogenem Verkehr sind störungsanfällig. Zugleich besteht oft ein Bedarf an schnelleren und häufigeren Verbindungen, was jedoch mit potentiellen negativen Effekten auf die Kapazität aufgewogen werden muss. Effiziente Fahrplankonstruktion kann die Nutzung solcher Linien verbessern. Dieses Ziel wird meist entweder aus der Sicht der Kapazitätsanalyse oder wirtschaftlichen Aspekten betrachtet. Da beide Betrachtungsweisen wichtig sind, strebt diese Arbeit die Kombination beider Felder an. Eine Methode für die Auswertung verschiedener Fahrpläne wird entwickelt. Bewährte Methoden werden in neuer Weise kombiniert um Werte für verschiedene Variablen als Input für die Auswertung von Alternativen zu erhalten. Das ermöglicht es potentielle Änderungen im Fahrplan mithilfe relevanter Werte zu vergleichen. Die Idee basiert auf einem Leistungsindex (TTPI), der den Nutzen eines Fahrplans für die Reisenden ausdrücken soll. Zu diesem Zweck werden Qualitätsindikatoren gewählt und Methoden zur Berechnung und Bearbeitung der Indikatoren entwickelt. Traditionelle Werte für die Abhängigkeiten zwischen den Indikatoren dienen dann dem Test verschiedener Modelkonfigurationen sowie der Auswertung von Alternativen, z. B unterschiedlicher Trassen oder Fahrpläne.

Für diese multidisziplinäre Aufgabe wurden mehrere Fallstudien für die südliche und westliche Hauptstrecke in Schweden durchgeführt. In einer Fragenbogenstudie mit den Schwerpunkten Mess- und Auswertungsmethoden wurde der Wert von Verspätungen für Reisende untersucht und Verhältnisse zwischen mehreren Indikatoren ermittelt. Die weiteren Fallstudien strebten das Finden relevanter Variablen und deren Anwendung zur Auswertung von Alternativen an. Statische und dynamische Variablen wurden unterschieden. Die statischen beschreiben den geplanten Fahrplan vor dem Betrieb, die dynamischen den wirklichen Ausfall oder das beispielsweise durch Simulation berechnete erwartete Resultat. In einer der Fallstudien wurde empirisches Datenmaterial für die Verspätungsdaten genutzt, in den weiteren das mikroskopische Simulationsprogramm RailSys. In einer der Studien wurde die Analyse mit dem makroskopischen Fahrplanungsprogramm TVEM (Lindfeldt, 2010) kombiniert. Die Eigenschaften der untersuchten Linien wurden mithilfe der gewählten Indikatoren analysiert. Weiterhin wurde die Relevanz verschiedener Methoden und Variablen für den Vergleich von Fahrten oder der Beurteilung von Änderungen in Fahrplänen beschrieben. Die gewählte Bewertungsmethode kombiniert Simulation und Fahrplananalyse um die benötigten Werte zu bestimmen. Mithilfe einer analytischen Funktion sollen die Variablen durch Anwenden von traditionellen Werten für die Zusammenhänge in einen Leistungsindex (PI) umgewandelt werden. Basierend auf einem PI für jede geplante Fahrplantrasse (TSPI) kann der Wert für den gesamten Fahrplan (TTPI) bestimmt werden. Dieser Index übersetzt die Qualität des Fahrplans in Fahrtzeit, das heißt resultiert in einer Zeit, die mit der fahrplanmäßigen Fahrtzeit für eine Fahrt vergleichbar ist, aber zusätzliche Information enthält. Diese Methode ermöglicht es, komplexe Fahrpläne bezüglich Robustheit gegen Störungen auszuwerten, was wertvoll für die Berechnung

der Wirtschaftlichkeit von Maßnahmen im Bahnnetz ist.
Wie eine der Fallstudien gezeigt hat, ist die Qualität in Form von Pünktlichkeit und Zuverlässigkeit wichtig für die Reisenden. Gleichzeitig beeinflusst die Ausformung des Fahrplans diese Eigenschaften deutlich. Fahrplananalyse und Simulation sind geeignete Methoden um die Werte der Variablen, die diese Eigenschaften beschreiben, zu bestimmen. Auswertung auf diese Weise wird empfohlen. Die Konfiguration des Models beeinflusst das Ergebnis, weshalb es wichtig ist geeignete Variablen und Parameter zu benutzen. Wird das berücksichtigt, kann die entwickelte Methode effizient für das Verbessern von Fahrplänen angewandt werden und die Wahl der besten Alternative unterstützen, z.B. bei geplanten Änderungen im Fahrplan oder der Wahl zwischen unterschiedlichen Trassen.

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Jennifer Warg

List of publications

Papers included in the thesis

Paper A: Fröidh, O., Warg, J., Sipilä, H., 2014. Capacity for express trains on mixed traffic lines. Published in: *International Journal of Rail Transportation 2014, vol. 2, iss. 1, pp. 17-27.*

Paper B: Warg, J., 2013. *Economic evaluation of capacity with simulation.* Published in: Proceedings of the 10th World Congress on Railway Research, Sydney, Australia.

Paper C: Warg, J., Bohlin, M., 2016. The Use of Railway Simulation as an Input to Economic Assessment. Accepted for publication in *Journal of Rail Transport Planning & Management.*

Related publications not included in the thesis

Sipilä, H., Warg, J., 2012. *Kapacitetsanalys av Södra Stambanan. Effekter av ökad trafik och ökad hastighet från 200 till 250 km/h (Capacity analysis of the Southern Main Line: Effects of increased traffic and increased speed from 200 to 250 km/h).* In Swedish. Technical report, KTH.

Warg, J., 2012. Effects of increased traffic volume and speed heterogeneity on capacity of a railway with dense mixed traffic. Published in: *Computer in Railways XIII – Proceedings of the 13th International Conference on Railway Engineering Design and Optimization (CompRail 2012)*, New Forest, Great Britain.

Fröidh, O., Kottenhoff, K., Warg, J., 2013. *Comfort evaluation of active secondary suspension.* Technical report. KTH Railway Group, Publication 13-03, Stockholm, Sweden.

Fröidh, O., Warg, J., 2013. *Europakorridoren: Kapacitet och restider (The European Corridor: Capacity and journey times).* In Swedish. Technical report. KTH, Stockholm, Sweden.

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Warg, J., Bohlin, M., 2015. The Use of Railway Simulation as an Input to Cost-Benefit Analysis. Published in: Hansen, I.A., Tomii, N., Hirai, C. (eds.), *Proceedings of 6th International Conference on Railway Operations Modelling and Analysis (RailTokyo)*, Tokyo, Japan.

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Abbreviations

CBA	Cost-benefit analysis
CS	Consumer surplus
PI	Performance index
PS	Producer surplus
RQ	Research question
SJ	*In English: Swedish State Railways ltd*
TSPI	Train slot performance index
TTPI	Timetable performance index
TVEM	Timetable Variant Evaluation Model
VOT	Value of travel time
VTTS	Value of travel time savings

Part 1

1 Introduction

1.1 Background

The demand for train traffic is increasing worldwide with an ongoing trend (UIC, 2015). This is also the case in Sweden. At the same time, punctuality has become increasingly important. As it does not reach the desired levels, passenger satisfaction has decreased. Service reliability is important, as low punctuality and large delays make people choose other means of travel or goods transport, thus lowering the service demand. The Swedish railway industry has formulated the objective to reach 95% punctuality by 2020. In 2015, punctuality measured as trains arriving within five minutes after the scheduled arrival time was 90.1% for passenger and 77.9% for freight trains, a slight increase compared to previous years' figures (Trafikverket, 2015).

Punctuality is highly related to capacity, which can be defined as "the maximum number of trains that would be able to operate on a given infrastructure under a particular set of operational conditions during a specific time interval" (Lai et al, 2015). Capacity utilisation is a measure how the timetable uses this capacity. This can for instance be estimated by the compression method described in UIC406 (UIC, 2013). According to this method, capacity utilisation is high on 18% of all line sections in Sweden, and very high on a further 9%. During the two peak hours, these numbers increase to 29% and 33%, respectively. A high utilisation (61-80%) is an indicator for sensitiveness to delays and difficulty to schedule new departures or track maintenance. At very high levels (>81%), these problems increase. Delays spread more easily, create new delays (secondary delays) and affect the system´s ability to recover. At the same time, there is a demand for improvements on many lines, for example more frequent or faster services or more frequent stops, or maintenance of the, to a large extent, quite old infrastructure or fleet. Another important fact is that on many Swedish lines, different freight and passenger services with varying speed and stopping pattern share the same track. This heterogeneity is strengthened by the fact that the Swedish railway market is liberalised in the sense that multiple operators can apply to operate services on the same line.

Altogether, this makes timetabling on Swedish railways complex and offering services that satisfy demand a difficult task. The question of how to operate the scarce resource a railway offers efficiently can be analysed from different perspectives. One is capacity, socio-economics another. Socio-economics aims to evaluate how measures affect society, mainly expressed in monetary terms. The two are closely connected, as the way the capacity is used results in effects on the users. An example is delay: Different timetable strategies can result in longer or shorter delays (or none at all), which for example affects travellers and operators, who in their turn might change their behaviour based on that, e.g. choose a road transport mode instead, which is affecting the available road capacity, the environment, etc. Analysis of this complex problem often focuses on only one of the fields depending on if it is treated as a technical or an economic issue. Socio-economic analysis is seldom included in capacity studies, and if so, it often overlooks dynamic characteristics such as delays

that capacity analysis can uncover.

1.2 Problem definition

Many factors regarding for example timetable, infrastructure, trains, service supply, operators or clients influence how well a railway system works. A railway line should meet the needs of its users, and supply be designed based on demand. However, it is not easy to define and measure this performance. This thesis treats that question with the focus on the timetable and its outcome with respect to both capacity and passenger valuations of travelling time and delays.

A timetable schedules the planned movement of a train. Operating trains with similar performance and stops can be scheduled quite easily: the minimum headway, a technical safety margin, decides the earliest departure time for a train following another. With increasing heterogeneity, more capacity is consumed, while the number of train paths that can be scheduled per time unit is reduced and the timetabling becomes more complex as different alternatives exist. Figure 1 shows three timetables to illustrate how scheduling can look for different service mixes.

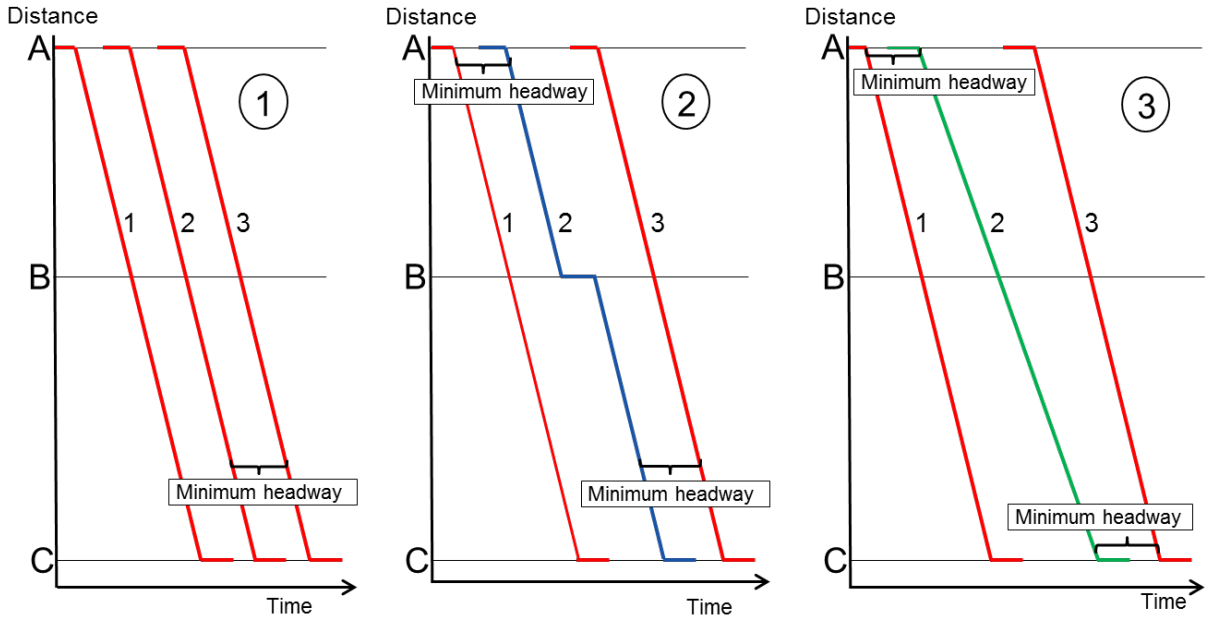


Figure 1: Three timetables: (1) for homogeneous services, (2) for heterogeneous services with the same speed but different stopping patterns, (3) heterogeneous services with different speeds. Each coloured line represents a train path, and A, B and C respectively are stations. The line colour indicates the type of service.

Keeping the same train order, timetable 2 in Figure 1 could also be scheduled as in Figure 2:

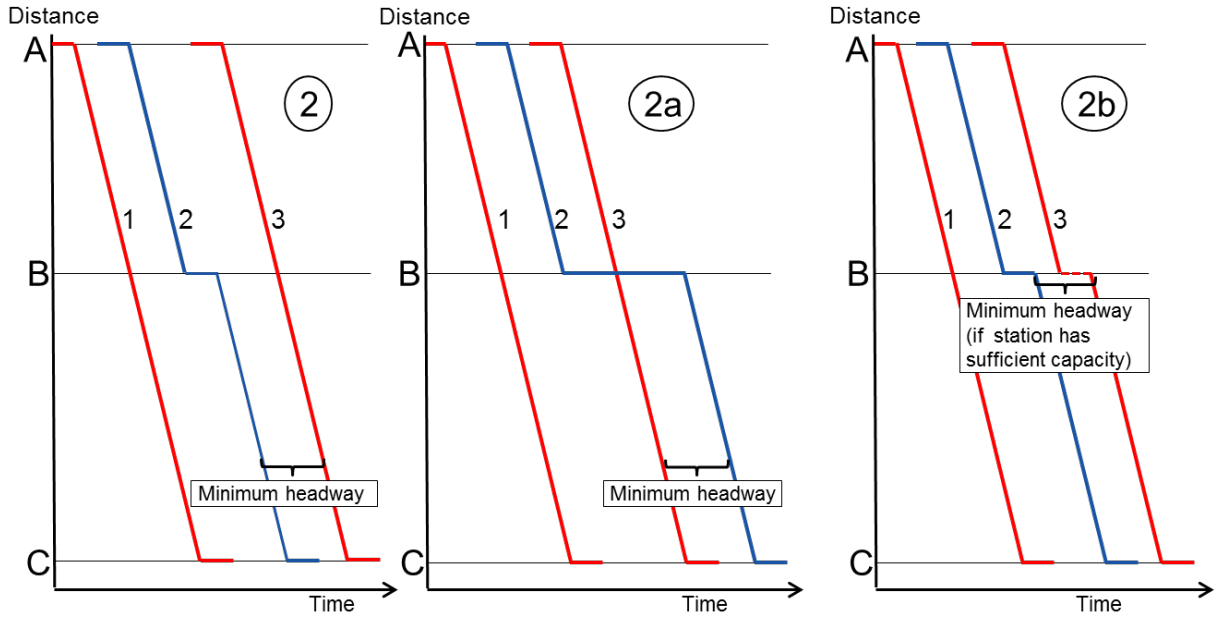


Figure 2: Timetable alternatives for timetable 2 in Figure 1 (services with the same speed but different stopping patterns)

In alternatives 2a and 2b in Figure 2, the departure time of the third train is not affected. Instead, train 2 has to wait at station B until train 3 has passed (case 2a), while train 3 has to stop at the station and wait in case 2b. Assuming sufficient capacity at station B, all solutions are technically possible and each has advantages and disadvantages compared to the others. To decide which one to choose, a selection criterion is needed. For instance, in Figure 2, solution 2 performs better than 2a and 2b regarding total travel time, whereas 2a is best if the travelling time and arrival time of the third train are the most important aspects. In suggestion 2b, the departure time for train 3 is prioritised at the same time as train 2 is not affected.

In order to decide which timetable is the most profitable, the performance has to be evaluated based on relevant characteristics. But not only the planned timetable is important, but also the operations. If a delay occurs both travelling and departure/arrival times can be affected, which makes delay and punctuality two important input variables. Delays risk spreading and being propagated throughout the network. In the cases shown where departures are scheduled with homogeneous headways, trains 2 and 3 will become as much delayed as the first one if no other buffers are included. This is exemplified in Figure 3, where the primary delay of the first train causes a secondary delay for the other two. High capacity utilisation can in this way increase the sensitivity for delays, leading to negative effects on demand.

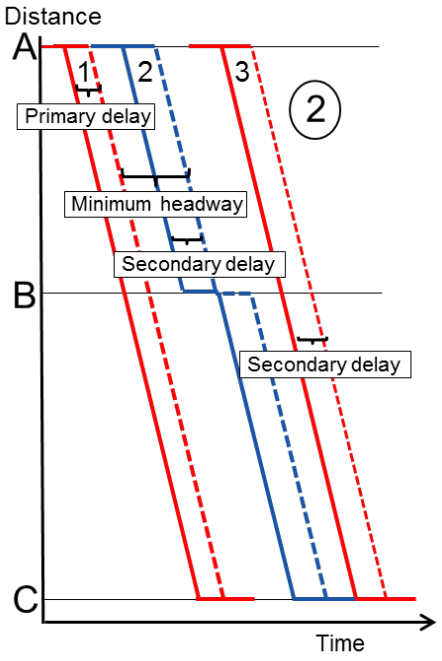


Figure 3: If train 1 is delayed, trains 2 and 3 will be delayed subsequently (dotted lines show the train paths for the delayed trains)

High capacity consumption, heterogeneous traffic, a need for increased traffic and at the same time higher punctuality and passenger satisfaction make it challenging to offer services that satisfy the demand. Time supplements or overtakings might become necessary to realise all planned services, but at the same time lead to longer journey times. Small adjustments, for example more buffer time in the timetable, can have substantial effects on punctuality. The need for improved supply through faster or more frequent services has to be counterbalanced with increased risk of delays. The timetable should be robust in the sense that spreading of delays is limited and the system can recover fast from a delay. All this should be taken into consideration when evaluating a timetable suggestion. Considering the complexities of timetabling, this raises the question of how timetables can be compared. How important is travel time for example compared to reliability?

Here, the second important focus of this thesis comes in: How are the users and society affected by a change in the timetable? Usually, alternatives are compared based on the negative and positive effects they generate. Public policy decisions should be based on the social benefits. Normally, they are added up in a social cost-benefit analysis (CBA) using weights that represent the users' preferences. Common components of a CBA are consumer surplus (CS) and producer surplus (PS), external effects, tax revenues and investment and maintenance costs. Consumer surplus represents the hypothetical sum of money a consumer is willing to pay for the analysed change, i.e. for the benefits he gets. Producer surplus summarises benefits for the producers, here mainly transport operators. Travel times often represent a large amount of the social benefits as reduced times are beneficial for both travellers and operators who can use the time gained in another way. This means for example that the choice of timetable suggestion in Figure 2 affects both CS and PS due to reduced/increased travel times. The remaining components of CBA are not affected by timetabling to the same extent.

The passengers' valuations of travelling time have been defined in several studies. Typically, different groups of passengers and journey purposes are distinguished. Provided the number of travellers per train, the social benefit of a change in travel time can be calculated for each train and the total effect of different alternatives compared. But as the example shows, there are more variables that affect performance. An important one is reliability. There are parameters describing the value of reliability compared to other variables, too. But both the amount of reliability

and its effect are difficult to measure, a problem that also occurs for other variables. In addition, it is difficult to choose the relevant variables and to evaluate them properly regarding the relationships between them. Characteristics of a timetable, especially concerning operation, can be difficult to estimate, which is also the case for attributes of trains, e.g. the number and journey purpose of travellers per train is often unknown for analysis of commercial reasons. These difficulties might be a reason why capacity characteristics are hardly ever included in economic assessments although they can affect the results significantly and their importance is highlighted in many economic studies and guidelines. At the same time, economic assessment is often missing in capacity analysis.

Another weakness of common methods is that timetable variables are often limited to averages if included. An average can be based on a wide range of different input data: values can be on the same level but also very different, in which case averages as a single statistical measure might not describe the data set accurately enough. Given heterogeneous traffic, an average without any data on variance and correlation might often miss the real characteristics. If, furthermore, a default value is used for the kind of system, results can become even more misleading. At the same time, capacity evaluation might result in choosing less efficient alternatives or lead to results that decision-makers do not know how to use if economics is not sufficiently included in capacity analysis. All this shows the importance of combining both fields.

1.3 Objectives, scope and limitations

The objective of this thesis is to evaluate timetable alternatives by using methods from both capacity analysis and economics. The aim of the research is to investigate how capacity and socio-economic analysis are connected in current practice and to develop a method to improve evaluation that includes both aspects. The focus is on the consumer surplus (CS) for passenger traffic based on timetable properties. Properties of a double-track line with dense, heterogeneous traffic must be clarified based on the timetable and its outcome. In the case studies, the Swedish Western and Southern Main lines are used. Since the focus is on timetabling, infrastructure design, dispatching rules, train types, service supply and variations during the day are only partly treated. Variables treating the operators' planning of personnel and trains are excluded. Demand and ticket prices are assumed to be constant. Analysis is limited to the named lines. Train connections and adjacent lines are not included.

1.4 Research questions

As stated earlier, evaluating a railway line and improving it is a complex problem that is treated in different ways, usually either from an economic point of view or by capacity analysis. To analyse the objectives of this thesis, the following two research questions were formulated:

RQ1: What variables impact the quality of a railway timetable?

RQ2: How can they be combined in an analytical efficiency model describing

capacity and CS for timetable strategies?

The term *quality* as it is used in this thesis contains aspects from both capacity and economics; It describes how the needs required by the demand are met regarding both planned and operated services. What variables the term contains and how these can be identified and used to compare timetable alternatives is the main objective of this thesis. The analytical efficiency model is in the following called timetable performance index (TTPI). In the articles, also metric and value are used as terms to specify the result that is used for comparing alternatives.

1.5 Outline of the thesis

This licentiate thesis builds on work presented in Fröidh et al (2014), Warg (2013) and Warg et al (2016), referred to as papers A, B and C in the thesis. Both methods and findings from capacity analysis and economics and their interface are treated. For this multidisciplinary task, several methods are combined. Initially, descriptive and exploratory research is used to gather variables to describe the quality of a timetable and parameters for including them in CBA. In all three papers, literature reviews contribute to the research questions above. Different qualitative and quantitative methods are used to determine what variables affect the quality of a railway timetable and in which way. In case studies, various variables are measured for different cases using analytical methods, statistical analysis and simulation. In addition, an investigation of passengers' valuation is done in a mixed methods study. This approach was chosen to explore the characteristics in different ways to test both the relevance of the variables and the methods. In this way, the chosen railway lines are described and the usefulness of certain variables and methods tested. With the help of this methodology, the aim is to find a way to connect the variables in a performance index for evaluating future scenarios. The methodology is further described in section 3.

After this introductory section, which provides an overview of background, objectives, research questions, methodology and contributions, it is shown how this thesis is positioned among other research. The following section documents the findings of the paper before the last section summarises the contributions of this work and gives a brief survey of possible future work.

1.6 Contribution

This thesis contributes to the area of railway timetable analysis and socio-economic evaluation in the following ways:

- It presents variables for measuring and analysing the quality of a train slot/timetable
- It shows how values for the variables can be identified using timetable analysis, empirical delay data and microscopic simulation
- It defines a new way to describe a train slot and a timetable using a train slot/timetable performance index (TSPI and TTPI)

- It shows the characteristics of double-track lines like the Swedish Western and Southern Main line and how changes in the service supply affect these characteristics

1.7 Documentation

Table 1 summarises how the papers contribute to answer the research questions:

Table 1: Overview of papers treading research questions RQ1 and RQ2

		Paper A: Capacity for express trains on mixed traffic lines	Paper B: Economic evaluation of capacity with simulation	Paper C: The Use of Railway Simulation as an Input to Economic Assessment
RQ1 Variables	Method	Case study with timetable analysis and simulation	Mixed methods study	- Analysis of timetable and empirical delay data - Simulation
	Contribution	Measure variables for timetable alternatives	Identify capacity variables and relationships	- Measure variables for alternative departures - Measure variables for timetable alternatives
RQ2 TSTP/ TTPI	Method	Combination of timetable analysis and simulation	Mixed methods study	Case study with empirical delay data using different variable/parameter configurations
	Contribution	Evaluating the best timetable for a given service supply by step-wise evaluation	Importance of and relationships between different variables	Influence of parameters

Paper A (Fröidh, O., Warg, J., Sipilä, H., 2014. *Capacity for express trains on mixed traffic lines.* Published in: *International Journal of Rail Transportation 2014, vol. 2, iss. 1, pp. 17-27*) treats the effects of raising the average speed for express trains operating in mixed traffic. In a performance analysis of different train configurations, running times were calculated for a selection of Swedish railway lines. For a train configuration that was shown to be adequate for operating on conventional Swedish lines, a capacity analysis was done on the Swedish Southern Main line to evaluate scenarios with different supply. Combining macroscopic timetable analysis and microscopic simulation, several variables describing the timetable from a capacity point of view are presented and an evaluation method using these is shown. Warg contributed the capacity evaluation and general information.

Paper B (Warg, J., 2013. Economic evaluation of capacity with simulation. Published in: *Proceedings of the 10th World Congress on Railway Research*, Sydney, Australia) connects capacity analysis with socio-economics by mapping out how common practice in both fields includes the other field and how this can be improved. The article explores variables that are used to describe the quality of a railway timetable. In a questionnaire study on express trains on the Swedish Western Main line, the importance of delays and the relationships between different quality-related variables

is analysed. A layout for a TTPI for evaluation based on relevant variables is also suggested.

In paper C (Warg, J., Bohlin, M., 2016. The Use of Railway Simulation as an Input to Economic Assessment. Accepted for publication in *Journal of Rail Transport Planning & Management*), different configurations for the TSPI are tested by applying combinations of variables and commonly used parameters on real delay data for express trains on the Western Main line. In the second part of the work, the TTPI is used to analyse timetable strategies in the way that was suggested in paper B: Changes in delays and punctuality are estimated by simulation and evaluated using the TTPI. Warg´s contribution accounts for most of the article.

2 Measuring timetable quality

In this thesis, a performance index (PI) is defined that describes the quality of a railway timetable with focus on the effect on passengers. Before the PI is presented, methods for measuring timetable quality are described and relevant variables presented. The fields of capacity and socio-economics are described and methods for capacity analysis and the use of passenger-related estimations presented and related to the methods used in the thesis.

2.1 Capacity

There are several definitions of capacity, both qualitative and quantitative, and it can be measured and evaluated in various ways. Traditionally, capacity is defined as the total number of vehicles that can pass an infrastructure under certain circumstances during a time unit. Pérez Herrero (2014) compared congestion on railways and roads using explicit formulas. While delays can be observed from reality and effects of additional trains estimated, describing the relationship between number of trains and resulting delays is difficult as perturbations also depend on many other factors. Abril et al (2008) divide these influencing factors into infrastructure (block and signalling system, single/double track, definition of lines/routes, network effect, track structure/speed limits and lengths of subdivisions, traffic and operation), traffic (new/existing line, train mix, regularity of timetables, traffic peaking factor and priority) and operational characteristics (track interruptions, train stop time, maximum trip time threshold, time window and quality of service/reliability/robustness). They also define the goal of capacity analysis for railways as “estimation of the maximum number of trains”. Capacity analysis generally aims to use existing capacity in a better way (Goverde 2013) or to increase capacity. Recently, timetable flexibility and resilience after delays have also gained in importance. Treating these goals requires the properties that influence capacity to be identified. Aiming for improvements, the impact of different components on capacity and the relationships between the key factors that affect capacity are valuable input. This is what is done in this thesis: aim to analyse timetables with a view to improvement.

Trade-offs between different aims are often necessary. An example can be found in Lindfeldt (2015), where the impact of train heterogeneity and number of trains is analysed. As in many other studies, train delays are used as performance indicator. This is also the case in Nicholson et al (2015), where number and length of delays are measured. In Büker et al (2012), punctuality, mean delay and delay variance are used as performance indicators. Timetabling aims mainly to schedule train slots without conflicts that at the same time meet the demand. Several tools have been developed to simplify this work, for example DONS (Designer of Network Schedules) which can also identify bottlenecks if scheduling is not possible under the given preconditions (Hooghiemstra 1996).

Many approaches have aimed to develop methods for improving capacity analysis

and timetabling. Common tools are analytical methods, simulation and optimisation. An overview describing analytical methods (max-plus algebra and stochastic models) as well as simulation can be found in Vromans et al (2006). Harrod (2012) presents model structures that are suitable for railway timetable planning and classifies them into mixed integer sequencing linear programs, binary integer occupancy programs, hypergraph and periodic event scheduling models. Optimisation aims to maximise or minimise an objective function by varying input data. Simulation on the other hand models reality. In capacity analysis it can be used to estimate the effect of changes. Analytical methods use algebraic and/or numerical methods to solve problems. A combination of methods can be adequate. Abril et al (2008) recommend starting with an analytical approach and continuing with optimisation and simulation. An example of combining the latter can be found in Nicholson et al (2015), where an optimisation-based decision support tool for dispatching is evaluated based on simulation of traffic management decisions.

Analysis also differs depending on the level of detail. While simulation is often quite detailed, analytical models tend to be macroscopic. Here again, a combination can be useful, as Goverde et al (2015) do: Continuing with a conflict analysis of lines, network timetables are optimised in the second step with the aim of reduced travel times. Delay propagation is estimated by a heuristic algorithm. The third step concentrates on corridors, aiming for an optimal speed profile.

2.2 Socio-economics and research connecting both fields

As described in section 1, the aim of socio-economics is to measure all effects a change has on society in monetary terms. Concerning passenger effects, in particular travel time, waiting time, transfers between trains and waiting time at the destination are included. Delays are an important criterion in capacity analysis, as well as capacity utilisation and the possibility to add train paths. Estimation of these requires quite a lot of effort. Normally, simple estimations and averages are used. For example, average delays are often included and valued as a multiple of travel time, e.g. 3.5 in the Swedish recommendations (Trafikverket 2016). The use of delays is limited, for instance in the German recommendations for future infrastructure investments (Intraplan 2006) they are only included if reductions are expected. Eliasson et al (2011) showed how the choice of input data for timetable parameters can give misleading results. A detailed capacity analysis can be helpful to avoid bias caused by inadequate input data. It is also useful when averages do not reflect reality sufficiently well. This might for example be the case for the delay length, as longer delays occurring occasionally have greater impact on travellers than shorter, more frequent delays according to Börjesson et al (2011).

Several authors have included aspects of both fields, e.g. by estimating passenger delays as Sels et al (2016) did by minimising the total expected passenger travel time with the help of optimisation. In the developed timetabling model, stochastically modelled primary delays are applied on the services and the resulting delay estimated depending on the delay distributions of two trains affecting each other and the number of passengers on the second train. The model optimises existing timetables

by reducing the total expected passenger travel time. Robonek et al (2016) also use passenger delay, in their case defined as the difference between demanded and scheduled arrival time. Jiang et al (2012) develop a tool called URT_PDSS (urban rail transit passenger delay simulation system) to investigate the relationship between train and passenger delays. While travellers sometimes benefit of short delays, substantial delays often spread in the network.

Andersson (2014) compares dispatching alternatives by estimating delays caused by the dispatching and calculates travellers´ costs based on delay minutes for different train types. Lindfeldt (2015) evaluates general travel costs based on ticket price, travel time, delay and waiting time for alternatives with different traffic mix on several infrastructure variants by using multiple simulation. Including delays is found to decrease the total number of trains that can be operated on a line. Sato et al (2013) consider travelling and waiting time as well as number of transfers in their timetable rescheduling algorithm. Frank (2013) uses a more extensive approach to include quality. With simple input data for estimating the maximum number of trains that can operate a line, quality is evaluated based on costs and benefits for the involved parties. Increased capacity, flexibility and decreased travel times are used as benefits. In Edwards et al (2016), infrastructural alternatives are compared by estimating both CS and PS for passenger and freight traffic, particularly based on the difference in travel time. Analysis is connected to demand data, considering delays caused if a train´s capacity is reached and a traveller has to wait for the next train. For the analysis, multiple timetables are created for each alternative using the MatLab-based combinatorial timetable evaluation tool TVEM (Lindfeldt, 2010), where infrastructure and traffic systems are modelled macroscopically. Results for the five best timetables are chosen for the evaluation. Delays arising during operation are not considered. The European project ON TIME (University of Birmingham, 2013) aims to “improve railway customer satisfaction through increased capacity and decreased delays for both passengers and freight”. For the objective function, the term “quality of service” is introduced. As Figure 4 shows, this term covers a large range of fields.

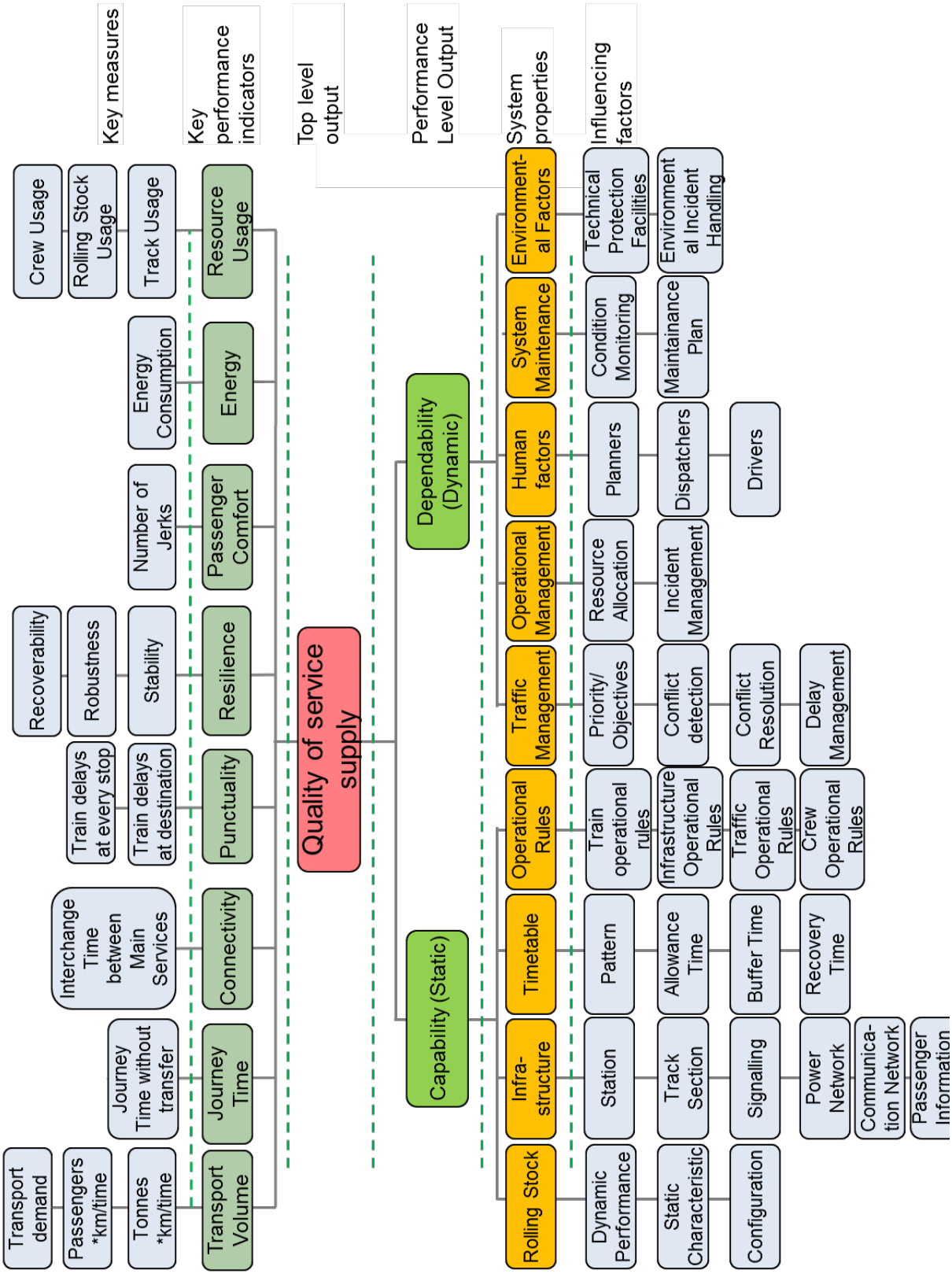
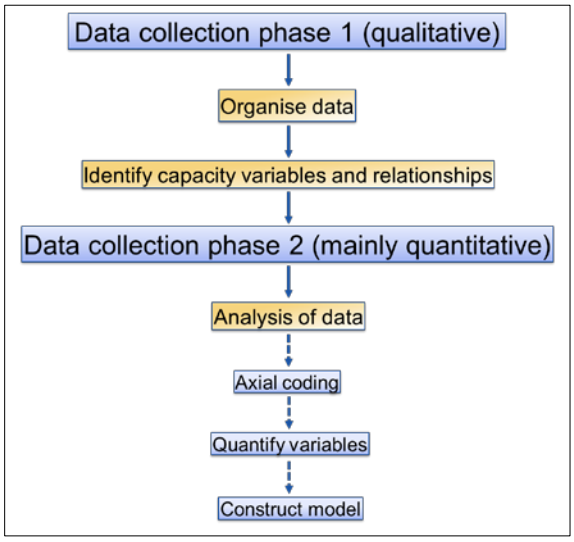


Figure 4: Components included in the term "quality of service" as defined in ON-TIME (University of Birmingham, 2013)

Optimising the defined objective functions for each performance index and combining them with adequate weights would lead to the most efficient solution. The work packages focus on a selection of fields. Punctuality and resilience are for example included in the work packages treating methods for real-time traffic management, operation management of large-scale disruptions and driver advisory systems. Punctuality is not part of the timetabling part (package 3), but delays and recovery time are considered. In the approach, running times and occupation are estimated on a microscopic level while a network timetable is created and simulated on macroscopic level using Monte Carlo simulation for random delays. The best timetable is chosen based on settle time weighted with journey times and further optimised regarding energy consumption.

2.3 Methods used in this thesis

The literature review shows the importance of evaluating timetables with respect to both capacity and socio-economics, but also that it is difficult to do so in a proper way. Many factors affect the timetable and its outcome and it is difficult to take several into account simultaneously. In order to answer the research questions, relevant variables have to be chosen and their values for the cases concerned defined. This requires both literature study but also practical cases. Capacity analysis is an important part of that work. Many approaches aim in different ways to estimate capacity and improve the use of available capacity. Some include effects on travellers as evaluation criteria. However, it was shown that these studies often focus on capacity with limited socio-economic input. On the other hand, capacity is barely considered in economic evaluations. The number of characteristics included in the methods is often limited. The importance of combining both is highlighted, but often difficult to realise. For the multidisciplinary task to merge capacity and socio-economics, the combination of several methods was found to be adequate for the purposes of the present thesis.



In the articles included in this thesis, two kinds of methods are developed: One for finding relevant variables and methods to reveal their values and connect them (Figure 5), the other one for the evaluation of the timetable itself.

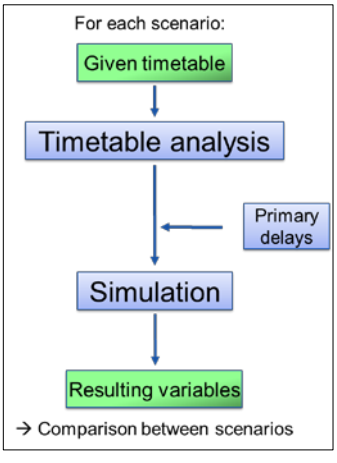


Figure 5 shows that the model was

Figure 5: Method for developing the model *Figure 6: Model structure*

developed in a mixed methods study (paper A) using qualitative and quantitative methods. Based on a literature review and interviews, an overview of variables, methods and relationships was created which was reinforced by the second part of the data collection where the focus was on a survey study of express trains on the Western Main line. The results in the form of relevant input variables for a future model as well as relationships between them were analysed and an evaluation structure designed. This structure is the one shown in Figure 6. It was applied and developed in several case studies. Axial coding, quantifying of variables and model construction was initiated. As the graphic shows, the basic idea is that a given timetable is analysed regarding the timetable itself as well as the result of operation. Based on the resulting variables, each alternative is evaluated and can be compared to another one. Variables like travel time and headways that are commonly used in economics can be read directly from the timetable. They were classified as static variables in this thesis in contrast to dynamic variables. The latter expression was introduced for variables describing the outcome of operation or its estimation (for instance optimisation or simulation). Each case study uses different methods in the presented components. This is illustrated in Table 2.

Table 2: Overview of case studies and applied methods (case study 2 (paper B) is not included as the model is not applied in that study)

	Case study 1 (paper A)	Case study 3 (paper C)	Case study 4 (paper C)
Comparison of	Scenarios	Departures	Scenarios
Timetable	Based on supply, optimized in TVEM	Real timetable	Scenarios based on real timetable
Timetable analysis	TVEM/RailSys	RailSys	RailSys
Analysis of operation	Simulation (RailSys)	Empirical data	Simulation (RailSys)
Evaluation	Comparison of resulting variables	Train slot performance index (TSPI)	Timetable performance index (TTPI)

While case studies 1 (paper A) and 4 (paper C) treat the evaluation of timetable scenarios, different departures in a timetable are compared in the third study (paper C). In case study 1, possibilities to increase the service supply are analysed, as well as the increase in speed heterogeneity by increasing the maximum speed of express trains from 200 to 250 km/h. The scenarios in case study 4 treat variations of delay level, frequency and supplement.

In case studies 3 and 4 timetable data comes from the Swedish timetable for 2014 (T14). The microscopic simulation tool RailSys (Radtke et al 2001) is used for timetable analysis. In RailSys, train types and infrastructure are coded and timetables scheduled based on that. This method makes it possible to obtain exact values at the same time as conflicts in the timetable are pointed out. It is especially suitable for

variables that cannot be read directly from the timetable itself, such as for example time supplement, as described in the next section. In the first case study, an additional timetable analysis is performed with TVEM. This tool reveals all alternative ways to schedule the defined services (comparable to what was demonstrated in Figure 2 in section 1.2 for the scheduling of three train services) and shows the possibilities for adding more train slots. This method is in particular suitable for future scenarios with unknown timetable, as the way of scheduling can affect both static and dynamic variables. It provides valuable information about the possibilities to schedule the planned supply, especially regarding flexibility. However, it was not applied in the remaining studies as these treat the real timetable and a total remake would entail too great effort due to the existing preconditions, e.g. the various connections to other lines.

The next step is the analysis of operation. Here, the timetable is evaluated regarding dynamic characteristics, e.g. delays. In case study 3, delay data for January-June 2014 is used to determine the dynamic variables. In the fourth case study, delay data from these statistics is applied on the scenarios and simulation executed in RailSys. Simulation is done for a certain number of circles by statistically adding delays according to distributions modelling the real entry, dwell time and run time disturbances. Simulation in RailSys was also used in case study 1, where the timetable alternative that performed best in the timetable analysis is simulated for each scenario.

Evaluation in the first case study is based on a comparison of resulting data, one at a time for each scenario. A common result is for example that the timetabling flexibility deteriorates with increased traffic. In the other two studies, the PI is used, meaning that selected variables are merged using a formula that represents the relationship between them. This PI is further described in the following section.

Unlike the method Goverde et al (2015) used, where macroscopic analysis was followed by microscopic (see section 2.2), analysis here starts on a macroscopic level and continues on a macroscopic. The method used in this thesis is based on both ex-ante and ex-post analysis, as both timetable criteria and traffic performance are included. The focus is turned onto the effects for travellers. For example, the heterogeneity on a line is not important in itself but rather how it affects travellers. This means that it might not be necessary to measure each criterion itself, when the effect on travellers can be covered in another way, for example by measurement of the delay. It is important that characteristics are not included several times.

Timetable analysis with TVEM makes it possible to identify further valuable variables for the evaluation. This method is for example also applied in Edwards et al (2016), but there, delays are not considered. Simulation was used to reveal the dynamic variables as it gives the opportunity to estimate how primary delays spread and what they result in. One reason for choosing simulation instead of optimisation is that traffic on the considered lines is heterogeneous. Optimisation is difficult and time-consuming for detailed models, which makes simulation more adequate. For this reason, it can be used for more in-depth analysis, for example, as here, to handle

delays, which is illustrated in Wolsey et al (1999). If the model is detailed and accurate enough, simulation can reflect reality quite well, which is an advantage when the quality of a timetable is to be analysed, even if it can never meet the real outcome in the way empirical delay data does. However, the latter can only be used for an existing situation, while simulation and optimisation can estimate the effects for adjusted scenarios. The model should therefore be calibrated using Real data. For the lines treated here, calibration was done in earlier projects and is regarded as sufficient as simulation results seem to be realistic and the methods adequate.

The described methods refer mainly to the choice and estimation of variables (RQ1). The next section is about the chosen variables in the papers included in this thesis. Referring to RQ2, the evaluation structure that was developed in the papers is then presented. The structure is based on the methods described here, and parameters from other research and common methods. Timetable quality is measured by means of variables describing each train slot focussing on travellers´ benefits. Together, they describe the whole timetable. To measure this quality, relevant variables have to be identified and related with parameters based on their relationships to each other. Performing this for different scenarios makes it possible to evaluate alternative cases and strategies. However, choosing and measuring the right variables and parameters can be difficult, especially if changes are to be analysed and input data is difficult to estimate.

2.4 Variables in this thesis

As described earlier, variables are in this research divided into two categories: Static, describing the timetable, and dynamic, describing how the timetable performs when it is operated. In the following, the variables measured in the case studies and used to evaluate timetables are listed. More variables were discussed, but not applied. The choice of variables was based on what was found to be relevant and generally applicable, as well as the possibilities the chosen methods offer. Furthermore, simple but efficient measures were preferred to simplify future application.

The static variables can be divided into variables that focus on the train path and variables that concentrate on the whole timetable or a group of services. The focus lies on the CS at the destination so that dwell times, deceleration and acceleration are included in the total time. However, technical minimum running time and time supplement are distinguished. Technical minimum running time describes the bare timetable time without delays. Time supplements are mostly added to balance uncertainties, recover from delays and/or facilitate the timetabling. The timetable time presented for the traveller contains time supplements. In reality, the total time it takes to travel from A to B is the sum of both together with the actual delay (Figure 7).

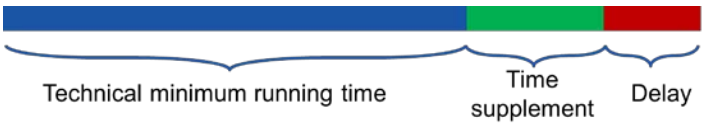


Figure 7: Travel time experienced by the traveller

Timetable flexibility refers to how the planned services as a whole can be scheduled on the given infrastructure. For instance, the timetable in case 1 in Figure 1 is not very flexible as departure time is the only thing that can be changed if shortest travel times and maximum service density are to be realised. A more flexible set-up allows more timetable suggestions and ways to satisfy the customer. For more complex timetables, where heterogeneous services have to be scheduled, this is an advantage as it allows the timetable to be better adjusted to the demand. Here, the time supplement is also an important criterion as scheduling becomes easier with homogenous traffic. In this thesis, the number of possible timetable alternatives based on a given service level and the possibility to add train paths are measured as indicators of quality. In addition, timetable alternatives were compared based on the possibility to have periodic timetables. It was shown that increased heterogeneity and traffic makes this more difficult. For example, the desired headway of 20 minutes between commuter trains had to be changed to irregular intervals in some alternatives in order to realise an operational timetable. This reduces its attractiveness for the traveller. Also the fact that on the studied lines, many services start or continue on adjacent lines requires a certain flexibility to allow the assumption that the timetable suggestion can fit into the adjacent lines´ schedule, which is not included in this study. Furthermore, it is important if delays require rescheduling.

The dynamic variables analysed in this thesis include punctuality [%], average delay based on different assumptions [min], median for delay, standard deviation/reliability ratio and resilience. As stated earlier, delay is influenced by various factors and not constant for each day, e.g. the scheduled travel time. For this reason, it is best described by statistical measurements for delay distributions. The listed variables are an extract of what can be used. Punctuality describes the proportion of trains on time (a common limit is to consider all arrivals within five minutes of planned time as on time), and average delay the deviation from the scheduled departure. Median and standard deviation give a hint about the shape of the delay distribution. There are various definitions of punctuality. In an international quality study by Finger (2012), trains arriving less than six minutes late were applied as the limit for trains being on time, the same practice as used for long-distance trains in Sweden. But also 15:59 minutes has been used in Sweden (Törnquist Krasemann (2014)). Different measurements provide different kinds of information and choosing the adequate one can be difficult. Figure 8 shows how the average delay values differ with the choice of data, raising the question of whether it is more relevant to analyse for instance the average delay for all departures, all late departures or all “on-time” departures based on the punctuality level.

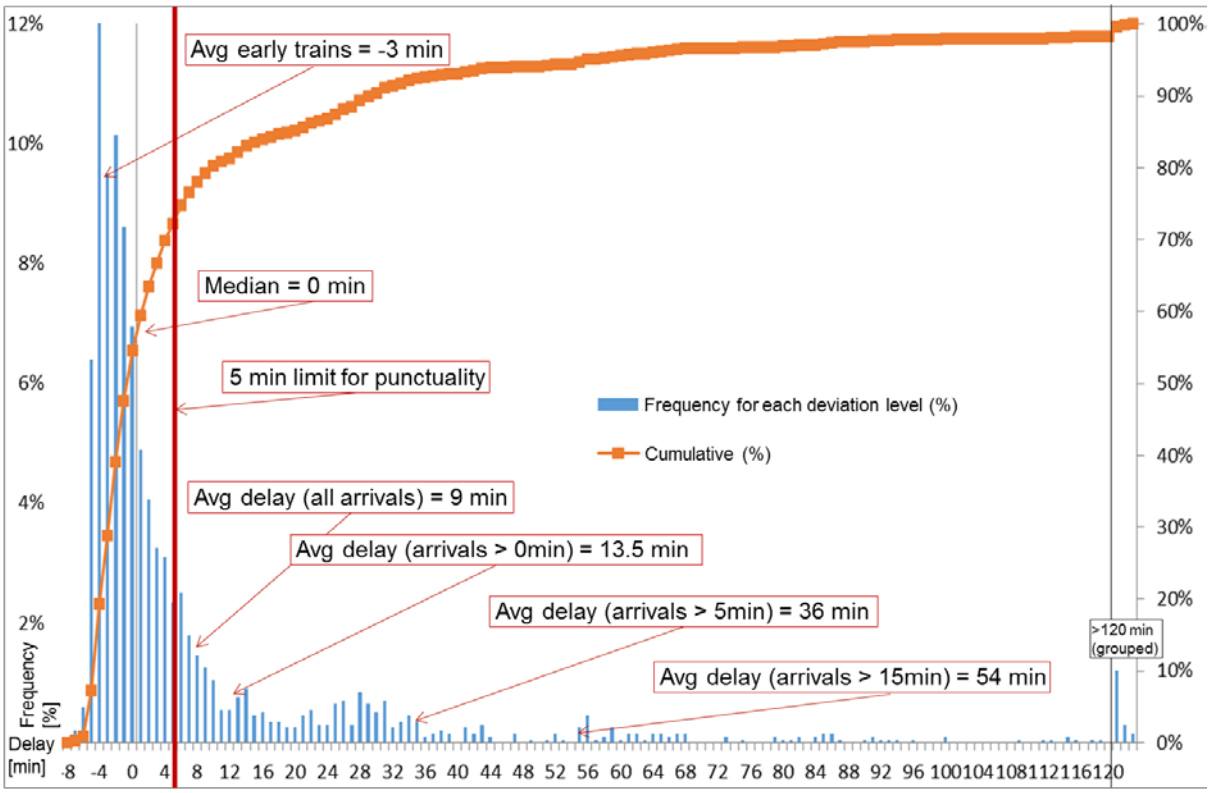


Figure 8: Deviation from the scheduled arrival time in Gothenburg (number of trains arriving x min early/late and cumulative percentage) and different statistical measurements for the arrival distribution. Delays exceeding 120 min are grouped (121-180 min, 181-240 and more). Source: Warg et al (2016)

The figure also shows the delay distribution. Values are widely spread with delays over 180 minutes. Such delays affect the average, at the same time as their impact on a traveller differs to the one a short delay has. The standard deviation is a measure that can be used for further description of the distribution, as two distributions with the same average can differ widely. A variable that describes the variability in travel time is reliability, often expressed as the variability related to travel time (Asensio et al 2008). As stated before, large delays occurring seldom have larger disutility for travellers than shorter, more frequent delays according to Börjesson et al (2010). In the questionnaire study (paper B), it is shown that large delays affect the choice of departure time when the next trip is planned. However, no correlation between the length of the delay and the effect could be found. The examples and findings show that it is important to take as many aspects as possible into account when evaluating a timetable.

2.5 Converting the variables into a performance index (PI)

In order to be able to use the results in the form of values for each variable, a relationship between the variables has to be found that makes it possible to compare and evaluate alternatives. The performance index (PI) in this thesis is time-based. It expresses the quality of a departure/timetable in time, which means a time

comparable to the scheduled time but adjusted based on further characteristics. The following two indices are defined:

$$Train\ slot\ performance\ index\ TSPI_s = \sum_{i=1}^{n} c_i * w_{si} \qquad \text{(Equation 1)}$$

$$Timetable\ value\ TTPI = \frac{\sum_{i=1}^{s} s_i}{s} \qquad \text{(Equation 2)}$$

where s=departure, w_{si} =value of the certain variable i for train slot s and an associated c_i = parameter describing the variable's relationship to the other variables. The TSPI describes a single train departure and can be used to compare similar departures and to detect less profitable ones. The fact that people have different desired departure times is not included here as the TSPI aims to compare the properties of the train slot independently of arrival/departure times. This means that it can be assumed that all trains depart at the same time and the traveller chooses the one with the shortest resulting departure value. Compared to Figure 7, where all variables are weighted the same, a parameter is used to adjust each variable according to the value for the user. The sum of all products of variables and belonging parameters is the total time, the TSPI. With TTPI, the whole timetable can be evaluated and compared to an alternative one with some restrictions concerning the variety of the service supply. Changes in the timetable can be tested in order to compare if the original situation can be improved. Both PIs are used in the case studies but there are still a great many limitations, which is further referred to in the section on future work.

Parameters and model configuration are chosen with the help of common methods and recommendations. The pairs of variables/parameters that are collected contain average delay, standard deviation and punctuality in addition to the static variables. In paper C, different model configurations with varying input variables and parameters were tested to compare departures and in a second step timetable alternatives. It was shown that the configuration influences the ranking of the departures to a large extent, but with the adequate choice it can be a useful method for comparing alternatives. Further work with variables and parameters is needed before a final model configuration for the TSPI and TTPI can be proposed.

3 Conclusions

Time savings and passenger valuations are a cornerstone of evaluating capacity usage and socio-economic benefits to reach a cost-efficient and smooth-running railway system. With increasing awareness of the importance of interaction between capacity and economics, research in these fields strives increasingly to consider components of the other field. This important connection was also the motivation for this thesis. Achieving improvements by timetable evaluation with focus on quality for travellers was defined as the overall aim. This comprises the following objectives:

- Identification of relevant variables describing quality
- Definition of an adequate method to identify the variables
- Development of a performance index (PI) that connects the variables and can be used to compare alternatives

Variables that describe capacity and quality were discussed and several of them measured in case studies where different methods were applied. Properties for the lines considered were presented, but also how adjustments affect these properties. It was also shown how different evaluation methods can contribute when a variable for a performance index is to be estimated. TVEM is for example useful for evaluating the flexibility of timetables, while RailSys is adequate for estimation of delays, especially for complex, heterogeneous timetables. The identified variables were used to evaluate the goodness of timetables. In some cases by directly comparing the variables themselves, for example the total average delay, in others by weighting several variables. While common methods from capacity analysis were used to identify the variables, the evaluation was based on methods from socio-economics, in particular concerning relationships between variables. A suggestion for two performance indices (TSPI and TTPI) based on variables combined by parameters describing the relationship was made. The configuration of these PIs is based on the available data and knowledge about relationships and can easily be adopted by adding/removing variables and parameters. The PIs can be used in an easy way when only little data is available, but also enable advanced analysis when the sources are extensive. In general, analysis that attempts to combine the fields of capacity and socio-economics is often limited to averages and a few variables, while this method makes it possible to take more aspects into consideration.

The thesis presents different ways of measuring and evaluating the quality of a railway timetable considering both capacity and socio-economics from a consumer point of view. It combines common practice from both fields and shows how simulation can be used to estimate the effects of strategies. A selection of methods was applied on two lines with dense heterogeneous traffic and demonstrated the characteristics of such lines from different points of view. This is valuable information for judging the quality level and evaluating adjustments.

It was confirmed that delays are important for travellers and affect their choice of departure. Both the risk of delay and the temporal quantity are important, and this

importance is influenced by a great many other variables. The common ways to include delays often simplify these characteristics. Input data is for example often limited to the average delay even if the delay distribution for two departures with the same average delay can be very different. Here, analytical methods and simulation are merged to identify input variables. This enables relevant characteristics to be evaluated. Further, a performance index that combines several variables is recommended and relationships between variables presented and discussed. This is done in two steps, first for train slots, later for a whole timetable. It is shown that the choice of variables and parameters is important as different model configurations change the order in which alternatives are prioritised. The resulting PI can be used to compare different departures but also alternative timetable suggestions. The first application can for instance be used to find less profitable departures in the timetable. Whether adding a departure lowers the value of the timetable instead of improving it can also be detected, which might for example be the case if a new operator applies for a similar departure to the existing ones that operate in a regular interval timetable. In the manner described, changes can be evaluated to find the best solution to improve perceived quality in rail services. This method is a new evaluation approach and can support timetable planners and decision-makers. The presented PI expresses the value in time, which increases transparency for the potential passenger. It can be included into other evaluation methods and improve their possibilities for evaluation; for socio-economics by adding capacity aspects such as delays, for capacity analysis by complementing the data with passenger valuations. In addition, it contributes to the development of the interaction between the fields.

This makes the thesis important for both capacity analysis and socio-economic evaluation. It becomes easier to include valuable information in a proper way and with consideration of a broader range of data. It is a first step towards a future method that can provide valuable help for dispatching, timetable planning, allocation of timetable slots, investments, etc.

4 Future work

The work presented here focuses on assessing changes in a timetable using simulation and suggests an evaluation model resulting in a PI, which was developed and tested in three case studies. It consists of variables describing the timetable or its effect on travellers and parameters for the relationships between the variables. It is configured by the choice of variables and parameters. Some were tested in the case studies included in this thesis, but the configuration should be further developed based on a new case study with simulation of more cases with small changes in the timetable. More alternatives should be simulated and different statistical measures for evaluation used to test the model. Additional static variables should be included, e.g. a further developed analysis of the effect of changes in frequency. An idea is also to adjust the PI to also consider arrival/departure times that are important for the travellers' choices. In addition to CS, other effects should also be included and a way to include freight traffic would also be valuable. Applicability on single-track lines or homogenous timetables would also be interesting to test. Furthermore, it would be interesting to use variables from the TVEM tool in the TTPI in the way it was done in paper A. Using multiple simulation methods as developed by Sipilä (2015) or Lindfeldt (2015) would be a valuable extension of the method where timetables that offer larger possibilities for changes are analysed (many of the services that operate on the analysed lines continue their journey on other lines, which makes it difficult to radically change the existing timetable). The proposed method can also be used to optimise timetables by maximising socio-economic effects. Another suggestion is to use the method to estimate the maximum number of trains in a timetable. An extension to network evaluation would also be valuable, as would the connection to demand forecast tools.

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