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CAPACITY AND PUNCTUALITY IN RAILWAY INVESTMENT SOCIO-ECONOMIC ASSESSMENT



Capacity and Punctuality in Railway Investment Socio-Economic Assessment

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Abstract

Background and objectives

Impacts of the infrastructure investments on railway capacity and traffic punctuality are both commonly assessed in socio-economic analyses. Both are also commonly considered as a justification for investments. However, there has not been an established method for measuring capacity and delays in socio-economic assessments, and moreover, there has not been a method to consider delays and their consequent impacts in the cost-benefit analyses.

This study aims to develop two methods to be applied in socio-economic assessment. The first method is aimed at determining whether the capacity of a line is sufficient or scarce, enabling the rail network manager to identify line saturation. The second is a method for the evaluation of delay propagation on a line given a set of parameters of the line, allowing the network manager to evaluate the effect of investments on train punctuality. Both methods are developed with the aim of being easy to apply by non-expert users in required socio-economic analyses.

Delay evaluation methods

An analysis of the delay propagation on real single and double tracks revealed that delays are propagated due to different reasons and, thus, separate models for single and double tracks had to be developed. The developed methods for single and double track sections resulted in the following formulas:

$$\text{Single track: } t_{d+,g,e} = 0.917 \cdot t_{d+,g,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x$$

Double track:

$$t_{d+,e} = 22,443 \cdot \sum_{b \in B} (w(b) \cdot bf_g^b) - 0,033 \cdot t_{mr,g} + 1,029 \cdot t_{d+,g,i} - 0,001 \cdot t_{d-,g,i}$$

These regressions provided goodness of 61.0% for single tracks and 73.9% for double tracks. Both methods give the most reliable results on tracks with a high number of trains.

Capacity consumption evaluation method

Based on a literature review, capacity can be estimated through three perspectives: using theoretical capacity (maximum number of trains on a given time), capacity consumption methods and capacity indices. Capacity consumption methods were recognized to have the highest potential. However, due to the lack of unambiguous guidance, a more detailed manual for Finnish circumstances was developed.

Following the new guidelines, capacity consumption is calculated for line sections for each hour to indicate the spare capacity of the line if train services can be more evenly spaced. The critical hours are when the value of capacity consumption rises above a given threshold value at any line section. These threshold values, originally defined by UIC, are 85% for suburban passenger traffic lines and 75% for other lines.

Applicability of the Methods in Socio-economic Assessment Cases

All developed methods have high potential for becoming the standard tools to be used in Finland. The developed methods are designed to evaluate the impact of various infrastructure investments on capacity consumption and the improvement of the punctuality of trains. The methods are applicable for investments that have an impact on the planned timetable. The clearer impact the methods have, the clearer results will be received.

Case study conclusions and further study recommendations

Performing capacity consumption and delay calculations for three actual socio-economic assessments revealed that the methods are suitable and don't bring a high additional workload to the socio-economic assessment process. Capacity consumption method revealed the desired information on where and when possible bottlenecks are occurring, and how severe these bottlenecks are.

Adding the value of delayed time to the cost-benefit calculations revealed the following increases in the cost-benefit ratios:

- Ylivieska–Iisalmi–Kontiomäki 0,73 → 0,78
- Luumäki–Imatra
 - Scenario 1: 0,41 → 0,49
 - Scenario 2: 0,60 → 0,66
- Espoo commuter track extension 0,88 → 0,91

Before performing the calculations, the presumption was that punctuality would play a major role when calculating the cost-benefit ratio. All these increments were lower than expected. Possible explanations and further study recommendations are:

- Upgrading the railway line will have only minor impact on total delays since the majority of delays occur at nodes of the network (e.g. railyards and stations). In studied cases, developing the line track will not remove these delays.
- The delay calculation method developed in this study examines the section being upgraded but it doesn't consider the propagation of delays outside the section via exchange connections (passenger trains waiting for delayed trains at stations) or rotation of rolling stock and personnel. By propagation via these linkages the eventual number of delays may be much higher.
- Low punctuality typically leads to passengers choosing other modes of transport. This leads to lower passenger numbers and reduced ticket revenue compared to the situation where punctuality is at a normal level. This impact is not evaluated in this study.
- Calculation of the delays is highly dependent on the input delay given in the formula. Evaluating the change of input delay when capacity increases or number of train changes is difficult. This may lead to underestimating the input delay and so the calculated delay.

Other noted recommendations for further study are:

- Margins were estimated and considered as constant numbers in the delay methods development process. As the margins have a major impact on the reliability, it might be valuable to re-run the regressions when more detailed information on the margins is generated. This will most likely increase the goodness of the regressions.
- The calculation process for capacity consumption requires multiple steps that could be automated with relatively low workload. An automated tool that would be used by all users, would decrease workload and reduce the risk for calculation mistakes.
- The value of time for delayed time in general was excluded from this study. It should be re-considered when the delay calculation tool is taken into the Finnish Transport Infrastructure Agency's socio-economic assessment instructions.

Kapasiteetin ja täsmällisyyden arvointi ratahankkeiden hankearvioinneissa. Väylävirasto. Helsinki 2019. Väyläviraston tutkimuksia 5/2019. 80 sivua ja 4 liitettä. ISSN 2490-0982, ISBN 978-952-317-666-9.

Asiasanat: ratahankkeet, rautatiet, kapasiteetti, täsmällisyys

Tiivistelmä

Tausta ja tavoitteet

Ratainvestointien vaikutuksia rataverkon kapasiteettiin ja liikenteen täsmällisyyteen arvioidaan usein hankearvioinneissa. Täsmällisyyden paranemista käytetään usein myös hankkeiden perusteluna. Kapasiteetin ja täsmällisyyden mittamiseen ei kuitenkaan ole ollut vakiintunutta menetelmää, eikä täsmällisyysvaikutuksia ole pystytty huomioimaan hyöty-kustannuslaskelmissa.

Tämän selityksen tavoitteena oli kehittää kaksi menetelmää, joiden avulla näitä vaikutuksia voidaan tarkastella ratahankkeiden hankearvioinneissa. Ensimmäisen menetelmän avulla arvioidaan rataverkon vapaan kapasiteetin määrää ja mahdollisuuksia kasvattaa junatarjontaa. Toisen menetelmän avulla arvioidaan tarkasteltavalla rataosuudella syntyviä täsmällisyysvaikutuksia valitulla junatarjonnalla. Molempien menetelmien kehitystyössä on otettu helpokäyttöisyyss huomioon siten, että ne eivät merkittävästi kasvata hankearvointien työmääriä.

Viiveiden laskentamenetelmät

Täsmällisyystietojen analysoinnin perusteella yksi- ja kaksiraiteisilla rataosuuksilla viiveiden syntymiseen vaikuttavat erilaiset tekijät. Tämän vuoksi yksi- ja kaksiraiteisille rataosuuksille kehitettiin eri muuttujista koostuvat laskentakaavat:

$$\text{Yksiraiteinen: } t_{d+,g,e} = 0.917 \cdot t_{d+,g,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x$$

Kaksiraiteinen:

$$t_{d+,e} = 22,443 \cdot \sum_{b \in B} (w(b) \cdot bf_g^b) - 0,033 \cdot t_{mr,g} + 1,029 \cdot t_{d+,g,i} - 0,001 \cdot t_{d-,g,i}$$

Laskentakaavat kuvaavat täsmällisyysvaikutuksia keskimäärin 61,0 % selitysasteella yksiraiteilla rataosilla ja 73,9 % selitysasteella kaksiraiteilla rataosilla. Tulokset ovat sitä luotettavampia, mitä enemmän tarkasteltavalla rataosuudella on liikennettä.

Kapasiteetin käyttöasteen laskentamenetelmä

Kansainvälisen kirjallisuuskatsauksen perusteella rataverkon kapasiteetin riittävyyttä voidaan arvioida kolmesta eri näkökulmasta: teoreettinen välityskyky (maksimijunamäärä tarkasteluajanjaksossa), kapasiteetin käyttöaste sekä erilaiset kapasiteettia kuvaavat indeksit. Näistä kapasiteetin käyttöasteen laskentaan perustuvien menetelmien todettiin vastaavan parhaiten hankearvointien tarpeita. Suomen olosuhteisiin päättiin kehittää yksityiskohtaisempi menetelmä ja ohjeistus, joka perustuu UIC 406 -menetelmään.

Kehityssä menetelmässä kapasiteetin käyttöaste lasketaan tarkasteltavan rataosuuden jokaiselle liikenepaikkavälille vuorokauden jokaisena tuntina. Rataosuuden kuormitus on kriittisellä tasolla, jos käyttöaste nousee jollain liikenepaikkavälillä yli annetun raja-arvon. UIC:n määrittämät raja-arvot ovat 85 % kaupunkiradoilla ja 75 % muilla rataosuuksilla.

Menetelmien sovellettavuus hankearvioinneissa

Kehitetyt laskentamenetelmät on mahdollista ottaa yleisesti käyttöön ratahankkeiden hankearvioinneissa. Menetelmien avulla voidaan arvioida erilaisten investointivaihtoehtojen vaikutuksia kapasiteetin käyttöästeeseen ja liikenteen täsmällisyyteen. Menetelmät soveltuват kaikkien sellaisten investointien tarkasteluun, joissa liikenteen aikataulu muuttuu.

Johtopäätökset tapaustutkimuksista ja jatkoselvitystarpeet

Kapasiteetin käyttöästeen ja viiveiden laskenta kolmelle aikaisemmin laaditulle hankearvointitapaikselle osoitti, että menetelmää voidaan soveltaa ilman merkittävää työmäärään kasvua. Kapasiteetin käyttöästeen laskennan avulla pystytettiin tunnistamaan välityskyvyn pullonkaulat ja niiden kriittisyys.

Hankkeiden täsmällisyysvaikutusten huomioiminen hyöty-kustannuslaskelmissa muutti hankkeiden hyöty-kustannussuheteita seuraavasti:

- Ylivieska–Iisalmi–Kontiomäki $0,73 \rightarrow 0,78$
- Luumäki–Imatra
 - Hankevaihtoehto 1: $0,41 \rightarrow 0,49$
 - Hankevaihtoehto 2: $0,60 \rightarrow 0,66$
- Espoon kaupunkirata $0,88 \rightarrow 0,91$

Ennen kyseisten hankkeiden täsmällisyysvaikutusten laskentaa oletuksena oli, että täsmällisyydellä olisi merkittävä vaikutus hankkeiden kannattavuuteen. Vaikutus hyöty-kustannussuheteeseen oli kuitenkin ennakkooletusta pienempi. Syitä tähän voivat olla mm.:

- Suurin osa rataverkolla syntyy viiveistä syntyy ratapihoilla ja muissa solmupisteissä. Tarkasteluissa hankkeissa investoinnit kohdistuvat linjaosuuksiin, jotka eivät poista näitä viiveitä.
- Viiveiden laskentamenetelmät tarkastelevat viiveitä vain tarkasteltavana olevalla rataosuudella, eivätkä ne huomioi viiveiden heijastumista rataosuuden ulkopuolelle vaihtoyhteyksien tai kalusto- ja henkilöstökierron kautta. Näiden kautta viiveiden todellinen määrä voi kertautua huomattavasti suuremmaksi.
- Heikentynyt täsmällisyys johtaa tavallisesti matkustajien siirtymiseen muihin kulkumuotoihin, mikä johtaa liikennöitsijän lippitulojen laskuun. Tämän vaikutuksen suuruutta ei tässä työssä arvioitu.
- Viiveiden laskentamenetelmissä tulos on hyvin riippuvainen laskennassa käytetystä ns. saapumisviiveestä, jonka määrittäminen luotettavasti voi olla vaikeaa. Tämä voi johtaa täsmällisyysvaikutusten aliarpointiin.

Muita mahdollisia jatkoselvitysten aiheita ovat:

- Laskennassa aikatauluihin sisältyvä pelivaransosalta käytettiin vakioarvoja, koska tarkkaa tietoa eri rataosuuksien ja junatyypien pelivaroiista ei ollut käytettävissä. Pelivarolla on merkittävä vaikutus laskentatuloksiin, jonka vuoksi regressiomallien tarkistaminen yksityiskohtaisempien pelivaratietojen perusteella parantaisi niiden luotettavuutta.
- Kapasiteetin käyttöästeen laskenta edellyttää useita sellaisia työvaiheita, jotka voitaisiin automatisoida suhteellisen pienellä työmäärellä. Automatisoitunut laskentatyökalu vähentäisi työmäärää ja virheiden mahdollisuutta laskentaprosessissa.
- Työssä ei arvioitu erikseen viiveiden ajan arvoa. Kun laskentamenetelmät viedään Väyläviraston hankearvointiohjeistukseen, tulee myös ajan arvoa tarkastella.

Uppskattning av kapacitet och punktlighet i projektbedömningar av banprojekt. Trafikledsverket. Helsingfors 2019. Trafikledsverkets undersökningar 5/2019. 80 sidor och 4 bilagor. ISSN 2490-0982, ISBN 978-952-317-666-9.

Sammandrag

Bakgrund och mål

Baninvesteringars effekter på bannätets kapacitet och trafikens punktlighet uppskattas ofta i projektbedömningar. Bättre punktlighet anges ofta även som motivering för projekten. Det har dock inte funnits någon fastställd metod för mätning av kapacitet och punktlighet och punktlighetseffekter har inte kunnat beaktas i kostnads-nyttoberäkningar.

Syftet med denna studie var att utveckla två metoder med vilka dessa effekter kan granskas i projektbedömningar av banprojekt. Med hjälp av den första metoden bedömer man mängden fri kapacitet i bannätet och möjligheterna att utöka tågutbudet. Med den andra metoden bedömer man vilka punktlighetseffekter som uppstår på det banavsnitt som granskas med valt tågutbud. I utvecklingsarbetet med båda metoderna har man satsat på att göra dem enkla att använda på så sätt att de inte påtagligt ökar arbetsmängden i projektbedömningarna.

Beräkningsmetoder för förseningar

En analys av punktlighetsdata visar att olika faktorer påverkar uppkomsten av förseningar på enkel- och dubbelspåriga banavsnitt. Av denna orsak utvecklade man kalkylformler med olika variabler för enkel- och dubbelspåriga banavsnitt:

Enkelspårigt banavsnitt: $t_{d+,g,e} = 0.917 \cdot t_{d+,g,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x$

Dubbelspårigt banavsnitt:

$$t_{d+,e} = 22,443 \cdot \sum_{b \in B} (w(b) \cdot bf_g^b) - 0,033 \cdot t_{mr,g} + 1,029 \cdot t_{d+,g,i} - 0,001 \cdot t_{d-,g,i}$$

Kalkylformlerna beskriver punktlighetseffekterna med en genomsnittlig förklaringsgrad på 61,0 procent på enkelspåriga banavsnitt och med en förklaringsgrad på 73,9 procent på dubbelspåriga banavsnitt. Resultaten är mer tillförlitliga ju mer trafik ett granskat banavsnitt har.

Metod för beräkning av kapacitetsutnyttjande

Utifrån en internationell litteraturöversikt kan bannätets kapacitet bedömas ur tre olika perspektiv: teoretisk genomströmningskapacitet (maximalt antal tåg under observationsperioden), kapacitetsutnyttjande samt olika index som beskriver kapaciteten. Av dessa konstaterades de metoder som baserar sig på beräkning av kapacitetsutnyttjande bäst motsvara behoven i projektbedömningarna. För Finlands förhållanden beslöt man utveckla en mer detaljerad metod inklusive instruktioner, som baseras på metoden UIC 406.

I metoden beräknas kapacitetsutnyttjandet för det banavsnitt som granskas för varje trafikplatsavsnitt under dygnets alla timmar. Belastningen på banavsnittet ligger på en kritisk nivå om kapacitetsutnyttjandet på något trafikplatsavsnitt överstiger det givna gränsvärdet. De gränsvärden som fastställs i UIC är 85 procent på stadsbanor och 75 procent på övriga banavsnitt.

Metodernas tillämplighet i projektbedömningar

De beräkningsmetoder som har utvecklats kan tas i allmänt bruk i projektbedömningar av banprojekt. Med hjälp av metoderna kan man bedöma vilka effekter olika investeringsalternativ har på kapacitetsutnyttjandet och trafikens punktlighet. Metoderna lämpar sig för granskning av alla sådana investeringar som medför en ändrad trafiktidtabell.

Slutsatser från fallstudierna och behov av fortsatta utredningar

Beräkningen av kapacitetsutnyttjande och förseningar för tre tidigare uppgjorda projektbedömningsfall visade att metoderna kan tillämpas utan att arbetsmängden ökar väsentligt. Med hjälp av beräkningen av kapacitetsutnyttjande kunde man identifiera flaskhalsarna i genomströmningen och få en uppfattning om hur kritiska de är.

När projektens punktlighetseffekter beaktades i kostnads-nyttoberäkningarna ändrades projektens kostnads-nyttoförhållanden enligt följande:

- Ylivieska–Idensalmi–Kontiomäki $0,73 \rightarrow 0,78$
- Luumäki–Imatra
 - Projektalternativ 1: $0,41 \rightarrow 0,49$
 - Projektalternativ 2: $0,60 \rightarrow 0,66$
- Esbo stadsbana $0,88 \rightarrow 0,91$

Före beräkningen av punktlighetseffekter för de aktuella projekten var hypotesen att punktligheten skulle ha en betydande inverkan på projektens lönsamhet. Inverkan på kostnads-nyttoförhållandet var dock mindre än väntat. Orsaker till detta var bland annat:

- Merparten av förseningarna i bannätet uppstår på bangårdarna och i andra knutpunkter. I de granskade projekten riktades investeringarna till sådana banavsnitt som inte avlägsnar dessa förseningar.
- Beräkningsmetoderna för förseningar granskar förseningar endast på det banavsnitt som är föremål för granskningen, och beaktar inte hur förseningarna återspeglas utanför banavsnittet via bytesförbindelser eller materiel- och personalmobilitet. Via dessa kan den verkliga mängden förseningar upprepas och bli betydligt större.
- En försämrad punktlighet leder i regel till att resenärerna väljer andra färdmedel, vilket leder till lägre biljettintäkter för trafikidkaren. Storleken av denna effekt har inte bedömts i detta arbete.
- Resultatet vid metoder för beräkning av förseningar är starkt beroende av vilken så kallad ankomstförsening som används i beräkningen, eftersom ankomstförseningen kan vara svår att fastställa på ett tillförlitligt sätt. Detta kan leda till en underskattning av punktlighetseffekterna.

Andra möjliga ämnen för fortsatta utredningar är:

- När det gäller det spelrum som ingår i tidtabellerna användes standardvärden i beräkningen eftersom exakta data om spelrum på olika banavsnitt och för olika tågtyper inte var tillgängliga. Spelrummen har en viktig inverkan på beräkningsresultaten, varför en justering av regressionsmodellerna utifrån mer detaljerade spelrumsdata skulle förbättra deras tillförlitlighet.
- Beräkning av kapacitetsutnyttjande förutsätter flera sådana arbetsfaser som skulle kunna automatiseras genom en förhållandevis liten arbetsmängd. Ett automatiserat beräkningsverktyg skulle minska arbetsmängden och felmöjligheterna i beräkningsprocessen.
- I arbetet bedömdes inte förseningarnas tidsvärde. När beräkningsmetoderna förs in i Trafikledsverkets projektbedömningsinstruktion ska även tidsvärdet granskas.

Foreword

The Finnish Transport Infrastructure Agency is responsible for developing and maintaining Finland's rail network. According to the policy of the Finnish Transport Infrastructure Agency, each major infrastructure investment must be supplemented by a socio-economic assessment. Assessment is intended to inform infrastructure development policy and decision making, as well as to further guide infrastructure and land use development planning.

Impacts of the infrastructure investments on railway capacity and traffic punctuality are both commonly assessed in socio-economic analyses. Both are also commonly considered as a justification for investments. However, there has not been an established method for measuring capacity and delays in socio-economic assessments, and moreover, there has not been a method to consider delays and their consequent impacts in the cost-benefit analyses. This has generally been recognized as a shortcoming in the socio-economic assessment of railway investments.

This study aims to develop methods for measuring capacity consumption and delays in socio-economic assessment. The study is part of the Finnish Transport Infrastructure Agency's development project in which methods for impact assessment and transport forecasts are upgraded. The Finnish Transport Infrastructure Agency Project manager was Anton Goebel. In addition, the steering group included Taneli Antikainen, Tehanu Tapola, Laura Aitolehti and Jukka Ronni.

The study has been written in co-operation with Ramboll Finland Oy, Ramboll Denmark A/S and Trenolab. The authors of the study are Alex Landex, Saara Haapala, Tuomo Lapp and Jukka-Pekka Pitkänen from Ramboll and Giorgio Medeossi from Trenolab.

Helsinki February 2019

Finnish Transport Infrastructure Agency

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1 Introduction

1.1 Background and objectives

1.1.1 Socio-economic assessment of infrastructure investments

According to the policy of the Finnish Transport Infrastructure Agency, each major infrastructure investment must be supplemented by a socio-economic assessment. Assessment is intended to inform infrastructure development policy and decision making, as well as to further guide infrastructure and land use development planning. An important part of the assessment is cost-benefit analysis in which impacts of the investment during 30 years' time span are turned into monetary values and compared with costs. The outcome of the cost-benefit analysis is the so-called cost-benefit ratio.

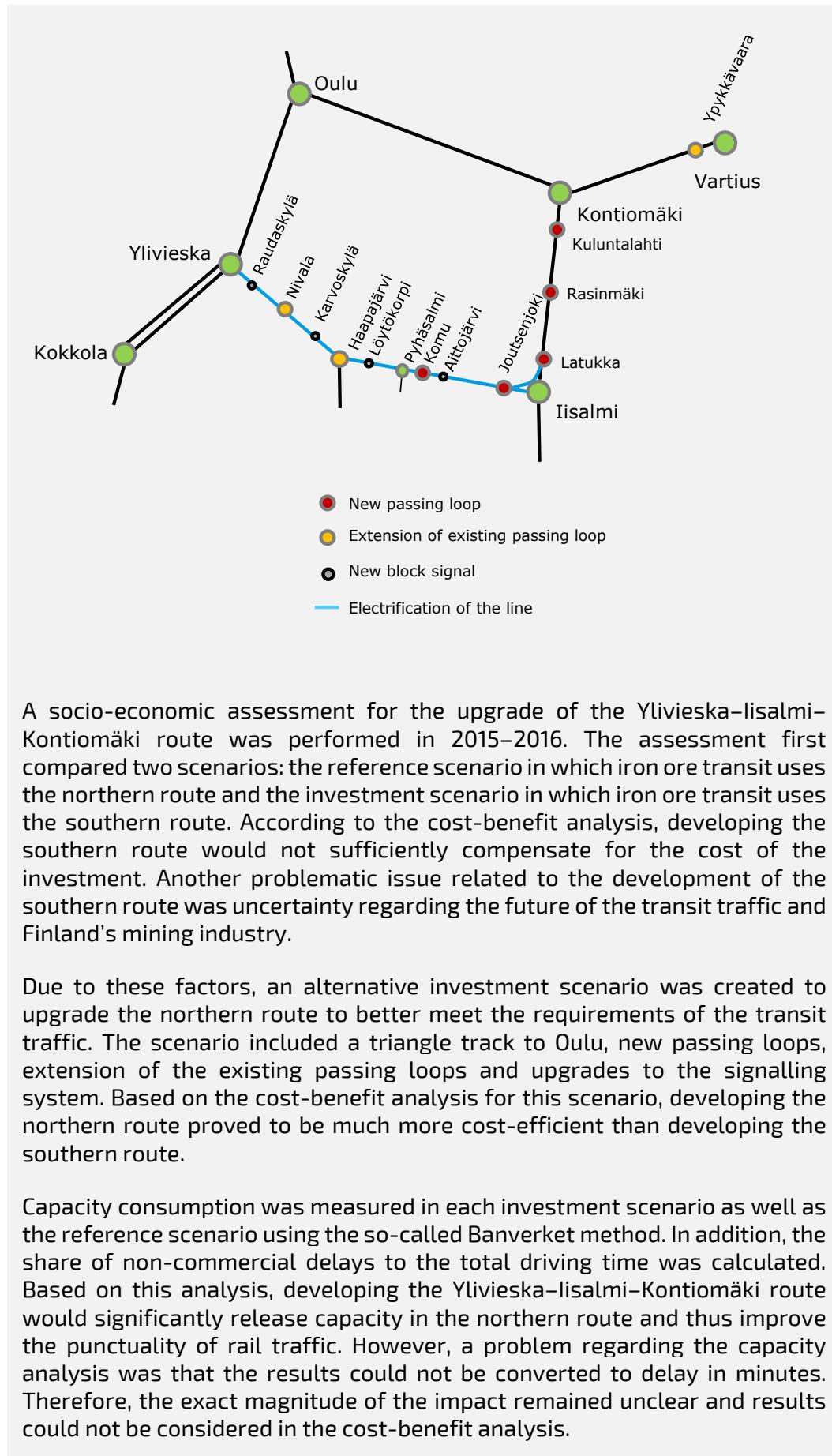
Impacts on railway capacity and traffic punctuality are both commonly assessed in socio-economic analyses at a qualitative level. Both are also often considered as a justification for investments. However, **there has not been an established method for measuring capacity and delays in socio-economic assessments, and moreover, there has not been a method to consider delays and their consequent impacts in the cost-benefit analyses.** This has generally been recognized as a shortcoming in the socio-economic assessment of railway investments. The following example of the Ylivieska–Kontiomäki–Vartius rail connection case further explains this challenge.

Case: Ylivieska–Kontiomäki–Vartius

The Ylivieska–Oulu–Kontiomäki–Vartius rail connection is one of the most congested parts of Finland's rail network when considering tons transported. It provides a route for iron ore transit from Kostamus, Russia to the Port of Kokkola. The sections Ylivieska–Oulu and Oulu–Kontiomäki also support passenger train traffic and both are important for Finland's forest and metal industries.

In principle, there are two alternative routes for iron ore transit from Kontiomäki to Ylivieska: the currently used northern route via Oulu and a southern route via Iisalmi. However, the southern route is not used significantly because the line between Ylivieska–Iisalmi is not electrified, there is a lack of sufficient passing loops and no triangle track at Iisalmi. The southern route also requires a third electric locomotive to be added for the Kontiomäki–Iisalmi section due to steep slopes.

In 2015, the Finnish Transport Agency prepared a plan to upgrade the southern route Ylivieska–Iisalmi–Kontiomäki to support iron ore transport. The goal of the plan was to reduce transport costs of the transit traffic and Finland's forest and mining industries. In addition, the aim was to release capacity in the northern route and thus improve traffic punctuality. The plan included electrification of the Ylivieska–Iisalmi line, new passing loops, extension of the existing passing loops, as well as upgrades to the signalling system.



1.1.2 Research questions and outlining

This research has two main objectives. The first is to define a reliable method for measuring capacity utilization and sufficiency of capacity. By using this method, rail network owners should be able to define when capacity is saturated, and when the number of trains cannot be increased. In addition, the method should be able to define the impact of various infrastructure investments on capacity consumption.

The second main objective is to define a method to take punctuality into account when performing a cost-benefit analysis. This requires a method that enables estimation of the amount of delays by a certain number of trains, train types and a certain number of passengers. The targeted outcome of this research is a proposal for how such methods are applied to socio-economic analyses.

The research is limited to primary delays; in other words, delays that are propagated in the particular section being analysed. **Cumulative delays and delays propagated through transit connections are consequently not included. Evaluating the value of delayed time is also not included.**

1.2 Experiences in using capacity calculation methods in Finland

The Finnish Rail Administration coordinated its first capacity consumption analyses in the late 1990's. This used the Banverket method, which was developed by the former Banverket (Swedish Rail Administration – currently known as Trafikverket, Swedish Transport Administration) and was used in Finland to analyse capacity consumption. The method is still used in some recent studies.

In 2003, a new method on how to calculate capacity consumption, called UIC 406, was introduced by the International Union of Railways (UIC). This method has similar characteristics to the Banverket method but the guidelines for the calculation are more flexible. The UIC 406 method has been used in several projects in Finland but, due to the flexibility of the guidelines, each user has made their own interpretation of how to calculate the results.

Overall, the UIC 406 method has been widely used in Europe and outside the continent. However, due to ambiguity in the UIC 406 manual, different interpretations of the method have been developed globally. Still, it is fair to say that the UIC 406 method is considered as the global standard for calculating capacity consumption. UIC updated the 406 Capacity leaflet in 2013, which gave more instructions on how the calculation should be performed.

In addition to capacity calculation, there have been academic studies and pilot projects on other analytical tools as well. Most of these studies have been coordinated by the Finnish Rail Administration or the Finnish Transport Agency. The problem so far with the calibrations of these methods has been the lack of comparative data and, because of this, none of the calculations performed in Finland have been fully reliable.

More reliable results have been achieved with railway simulation software which has been in active use in Finland for more than a decade. The Finnish Rail Administration invested in Swiss-made OpenTrack software in 2004 which has since become a standard tool for rail capacity analysis in Finland.

1.3 Study phases

The report begins with a brief overview of existing methods for railway capacity calculations. Secondly, an evaluation on these methods is given, followed by a more detailed formula for capacity consumption calculations. Next, an analysis on punctuality propagation is introduced with an explanation of the development of a new approach for delay evaluation. The outcome of the development of these methods results in three formulas: one for calculating capacity consumption on a certain track and, separately, two formulas for evaluating delays on single and double track lines. Usability of these methods is evaluated through a case study, method evaluation and conclusions. The report structure and conclusions of each chapter are summarised in table 1.

Table 1. Report structure.

METHOD DEVELOPMENT	CHAPTER	CHAPTER CONCLUSIONS
	1. Introduction <ul style="list-style-type: none"> • Background and research objectives 	<p>As part of previous socio-economic assessments in Finland, punctuality has been evaluated only through general capacity consumption methods. Capacity consumption methods do not provide numerical values for punctuality evaluation; thus, one must be developed as part of this research.</p>
	2. Literature review <ul style="list-style-type: none"> • Benchmark: Socio-economical assessment and punctuality forecasting in other countries • Existing method overview and evaluation 	<p>An international benchmarking study is performed with a finding that no detailed punctuality evaluation methods exist which could be utilised in Finnish socio-economical assessments. Railway investment options are evaluated using various capacity and capacity consumption related methods.</p> <p>Three approaches for estimating capacity utilization exist: Capacity consumption, capacity and capacity indices. Through an evaluation of the existing methods, it is evident that capacity consumption method UIC 406 does provide the highest potential for timetable evaluation. However, the current version of UIC 406 requires clarification.</p> <p>UIC 406 does not solve all research questions as it doesn't provide any numerical value for delay evaluation. It forms only one of the matters affecting total delays. It shall be further studied, whether a new <i>delay calculation method</i> could be generated using linear regression or other mathematical analyses.</p>
	3. The methods for socio-economic assessments <ul style="list-style-type: none"> • The possibility of utilizing capacity consumption for evaluating delays is analysed. 	<p>As part of delay evaluation in socio-economical assessments, two methods will be used: first, the <i>Finnish approach for capacity consumption evaluation</i> and, second, a new <i>delay calculation method</i>.</p>
	4. Development of capacity consumption calculation method	<p>A set of three new methods is created: a detailed method for capacity consumption analysis and two separate methods for delay evaluation in single and double track cases.</p>
	5. Development of delay calculation method	

6. Case studies

- The usability of the new methods is reviewed through three case studies in Finland.

The three case studies reveal that the clarified capacity consumption method gives valuable information on how the capacity utilization varies on one day. Furthermore, the delay methods reveal the following numerical increases in cost-benefit analyses:

- Case 1: 0,73 → 0,78
 - Case 2: 0,41 → 0,49 and 0,60 → 0,66
 - Case 3: 0,88 → 0,91
-

7. Conclusions

- Method evaluation and applicability in various cases
- Suggested further studies

The methods are briefly overviewed and evaluated with an outcome: that they are suitable for all socio-economic assessment cases affecting the planned timetable. While the capacity consumption method can be applied for any timetables, the delay methods provide most reliable results with timetables having enough operations (>15 trains/day).

However, calibration of the methods and understanding the results require more testing in real-life projects. Propagation of delays via train exchange connections and the impact of punctuality on passenger volumes require further study.

2 Literature review

2.1 Capacity and punctuality evaluation in other countries' socio-economical assessments

2.1.1 International benchmark

Due to the lack of existing delay calculation methods in Finland, the literature review begins with an international benchmark study which aims to identify any existing delay calculation methods used elsewhere. Seven European countries were studied: Sweden, Norway, Denmark, Italy, France, Switzerland and the United Kingdom.

Sweden

Trafikverket, the Swedish Rail Administration, has the overall responsibility for the rail transport system in Sweden and utilises methods for capacity analysis for infrastructure investments, future traffic and timetables (Trafikverket 2016).

Since 2016, Trafikverket has been developing a method to evaluate delays in socio-economic calculations. Results of the study will be published in 2019. According to preliminary results, the method will consist of two models: the first one calculates a probability for a train to be delayed, and the second one calculates a value for the number of delay minutes that the train is delayed. The formula for the probability is:

$$P(Y = 1) = \frac{\exp(x'\beta)}{1 + \exp(x'\beta)}$$

$$x' \beta = a1_{p,g} + a2_{p,g}\ln(\text{distsum}) + a3_{p,g}\text{espandel} + a4_{p,g}\ln(\text{kapb}) + a5_{p,g}\text{stopp}$$

where:

distsum = accumulated distance from start node to end node

espandel = ratio of single track section related to the full length of the line

kapb = weighted average of capacity usage of each node

stopp = number of stops where the train stops for passenger exchange.

p = personståg (passenger train)

g = godståg (freight train)

Parameter	Passenger trains	Freight trains
a1	-0,7087	-1,2513
a2	0,2019	0,0915
a3	0,4513	0,0887
a4	0,4724	0,0674
a5	-0,6788	-0,0808

The model for the value of the waiting time:

$$m = b1_{p,g} + b2_{p,g}distsum + b3_{p,g}espanel + b4_{p,g}stopp$$

Parameter	Passenger trains	Freight trains
b1	3,513845	39,86823
b2	0,02123	0,0501
b3	0	2,5602
b4	-0,41460	1,9948

Before developing the above method, two methods were used to describe the state of the capacity: capacity utilisation and capacity constraints. The calculations were based on the UIC 406 method adapted for use in Sweden (Trafikverket 2016).

Norway

The infrastructure manager evaluates the capacity, declares the infrastructure saturated, and proposes improvement plans. Saturation is declared when the capacity exceeds a certain threshold.

There is no official method to estimate capacity as such. However, Jernbaneverket (currently Jernbanedirektoratet) uses the UIC 405 and 406 capacity methods adapted for use in Norway. Punctuality is not considered as such in the timetabling process. For capacity improvement projects, robustness and delays are considered. Delays are stated based on the performed operation.

Denmark

The infrastructure manager evaluates the capacity, can declare the infrastructure saturated, and propose improvement plans.

There is no official method to estimate capacity as such. However, Banedanmark uses the widely accepted UIC 406 capacity method or the more simplified "standard train path method". Robustness and delays are not considered as such in the timetabling process. For capacity improvement projects, robustness and delays may be considered. Delays are stated based on the performed operation.

Italy

Only the infrastructure manager is entitled to officially evaluate the capacity of infrastructure and declare it saturated.

There is, however, no official method to estimate capacity as such and no quantitative method is used to rank improvements. Further, no official quantitative method to estimate the impact of investments is used. Robustness is not considered explicitly.

France

Capacity is evaluated officially by the infrastructure manager (SNCF Réseau), who asks the government or local authorities to fund capacity improvement programs. However, quite often capacity studies are carried out or financed by the operator (SNCF Mobilité) and accepted by the infrastructure manager.

There is no official method to estimate capacity as such. SNCF bases its evaluation on the timetable draft which includes a certain set of "timetabling norms". The only official method considering robustness and delays is the "Test 10 min" ("Test de Robustesse"), offering a light delay analysis using a simulation tool.

Switzerland

Not being part of the EU, Switzerland has a different approach towards the identification and selection of investments. Possible investments are evaluated by SBB (Swiss Federal Railways), but all significant investments are always widely discussed and, in several cases, proposed by the regional authorities.

Capacity is not evaluated explicitly, since the only requirement for investments is that the specified goals are fully reflected in a feasible timetable. Robustness or delays are not considered. However, the so called OnTime -system is used by SBB for short-term network-wide robustness evaluations, but not to support infrastructure-related studies.

The United Kingdom

The infrastructure manager evaluates the capacity, declares infrastructure saturated, and proposes improvement plans. Saturation is declared when utilization is above a certain threshold or when the infrastructure manager is not able to develop schedules in an acceptable way.

The official capacity method is the Capacity Utilization Index, "CUI". No official method considering robustness or delays exists. However, simulation studies have been carried out to evaluate the impact of infrastructure improvements or new timetables on delays.

2.1.2 Conclusions from the international benchmark

Based on the benchmark, there are various ways to estimate capacity, but no method for evaluating delays quantitatively exists. It is obvious that a delay evaluation method must be developed from scratch. Firstly, this new method should meet the requirements of the cost-benefit analysis and secondly, it would be a benefit if the same method could also evaluate usage of capacity. The development process will start from overviewing and evaluating the existing capacity methods, which are described in the following section.

2.2 Overview of existing methods

2.2.1 Three analytical approaches to evaluate rail capacity

This section introduces, at a general level, how capacity and performance of railway section can be evaluated. The different methods can be roughly grouped into three categories: capacity, capacity consumption, and others (indices and simulation).

Understanding requires first defining a few terms (see graphical explanations in Figure 1).

- The infrastructure is divided into block sections, which means the length of track between two block signals. The safety system and the signals ensure that only one train can at a time be hosted in a block section.
- Headway means the closeness of two consecutive trains in distance or time. Due to the principles of signalling system, two trains cannot be located closer than the minimum headway time.
- Buffer time is the time difference between actual headway and minimum headway time.

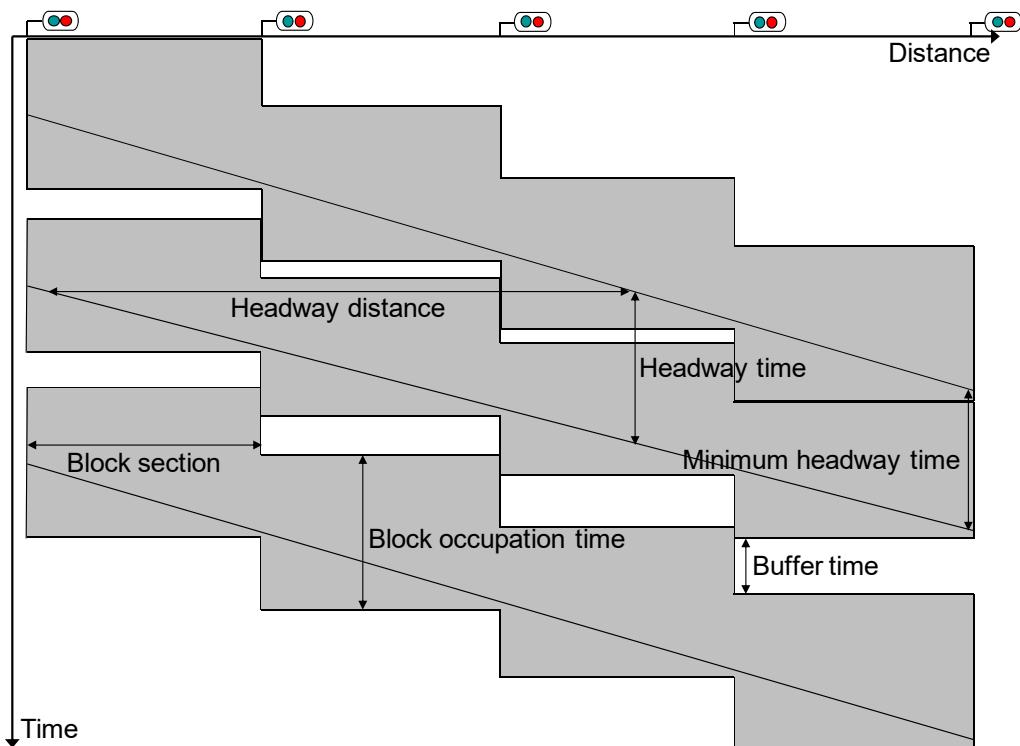


Figure 1. Basic terms of railway safety system illustrated on a graphical timetable (Landex & Kaas 2005).

2.2.2 Calculation of rail capacity

Approach description

Rail capacity calculation methods aim to calculate the maximum throughput of the studied line section or station area. As a result, these methods will describe how many trains may be operated along a selected segment within a given time period. The basic idea of these methods can be described in the following formula:

$$C = \frac{\text{studied time period}}{T_i}$$

where T_i , in the denominator is the minimum headway (e.g. seconds) between two consecutive trains. In different methods, it is defined based on, e.g. characteristics of signalling systems and/or speed profiles of the trains (Pitkänen 2005). This method describes the capacity method purely from the point of view of the infrastructure manager and/or the train operator. However, as Sameni, et al. (2011) remind, there are also other approaches, such as the passenger or cargo customer point of view. While the infrastructure manager's point of view leads to a measurement unit of [trains/day], other perspectives would lead to capacity units, such as [number of passengers/hour] or [passenger-km].

Application: UIC 405

Developed by the International Union of Railway (UIC), the UIC 405 method is known as the first way of providing an analytical method to measure capacity. It is based on the following formula:

$$P = \frac{T}{t + t_b + t_c}$$

where P is the capacity (daily, hourly), t is the average minimum headway, t_b is a running time margin and t_c is an extra time based on the number of the intermediate block sections on the line (Rotoli, et al. 2016).

The UIC 405 method does not require a large amount of data or work effort. However, the length (or the travel time) of the relevant block section of the line must be known, or at least hypothesized, which involves a detailed knowledge of the infrastructure (Rotoli, et al. 2016).

Application: CAPACITY Method

The CAPACITY model was developed by Swiss Federal Railways (SBB). It calculates capacity of a railway line with the following formula that is not dependent on a planned timetable:

$$L = \frac{T}{t} * C * V$$

where L is capacity of the railway section during reference period T [trains], T is length of the reference period [min], C is the greatest possible capacity consumption [%], V is the number of tracks and t is the expected average value

of train reservation times, which is dependent on the proportion of different types of train.

Application: CAP 1 and CAP 2 Methods

CAP 1 and CAP 2 models are SBB's further versions of the CAPACITY model. Like the original version, the aim of CAP 1 and 2 models is also to account for the characteristics of infrastructure and surrounding rail network, as well as the opportunity to evaluate train type distribution without an existent timetable.

To fulfil these targets, developers of the model decided to create two-part models instead of one all-inclusive model. The CAP 1 part of the model is designed to evaluate the throughput of double or multi-track sections. In the model, there is an assumption made that on a double or multi-track section only one-way traffic is operated on one track. The other part of the model, CAP 2, is based on similar principles as the CAP 1 model, but CAP 2 is suitable for calculating the capacity of single track sections (Pitkänen 2005).

2.2.3 Calculation of capacity consumption

Approach description

The methods that calculate capacity consumption result in a ratio of the time that is reserved for train operations during a studied time period (time period minus unutilised time during it) and the studied time period. The result is always shown as a percentage as shown in the formula below.

$$Cc\% = 100 \times \frac{\text{Time reserved by train operations}}{\text{time period}}$$

The resulting capacity consumption value will be compared in a reference-table, which includes a set of threshold values to indicate the utilization level of a track. Table 2 below provides an example of threshold values published by the original developer of consumption methods, the International Union of Railway (UIC).

Table 2. An example of Threshold Values in Capacity Consumption Calculations (UIC 2013).

Type of Line	Peak Hour	Daily Period
Dedicated suburban passenger traffic	85 %	70 %
Dedicated high speed line	75 %	60 %
Mixed-traffic lines	75 %	60 %

Application: UIC 406

Developed by the International Union of Railways (UIC), UIC 406 provides a unique approach to capacity evaluation in the shape of the compression method. UIC 406 has multiple national interpretations that are widely used in Europe. To measure railway capacity consumption, timetable graphs can be used whereby the given infrastructure and the type of rolling stock are implicitly included as they determine the size of the blocking stairs. Capacity consumption can be intuitively illustrated by compressing the timetable graphs so that the buffer times are equal to zero (see Figure 2). (Landex 2008).

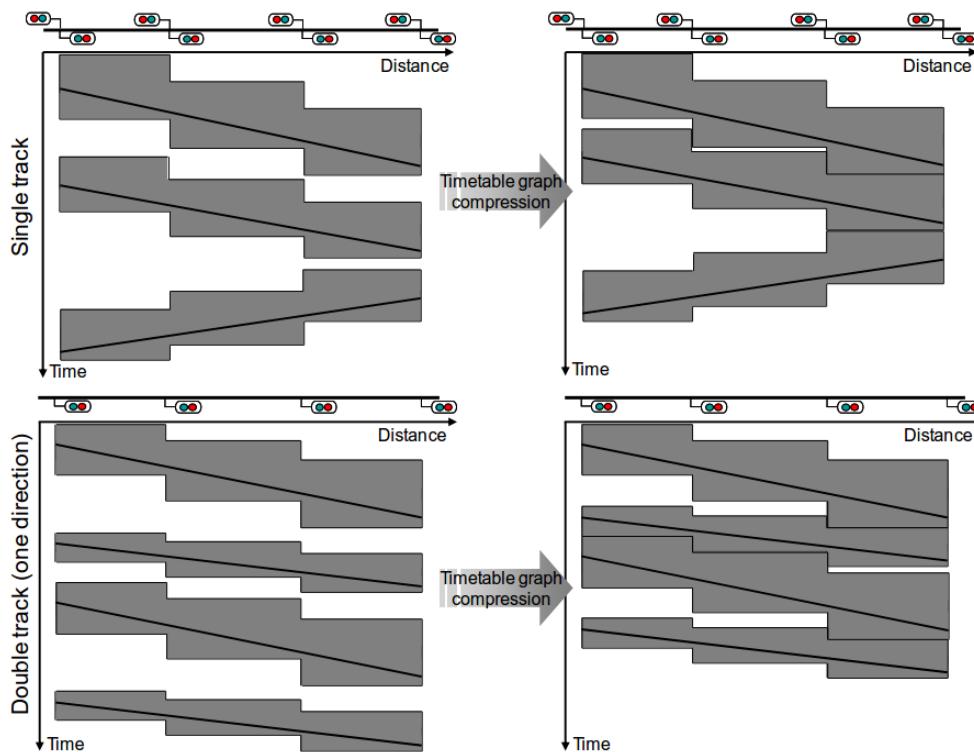


Figure 2. Principle of UIC 406 compression method visualized graphically (Landex 2008).

A numerical estimation of capacity consumption can be worked out based on the total capacity consumption measured in time (T) and the chosen time window:

$$\text{Capacity consumption (\%)} = \frac{\text{Occupancy time} + \text{Additional times}}{\text{Defined time period}} * 100$$

'Additional times' is a sum of any time value added to secure the quality of operation (UIC 2013). The results are compared with UIC's original threshold value table (presented earlier as table 2).

Application: Banverket

The Banverket method is a Swedish interpretation of the original UIC 406 method. Banverket can be used for both single and double track sections, if information on graphical timetables, types of trains, and infrastructure is available. Banverket calculates capacity consumption as the ratio of total occupancy time and examination duration:

$$Cc = \frac{T}{a * T_t}$$

Cc = Capacity consumption

T = The sum of block occupation times in the significant distance between signals during the study time period [h]

a = coefficient (a = 1, when calculating peak hour and a=0,8 when calculating daily capacity)

T_t = Study time duration

The total occupancy time is calculated separately for single and double track lines based on certain constant values. As an outcome, the method gives similar percentage values as UIC 406 -method (table 2). The results are also interpreted in a similar way.

Application: Capacity Utilization Index (CUI)

Capacity Utilization Index (CUI) is a British interpretation of the UIC 406 method and it is currently widely used in Britain. However, instead of focusing on a certain link (i.e. section of line between nodes), the CUI method focuses on a certain route including the same traffic (Armstrong et al. 2011).

Application: Train Mix

The Train Mix is a Danish interpretation that examines a plan of operation (number of trains per hour and stop pattern) and calculates the capacity consumption for all possible combinations of train orders. Therefore, the method is used in the early phases of assessment, where an exact timetable is not yet planned. Train Mix method gives information about how the infrastructure can handle different timetables (Landex 2008).

2.2.4 Other approaches

SAHR and SSHR Heterogeneity Indices

Heterogeneity has a clear negative correlation to disturbance tolerance. To evaluate the heterogeneity of timetables Vromans (2005) has developed two simple measurements: Sum of Shortest Headway time Reciprocals (SSHR) and Sum of Arrival Headway time Reciprocals (SAHR). The first measure looks at the headway both at the start and at the end of the line section, and therefore takes into consideration both the heterogeneity in speed of the trains and the spread of the trains over time. The second measure, SAHR, focuses only on the headway at the end of the line section, under the assumption that the headway at the end is more important than at the start.

SSHR and SAHR are both used to evaluate punctuality changes, however they do not predict the exact size of a delay reduction (Vromans, et al., 2006).

The methods are further developed by Landex (2008) into new measures for heterogeneity that are independent from traffic density and the number of trains. Landex's (2008) method can be used to define traffic homogeneity for a certain timetable. The output of the calculation is a value between zero and one. The method is based on train departure and arrival times, the length of which depends on train driving time differences.

Railway Yard Conflict Indices

Index Based on Railway Lay-out

Railway yards and the interoperability of routes are examined using conflict indices. An index based on railway lay-out is the simplest method of calculation, which acknowledges only the train itineraries and the amount of conflicts between them. The method is used when there is no information on the maximum amount of trains at the train station (Pitkänen 2005).

Index Based on Conflict Probability

If only a few trains turn at a station, the indicators based on railway lay-out do not have a significant effect on traffic fluency and hence a more complex indicator is needed. An index based on conflict probability can be used when one has knowledge about the amount of trains and when more specific information about a station's infrastructure and its enabling traffic fluency is required (Pitkänen 2005).

Indicator Based on Minimum Train Headways

The most accurate estimate of traffic fluency is determined by a method that also considers the effects of shifts in train quantities. Information about signal interval holding times is required as a basic input (Pitkänen 2005).

Microscopic Simulation

In addition to calculation methods, railway capacity can be estimated through microscopic simulation. Simulation can especially be applied to cases where detailed information about the impacts of various alternative infrastructure scenarios or fault situations are needed. Simulation model parameters can also be added with stochastic alteration factors caused by human behaviour.

2.3 Evaluation of existing capacity methods

In this section, methods are evaluated from the perspective of their applicability to the Finnish rail network and use in Finnish feasibility studies. The overall evaluation is presented in Table 3 (methods to calculate rail capacity), Table 4 (methods to calculate capacity consumption) and Table 5 (indices to evaluate railway operations). After the tables, recommendations are provided for next steps with related arguments. The evaluation of methods considers applicability and light usability processes that are recognized to be critical for the Finnish socio-economic assessments:

Table 3. Summary of Methods to Calculate Rail Capacity. Colour range from green to red indicates ease and applicability of method.

Method	UIC 405	CAPACITY method	CAP 1 & CAP 2
Applicability for single track sections	Applicable	Applicable	Applicable
Applicability for double track sections	Applicable	Applicable	Applicable
Amount of initial data required	No existing timetable is required	No existing timetable is required	No existing timetable is required
Required work-load	Low	Low	Low
Possibility of automation	Easy to automate	Easy to automate	Easy to automate
Used elsewhere in practice	Old method that was used in Europe before UIC 406, currently the calculations focus on capacity consumption calculations	Experience only in Finland	Used only in research projects
Reliability of results	Result changes in case of any parameters change (trains, infrastructure, timetable, signalling)	Result changes in case of any parameters change (trains, infrastructure, timetable, signalling)	Result changes in case of any parameters change (trains, infrastructure, timetable, signalling)

The core problem of the capacity methods is the fact that the results are always dependent on certain assumptions of infrastructure, rolling stock and timetable. If one of the parameters is modified, the result will be completely different. In the cost-benefit analysis, it is often the case that all these parameters can differ between studied alternatives. This makes an absolute comparison impossible; consequently, the capacity calculation methods (UIC 405, CAPACITY and CAP1/CAP2) will not be considered further in this study.

Table 4. Summary of the Capacity Indices. Colour range from green to red indicates ease and applicability of method.

Method	SAHR and SSHR	Homo-geneity	Landex method	Railway yard conflict indexes	Simulation
Applicability for single track sections	Applicable	Applicable	Applicable	Applicable	Applicable
Applicability for double track sections	Applicable	Applicable	Applicable	Applicable	Applicable
Amount of initial data required	Timetable is required	Timetable is required	Timetable is required	Medium	Building simulation models requires detailed plans of vehicles, infrastructure and timetable
Required work-load	Low	Low	Low	Low	High
Possibility of automation	Possible	Possible	Possible	Possible	Not possible to automate model building
Used elsewhere in practice	Not applied in line sections	Applied only in scientific research	Applied only in scientific research	Applied only for point locations and no experience from wider study areas	Method widely used
Reliability of results	Result only relative comparisons	Result only relative comparisons	Result interpretation requires expertise	Result only relative comparisons	Results are reliable if initial data was detailed

Indices based on heterogeneity are best suited when comparing different timetable alternatives. They can help in ranking different alternatives based on punctuality and robustness, but they can only be used for relative comparison as they **do not give any absolute values for capacity (nor punctuality) as outputs**. In addition, with the studied methods, it is not possible to analyse network effects; instead they are only suitable for analysing individual sections or stations.

As described previously, heterogeneous rail traffic tends to recover faster from single delays and causes fewer consecutive delays due to the shorter sections where trains catch up to one another. This allows timetables to be built with higher capacity consumptions. These indexes can be used to complement other methods but are too simple to work as an independent method.

Simulation programs offer good and accurate tools to model alternative scenarios. The user can produce many different variables for use as initial data in other analytical methods. Simulation is a very good tool when the number of studied infrastructure alternatives is limited. In early stages of planning, however, when possible investments can vary significantly, simulation can be very time consuming. Thus, **for the purposes of early-stage cost-benefit analysis, a more agile method is needed.**

Table 5. Methods to Calculate Capacity Consumption. Colour range from green to red indicates ease and applicability of method.

Method	UIC 406	Banverket method	CUI	Train Mix
Applicability for single track sections	Little experience outside of Finland, but based on literature, calibration should be possible	A manual for single track section exists, but it requires generalizations	Little experience outside of Finland, but based on literature, calibration should be possible	Little experience
Applicability for double track sections	Widely used around the world	Clear manual exists but the method has generalizations	Used in the UK	Applicable
Amount of data needed	Timetable is required	Timetable is required	Timetable is required	No existing timetable is required
Amount of initial data required	If timetable is available, fast calculation method	If timetable is accessible, fast calculation method	If timetable is accessible, fast calculation method	Hundreds of possible variations, but they can be analysed automatically
Possibility of automation	Possible, but automation will require generalizations	Possible	Possible, but automation will require generalizations	Automation is required
Used elsewhere in practice	Widely used	Old method and not used anymore	Used in the UK, but it is a version of the more widely used UIC 406 method	Method used only on research
Reliability of results	Without national guidelines the result is user-dependent and result interpretation requires expertise	Generalizations cause unreliability	Result interpretation requires expertise	Result interpretation is hard and complicated to apply in practice

The UIC 406 method is already widely used in other European countries, especially on double track lines. Currently, the **UIC 406 method does not have an unambiguous calculation guideline that would be applicable on single track sections**. In general, the UIC 406 manual leaves plenty of room for interpretation, and therefore the guidelines should be clarified to meet the Finnish circumstances.

Compared to the Banverket method, UIC 406 requires more initial data, is more time consuming and less automated. The Banverket method is faster to use and requires less initial data. The Banverket method may appear simplistic at first, but with experience of the analysed rail network, the results can produce important information. The difference between the UIC 406 and Banverket methods is that UIC 406 considers what happens in the line section between two stations. According to Almkvist (2006), it is possible to develop the Banverket method further to consider blocking as well, but that would result in a time consuming and labour intensive method. Additionally, the Banverket method contains numerous simplified assumptions, especially when estimating total occupancy times (T).

The Capacity Utilisation Index (CUI) used in the UK is based on minimum headways and requires less detail compared to the UIC 406 method. CUI is defined there as 'the time taken to operate a squeezed or minimum technically possible timetable compared to the time taken to operate the actual timetable' (Rotoli et al. 2016). The method provides only an estimate of capacity sensitivity and identifies bottlenecks and areas for improvement.

Based on the analysis of the characteristics, and especially the limitations of different methods described above, it is recommended that the Finnish calculation method should be based on the UIC 406 method. The main reasons for this recommendation include that UIC 406 provides more flexibility for calibration and it is becoming a standard for capacity evaluation in Europe. Most of the studied countries are committed to the use and development of UIC 406 and there is a lot of academic research related to developing the method. This makes UIC 406 an attractive choice for Finland. By selecting UIC 406 and developing the calculation guidelines for Finnish circumstances, an active dialogue is enabled and joint research projects with other countries are possible. Chapter 3 describes the initial thoughts on developing the UIC 406 method towards the delay evaluation perspective.

3 The methods for socio-economic assessments

3.1 Approach for the Estimation of Delays

For given section of infrastructure, it is possible to carry a higher number of trains if higher delays are acceptable. As a result, acceptable delays must be considered in the estimation of the potential (capacity) of railway infrastructure: the maximum capacity of a line is the number of trains that can be carried with acceptable delays.

However, the relationship between capacity and delay is not linear: in particular, on single-track lines, capacity is only one parameter influencing delays in addition to **the number of trains, crossings and the buffer on a line as well as the initial delays**.

An example showing that capacity usage alone is not enough to estimate delays is shown in Figure 3 and Figure 4. The figures represent the same set of stations (interconnected by single-track lines) and time horizon, but different trains and timetables are defined. In Figure 3, four trains are scheduled, while in Figure 4, only three trains are scheduled. Thus, there is a higher use of capacity in the first case. Estimating delays by only considering capacity would lead to consider the first case more likely to be subject to delays. However, the first case also has fewer crossings (denoted by blue dots). In the second case, a delay on any of the first two trains would propagate to the next train, due to the two crossings. In the first case, only the second and third train could cause a delay to one another, not affecting the other two trains. Thus, a smaller number of crossings should be considered in order to effectively estimate the final delay of a single-track system.

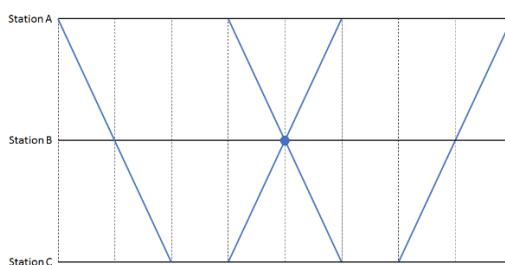


Figure 3. Single-track Line with 4 Trains and 1 Crossing.

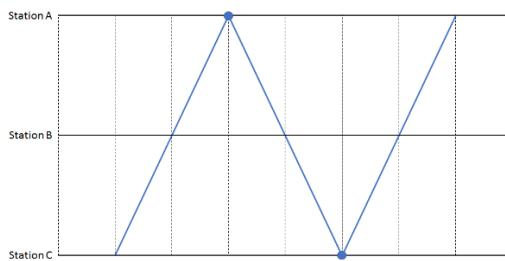


Figure 4. Single-track Line with 3 Trains and 2 Crossings.

Generally, it is true that higher capacity consumption corresponds to higher delays. However, as has just been discussed, there is no direct and precise relationship between the two values. Rather, **capacity is only one of the factors that influences final delays**. In other words, at a given capacity consumption level, different final delays may result from the same initial delays when all other information is unknown.

This inconsistent correlation of capacity (or capacity consumption) with delays leads to the conclusion that in order to estimate delay evaluation in a numerical way, a new approach must be developed. This approach, that in later chapters shall be called the delay calculation method, must consider timetable features and, as an outcome, evaluate punctuality as a numerical value. If such a tool can be developed, it can be included in the railway investment cost-benefit analyses afterwards. The development of this delay calculation method will be done through mathematical regression analysis and will be discussed in more detail in chapter 5.

Although the existing methods that were discussed in the previous chapter won't provide the desired features to evaluate punctuality, they provide high potential for other purposes for socio-economic assessments. The first step of socio-economic assessments is to create as optimal a timetable as possible (or to point out whether a desired timetable is possible at all) and the reviewed capacity methods provide great potential to achieve this.

Summary: Set of calculation methods

Due to the findings that:

- The existing capacity evaluation methods do not provide the potential for delay evaluation in a numerical way; and
- No numerical delay calculation methods exist

it is suggested that two new methods will be used in the Finnish socio-economic assessments.

Firstly, a capacity consumption calculation method will be used to evaluate the utilization of any timetables, to estimate whether new trains can be added to a track and/or whether there is a need for further changes in infrastructure. The highest potential for the Finnish approach is provided by the existing UIC 406 method although it requires further development. This will be discussed in chapter 4.

Secondly, a totally new delay calculation method will be created from scratch. The new method should meet the following requirements: evaluates delays in a numerical way [yearly average amount of delayed seconds per operated train], workload of the method is not significant, and input information is publicly available. Development of the delay method will be discussed in chapter 5.

3.2 The impact on timetable-dependency

A timetable is developed as a first step based on the future service concept. The timetable is used to estimate capacity consumption as well as delays. The main disadvantage of the timetable-dependent approach is that it requires a complete timetable as an input: this appears particularly demanding on single-track lines, where timetable planning is more complex due to the constraints of the infrastructure. Thus, using a timetable-independent approach - although probably less accurate - would require significantly less effort than the timetable-dependent approach.

A timetable-independent capacity estimation would still use the future service concept as an input, as well as obviously the characteristics of the infrastructure: as a first step the running- and blocking-times would be calculated for each service considering a certain margin. Capacity utilisation would be estimated based on the mix of running- blocking times and the number of services/day of each group. However, as discussed in the research by Eliasson & Börjesson (2013), building a timetable-independent tool for feasibility studies or cost-benefit analyses is questionable and should be considered thoroughly. Thus, a delay calculation method that will be discussed in detail in chapter 5, is created from the perspective of timetable-dependency.

4 Finnish guideline to calculate capacity consumption

4.1 UIC 406 method's needs for further development

International Union of Railways (UIC) has defined capacity consumption as an indicator describing the usage of rail infrastructure on a given railway line (UIC 2013). The consumption of railway capacity does not only depend on how many trains are operated, but also how the capacity is utilised. For example, a heterogeneous operation, where fast trains catch up with slower trains, results in higher capacity consumption than a homogeneous operation where all trains are operated with the same speed. Generally capacity consumption is defined as the ratio of reserved time during a studied time period. UIC 406 (2013) has defined the numerator "reserved time" as:

$$\text{Capacity consumption (\%)} = \frac{\text{Occupancy time} + \text{Additional times}}{\text{Defined time period}} * 100$$

Where 'additional times' is a sum of any time value added to secure the quality of operation (UIC 2013). The principle of the above formula can be applied to any track sections (single or double). However, the formula is open to various interpretations, thus enabling a risk of making the results non-comparable and user-dependent.

The following shortcomings have been recognized:

1. **Defined time period, studied operations and result interpretation.** Typically, the level of capacity consumption does not remain at the same level through the whole 24 hours and at all parts of a study area. Further definition is thus required, of what is included in each partial calculation and how the results will be interpreted. This will be further discussed in section 4.2.2.
2. **Occupancy time.** Occupancy time is the major term affecting capacity consumption. While the basic principle of defining occupancy time is clear and intuitive, the original manual doesn't describe how to define the value for minimum headway. In chapter 4.2.3, a formula for defining minimum headway is introduced.
3. **Additional times.** There are various additional reservation times that should be considered in the capacity consumption calculations. To get comparable results, these reservation times are listed with a brief explanation.

Practical use of each term, as well as an example of the whole calculation process, are described in appendices 1 (in English) and 3 (in Finnish).

4.2 Defined approach

4.2.1 Defined formula

The defined formula for capacity consumption calculations is:

$$K = \frac{h_A + t_D + t_{EPD} + t_M + t_S}{T}, \text{ where}$$

Term	Explanation and unit	Description
K	Capacity consumption [%]	The amount of capacity used for a given timetable on a given infrastructure
T	Defined time period [min]	Analysed time period, typically 1h, 20 or 24 hours.
h_A	Sum of minimum headway times [min]	The sum of time intervals between two consecutive trains that are running in the same direction
t_D	Sum of driving time differences [min]	The sum of time intervals between two consecutive trains running in the same direction and having uneven driving times
t_{EPD}	Earliest possible departure time compared to the beginning of the time period [min]	Time interval referring to the impact of partial trains in the beginning of the time period
t_M	Sum of supplementary time for maintenance [min]	Additional time that a certain line section is not in use for normal operations due to maintenance or other rail work
t_S	Sum of station and crossing times [min]	The amount of time needed for switch turning operations during the time period

Compared to the original UIC 406 -formula, especially the definition of a time period and minimum headway times, are given detailed explanations. These are discussed next.

4.2.2 Defining time period, studied operations and result interpretation

Multiple calculations must be done to get the overall picture of the consumption in different parts of the case study area. Repetition of the calculations of partial cases will lead into a list of so-called partial calculation results. This chapter reviews how to divide the case study area into these partial calculations. The division will depend on the following four variables:

Infrastructure. Both single and double track lines are split into line sections, connected by node points. These node points are overtaking places, line end, passing stations, transition stations (such as places where double track transforms into single track line) and junction points (Figure 5).

The number of required partial calculations depends on the way the infrastructure is built up. On single track lines traffic is homogeneous within each line section and the train order can change only at node points. These nodes, such as passing stations, are the only places where trains can pass each other. Double track lines are more versatile environments where trains can meet freely. That makes capacity consumption calculations heavier on double track lines.

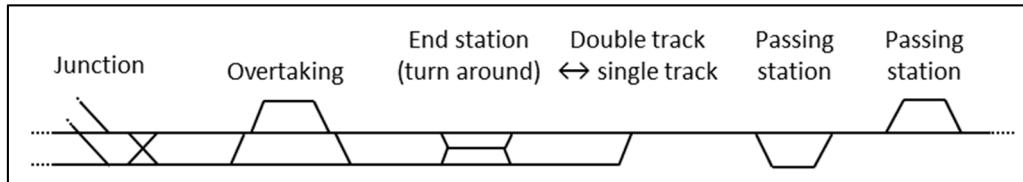


Figure 5. Infrastructure split into line sections.

Direction. Calculating capacity consumption values for double track lines requires calculations for both directions separately. This is because double tracks are usually independent, unique systems without any interaction with each other. However, in some special cases, double tracks are used for one direction only and these cases must be considered separately and/or analysed similarly as single tracks.

Time period. Capacity consumption varies over time and therefore it is not recommended to calculate capacity consumption at once for a whole 24 hours. Instead, capacity consumption is calculated for each hour separately to get an idea of how the consumption varies during the day. The UIC 406 manual (2013) suggests not performing calculations for periods shorter than 2 hours. This is probably due to the uncertainty of which trains to include in the analysis, if there are trains that are operating only partially during the desired time period. Splitting the timetable into shorter sections is, however, valuable to point out the highest peaks and bottleneck areas. Tackling this issue is discussed more in appendixes 1 and 3 (see especially term t_{EPD} , earliest possible departure).

Margins. Typically train timetables include a certain amount of extra running and dwell time to absorb minor disruptions. The impact of these and other possible margins can be analysed through performing the calculations separately, including and excluding them. Practical instructions for this are discussed in appendixes 1 and 3.

4.2.3 Deriving formula for minimum headway

Minimum headway represents the shortest time between two consecutive trains that are heading in the same direction. Headway is a significant factor in determining how much a timetable can be compressed, and it depends on driving speeds as well as local signalling.

Before getting into the derivation of the formula, we must understand how the number of block sections affects the minimum headway. Figure 6 explains how a single track section, with one or two block sections, is occupied by two trains. Even though one block section can host one train at a time, train i shouldn't enter the first block section before train j has left it and a safety margin has passed. If train i left earlier, it would be signalled to stop at the middle signal, making the operations unsmooth.

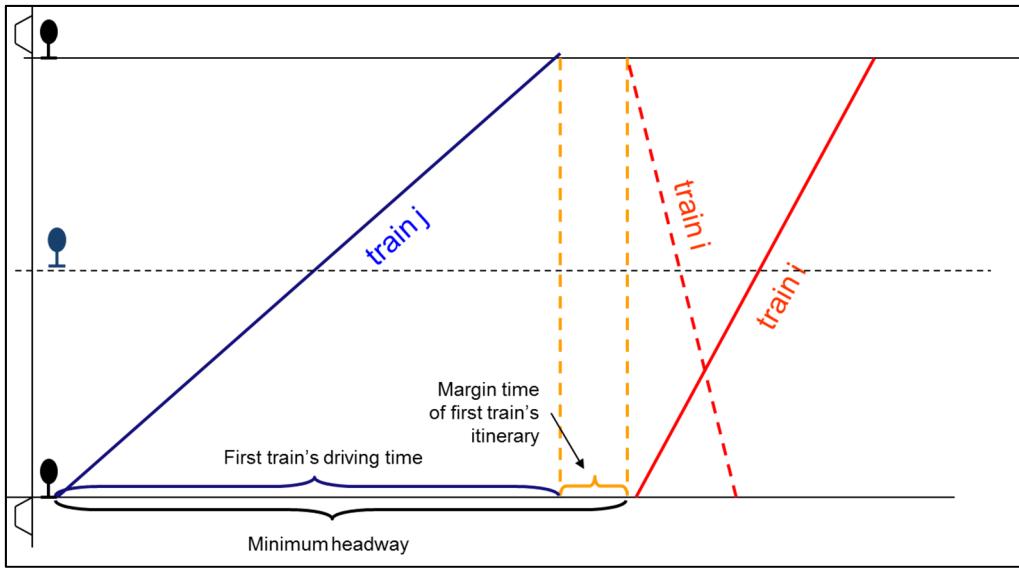


Figure 6. Minimum headway on single or double track line sections with one or two blocking sections.

Thus, if the number of blocking sections is one or two, the actual minimum headway is the sum of first train's driving time from first station to last station, plus safety time for the itinerary to release. The formula remains the same in cases where trains are operating with the same speed.

On line sections with three or more block sections, the following train (Figure 7, train i) cannot depart after the itinerary of the previous train j has released. To enable smooth operations without braking for signals, the following train can enter the line only after the first train has passed the second signal. Figure 7 illustrates this with two examples (left: operations with same speed, right: operations with different speeds). The formula for minimum headway time will be the sum of driving time difference (if any), two times the faster train's driving time on one block section, plus a margin time of the first train's itinerary release.

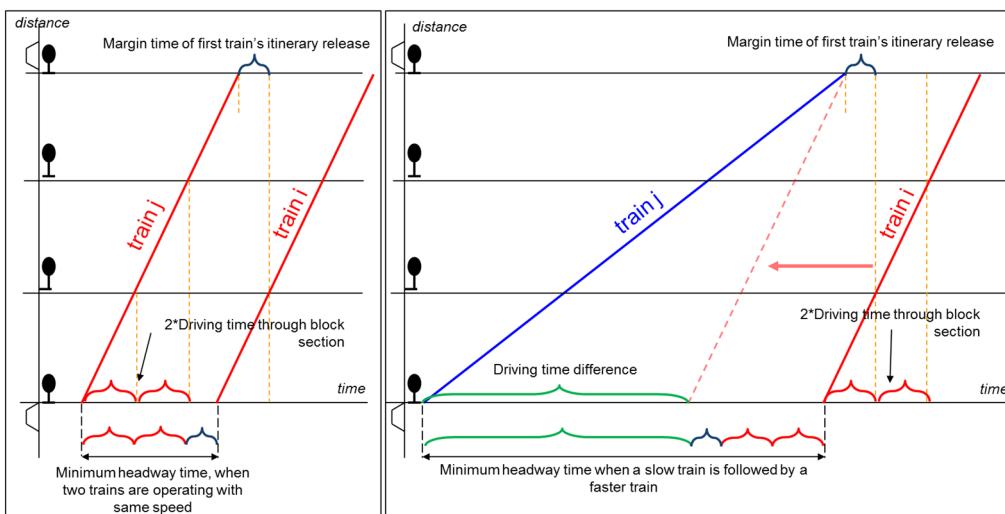


Figure 7. Minimum headway on single or double track line sections with three or more blocking sections (left: operations with same speed, right: operations with different speeds).

In the suggested capacity consumption formula, the impact of driving time differences and itinerary release margin times are considered separately (see terms h_A and t_D). The next two tables 6 and 7 summarise the discussed impacts in the simplest cases, where two consequent trains are running with similar driving speeds and the impact of margin times are ignored.

Table 6. Summary of Track and Block Section Number Impact on Train operations.

		Number of tracks	
		Single track	Two or more tracks (all trains heading towards the same direction)
Number of block sections	1 or 2 block sections	<ul style="list-style-type: none"> - None of the following trains (from any directions) can enter the track section before the previous one has left, and the itinerary has released. 	
	3 or more block sections	<ul style="list-style-type: none"> - Trains towards opposite directions cannot enter the track section before the previous one has left, and the itinerary has released. - Trains towards the same direction can depart once the previous train has passed two blocking sections forward. 	

The above points can be put into mathematical form as shown in Table 7.

Table 7. The minimum headways formula dependence on the circumstances.

		Number of tracks	
		Single track	Two or more tracks (all trains heading towards same direction)
Number of block sections	1 or 2 block sections	$h = \frac{D_{node}}{v/dV}$	
	3 or more block sections	<p>Following train heading towards opposite direction: $h = \frac{D_{node}}{v/dV}$</p> <p>Following train heading towards same direction: $h = \frac{2 * D_{signal}}{v/dV}$</p>	

In the table above, h is minimum headway, D_{node} is the distance between node points, D_{signal} is the average block section distance in the study area and v is the first train's driving time, which is corrected with a coefficient dV . dV is required to consider the impact of acceleration and deceleration.

The formulas can be further compressed and defined to the final form:

$$h_i = \frac{n * d * 3600}{s} \quad , \text{ where}$$

h_i [s]	Minimum headway on the line section i
n	constant value that depends on the number of block sections on line i $n = 1$, if line section i includes only one block section $n = 2$, if line section i includes multiple block sections
d [km]	Average block section length in the line section, which is calculated as following: $d = \frac{\text{line section i length [km]}}{\text{number of block sections on line section i}}$
s [km/h]	average travel speed on line section i, which is calculated as follows:

$$s = \frac{\text{length of line section i [km]}}{\text{average travel time [h]}}$$

The practical use of this formula is further discussed in appendixes 1 and 3.

4.2.4 Additional times

Additional time is a sum of various extra times needed for safe operations. This includes terms such as itinerary release times, safety times for switches and maintenance work. These are further discussed in appendixes 1 and 3.

5 Delay estimation method

5.1 Analysis

The main goal of this chapter is to estimate the relationship between some capacity-related parameters and delays. While a direct relationship between capacity and delays can be identified for double track lines, as demonstrated by multiple authors (see Medeossi 2010), this study confirms that on single-track lines, no direct relationship can be identified consistently with the theoretical evidences first identified by Potthoff (1962).

As a result, single and double tracks have to be analysed separately using *ad-hoc* models. The definition of the relationship requires a large set of data, in particular on delays corresponding to an increasing capacity usage. This can be obtained in either of two ways: analysing the operational data of a set of lines, including some heavily-used ones or using simulation to increase the traffic density and obtain the corresponding delays.

Before starting the development of a method for the estimation of delays, an analysis of real data is required to understand where and how delays propagate. The figures below show the graphic timetable of three months of operations on the Turku-Helsinki line. In Figure 8, it is possible to observe the effect of a delayed arrival at a crossing. Figure 8 shows that punctuality of train 979 (represented by the thick red line in Figure 8) decreases markedly at the crossings in Karjaa and Salo, due to the late-arriving green trains in the opposite direction.

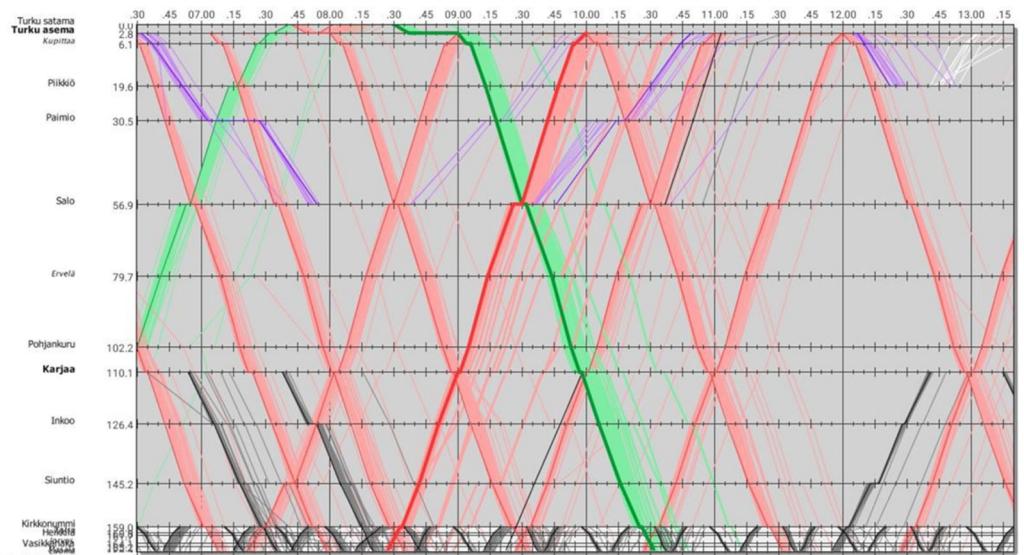


Figure 8. Analysis of real operations on the Turku-Helsinki Line.

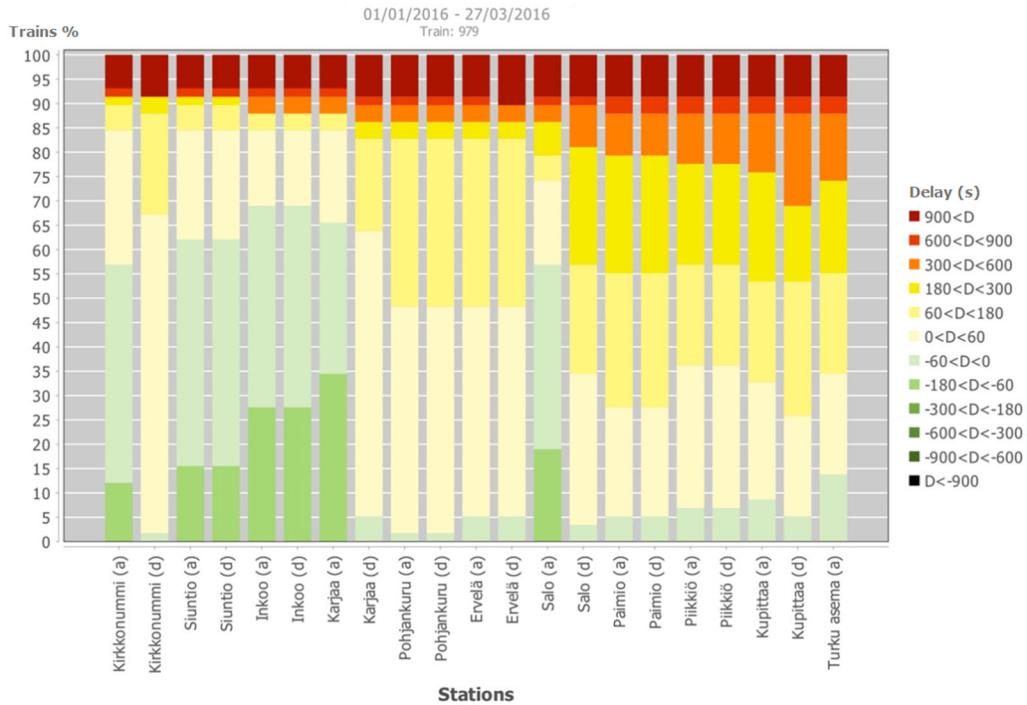


Figure 9. Variation of delay along the route of Train 979. Stations along the route are represented horizontally, while the bars of different colours represent the percentage of trains within specific delay ranges. Punctuality decreases at the stations of Karjaa and Salo due to late-arriving trains from the opposite direction.

Figure 10 below shows the graphic timetable of real operations of the Oulu-Kontiomäki line, mostly used by freight trains with markedly higher departure variability. As clearly appears when comparing Figure 8 and Figure 10, the test lines considered in this study show very different types of traffic and delays. This difference is also evident in Figure 11, which shows per-day delay propagation on each single-track line. The diagrams present delay propagation per day, with delays above 15 and 30 minutes marked in yellow and red respectively.

The Turku–Kirkkonummi and Luumäki–Imatra lines have few days with extreme delays. These are more common on the Oulu–Kontiomäki line, resulting from the large number of freight trains. Table 8 provides the key indicators of diagrams (a), (b), and (c) (Figure 11).

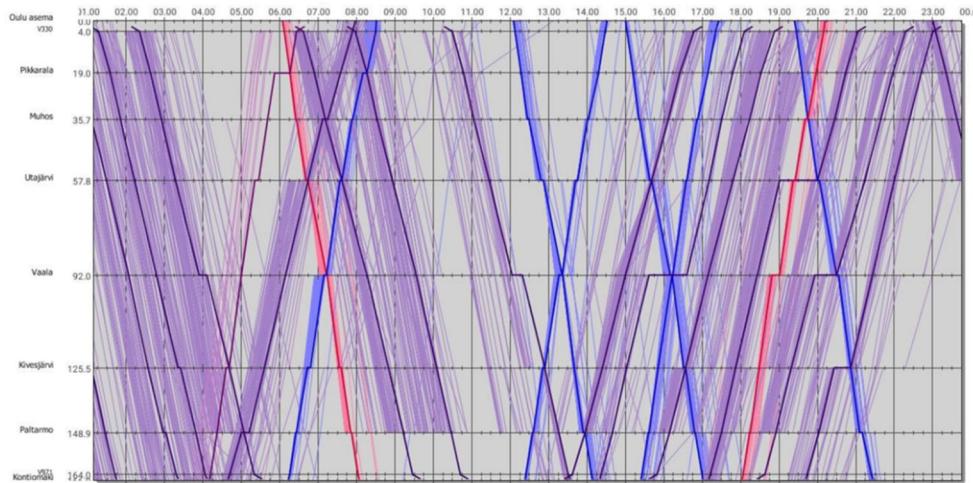


Figure 10. Analysis of real operations on the Oulu–Kontiomäki line.

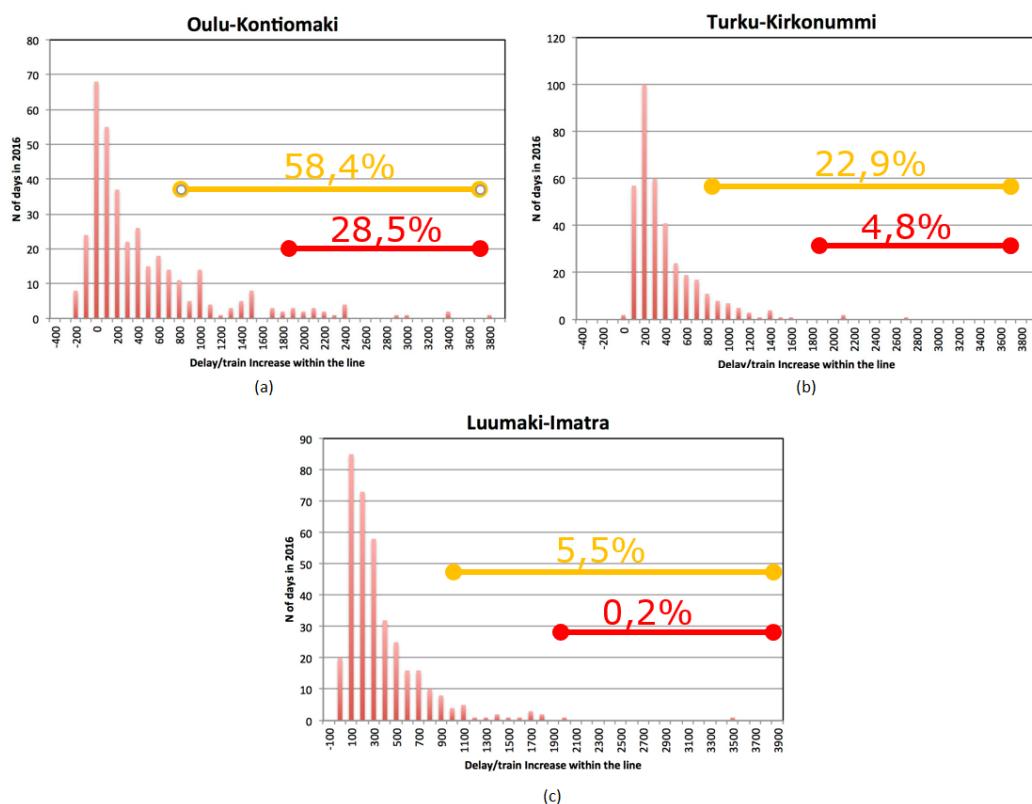


Figure 11. Delay propagation on the three study lines. Delays above 15 minutes are marked in yellow. Delays above 30 minutes are marked in red. The percentage of trains above either delay-propagation threshold is illustrated using the same colours.

Table 8. Key delay indicators for the three test lines.

	Mean	Median	Standard deviation
(a) Oulu–Kontiomäki	467	231	677
(b) Turku–Helsinki	410	290	433
(c) Luumäki–Imatra	375	258	420

5.2 Approach for delay estimation method

Theoretically, delays would propagate indefinitely on a line used at its maximum theoretical capacity with no margins nor buffer times, as shown in Figure 12, where c_{th} indicates the theoretical capacity. The maximum capacity consumption is the maximum number of trains that can be reasonably operated without exceeding the acceptable delays.

Similarly, Figure 13 shows the relationship between capacity and delays. Maximum capacity consumption is a function of the input delays: if trains start very accurately and running times are respected, the same delay is obtained with a higher number of trains (green curve). Conversely, poor performances (red curve) force a reduction in the number of services.

Finally, Figure 14 describes the relationship between capacity, delays, and margins. Margins allow for recovery from delays: the more margins inserted in a timetable, the more trains can be added. However, adding margins (green curve) also means increasing the running times of trains. Thus, it will be possible to insert fewer trains. Moreover, the running times are longer, reducing the appeal of the services.

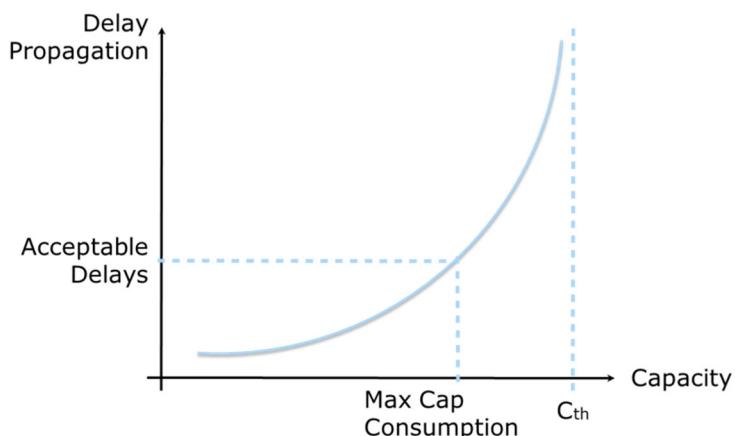


Figure 12. Relationship between capacity and delay.

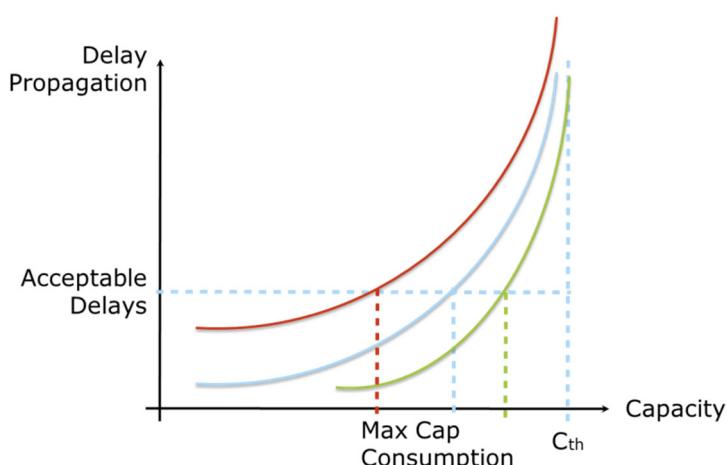


Figure 13. Relationship between capacity and initial delay.

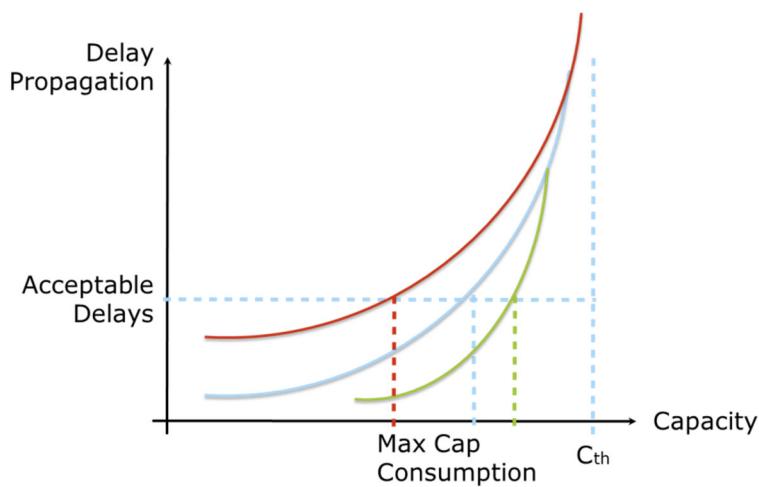


Figure 14. Relationship between capacity, delay, and margins.

It is easy to use simulation, or other techniques, to estimate the capacity-reliability curves on double track lines, where capacity utilization can be increased constantly by reducing the headway time among services. The calculation can then be repeated, obtaining at each step the delay propagation corresponding to that capacity utilization. This process is summarized in Figure 15.

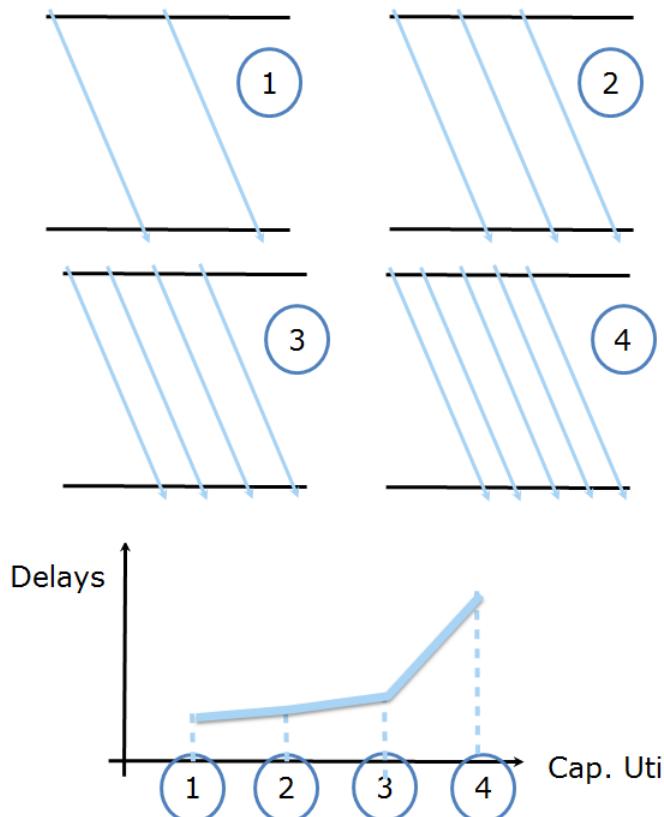


Figure 15. Capacity and delays on double track lines.

The single-track case faces different issues. On a single track line, it is not possible to gradually increase capacity consumption, since in most cases the resulting timetable would contain impossible crossings on the open line.

Moreover, the propagation of delays does not only occur in one direction, since at crossing stations delays are propagated in the opposite direction (as illustrated in the previous Turku–Helsinki example, see Figure 8). As a result, separated models must be developed for single- and double-track lines.

5.3 Estimating delays on single-track lines

5.3.1 Approach

The propagation of delays P on a single-track segment is a function of:

- the number of crossings N_x in the timetable (which depends on the capacity utilisation);
- the initial delay $t_{d,i}$
- the margin t_m (implicit + explicit).

In a timetable we can distinguish between "explicit" and "implicit" margins. "Explicit" margins are inserted by planners to compensate for delays and "implicit" margins are all waiting times at and before crossings, due to the combination of the structure of the timetable (faster and slower services) and of the line (variable running times in the various line sections). These "implicit" margins also compensate for delays.

If $t_m = 0$, the propagation would continue at all crossings, and thus every initial delay, $t_{d,i}$, would propagate to all trains of the day. With increasing t_m , the propagation of delays decreases; if $t_m > t_{d,i}$ there is no delay propagation.

Simple example

Let us now consider a simple line with one intermediate crossing point, and the same running time on the two lines. An "explicit" margin $t_m = 1$ is inserted in the running times. The total delay at arrival from an initial delay $t_{d,i} = 4$ would be calculated as described in Figure 16. Note that if there was one fewer train (and consequently two fewer crossings), the delay would shrink to $t_{d,e} = 3 + 2 + 1$.

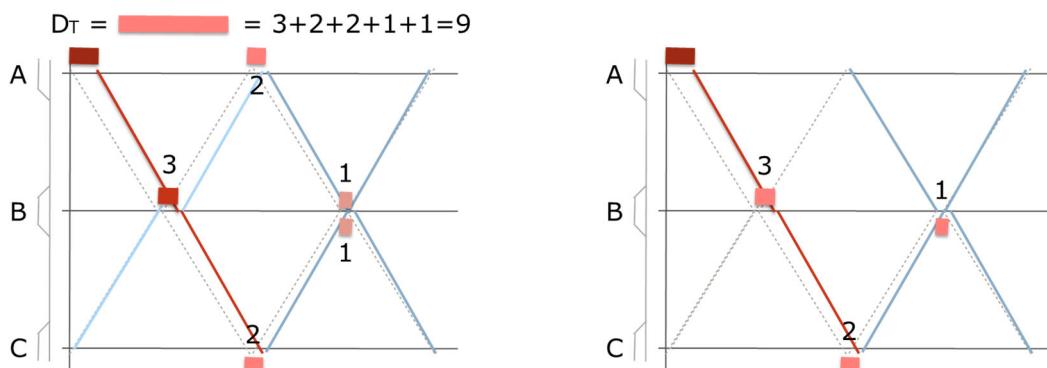


Figure 16. Estimation of delays on single track lines.

In real conditions, the estimation of delay is remarkably more complex due to:

- The presence of variable "implicit" margins, and their variable impact based on their location.
- The variable impact of crossings based on their location and the characteristics of the station (e.g. simultaneous entries, etc.)
- The variability of running times.

Key parameters in the model

When starting the analysis of the open data provided by the Finnish Transport Infrastructure Agency, the set (t_m , N_x , t_d) was slightly improved considering that:

- the explicit margin t_{mr} is inserted by the planners, but it cannot be found in the open data feeds. A fixed percentage of 10 % for all passenger trains and 12 % for freight trains was used.
- the initial delay $t_{d,i}$ of some trains is negative, and early-running trains might still lead to conflicts, although with a lower probability; thus, the initial positive and negative delays were separated ($t_{d,i+}$, $t_{d,i-}$)

The initial and arrival delays ($t_{d,i+}$, $t_{d,i-}$, t_{d+e}) include all delays regardless of the cause of the delay. For the initial delays this is not a problem because infrastructure investments can only affect delays that propagate in the track section to which the investment is related to. Therefore, all delays must be included in the initial delays as the goal is specifically to assess how these delays propagate in a certain track section.

Arrival delays also include all delays regardless of the cause of the delay, but the days with heaviest delay propagation (Figure 23) within each line are filtered out: these days de-facto include major failures at trains or infrastructure, which would lead to an under-estimation of the benefits of the investments. In principle, all delays that occur in the track section being analysed, and which are caused by failures, accidents, weather conditions and other causes not related to capacity, should be filtered out of the arrival delays because these delays can't be affected by infrastructure investments. Infrastructure investments have an effect mainly on delays caused by other trains. However, filtering the delays based on the cause of the delay would be very challenging. In practice each delay should be evaluated if it could have been affected by the infrastructure investment. Additionally, in Finland the causes for the delays are only recorded at certain monitoring stations and after certain thresholds. The delays can be allocated on a particular track section only if the initial and arrival station of the track section are monitoring stations. Furthermore, not all delays are marked with their cause, since the cause is given only after the delay reaches the threshold value.

Due to these reasons, all delays were considered in the analysis. The effects of major incidents on the results were minimized by filtering out abnormally large delays. This so-called tail filtering is described more precisely in section 5.3.2.

Preparing the input data

Data are prepared in a series of steps:

1. The list of stations on the line is defined.
2. The open data feeds are filtered obtaining a set of files, each containing the planned and actual trains on the line on a single day.
3. The running time margins are estimated on the planned timetable as a fixed percent of running time (5% for commuter trains, 10% for long-distance passenger trains and 12% for freight trains)
4. The number of crossings on each day is estimated.
5. The files of all days are merged in a single file (table).
6. The initial delays and end delays of each train are estimated in the aggregated file. The number of crossings is added as an additional column.
7. The mean delays and number of crossings per train on each day are calculated. Data were then aggregated for each line and day, considering one year of data, and used as input for the regression.

The workflow for input data preparation is described in Figure 17.

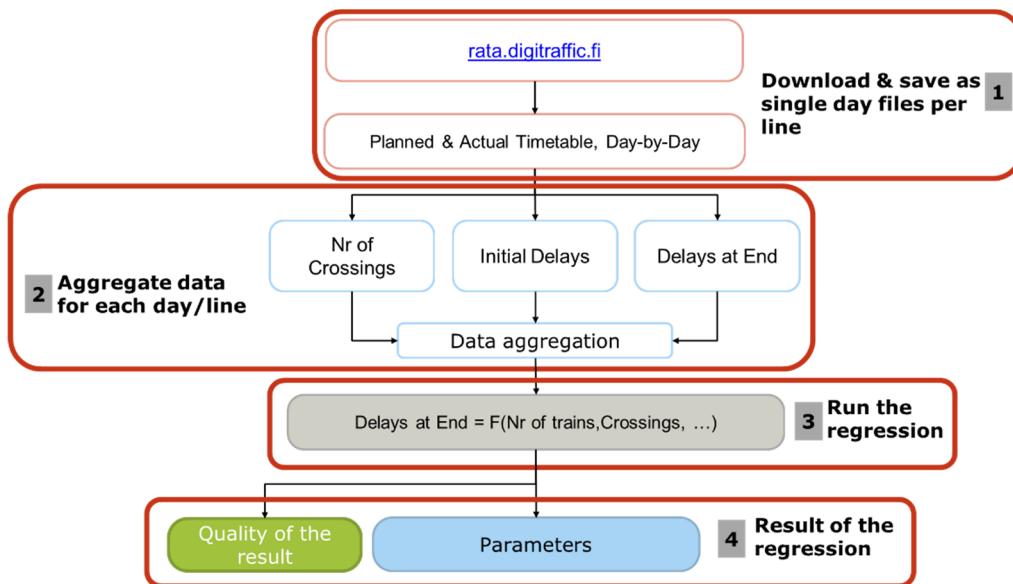


Figure 17. Workflow for input data preparation as part of developing delay function for single track lines.

Understanding variability of delays: simulation

Analysis of historical data alone can suffer from limitations when they do not cover the whole set of combinations that the parameters considered may assume. Running simulations can solve this issue, as it is possible to first define different timetables, each with different parameters representing them, and then simulate them to determine output delays. Simulations were run on timetables with a different number of crossings per train, with different values of input delays. This way, it is possible to understand how delays change by altering one parameter at a time. For example, it is easier to answer questions

such as "how do delays change when crossings increase?". This example may be tackled by defining one or more fixed values of all parameters except for crossings, and then observing the variation of delays with varying crossings.

A simulation was run to observe delay variations when changing parameters that change in the timetables considered, that is crossings and positive input delays. Margins are a fixed percentage of running times and were thus not included. This also made the formula more user-friendly.

The microscopic simulation tool was used to run the simulation. Besides being the most used tool in its field worldwide, OpenTrack is the standard railway simulation software deployed in Finland. OpenTrack solves the motion equation of trains moving on a microscopic model of the infrastructure. This is done with a mixed continuous-discrete process that combines the continuous dynamic behaviour of the train with the discrete changes of signal conditions and of the interlocking system.

The microscopic model of the line was created based on the signalling diagrams, the official rolling stock characteristics, and the timetable created as a regular pattern of trains extracted from the current timetable.

Regression

The formula to estimate delays at the end of a line has parameters that are determined through mathematical regression, considering both aggregated real data and aggregated results of the simulations. Three different approaches may be used: using real data only, using simulation results only, or using an intermediate approach, considering both data. This decision is discussed as follows.

The workflow for mathematical regression is described in Figure 18.

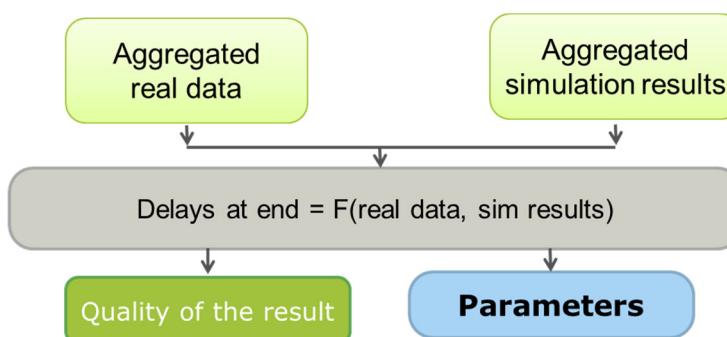


Figure 18. Workflow for mathematical regression as part of developing delay function for single track lines.

Simulations

First, we define the data that were studied. The Ylivieska–Oulu line was used as test line for all cases. The different scenarios that were studied were each characterised by two parameters: crossings and positive input delays per train.

Since timetables were defined by defining trains at regular time intervals, the number of crossings per train depends directly on the headway. The following table describes the crossings per train for each value of headway:

Table 9. Relationship between headway and average number of crossings in simulation study as part of delay evaluation method development.

Headway [s]	25	30	35	40	50	60	80	100	120	180	240	480
Crossings per train	8.84	6.46	5.46	3.95	3.14	2.22	1.24	1	0.57	0.38	0.16	0.08

Positive input delays were defined with the following values: 120, 240, 360, 480 and 600 seconds. For each combination of (crossings, input delay), 100 simulation runs were executed. Thus, a total of $12 \times 5 \times 100 = 6,000$ simulations were run. Multiple simulations were used to produce different random distributions of the average input delay between trains (having all trains with the same input delay would not represent a realistic situation, as the variance of delay would be null, and timetables would simply be translated).

First, the mathematical relationship between output delay and each of the two input parameters (i.e. input delay and crossings) is studied. This is achieved by analysing how output delays change when only one of the two input parameters change.

In the figure below, the relationship between output and input delay is studied. The x-axis shows the amount of input delay, while the y-axis shows the amount of output delay. Each line depicts the variation of delay for a fixed headway, while the vertical bars show the average across all values of headways (and thus crossings). The graph in the figure shows that the relationship between input and output delays is more than linear, i.e., it is described by an equation with degree greater than 1.

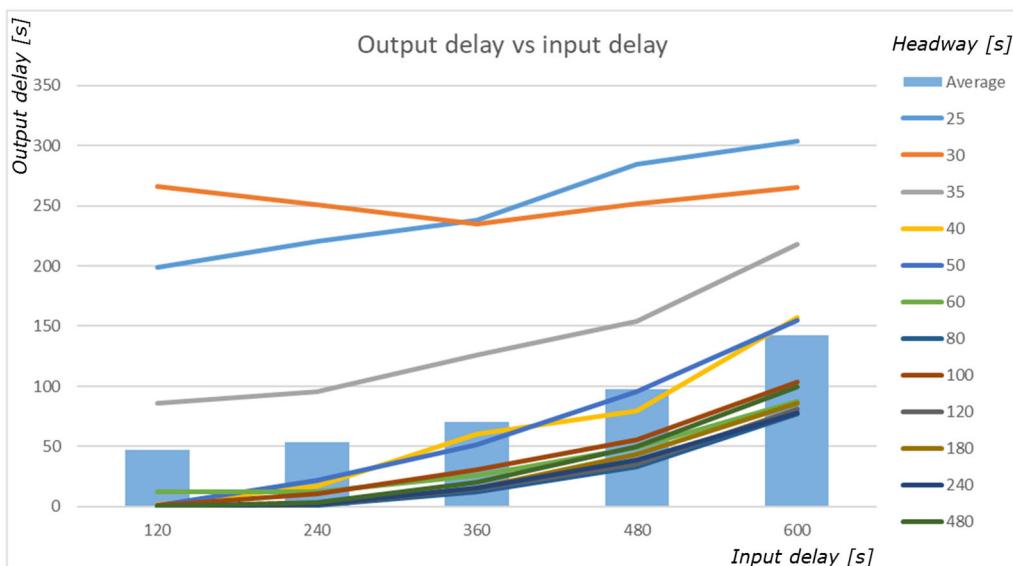


Figure 19. Relationship between output and input delay with various headways.

Similarly, the following figure analyses the relationship between crossings and output delays. The behaviour of this line, representing the average delays per each crossing value considering all input delay values, is different from what was observed in the previous figure. For small values of crossings (up to around 2 crossings per train), there is no appreciable tendency. Around 3 crossings/train, output delay starts increasing, and then starts "exploding". The reason why the "explosion" does not continue in the last point of the graph (around 9 crossings/train) is that deadlocks prevent trains from arriving at all, and the increase is thus not observable in the graph. In other words, trains that couldn't run through the whole line due to deadlocks, were excluded in the analysis. These are also typically the same trains that would have been most delayed at the final station.

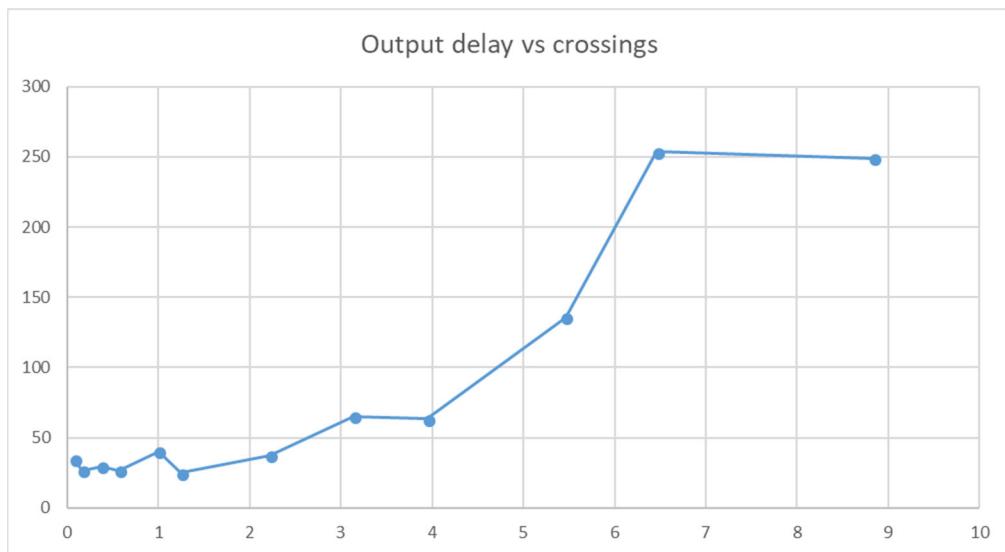


Figure 20. Relationship between average output delay (Y-axis) in seconds and crossings (X-axis).

As the goal is to obtain a mathematical formula that considers both phenomena, the type of formula describing each of the two phenomena should be identified first. Graphical comparison of the obtained graphs with trend lines is a good way to do so, and results are shown in the next two figures. As the analysis of both phenomena showed a non-linear relationship, quadratic formulas, which are the simplest ones, are tested first. The first graph shows that the relationship between output delays and input delays is very well represented by a quadratic formula. The second graph does not provide results of the same quality; however, it provides a reasonable approximation of the values observed in simulation results. Thus, the interaction between output delays and both input delays and crossings will be studied using quadratic formulas.

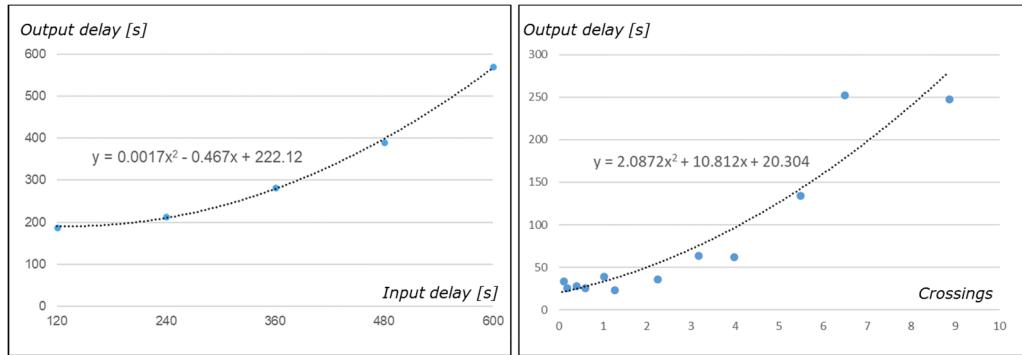


Figure 21. Left: Relationship between output delay and input delay. Right: Relationship between output delay and crossings.

5.3.2 Single-track regression parameters estimation

Considering the analysis of the simulation results, the basic regression model for the single-track case is a combination of two quadratic formulas, one considering positive input delays and one considering crossings. The notation used is the following:

$t_{d+,e}$ = mean non-negative delay at the end of the line

$t_{d+,i}$ = mean non-negative initial delay of all trains

$N_{x,t}$ = number of crossings/train

Given these parameters, the expected output positive delay of a group of trains is given by the following formula:

$$t_{d+,e} = f(t_{d+,i}, N_{x,t}) = \alpha + \beta \cdot t_{d+,i}^2 + \gamma \cdot t_{d+,i} + \delta \cdot N_{x,t}^2 + \epsilon \cdot N_{x,t}$$

Given that the observations were made on simulation results, regression is first run on simulation results. This allows a set of parameters to be obtained that may be tested against Finnish historical data, allowing understanding of whether simulation results fully reflect real Finnish operations, or if they need some adjustment.

Regression results on simulated data are the following:

$\alpha = 0$ (no intercept imposed in order to have parameter-driven formula)

$\beta = 0.0005$

$\gamma = -0.152$

$\delta = 2.127$

$\epsilon = 10.392$

First, obtained parameters are compared with those of the fitting formulas described in the previous two figures. Fitting formulas were:

- Input delays: $y = 0.0017 x^2 - 0.467x + 222.12$
- Crossings: $y = 2.087 x^2 + 10.812x + 20.304$

Parameters for crossings fitting are similar to the δ and ϵ values from regression. Contrarily, parameters for input delays fitting are around 3 times the β and γ values from regression. This indicates that the combined formula is driven by crossings more than by input delays. This is a good result, as crossings are a characteristic of the timetable, while input delays may vary. Thus, a crossings-driven formula provides more reliable results to the planner.

After obtaining a regression formula, it may be applied and evaluated considering real historical data from Finland. Considered data included 1-year worth of actual data from 12 single-track lines: Kouvola–Pieksämäki, Parikkala–Joensuu, Tampere–Seinäjoki, Kirkkonummi–Turku, Turku–Toijala, Orivesi–Jyväskylä, Seinäjoki–Vaasa, Seinäjoki–Kokkola, Ylivieska–Iisalmi, Oulu–Kontiomäki, Luumäki–Imatra and Luumäki–Vainikkala.

First, "bad days" were filtered out from input data by excluding extreme values of delay propagation, defined as the difference between positive output delay $t_{d+,o}$ and positive input delay $t_{d+,i}$. Filtering was performed separately for each considered line, as each line has different characteristics, see Figure 22.

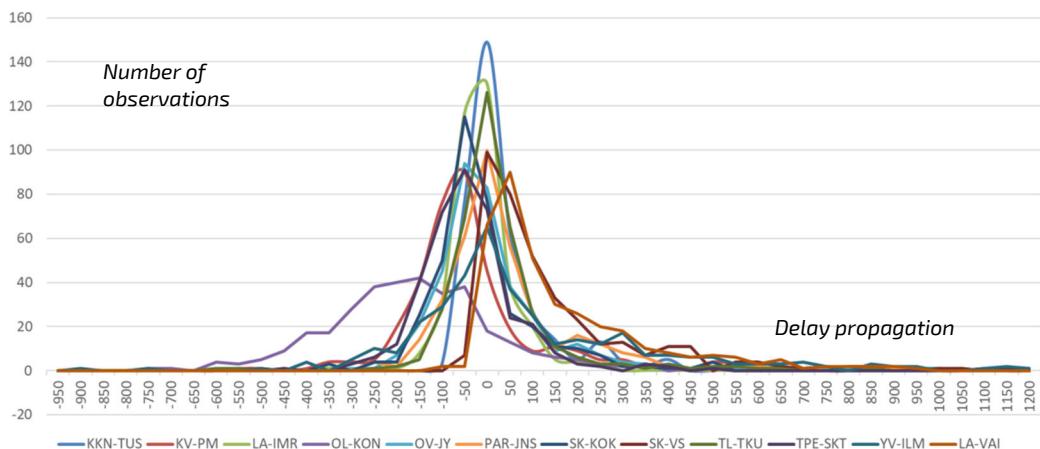


Figure 22. Delay propagation per line.

Given these input data, the proposed regression formula is studied to analyse how good it is to estimate output delays. Regression results are evaluated through the "goodness" of the regression, defined by the following formula:

$$\text{goodness} = 1 - \frac{\sum(|t_{d+,e} - t_{d+,o}|)}{\sum t_{d+,o}}$$

This formula measures how close estimated delays are to the real measured ones. Goodness may only be equal to 1 if the numerator is equal to 0, that is if $t_{d+,e} = t_{d+,o}$ which corresponds to a perfect estimation. In the following, goodness will always be referred to in percentage terms (i.e. 1 = 100%).

The goodness of the proposed formula with historical Finnish actual data is low, equal to just 10.8%. Thus, there is the need to find a way to make simulation results and actual data meet, so that both are considered.

A first alternative attempt is done by performing the regression on actual data only, without taking simulation results into account (except for their role in determining the quadratic form of the formula). Results of this attempt are counter-intuitive for crossings, providing a value of $\delta = -19.002$. This parameter is associated to the quadratic term of crossings, thus the formula would lead to saving delay with increasing crossings, which is the opposite of what was observed in the simulation results. The reason for this wrong observation is that, in real data, there are very few cases with a critical values of crossings per train. In fact, the average is just 0.89 crossings/train, a value around which simulation results did not show a clear relationship between output delays and crossings.

To have a formula that considers both input delays and crossings it is thus necessary to look for a mixed approach. Devising the new approach, two facts are observed:

- Crossings in real data are insufficient for understanding the whole phenomenon;
- Simulation-based regression results provide a crossings-driven formula.

For these two reasons, the mixed approach considers crossings parameters from simulated data, and then "trains" the formula to consider real data by calculating parameters for input delays. Since parameter results are kept for crossings from regression performed on simulation results, regression is performed on actual data considering the following formula:

$$t_{d+g,e} = \beta \cdot t_{d+g,i}^2 + \gamma \cdot t_{d+g,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x$$

where 2.127 and 10.392 are the values of the δ and ϵ parameters from regression on simulation results, respectively. The new actual data-based regression will thus only determine the values of β and γ .

Execution of regression provides a goodness of 61.0%, much greater than the previously obtained 10.8%, with the following parameters:

$$\begin{aligned}\beta &= -0.00005 \\ \gamma &= 0.953\end{aligned}$$

The value of the β parameter, associated to the quadratic term of input delays, is negative, and thus counter-intuitive. It is however very small, leading to a new question: does it really impact the results? The answer to this question can be given by performing the regression once again, removing the β parameter. The new results provide a slightly different value of $\gamma = 0.918$, with same goodness of 61.0%. This indicates that the quadratic term for initial delays in the formula does not provide any benefit and is thus removed.

The final proposed formula for estimating output delays on a single-track line is the following:

$$t_{d+g,e} = 0.917 \cdot t_{d+g,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x$$

This formula is easy to use, and only has a single quadratic term on its driving factor, i.e. crossings. The formula states that 91.7% of initial delays propagate to the end (i.e. the 0.917 factor). The effect of crossings may be summarised by the following graph, which shows the relationship between crossings per train and output delay.

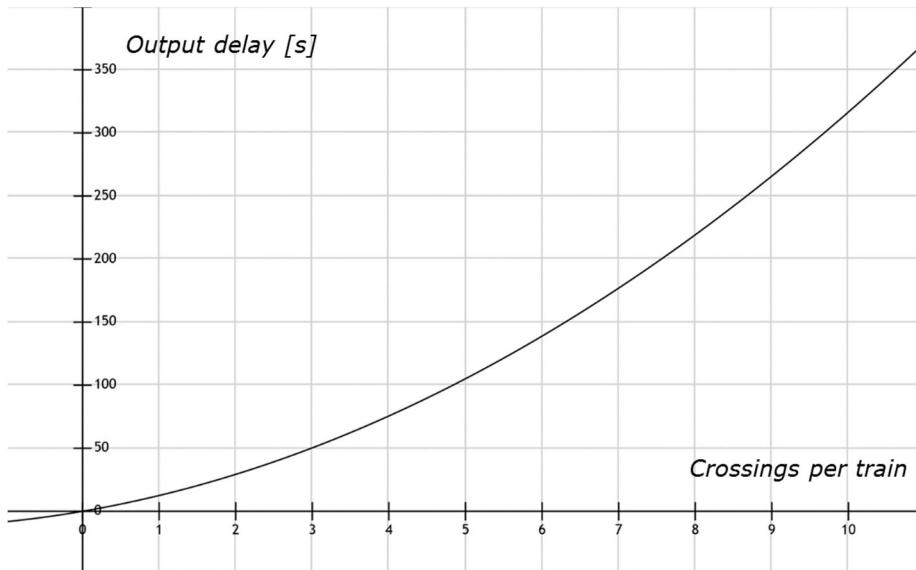


Figure 23. Relationship between crossings per train and output delay with the final single track delay formula.

Single track formula validation

The reported 61% goodness is a global average among all lines, not providing detailed information on how well the formula performs on individual lines. Applying the formula and analysing results line by line allows understanding how well the formula performs under different conditions, i.e., if there are some characteristics of the lines under which the formula performs best or worse. The following table 10 summarises the results of this analysis:

Table 10. Single track formula results on real test lines.

Line	Passenger trains/day	Freight trains/day	Positive input delay/train	Negative input delay/train	Crossings/s train	Goodness	
KKN-TUS	28.2	26.1	2.1	118.1	53.1	17.4	61.8%
KV-PM	23.8	11.6	12.2	285.8	310.6	39.7	51.1%
LA-IMR	45.1	13.4	31.7	289.8	457.9	30.4	82.7%
LA-VAI	16.9	8.8	8.2	205.6	339.7	8.7	57.6%
OL-KON	21.1	6.9	14.3	478.4	289.4	24.4	40.9%
OV-JY	33.7	16.9	16.7	249.7	282.0	27.6	68.8%
PAR-JNS	23.7	11.3	12.4	290.4	317.3	23.2	71.8%
SK-KOK	26.5	17.9	8.6	226.2	212.1	30.2	63.3%
SK-VS	9.7	8.6	1.1	71.3	170.3	4.6	31.9%
TL-TKU	17.4	12.3	5.0	154.3	272.5	9.9	65.1%
TPE-SKT	38.1	26.8	11.2	249.0	172.8	32.5	63.9%
YV-ILM	12.8	2.0	10.8	314.6	477.7	13.1	59.3%

The goodness is above 50% for 8 out of 10 lines. The two lines with the worst goodness are Oulu–Kontiomäki and Seinäjoki–Vaasa. These two lines are those with the extreme positive input delay values: while the per-line positive input delay is 261 seconds per train, the average positive input delays for these two lines are 478.4 and 71.3 seconds per train, respectively. Further, the Seinäjoki–Vaasa line is the one with the smallest number of trains. These two factors combined result in the lowest goodness among the 10 lines. Generally, this indicates that good results may be expected when applying the formula to a case with positive input delay comparable with the one studied here (i.e., 260 seconds per train), and with a total number of trains that is not too small (the Ylivieska–Iisalmi line only has 12.8 trains, but its goodness is 59.3%, thus having at least 12 or 13 trains may be sufficient).

5.4 Estimating delays on double-track lines

5.4.1 Approach

The key parameters to identify the propagation of delays on double-track lines are the buffer times, the margins and the initial delays. The buffer times are the additional spacing between trains, which reduce the risk of delay propagation.

Margins are inserted in the timetable to allow recovering the unavoidable variabilities in real running and stop times; the effective amount of margins and buffer times is given by the way the timetable is designed. Specifically, the propagation of delays is function of:

- the buffer times B , and especially the number of points in which the buffer is limited, the so called “critical headways” b .
- the initial delay $t_{d,i}$,
- the running and stop time margins t_{mr} and t_{ms}
- the position of margins and buffer times along the line.

If $b = t_{mr} = t_{ms} = 0$, the propagation would continue at all crossings, and thus every initial delay $t_{d,i}$ would propagate to all trains of the day.

With increasing t_m and b the propagation of delays decreases; “if both b and t_m are greater than $t_{d,i}$ there is no delay propagation.”

Simple example

Let us consider a simple line with one intermediate stop, and the same running time on the two sections. The margins are marked in green, and the critical headway times in red and orange. The delay between trains is propagated at each single critical headway (Figure 24, left). As a next step, let us now add a departure (input) delay of 10 to the first train (Figure 24, right). The delays at the end depend on the number of critical headways and the margins.

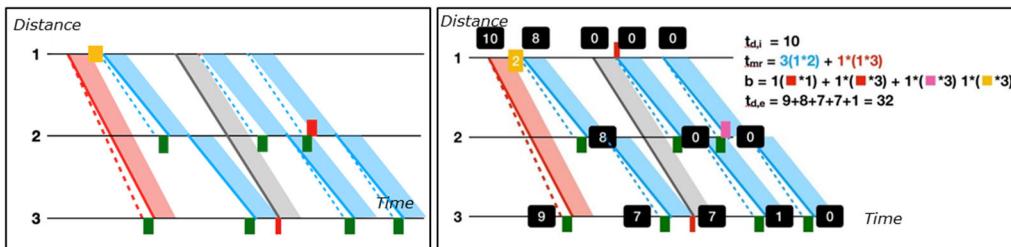


Figure 24. Double track parameters, simple example.

5.4.2 Double track regression parameters estimation

Data are prepared for the regression in a series of steps:

1. The day is separated into a few parts (in the following named time bands) following the variation in the number of services / hour.
2. Each station along the line receives a number, given by its ordinal position along the line [1..N].
3. The planned and actual timetable data, as obtained by aggregating the open data for all trains, is exported as a csv file using the ordinal list of stations obtained at the previous step.
4. The running and stop time margins for each train are derived from the planned timetable, and saved in a second csv file, together with their ordinal position along the line.
5. The same minimum headway times H for each section estimated in the capacity analysis are used as input for the estimation of the critical headway times. For each train and at each station, the critical headways b , with b = planned headway-minimum headway, that fall within given thresholds (0–1 min, 1–2 min, ...) are counted and saved in a third text file.

The description of the corridor (i.e. the ordered sequence of stations it is composed of) and the three csv files (each with planned and actual timetables, running and stop margins, and minimum headway times) are the inputs for the regression.

The complete workflow is presented in Figure 25.

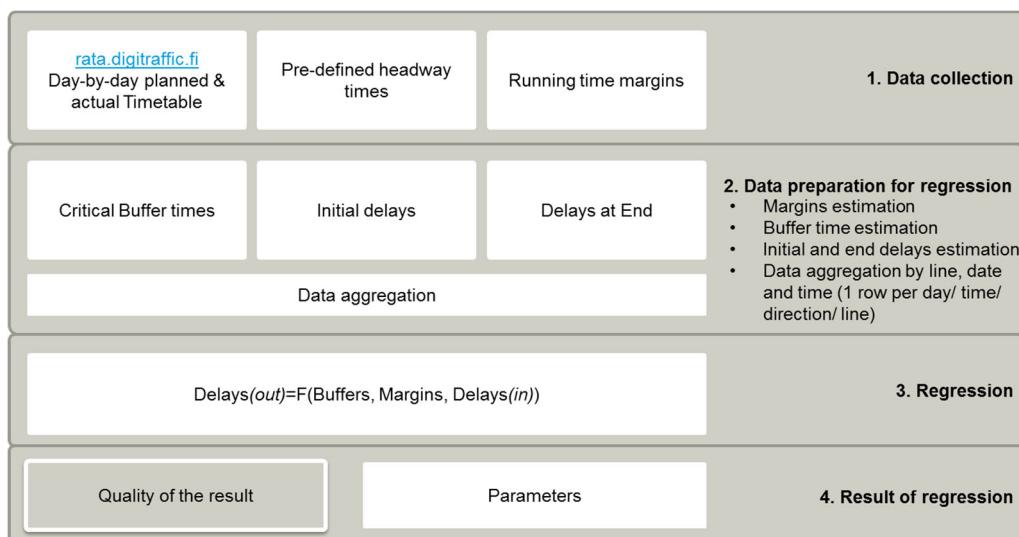


Figure 25. Double track regression workflow.

On double track lines, delays depend on the amount of margin, buffer times, and input delays. Thus, the following notation is used:

bf_g^b	number of buffers in a threshold b for a group of trains g , with thresholds defined for buffers from a minimum and a maximum size
$w(b)$	weight of buffer b
$t_{mr,g}$	mean margin of trains in group g
$t_{d+,g,i}$	average positive input delay for trains in group g
$t_{d-,g,i}$	average negative input delay for trains in group g

Delays are inversely proportional to the amount of margin and buffer times, the relationship, estimated for each time band on a line is:

$$t_{d+,g,e} = \alpha + \beta \cdot \sum_{b \in B} (w(b) \cdot bf_g^b) + \gamma \cdot t_{mr,g} + \delta \cdot t_{d+,g,i} + \epsilon \cdot t_{d-,g,i}$$

The effect of buffer times is evaluated considering the criticality of having a small buffer time, and the $w(b)$ function is defined to reflect this criticality, as follows:

$$w(b) = 2^{-s(b)}$$

where $s(b)$ is the maximum value of buffer, expressed in minutes, counted in the discrete buffer b . E.g., a buffer threshold b counting buffers between 60 and 120 seconds has $s(b) = 2$ (the largest values of the buffers it counts, in minutes). Considering discrete buffer thresholds of a size of 1 minute, the $w(b)$ function varies as shown in Figure 26.

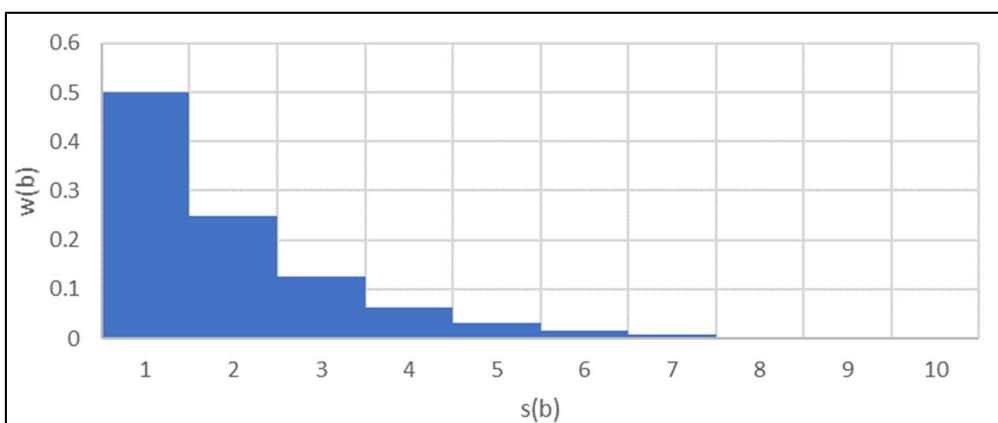


Figure 26. Variation of $w(b)$ over different buffers.

Input data included 20 lines, i.e., 10 double-track lines with both directions considered separately. The 10 considered lines are: Riihimäki–Tampere, Helsinki–Lahti, Ring rail line (Commuter tracks), Helsinki–Kerava (Commuter tracks), Kerava–Riihimäki, Helsinki–Leppävaara (Commuter tracks), Helsinki–Kirkkonummi, Tampere–Orivesi, Lahti–Kouvola–Luumäki, and Riihimäki–Lahti. One year of traffic data were considered.

Train groups were formed per each line based on temporal information, considering peak traffic time bands, where relationships between parameters and output delays can be better observed. The two considered peak traffic time bands were 07:00-09:00 and 16:00-18:00. Buffer thresholds were subdivided into 5 groups: from 0 to 1 minute, from 1 to 2 minutes, from 2 to 3 minutes, from 3 to 4 minutes, and from 4 to 5 minutes. Larger buffers were not considered. Further, train groups with no most critical buffers (i.e., without any buffer between 0 and 1 minute) were not considered.

Regression results on the data considered provided the following parameters:

Intercept 0.000 (no intercept imposed in order to have parameter-driven formula)
 Buffer 22.443
 Margin -0.033
 Positive input delay 1.029
 Negative input delay -0.001

The final version of the double track delay formula is:

$$t_{d+,e} = 22,443 \cdot \sum_{b \in B} (w(b) \cdot bf_g^b) - 0,033 \cdot t_{mr,g} + 1,029 \cdot t_{d+,g,i} - 0,001 \cdot t_{d-,g,i}$$

The goodness of this regression is 73.91%, a value higher than the one obtained for the single-track case.

Resulting parameters appear to have reasonable values. Margins allow saving delays equal to 3.3% of their value. Positive input delays propagate to the end, causing 2.9% additional delay. Negative input delays allow saving just 0.1% of delays and have very little effect on the system. The effect of buffers is more difficult to understand, as the β parameter is associated to a summation representing the "buffer weight", needed to coherently represent the exponentially increasing negative effect of buffers when there is a larger number of critical buffers (i.e., when many trains are very close to each other, thus increasing the chance of delay propagation).

Double track formula validation

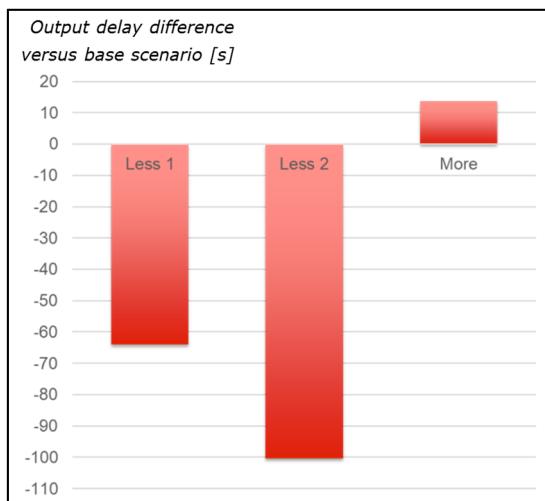
After developing the method, the regression results are validated to see the impact of small timetable changes on expected delay. Four scenarios from UK's Crossrail line were studied. The obtained formula was applied for each of the four scenarios, allowing the user to evaluate the provided results in a simple way. For the sake of simplicity, input delay is assumed to be null for all scenarios, thus allowing an easy analysis of the expected effect of all timetable-dependent parameters on output delay. The four scenarios are now illustrated.

The Base scenario represents the current timetable of the test track area. First, in Scenario 1, eight trains are added to the timetable, resulting in a high number of small buffers. Afterwards, two less crowded timetables are tested, first with removing almost half the trains from the original scenario and next removing half of the trains of the third scenario. A summary of these four scenarios, their parameters and expected delays are listed below (Table 11).

Table 11. Validation of double track delay function.

	Sc 0 "Base scenario"	Sc 1 "More Scenario"	Sc 2 "Less 1"	Sc 3 "Less 2"
Number of trains	40	48	22	11
0–1 min buffers	397	559	37	0
Buffer weight	210,668	291,219	36,688	0
Margin	547,5	678	0	0
Expected delay [s/train/day]	100,4	114,1	36,4	0

In summary, output delay across scenarios varies, compared with the base scenario, as illustrated in the following Figure 29:

*Figure 27. Validation results of double track delay function.*

This test case study shows that the proposed mathematical model is reasonable in reflecting changes to planned timetables and provides results that are sensible, and easy to use and understandable by the timetable planner.

6 Case studies

6.1 General overview

Case selection criteria

Three case studies were chosen to test the developed methods. Two case studies were selected to test the delay calculation tool for single track sections:

- upgrade of the Ylivieska–Iisalmi–Kontiomäki rail connection
- upgrade of the Luumäki–Imatra rail corridor

One case study (Espoo commuter track extension) was chosen to test the method for double track. All case studies were chosen where a cost-benefit analysis has been prepared in recent years, and the impact of improved punctuality on the overall feasibility of the investment can be estimated.

To evaluate the delay methods' impacts on cost-benefit ratios, the estimated delay reductions were turned into monetary value by using passenger forecasts. Value of time was based on reference values of the Finnish Transport Agency (2013).

The following chapters will focus on describing the results from using the new methods. A practical description of how the calculations are performed is described in English and Finnish in appendixes 2 and 4 respectively.

Source information

- Timetables were received from the original feasibility studies.
- The input delays were defined from actual operations during timetable period 1/2018, which represented one of the lowest punctuality periods (Figure 28).

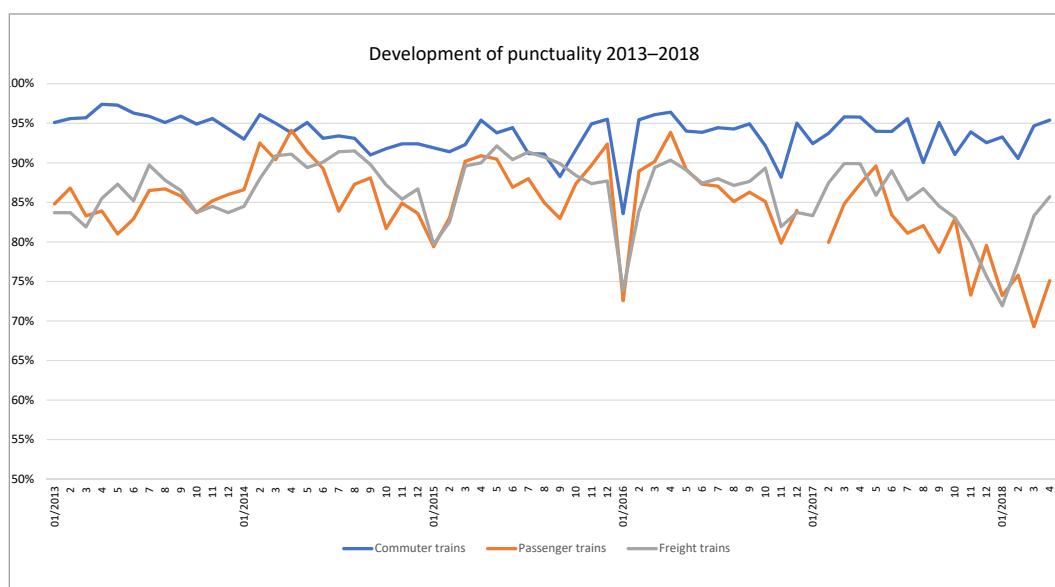


Figure 28. Development of average punctuality in 2013–2018 in Finland.

6.2 Upgrade of the Ylivieska–Iisalmi–Kontiomäki rail connection

Description

The goal of the investment was to re-route transit traffic between Vartius and port of Kokkola via the Ylivieska–Iisalmi rail corridor, in order to release capacity between Ylivieska and Oulu, which is part of Finland's main railway line and an important corridor for both passenger and freight traffic. The Ylivieska–Iisalmi rail corridor frequently has punctuality problems. Removing transit traffic would improve the punctuality of both passenger and freight traffic and enable an increased train supply. The investment includes electrification of the Ylivieska–Iisalmi rail corridor as well as building new and extended passing loops. A more detailed description of the investment and its goals is presented in chapter 1.1.

To perform a delay calculation the case is divided into two study sections (Ylivieska–Oulu and Ylivieska–Iisalmi) which are calculated separately. Between Ylivieska and Oulu punctuality is expected to improve as transit traffic trains are re-routed via Iisalmi. Between Ylivieska and Iisalmi punctuality is, in turn, expected to deteriorate as number of trains increases. The Iisalmi–Kontiomäki and Oulu–Kontiomäki rail corridors were not examined in this case study.

The technical input information regarding delay and capacity consumption calculations are collected in the following tables separately for Ylivieska–Oulu and Ylivieska–Iisalmi tracks.

Table 12. *Feasibility study description between Ylivieska and Oulu stations.
Abbreviations: YV=Ylivieska, OL=Oulu.*

	Scenario 0: Current infrastructure	Scenario 1: Investment
Timetable, reference day	Timetable planned as part of the feasibility study	Timetable is the same as for scenario 0, except 6 freight trains removed.
Operations	36 passenger trains, 14 freight trains. Existing infrastructure.	36 passenger trains, 8 freight trains. Two new passing loops and new block sections for four line sections.
Crossings	56 crossings	30 crossings
Input delay	Input delays defined from actual operations during timetable period 1/2018. Passenger trains: YV→OL: 614 s/train, 18 trains OL→YV: 368 s/train, 18 trains Freight trains: YV→OL: 738 s/train, 7 trains OL→YV: 1371 s/train, 7 trains Average input delay: 648 s/train	Investment has no clear impact on input delays. Relative amounts of freight and passenger trains changes and has an impact on average input delay: Passenger trains: YV→OL: 614 s/train, 18 trains OL→YV: 368 s/train, 18 trains Freight trains: YV→OL: 738 s/train, 4 trains OL→YV: 1371 s/train, 4 trains Average input delay: 593 s/train

Table 13. *Feasibility study description between Ylivieska and Iisalmi stations. Abbreviations: YV=Ylivieska, ILM=Iisalmi.*

Scenario 0: Current infrastructure	Scenario 1: Investment
Timetable, reference day Timetable planned as part of the feasibility study	Timetable is the same as for scenario 0, except 6 new freight trains inserted.
Operations 4 passenger trains, 27 freight trains. Existing infrastructure.	4 passenger trains, 21 freight trains. Investment has no impact on infrastructure or speeds.
Crossings 37 crossings	17 crossings
Input delay Input delays defined from actual operations during timetable period 1/2018. Passenger trains: YV→ILM: 117 s/train, 2 trains ILM→YV: 359 s/train, 2 trains Freight trains: YV→ILM: 557 s/train, 14 trains ILM→YV: 891 s/train, 13 trains Average weighted input delay: 655 s/train	Investment has no clear impact on input delays. Relative amounts of freight and passenger trains changes and has an impact on average input delay: Passenger trains: YV→ILM: 117 s/train, 2 trains ILM→YV: 359 s/train, 2 trains Freight trains: YV→ILM: 557 s/train, 11 trains ILM→YV: 891 s/train, 10 trains Average weighted input delay: 639 s/train

Impact on Capacity Consumption

Capacity consumption was calculated separately with and without running time margins for the Ylivieska–Oulu and Ylivieska–Iisalmi track sections. The calculation started with defining the minimum headway times (table 14).

Table 14. Minimum headway times used for capacity consumption calculations in Ylivieska–Oulu and Ylivieska–Iisalmi case studies.

Ylivieska–Oulu		Ylivieska–Iisalmi					
SC0, SC1		SC0			SC1		
OL__V330	↓ ↑	Ylivieska	↓	↑	↓	↑	
Kempele	0:05:53	0:05:48	Nivala	0:26:47	0:27:51	0:17:51	0:18:34
Liminka	0:04:52	0:05:33	Haapajärvi	0:26:00	0:26:09	0:17:20	0:17:26
Tikkaperä	0:04:38	0:05:25	Pyhäsalmi	0:31:21	0:29:04	0:20:54	0:19:23
Hirvineva	0:05:18	0:04:44	Pyhäkumpu	0:03:09	0:03:00	0:03:09	0:03:00
Ruukki	0:05:49	0:06:00	Komu	0:05:52	0:06:43	0:05:52	0:06:43
Tuomioja	0:06:55	0:07:10	Kiuruvesi	0:22:08	0:22:00	0:14:45	0:14:40
Ahonpää	0:05:06	0:04:58	Runni	0:14:26	0:15:16	0:09:37	0:10:11
Vihanti	0:06:44	0:06:08	Joutsenjoki	0:10:04	0:10:32	0:06:43	0:07:01
Kilpua	0:05:30	0:05:19	Iisalmi	0:03:00	0:03:00	0:03:00	0:03:00
Oulainen	0:06:48	0:06:37					
Kangas	0:06:49	0:06:30					
Ylivieska	0:07:47	0:08:29					

Capacity consumption for the Ylivieska–Oulu line is illustrated in Figure 29. Consumption remains relatively stable through the day. Capacity consumption rises above 75% only once during the day and above 60% five times a day. These peaks are marked with black arrows.

Based on the calculation guidelines for single track lines, capacity consumption is calculated for each line section separately. Capacity consumption rises above 60% five times a day, influenced mostly by the section between Oulainen and Kangas. One main reason for this result is the relatively high minimum headway values on this section.

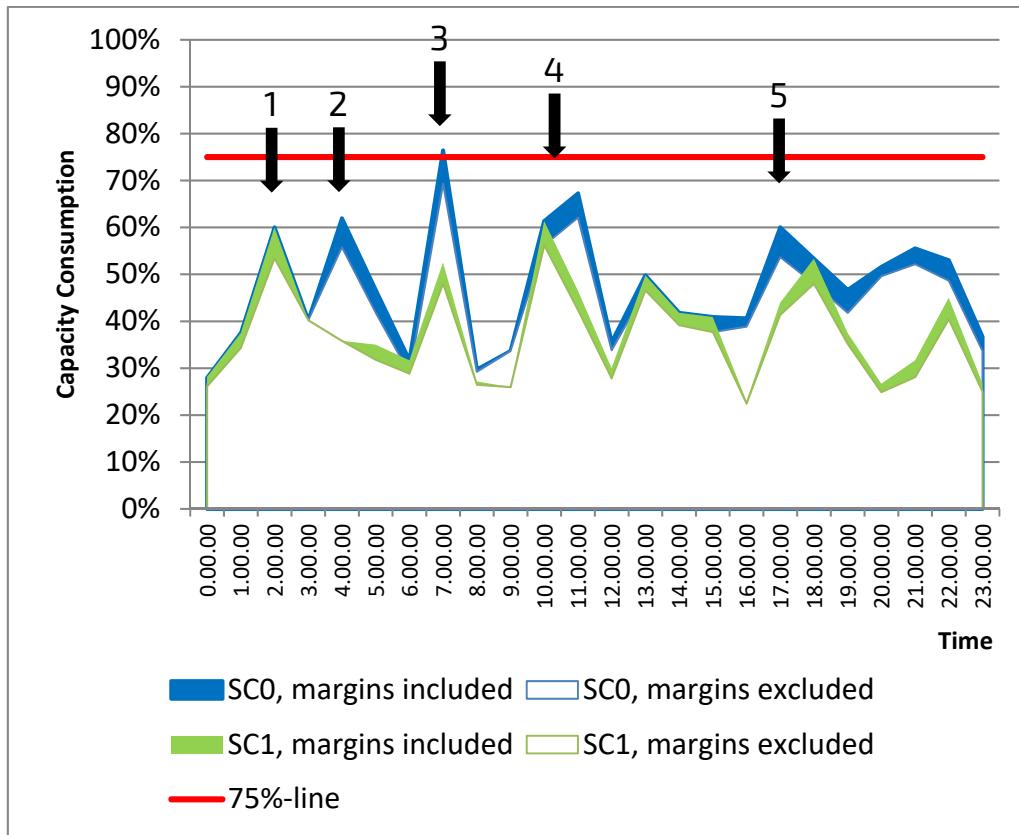
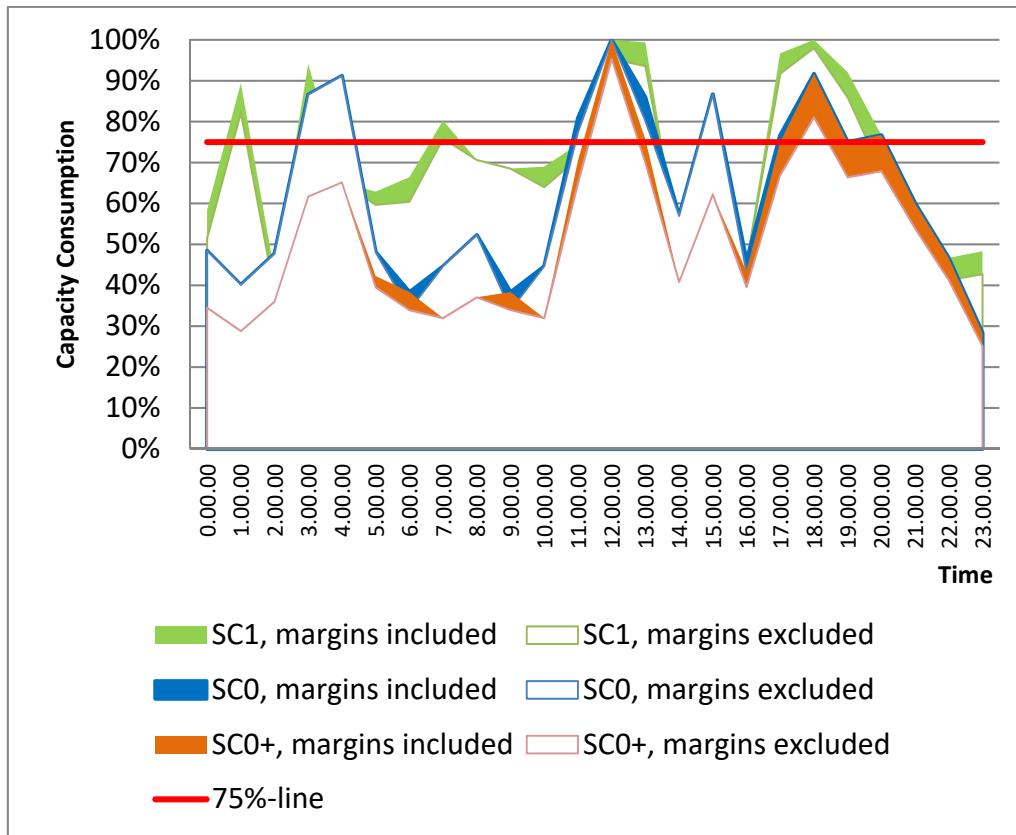


Figure 29. Capacity consumption on Ylivieska–Oulu track.

On the Ylivieska–Oulu track, the investment has a minor impact on the capacity consumption values as the only difference between the scenarios is removal of six trains (there is no difference in minimum headway values). However, lowering the highest peaks may have an important role in delay propagation in actual operations.

On the Ylivieska–Iisalmi track there are two major changes after the investment: firstly, increasing the speed limits affects the headway times. Secondly, six new trains are added in the timetable. To see the impact of these changes clearly, the calculation was repeated three times: for scenario 0 (no changes), for scenario 1 (new headway times + new trains), and for a virtual scenario 0+ (only new headway times). Scenarios 0 and 0+ have the same timetable.

The hourly variation of capacity consumption follows the same curve between scenario 0 and 0+. Scenario 1 has higher values due to the new trains.



*Figure 30. Capacity consumption on the Ylivieska–Iisalmi line.
SC0+ = new blocking sections but no new trains introduced.*

Overall, capacity is highly utilised between Ylivieska and Iisalmi and there are no quiet periods for unpunctual traffic to recover from delays.

Impact on Punctuality

Impact on punctuality on the Ylivieska–Oulu and Ylivieska–Iisalmi track sections was analysed using the formula for single track lines:

$$t_{d+,g,e} = 0.917 \cdot t_{d+,g,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x,$$

where $t_{d+,g,e}$ is output delay, $t_{d+,g,i}$ is input delay and N_x is the ratio of number of crossings to number of trains. The parameters are listed in the table below.

Table 15. Summary of Ylivieska–Iisalmi–Kontiomäki delay analysis.

	Ylivieska–Oulu Scenario 0	Ylivieska–Oulu Scenario 1	Ylivieska– Iisalmi Scenario 0	Ylivieska– Iisalmi Scenario 1
$t_{d+,g,i}$	648 s/train	593 s/train	639 s/train	655 s/train
N_x	= $\frac{56}{(36 + 14)}$ = 1,12	= $\frac{30}{(36 + 8)}$ = 0,68	= $\frac{17}{(4 + 21)}$ = 0,68	= $\frac{37}{(4 + 27)}$ = 1,19
$t_{d+,g}$	609 s/train	552 s/train	594 s/train	616 s/train

The investment reduces delays by 57 s/train on Ylivieska–Oulu line and increases delays by 22 seconds per train on Ylivieska–Iisalmi-line.

Impact on Feasibility Study Results

Estimated reduction of delay per train was turned into monetary value by using passenger forecast. Value of time was based on reference values of the Finnish Transport Agency. Total monetary benefits were calculated for a 30 year time span and discounted to current value. According to the calculation, reduction of delay by 57 seconds per train leads to following monetary savings in the 30 year time span.

• Passenger time savings	3,6 M€
• Capital and labour costs (passenger trains)	1,2 M€
• Capital and labour costs (freight trains)	0,8 M€
• Total	5,6 M€

This increase of benefits would have a minor impact on the investment cost-benefit ratio, which would raise from 0,73 to 0,78.

6.3 Upgrade of the Luumäki–Imatra rail corridor

Description

The second case study for single track sections is the upgrade of the Luumäki–Imatra rail corridor. This corridor is especially important for freight traffic and the forest industry of South-eastern Finland. The upgrade was considered necessary because the current single track rail line is congested and punctuality problems occur regularly. The planned investment includes several alternatives of which two were examined in this study:

- Scenario 1: double track on the complete section Luumäki–Imatra
- Scenario 2: double track between Joutseno and Imatra as well as upgrading passing loops and other minor investments that enable higher passenger service speeds.

The technical input information regarding delay and capacity consumption calculations is collected in table 16.

Table 16. Summary of Luumäki–Imatra case study. Abbreviations:
LÄ=Luumäki, IMR=Imatra.

	Scenario 0: Current infrastructure	Scenario 1: Double track Joutseno– Imatra asema	Scenario 2: Double track Luumäki– Imatra
Timetable, reference day	Timetable planned as part of the feasibility study.	Timetable planned as part of the feasibility study. Timetable nearly the same as for scenario 0.	Timetable planned as part of the feasibility study. Timetable nearly the same as for scenario 0.
Operations	31 trains on both directions.	Investment has no impact on number but enables higher passenger train speeds.	Investment has no impact on number but enables higher passenger train speeds.
Crossings	65 crossings	59 crossings on single track section. No passing on double track section.	No passing.
Input delay	LÄ→IMR: 824 s/train* IMR→LÄ: 558 s/train* Average input delay: 691 s/train	Investment reduces all delay issues due to L2 delay code between JTS and IMR. JTS-IMR-represents 28% of the case area length and delay code L2 represents 33% of all delays in the area**. $= 691 \frac{s}{train} * (1 - 33\% * 28\%)$ $= 627 \frac{s}{train}$	Investment reduces all delay issues due to L2 delay code between LÄ and IMR. LÄ–IMR represents 100% of the case area length and delay code L2 represents 33% of all delays in the area**. $= 691 \frac{s}{train} * (1 - 33\% * 100\%)$ $= 462 \frac{s}{train}$
Negative input delay	No need to define for single track line analysis.	No need to define for single track line analysis.	LÄ→IMR: 852 s/train IMR→LÄ: 359 s/train Average negative input delay 605 s/train

*) No need to consider the relative amounts of freight and passenger trains as the operations remain constant through all scenarios.

**) Analysis period 1/2015–12/2015.

Impact on Capacity Consumption

The calculation started with defining minimum headway times. The same headway values were used for each scenario as the investment had no impact on train speeds.

Table 17. Minimum headway times used for capacity consumption calculations in Luumäki–Imatra case study.

Luumäki–Imatra asema		
SC0, SC1, SC2		
Luumäki	↓	↑
Rasinsuo	0:05:58	0:05:55
Törölä	0:04:55	0:04:41
Tapavainola	0:04:03	0:04:03
Lappeenranta	0:06:05	0:06:11
Lauritsala	0:04:30	0:04:03
Muukko	0:04:22	0:04:46
Joutseno	0:06:55	0:07:11
Rauha	0:05:19	0:04:32
Imatra asema	0:04:44	0:04:38

The hourly variation of capacity consumption reveals two higher peaks on the consumption. Firstly, the morning peak (Peak 1) rises to 90%, meaning it has a high risk of influencing delay propagation. Another peak (Peak 2) occurs during period 23–24. Both peaks occur on a line section between Joutseno and Muukko stations, which also has the highest minimum headway time.

Scenarios 1 and 2 required calculations separately for each direction. For simplicity, the results are illustrated with average values between both directions.

The lines do not follow exactly the same curve, as the operations were re-planned for the double track lines. Even though the operations stayed the same, the exact timetables varied a little. For example, scenario 2 has higher capacity consumption between 15 and 16 hours than scenario 1, even though scenario 2 has double track.

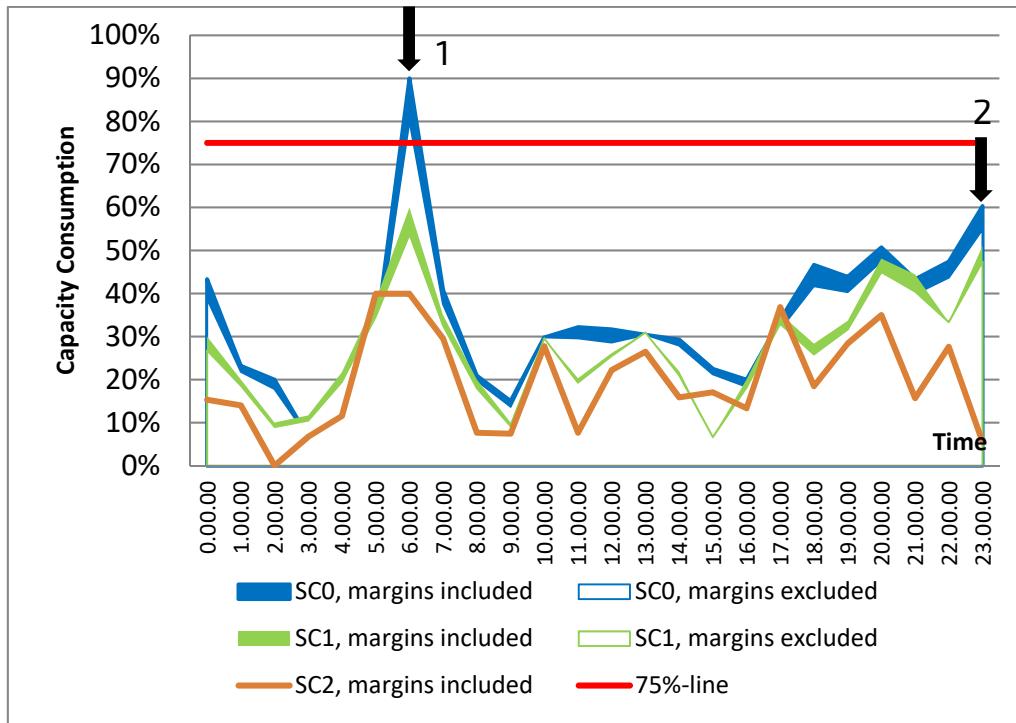


Figure 31. Hourly Variation of Capacity Consumption in the Luumäki–Imatra asema Track Section.

On the Luumäki – Imatra track capacity consumption has two higher peaks and, at other times, consumption remains at around 30 percent. Further studies are required to determine if re-arranging the operations during the peaks would decrease the highest peaks.

Impact on Punctuality

The impact on punctuality was analysed using the single track method on both scenarios 0 and 1, although scenario 1 has a short double track section. Another option to analyse scenario 1 would have been to analyse it in two parts. However, as the double track part is relatively short, the effect of it was estimated to be minor. Therefore, the single track method was utilised for the whole study area, simply ignoring the crossings between Joutseno and Imatra stations.

$$t_{d+g,e} = 0.917 \cdot t_{d+g,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x$$

where $t_{d+g,e}$ is output delay, $t_{d+g,i}$ is input delay and N_x is the ratio of number of crossings to number of trains. Scenario 2 was calculated using the double track method:

$$t_{d+g,e} = \alpha + \beta \cdot \sum_{b \in B} (w(b) \cdot bf_g^b) + \gamma \cdot t_{mr,g} + \delta \cdot t_{d+g,i} + \epsilon \cdot t_{d-g,i}$$

where $\sum_{b \in B} (w(b) \cdot bf_g^b)$ is a term describing the buffers (defined with an external calculation program), $t_{mr,g}$ is mean margin of trains (also defined with the external program), $t_{d+g,i}$ is input delay and $t_{d-g,i}$ is negative input delay. All parameters are listed in table 18.

Table 18. Summary of Luumäki–Imatra delay analysis. Abbreviations:
LÄ=Luumäki, IMR=Imatra, JTS=Joutseno.

	Scenario 0: Single track LÄ-IMR	Scenario 1: Single track LÄ-JTS, double track JTS-IMR	Scenario 2: Double track LÄ → IMR	Scenario 2: Double track IMR → LÄ
$t_{d+g,i}$	691 s/train	525 s/train	460 s/train	460 s/train
$t_{d-g,i}$	-	-	605 s/train	605 s/train
N_x	$= \frac{65}{62} = 1,048$	$= \frac{59}{62} = 0,95$	-	-
$\sum_{b \in B} (w(b) \cdot bf_g^b)$	-	-	0,0484	0,065
$t_{mr,g}$	-	-	256	246
$t_{d+g,g}$	647 s/train	493 s/train	468 s/train	468 s/train

Impact on Feasibility Study Results

Scenario 1: double track between Luumäki and Imatra

According to the calculation, a reduction of delay by 180 seconds per train leads to the following monetary savings in a 30 year time span.

- Passenger time savings 13,2 M€
- Capital and labour costs (passenger trains) 4,2 M€
- Capital and labour costs (freight trains) 3,0 M€
- Total 20,5 M€

These savings would raise the investment cost-benefit ratio from 0,41 to 0,49.

Scenario 2: double track between Joutseno and Imatra

According to the calculation, a reduction of delay by 180 seconds per train leads to the following monetary savings in a 30 year time span.

- Passenger time savings 4,5 M€
- Capital and labour costs (passenger trains) 1,4 M€
- Capital and labour costs (freight trains) 1,0 M€
- Total 6,9 M€

These savings would raise the investment cost-benefit ratio from 0,60 to 0,66.

6.4 Espoo commuter track extension

Description

Extension of the Helsinki–Leppävaara commuter rail line was chosen to test the method for double track sections. The investment includes extension of the Helsinki–Leppävaara commuter rail line to Kauklahti. It enables relocating commuter trains from the current double track line to a new commuter track line and hence improving the punctuality of traffic, especially long-distance traffic, between Helsinki and Turku. In the feasibility study both the extension to Espoo and Kauklahti were studied, but in this case only extension to Kauklahti is examined.

The technical input information regarding delay and capacity consumption calculations is collected in table 19.

Table 19. *Summary of Espoo commuter track extension case study.*
Abbreviations: PSL=Pasila, KLH=Kauklahti.

	Scenario 0: Current infrastructure	Scenario 1: Espoo commuter track rail extension
Timetable, reference day	Actual timetable in timetable period 03/2017 used in the analysis, reference day: Wednesday	Basis of the timetable is the same as for scenario 0. All trains on E-line are removed from the timetable. After the removal, the timetable was "optimized" to balance the high variability of headway times. The maximum changes compared to the original timetable was 4 minutes.
Operations	99 trains on a reference day on both directions. No freight trains.	66 trains on a reference day on both directions. Investment has no impact on speeds or minimum headways. No freight trains.
Crossings	No passing or crossings.	No passing or crossings.
Input delay	PSL → KLH: 82 s/train KLH → PSL: 86 s/train	Investment has no clear impact on input delays. Same input delays used as for Scenario 0.
Negative input delay	PSL → KLH: 14 s/train KLH → PSL: 19 s/train	

Impact on Capacity Consumption

The capacity analyses were calculated separately for both directions between Pasila and Kauklahti stations. As for the intermediate calculation step, minimum technical headway times were defined.

As the level of timetable detail is limited to whole minutes and line sections are short in the area, a detailed analysis of headway times might lead to unreliable results. Therefore, four minutes constant minimum headway was used in the analysis.

The graphs shown in figures 32 and 33 illustrate how the tracks are mostly utilised during the morning and evening peak hours. In the direction from Kauklahti to Pasila, the track utilization rises above 75% for a short period in the peak hour. A smaller peak occurs during the evening time.

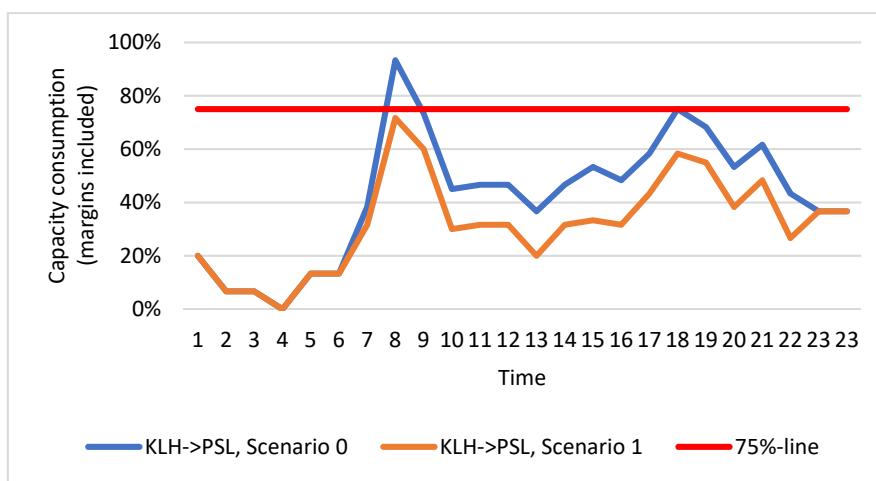


Figure 32. Capacity consumption values on Scenario 0 and Scenario 1 in KLH-PSL-direction.

In the direction from Pasila to Kauklahti, capacity consumption rises above 75% during the morning and evening peak hour.

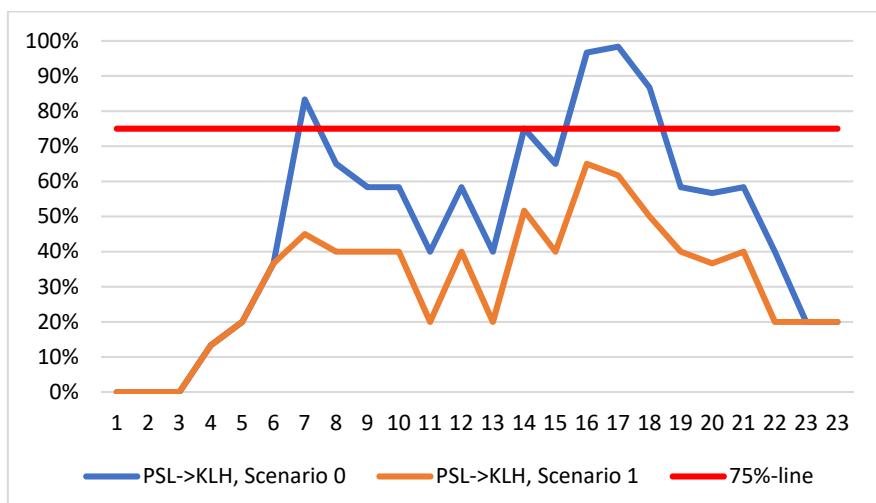


Figure 33. Capacity consumption values on Scenario 0 and Scenario 1 in PSL-KLH-direction.

The investment on the commuter track enables removal of commuter line E services from the timetable. E-line operates during day time and decreases the consumption by 15–20%. There is no impact on consumption during late evening or night time. During the day hours, capacity consumption decreases relatively evenly as E-line operates with a constant 10 minute headway for the whole day. The slight variation of the reduction is due to the surrounding trains.

Impact on Punctuality

The impact on punctuality was analysed using the method for double track sections:

$$t_{d+,g,e} = \alpha + \beta \cdot \sum_{b \in B} (w(b) \cdot bf_g^b) + \gamma \cdot t_{mr,g} + \delta \cdot t_{d+,g,i} + \epsilon \cdot t_{d-,g,i},$$

where $\sum_{b \in B} (w(b) \cdot bf_g^b)$ is a term describing the buffers (defined with an external calculation program), $t_{mr,g}$ is mean margin of trains (also defined with the external program), $t_{d+,g,i}$ is input delay and $t_{d-,g,i}$ is negative input delay. All parameters are listed in table 20.

Table 20. Summary of Espoo commuter track extension delay results.
Abbreviations: PSL=Pasila, KLH=Kauklahti.

Scenario 0: Current infrastructure		Scenario 1: Investment	
		PSL→KLH	KLH→PSL
$t_{d+,g,i}$		82 s/train	86 s/train
$t_{d-,g,i}$		14 s/train	19 s/train
$\sum_{b \in B} (w(b) \cdot bf_g^b)$		0,416	0,511
$t_{mr,g}$		66,7	66,9
$t_{d+,g,e}$	92 s/train	97 s/train	82 s/train
			87 s/train

Impact on Feasibility Study Results

According to the calculation, a reduction of delay by 10 seconds per train leads to the following monetary savings in a 30 year time span.

- Passenger time savings 7,6 M€
- Capital and labour costs (passenger trains) 0,9 M€
- Total 8,5 M€

These savings would raise the investment cost-benefit ratio from 0,88 to 0,91.

7 Conclusions and discussion

Background and objectives

Impacts of the infrastructure investments on railway capacity and traffic punctuality are both commonly assessed in socio-economic analyses. Both are also commonly considered as a justification for investments. However, there has not been an established method for measuring capacity and delays in socio-economic assessments, and moreover, there has not been a method to consider delays and their consequent impacts in the cost-benefit analyses.

This study aims to develop two methods to be applied in socio-economic assessment. The first method is aimed at determining whether the capacity of a line is sufficient or scarce, enabling the rail network manager to identify line saturation. The second is a method for the evaluation of delay propagation on a line given a set of parameters of the line, allowing the network manager to evaluate the effect of investments on train punctuality. Both methods are developed with the aim of being easy to apply by non-expert users in required socio-economic analyses.

Delay evaluation methods

An analysis of the delay propagation on real single and double tracks revealed that delays are propagated due to different reasons and, thus, separate models for single and double tracks had to be developed. The developed methods for single and double track sections resulted in the following formulas:

$$\text{Single track: } t_{d+,g,e} = 0.917 \cdot t_{d+,g,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x$$

Double track:

$$t_{d+,e} = 22,443 \cdot \sum_{b \in B} (w(b) \cdot bf_g^b) - 0,033 \cdot t_{mr,g} + 1,029 \cdot t_{d+,g,i} - 0,001 \cdot t_{d-,g,i}$$

The goodness of these regressions provided goodness of 61.0% for single tracks and 73.9% for double tracks. Both methods give the most reliable results on tracks with a high number of trains.

Capacity consumption evaluation method

Based on a literature review, capacity can be estimated through three perspectives: using theoretical capacity (maximum number of trains on a given time), capacity consumption methods and capacity indices. Capacity consumption methods were recognized to have the highest potential. However, due to the lack of unambiguous guidance, a more detailed manual for Finnish circumstances was developed.

Following the new guidelines, capacity consumption is calculated for line sections for each hour to indicate the spare capacity of the line if train services can be more evenly spaced. The critical hours are when the value of capacity consumption rises above a given threshold value at any line section. These

threshold values, originally defined by UIC, are 85% for suburban passenger traffic lines and 75% for other lines

Applicability of the Methods in Socio-economic Assessment Cases

All developed methods have high potential for becoming the standard tools to be used in Finland. The developed methods are designed to evaluate the impact of various infrastructure investments on capacity consumption and the improvement of the punctuality of trains. The methods are applicable for investments that have an impact on the planned timetable. The clearer impact the methods have, the clearer results will be received. This chapter assesses which kinds of investment types, and their effects on punctuality, can be evaluated with the developed method. Applicability of the capacity consumption and delay evaluation methods for typical investment types in socio-economic assessments is shown in table 21.

Table 21. *Investment types and their impacts on traffic and traffic punctuality and the suitability of the developed calculation method.*

Case	Method applicability if timetable remains the same		Method applicability if timetable changes	
	Delay evaluation method	Capacity consumption	Delay evaluation method	Capacity consumption
Increased axle load	Only minor potential decrease due to longer acceleration/ deceleration times and hence this is not considered in the method.	Only minor potential decrease due to longer acceleration/ deceleration times and hence this is not considered in the method.	Generally affects the amount of trains. This is included in the method.	Generally affects the amount of trains. This is included in the method.
Increased speed profile	This is included in the method double track method but not in the single-track method.	Included in the method in case calculation is performed excluding the running time margins.	Single track: Included in the method if affects the amount of train crossings. Double track: Included in the method.	Included in the method.
New block signals	Single track: not included, Double track: included	Included in the method.	Single track: not included, Double track: included	Included in the method.
New passing loop	If timetable remains the same, the new passing loop won't have an effect and therefore this is not included in the method.	If timetable remains the same, the new passing loop won't have an effect and therefore this is not included in the method.	Included in the method.	Included in the method.
Triangle track	Not a relevant case. If this type of investment is done, the timetable will most likely change.	Not a relevant case. If this type of investment is done, the timetable will most likely change.	If timetable changes, the effect will be considered through re-estimating the coefficients.	Included in the method.
Third track (independent single track, long passing loop, peak hour single track)	Not a relevant case. If this type of investment is done, the timetable will most likely change.	Not a relevant case. If this type of investment is done, the timetable will most likely change.	Included in the method.	Included in the method.
Extended existing passing loop + partial double track (long trains cannot cross, all trains can cross, partial double track (dynamic crossing), partial quadruple track)	Not a relevant case. If this type of investment is done, the timetable will most likely change.	Not a relevant case. If this type of investment is done, the timetable will most likely change.	All other cases are included in the method except partial quadruple track.	Included in the method.

The above table reveals that the methods are applicable for various cases, especially for investments that have an impact on the planned timetable. The clearer impact the methods have, the clearer results will be received.

Case study conclusions and further study recommendations

Performing capacity consumption and delay calculations for three actual socio-economic assessments revealed that the methods are suitable and don't bring a high additional workload to the socio-economic assessment process. Capacity consumption method revealed the desired information on where and when possible bottlenecks are occurring, and how severe these bottlenecks are.

Adding the value of delayed time to the cost-benefit calculations revealed the following increases in the cost-benefit ratios:

- Ylivieska–Iisalmi–Kontiomäki 0,73 → 0,78
- Luumäki–Imatra
 - Scenario 1: 0,41 → 0,49
 - Scenario 2: 0,60 → 0,66
- Espoo commuter track extension 0,88 → 0,91

Before performing the calculations, the presumption was that punctuality would play a major role when calculating the cost-benefit ratio. All these increments were lower than expected. Possible explanations and further study recommendations are:

- Upgrading the railway line will have only minor impact on total delays since the majority of delays occur at nodes of the network (e.g. railyards and stations). In studied cases, developing the line track will not remove these delays. A further study to observe punctuality issues at node points is suggested.
- The delay calculation method developed in this study examines the section being upgraded but it doesn't consider the propagation of delays outside the section via exchange connections (passenger trains waiting for delayed trains at stations) or rotation of rolling stock and personnel. By propagation via these linkages the eventual number of delays may be much higher. A further study to observe propagated delays is suggested.
- Low punctuality typically leads to passengers choosing other modes of transport. This leads to lower passenger numbers and reduced ticket revenue compared to the situation where punctuality is at a normal level. This impact is not evaluated in this study. In principle it could be taken into account by using higher value for delayed time. A further study to observe passenger behaviour is suggested.
- Calculation of the delays is highly dependent on the input delay given in the formula. Evaluating the change of input delay when capacity increases or number of train changes is difficult. This may lead to underestimating the input delay and so the calculated delay. A further study to define how input delays are affected by the investment is recommended.

Other noted recommendations for further study are:

- Margins were estimated and considered as constant numbers in the delay methods development process. As the margins have a major impact on the reliability, it might be valuable to re-run the regressions when more detailed information on the margins is generated. This will most likely increase the goodness of the regressions.
- The calculation process for capacity consumption requires multiple steps that could be automated with relatively low workload. An automated tool that would be used by all users, would decrease workload and reduce the risk for calculation mistakes.
- The value of time for delayed time in general was excluded from this study. It should be re-considered when the delay calculation tool is taken into the Finnish Transport Infrastructure Agency's socio-economic assessment instructions.

Simultaneously with this study, Swedish Trafikverket has been developing a method to evaluate delays in socio-economic calculations. According to the preliminary results the method appears comprehensive, but due to its recency, the method could not be tested at Finland's rail network yet. Therefore it is recommended that applicability and convertibility of the method for Finland's rail network is studied in future.

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User's manual: Capacity Consumption Calculations in Finland

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1.1 General

1.1.1 Overview

Capacity consumption is an indicator that describes the usage of rail infrastructure on a given railway line (UIC 2013). The consumption of railway capacity does not only depend on how many trains are operated, but also on how the capacity is utilized. For example, a heterogeneous operation, where fast trains catch up with slower trains, results in higher capacity consumption than a homogeneous operation where all trains are operated with the same speed.

Capacity consumption analysis can be used to analyse the functionalities of a planned timetable. Lack of capacity means that it is not always possible to create the desired timetable, and it may be necessary to remove selected trains from a timetable, or homogenize the operation, for example, by slowing down the fastest trains and/or giving the trains additional stops.

Capacity consumption can be visualised as compressing graphical timetables on a defined line or line section. All train paths are “pushed” together as much as the minimum headway times (marked with grey boxes in Figure 1) allow. The compression must be done with respect to the train order and the running times. This means that no changes are permitted in the running times, running time margin, dwell times or block occupation times. Furthermore, only scheduled overtaking and scheduled crossings are allowed (Figure 1).

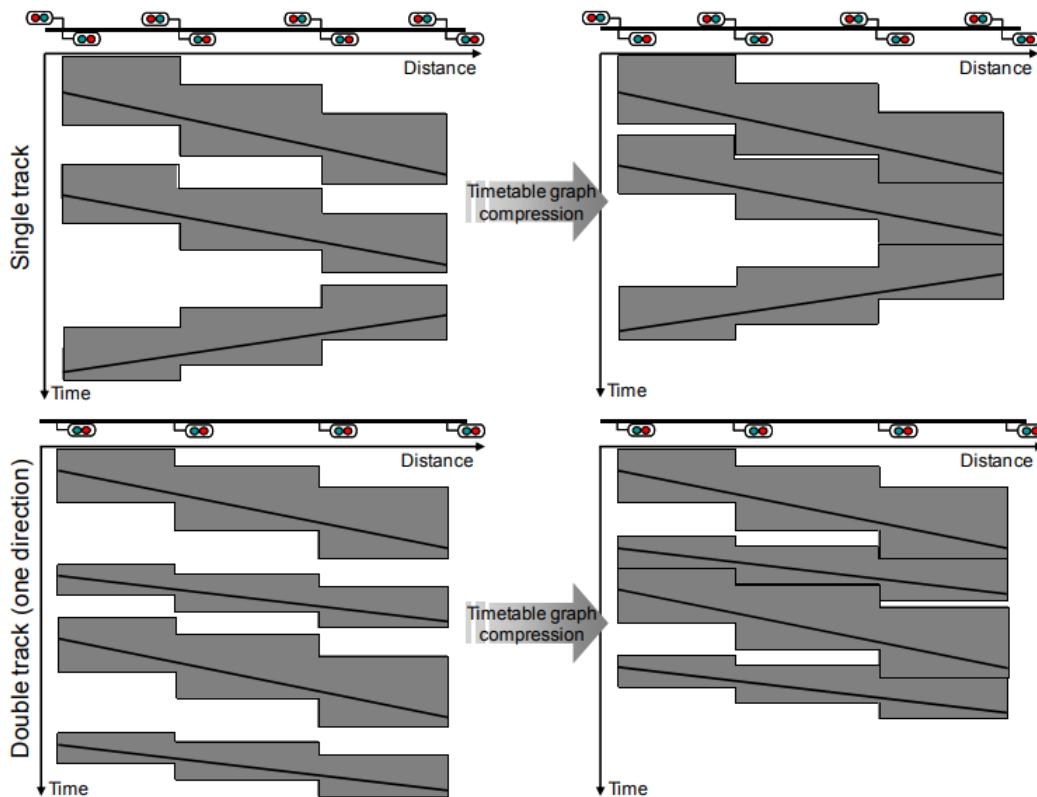


Figure 1. Visualization of the capacity consumption compression method (Landex, 2008). A homogeneous timetable can be compressed more than a heterogeneous timetable, and thus leads to a smaller capacity consumption value.

The general form of the capacity consumption formula is originally defined by the UIC, and it is widely used internationally. However, due to the level of detail of the original leaflet, multiple interpretations have been generated to meet national requirements. The purpose of this appendix is to introduce a practical overview of how this method will be applied to the Finnish railway network. The form of the Finnish capacity consumption calculation formula is as follows:

$$K = \frac{h_A + t_D + t_{EPD} + t_M + t_S}{T} \quad , \text{ where}$$

Term and unit	Description
K Capacity consumption [%]	The amount of capacity used for a given timetable on a given infrastructure
T Time period [min]	Analysed time period, typically 1, 20 or 24 hours.
h_A Sum of minimum headway times [min]	The sum of time intervals between two consecutive trains that are running in the same direction
t_D Sum of driving time differences [min]	The sum of time intervals between two consecutive trains running on the same direction and having uneven driving times
t_{EPD} Earliest possible departure time compared to the beginning of the time period [min]	Time interval referring to the impact of partial trains in the beginning of the time period
t_M Sum of supplementary time for maintenance [min]	Additional time that a certain line section is not in use for normal operations due to maintenance or other rail work
t_S Sum of station and crossing times [min]	The amount of time needed for switch turning operations during the time period

The terms, input data requirements and calculation steps are reviewed in this user's guide. The calculation steps are summarized in Figure 2.

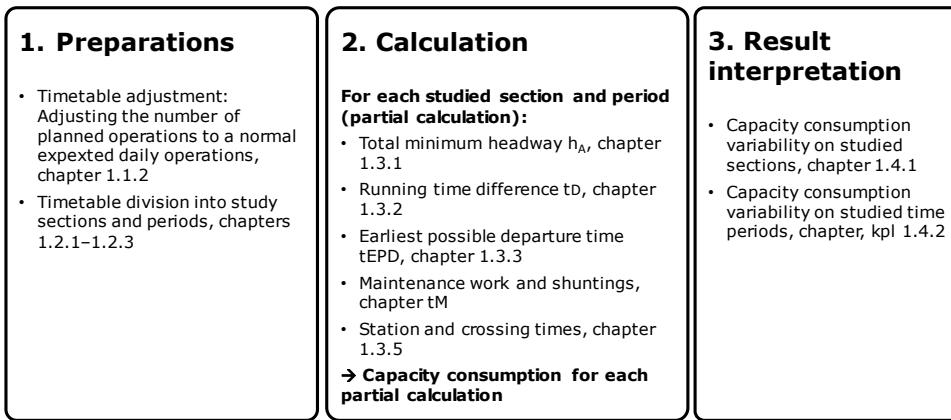


Figure 2. Capacity consumption calculation steps.

1.1.2 Input data requirements

Planned numerical timetable on a reference day

The central initial data source for capacity consumption calculations is the planned timetable on the studied track section, that covers all planned operations during the studied time span. The level of detail in the selected timetable may vary from seconds (operator's timetable) to whole minutes (customer timetable). The timetable should include realistic planned arrival and departure times.

As a part of socio-economic analyses, capacity consumption value will be calculated using a timetable on a reference day. On most lines, this reference day is one of the weekdays, however, depending on the operations, there might be a need to perform calculations separately for Saturdays or Sundays. Calculation should always be done on the busiest day.

In Finland, freight operations typically vary remarkably from day to day and these changes are made with a short notice. For operators cancelling a train is easier than applying extra capacity and, therefore, freight train operators tend to over-reserve capacity slots. This can be seen by comparing actual operations with their planned timetable. Passenger train operations are more stable and hence the same issue won't occur there. In practice, performing capacity consumption calculations for an actual timetable which includes mostly freight train operations will most probably lead to higher consumption than an average day's operations. This can be considered as the maximum capacity consumption value. It is recommended to modify the studied planned timetable to represent a reference day by excluding selected freight trains.

Running time margin (RTM)

Running time margin means the difference between the planned running time and the technical minimum running time stated in [min] or [%]. Minimum running time means the period that a certain rolling stock requires, and it is affected by the track length, geometrics and rolling stock features. As typically train operations face small disruptions or uncertainties through an operation, an

extra time is typically included in a planned timetable to absorb the impact of these minor disruptions and to reduce the risk of consecutive delays.

Capacity consumption values can be calculated either with or without these running time margins. Including margins in the calculations usually makes sense when analyzing current timetables on an existing line. In these cases there is usually a reason (e.g. punctuality, transfers to other connections, clock-face scheduling, etc.) why margins are needed and usually those can't be removed. However, in some cases it is interesting to understand how much capacity is lost due to the current margins, and thus there may be a need to calculate the results separately including and excluding them. This is especially true when analyzing new railway lines and there is a need to understand how many trains the new infrastructure will be able to facilitate with different assumptions about train operations (including different margins). Overall, in many cases it is recommended to calculate both including and excluding margins to find out the impact of the margins (Figure 2).

Besides running time margins, typically also dwell times include a certain amount of margin (Figure 3). Analyzing the amount of dwell time margin is however challenging. For example, understanding freight trains' shunting processes may need interviews with the operator. In order to perform reliable capacity consumption calculations, it is suggested that the impact of dwell time margins is not considered for socio-economical assessments.

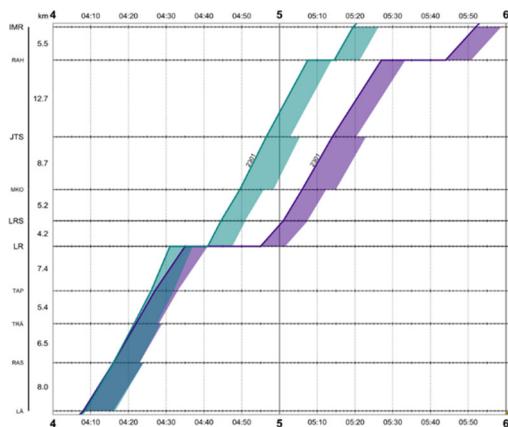


Figure 3. Purple timetable graph illustrates a planned timetable and green timetable graph illustrates a representative train without running and dwell time margins. If the margins are ignored, the total travel time from first node point to last node point is significantly shortened.

The number of margins are considered in the timetable planning phase. If the percentage shares are known, the actual driving times can be calculated using the following formula:

$$\text{Minimum running time} = \text{Planned running time} * (1 - \text{running time margin [%]})$$

The amount of percentage margin varies between track sections and train types. In case more detailed information is not available, the following default values can be used:

- Commuter trains: 5 %
- Long-distance passenger trains: 10 %
- Freight trains: 12 %

When performing capacity consumption calculations excluding margin times, a timetable from which margin times are already removed using the above formula should be used as a basis for the calculation.

Signalling

Minimum headway is one of the terms that affects the minimum closeness of two timetable graphs. It depends on the number of blocking sections on a line section. One block section can host one train at the time, and this is monitored by the interlocking system. In Finland, signal positions and types are stored in Line Chart documents.

Station safety margins

Depending on the interlocking system and placement of signals, in some stations two trains cannot arrive at a station simultaneously. In these cases, the safety margins between two approaching trains can be different and, depend on tracks used, approach direction of each train, location of signals and switches etc. To get the full understanding of the factors influencing the safety margins it is advised to study the most recent plans of the studied track and to contact the local traffic control centre and/or Finnish Transport Infrastructure Agency for more information on the interlocking rules.

Infrastructure limitations

Infrastructure may have limitations that impact on how a certain timetable is built up, or on how trains can be operated on a certain timetable. For example, in Finland some passing loops are too short to host the longest freight trains, which means that not all trains can pass each other at all passing loops. These restrictions are considered as part of the timetable planning process and thus are included in the planned timetable. As part of the capacity consumption calculations, there is no need to re-consider these limitations.

1.2 Partial calculation definition

1.2.1 Infrastructure division into study areas

The number of required partial calculations depends on the way the infrastructure is built up. On single track lines traffic is homogeneous within each line section and the train order can change only at node points. These nodes, such as passing stations, are the only places where trains can pass each other. Double track lines are more versatile environments where trains can meet freely. That makes capacity consumption calculations heavier on double track lines. Both single and double track lines are split into line sections, connected by node points. These node points are overtaking places, line end and passing stations, transition stations (such as places where double track transforms into single track line) and junction points (Figure 4).

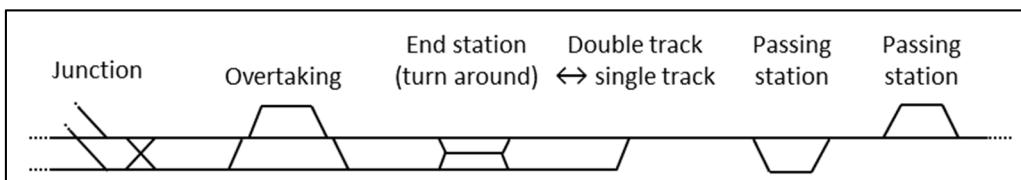


Figure 4. Dividing the railway network into line sections.

For single track lines, capacity consumption is calculated only from node to node, and both directions' capacity consumption values are calculated together. In the following Figure 5 node points are numbered from 1 to N. The required partial calculations are marked with ✓. Note that in the figure both directions are marked separately, however on single track sections both directions are interacting and will be calculated at once.

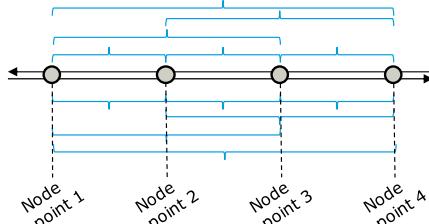
For double track sections, it is suggested that all possible line section combinations are calculated separately. Calculations must also be performed separately for both directions as the tracks on double track are independent, unique systems and infrastructures. That increases the number of calculations remarkably. In the following Figure 5 node points are numbered from 1 to N. The required partial calculations are marked with ✓.

However, in cases where it is clear that some node points (**single- or double track**) cannot be used for changing the number of trains or train order, that node point in question can be ignored in the division process.

Study areas on double track sections		Study area's first node point				
		1	2	...	N-1	N
Study area's last node point	1	✓	✓	✓	✓	✓
	2	✓	✓	✓	✓	✓
	...	✓	✓	✓	✓	✓
	N-1	✓	✓	✓	✓	✓
	N	✓	✓	✓	✓	✓

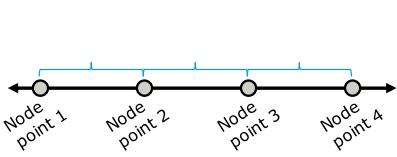
Study areas on single track sections		Study area's first node point				
		1	2	...	N-1	N
Study area's last node point	1	✓				
	2	✓				
	...		✓			
	N-1			✓		
	N				✓	

Study areas illustrated on a double track section with four node points:



Node point 1 Node point 2 Node point 3 Node point 4

Study areas illustrated on a single track section with four node points:



Node point 1 Node point 2 Node point 3 Node point 4

Figure 5. Study areas illustrated on a single and double track sections. For single track sections, both directions are analysed at once.

1.2.2 Timetable division into time periods

To get an overview of how the capacity consumption varies over time, the calculation is suggested to be performed for each hour separately. This gives the planners and analysts the opportunity to identify capacity problems that are not observed if only longer time periods are examined. Capacity consumption for the whole 24-hour period results in an average value that gives only a rough estimate on the track's overall capacity consumption. Performing the calculations hour-by-hour is suggested (for example time periods 0–1 am, 1–2 am, etc. This gives more detailed understanding on how the track is stressed during the day and which parts of the day are more likely to be unpunctual.

1.2.3 Summary of study areas and time periods (partial calculations)

As part of capacity consumption calculations, the timetable and infrastructure are divided into study areas and time periods. The division is so called partial calculations, for which the calculation is performed in turns. Comparison of the results of partial calculations enables understanding the capacity consumption variability at different locations and times of the day.

1.3 Calculation

1.3.1 Definition of total minimum headway time h_A

Definition of a line section's minimum headway h_i

Calculation begins with defining a minimum headway time for each line section. Minimum headway depends on the interlocking and average operations. For a given line section i , minimum headway is calculated as follows:

$$h_i = \frac{(n * d * 60 \text{ min/h})}{s} \quad , \text{ where}$$

h_i [min] Minimum headway time for train i

n Multiplication factor that depends on the number of block sections between two stations:

$n = 1$, if number of block sections is 1

$n = 2$, if number of block sections is higher than 1

d [km] Average length of block sections, calculated as follows:

$$d = \frac{\text{length of line section } i \text{ [km]}}{\text{number of block sections on line section } i}$$

s [km/h] Weighted average speed, calculated as follows:

$$s = \frac{\text{distance between stations [km]}}{\text{average travel time between stations [h]}}$$

In Finland, the level of detail in passenger timetables is mostly one minute. When using these values, the calculation may result in higher degree of uncertainty on the headway results especially in the dense areas, such as Helsinki region.

Adding minimum headway value h_i for trains

As part of socio-economical assessments, capacity consumption is suggested to be calculated for each hour separately. When the time period is relatively short, not all trains are necessarily running only during the timetable period. This results in a need to either *include* or *exclude* a set of trains in a partial calculation. When it comes to adding minimum headway value for trains, each train departing from their first station during the time period will be included in the analysis. Note, that in case a train is not passing all node points of a double track sections, the definition of a "first station" is not the same as the first station of the study area.

Once the set of trains to be analysed is selected, they are reviewed and checked, whether they are added a headway value. Adding the right value depends on the number of tracks.

For double track sections, adding the value for minimum headway depends on the next following train's operations. The train to be analysed is compared with the next following train to find a critical line section i , which minimum headway value h_i will be added to the calculation.

Case	Critical line section i
Analysed train is followed by a slower train $RT(i.\text{train}) - RT(i + 1.\text{train}) < 0$	The line section, where the analysed train runs first, is critical
Analysed train is followed by a faster train $RT(i.\text{train}) - RT(i + 1.\text{train}) > 0$	The line section, where the analysed train runs last, is critical
Analysed train is followed by an as fast train $RT(i.\text{train}) - RT(i + 1.\text{train}) = 0$	The line section, which minimum headway value is highest, is critical

In the above table, running time (RT) by default means the running time from first station to last station (including possible station stops in the middle) on the analysed area. However, in case either trains is not operating through the whole analysed period, running time is calculated on only that area through which both trains are operating.

The rule for adding headways can easily be understood from a graphical timetable. The theory of capacity consumption is based on compressing a timetable as much as possible. When timetable graphs are pushed together without changing the train order, the first touching part of the line depends on its steepness (Figure 6). The horizontal lines in Figure 5 represent node points.

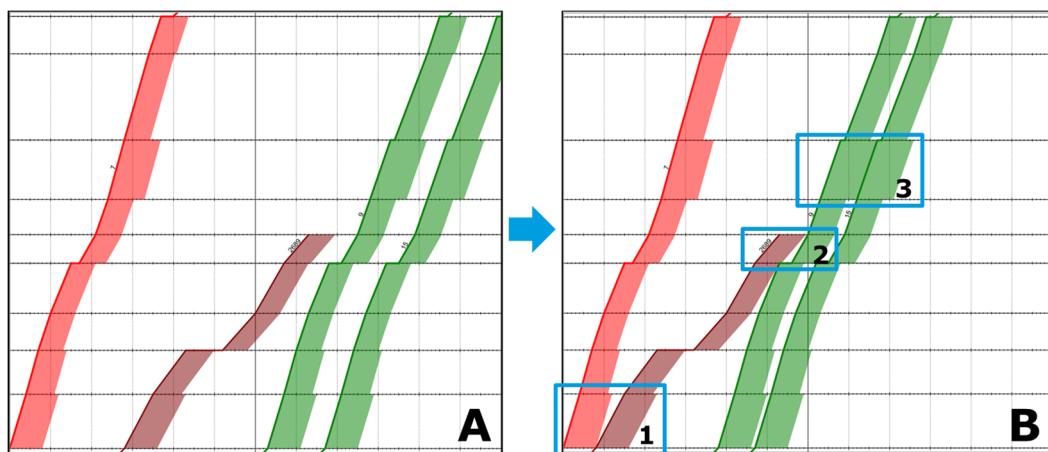


Figure 6. Rule for finding critical line section and adding headways on double track line illustrated on a graphical timetable.

Graphical timetable A illustrates a planned timetable including three fast passenger trains and one slower freight train. The timetable can be compressed as much as the first touching parts allow (Graph B). The red train is followed by a slower (brown) train that touches it in the beginning, and therefore the first line section becomes critical. Headway of line section 1 will be added. Similarly, the brown train is followed by a faster green train, and the last line section becomes critical. The line section numbered with 2 becomes most critical. Thirdly, the first green train is followed by a fast train, and therefore the line section for which minimum headway is highest becomes critical. The headway of the line section numbered with 3 will be added.

Unlike double track sections, which are calculated covering multiple line sections at once, **single track sections** are always analysed in short sections, so no rule for choosing an appropriate value among others is needed. However, single track lines have operations in both directions and only the parallel operations will be given a headway value.

Case	Headway h_i to be added
Analysed train i is followed by a train $i+1$ running on the same direction.	Analysed train will be given the headway value on the particular line section
Direction(i.train) = Direction ($i + 1$.train)	
Analysed train i is followed by a train $i+1$ running on the opposite direction.	No headway will be added
Direction(i.train) ≠ Direction ($i + 1$.train)	

The examples above illustrate how all trains are compared with the next following train. As described in the double track example, the last green train wouldn't get any headway value as there aren't any following trains. Hence, the last train of the time period will be compared to the first train operating after the end of the time period. In case that is the very last train of the day, it will be compared to a similar train.

Special case for double track lines: how to consider passing

Passing events are special cases on double track line analyses. As the order of trains changes, the overtaken train can be analysed by cutting it into two trains and considering the pieces individually. The faster trains are considered as normal operations. The overtaken train's two pieces can also be considered as normal operations, if it is known that the longer stop isn't due to loading or unloading. If the longer stop is required, the dwell time cannot be compressed. Figure 7 illustrates how a purple train is overtaken by two faster trains and a stopping time is compressed.

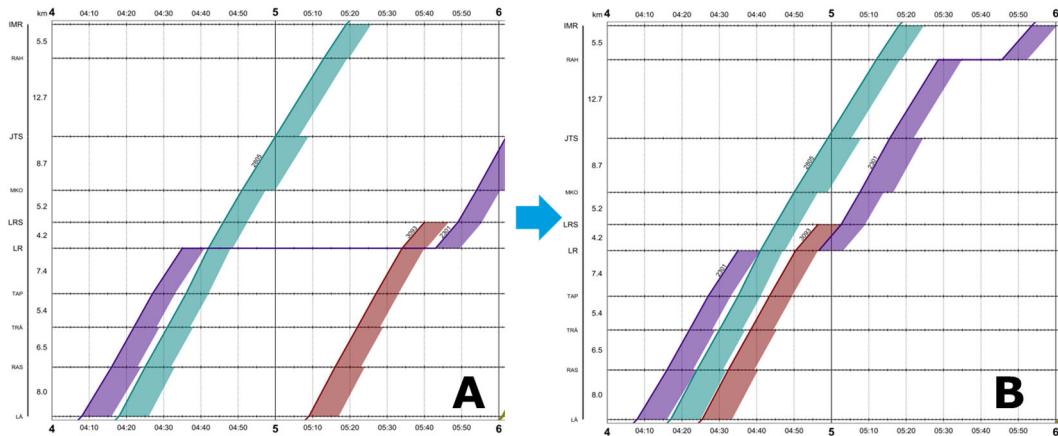


Figure 7. Illustration on how to consider passing events on a double track line.

Defining the total minimum headway h_A

After selecting the relevant trains for each capacity consumption scenario, and analyzing individual headway times for each of them, the total headway time (h_A) can be calculated by simply summing them together:

$$h_A = \sum_i h_i, \text{ where}$$

h_A represents sum of all headway times and h_i represents the headway value added for train i in a certain partial calculation. This value as such represents one of the terms for calculating capacity consumption.

1.3.2 Definition of running time difference t_D

General

Running time difference is a factor describing the extra time needed in case a slow train is followed by a faster train. This period, in practice, can be used for operating similar slow trains. If a slow train is followed by a faster one, the faster train cannot depart right after the slower one without having to run slower than planned. Therefore, the difference in running times is added into the capacity consumption formula. High differences in running times influence a higher capacity consumption value.

Adding running time difference for analysed trains

The rule of adding running time difference is based on comparing consecutive trains, similar to the rule of adding minimum headway value. Also, the same set of trains is selected as for the analysis; the trains to be selected are the ones that depart from their original station/node point during the studied time period.

Once the set trans to be analyzed is selected, the running time difference will be calculated for each of them . The calculation depends the operations of the following consecutive train:

Case	Running time difference to be added
Analysed train i is followed by a slower or equally fast train i+1, that runs on the same direction Direction(i. train) = Direction (i + 1. train); RT(i. train) – RT(i + 1. train) ≤ 0	0
Analysed train i is followed by a faster train i+1, that runs on the same direction Direction(i. train) = Direction; RT (i. train) – RT(i + 1. train) > 0	The analysed train is given a running time difference value: Running time difference = RT (i. train) – RT(i + 1. train)
Analysed trains i is followed by a train that runs Running time (i. train), that is spent at on the opposite direction (possible only on the analysed line section. single track sections) Direction(i. train) ≠ Direction (i + 1. train)	

* Running time either includes or excludes margins

When analyzing the last train, the train must be compared to the first train that is not operating during the time period. In case that is the last train of the day, it will be compared to the first train of the following morning.

For double track cases, that may cover multiple line sections, it is normal that not all trains are operating through the whole case study area. In these cases, defining "the following train" isn't as simple as it depends on the study area. Figure 8 illustrates an example, where a blue train is followed by a green train between stations A and B and by a red train between stations B and C. Both red and green trains can be defined as the following train depending on the scenario. In case the scenario covers only stations between A and B, the green train will be named as the following train and the running time difference is calculated between that area. In case the scenario covers area from A to C, the blue train will be compared with the red train.

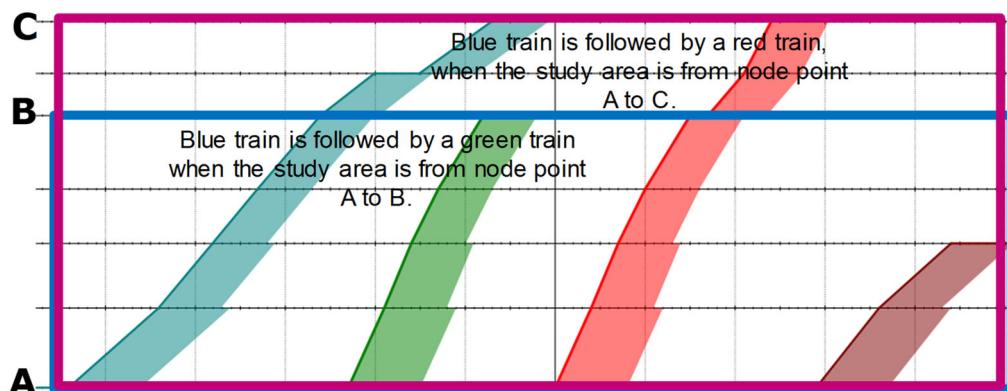


Figure 8. Definition of a Following Train Illustrated on a Graphical Timetable.

The rule for adding running time difference time for opposite directions is visualized in Figure 9. The example is applicable only for single track sections.

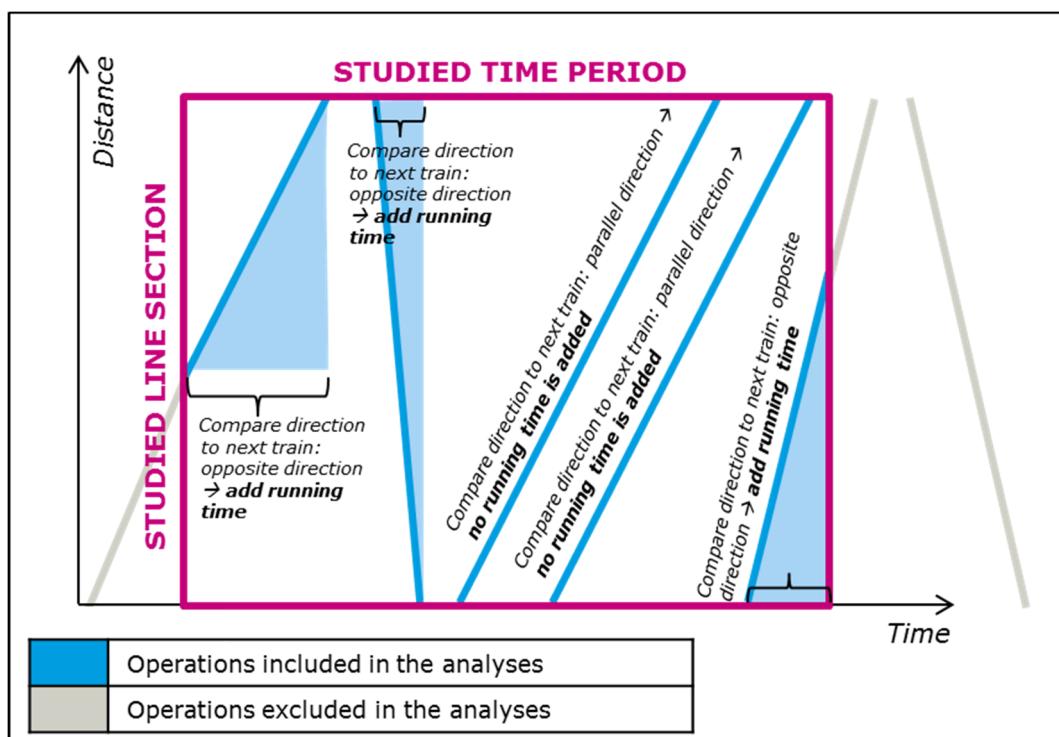


Figure 9. Principle of adding reservation time for single track lines illustrated on a graphical timetable.

1.3.3 Definition of earliest possible departure time t_{EPD}

The earliest possible departure is a term needed to describe the impact of trains that are operating only partially during the time period. These trains depart from their first station before the beginning of the time period but depart their last station during the time period and hence, by definition, won't be considered as trains that depart during the time slot. The principle of adding value for earliest possible departure time depends on how the trains are planned to operate during the beginning of the studied time period. Four options exist:

Case	Practical overview and earliest possible departure to be added
Double track, No partial train in the scenario (Figure 10)	All trains are either departing during the scenario or departing to their final station before the beginning of the scenario $t_{EPD} = 0$
Double track, One partial train in the scenario (Figure 11)	One train departs before the beginning of the scenario and arrives to its final station during the timetable period $t_{EPD} =$ Arrival time _{partial train} + headway _{last line section} – running time _{first train} – beginning time of the time period If earliest possible departure gets a negative value, no earliest possible departure time is added (Figure 14).
Double track, Multiple partial trains in the scenario (Figure 12)	More than one train depart before the beginning of the scenario and arrives to its final station during the timetable period Only the last partial train will be considered, consideration similarly if only one partial train exists.
Double track, One or multiple trains running through the scenario (Figure 13)	One or more trains depart from their first station before the beginning of the time slot and arrives to the last station after the end of the time slot. $t_{EPD} =$ the length of the time period (typically 60 min). These cases always results in a capacity consumption of 100%.
Single track section	T_{EPD} is always 0.

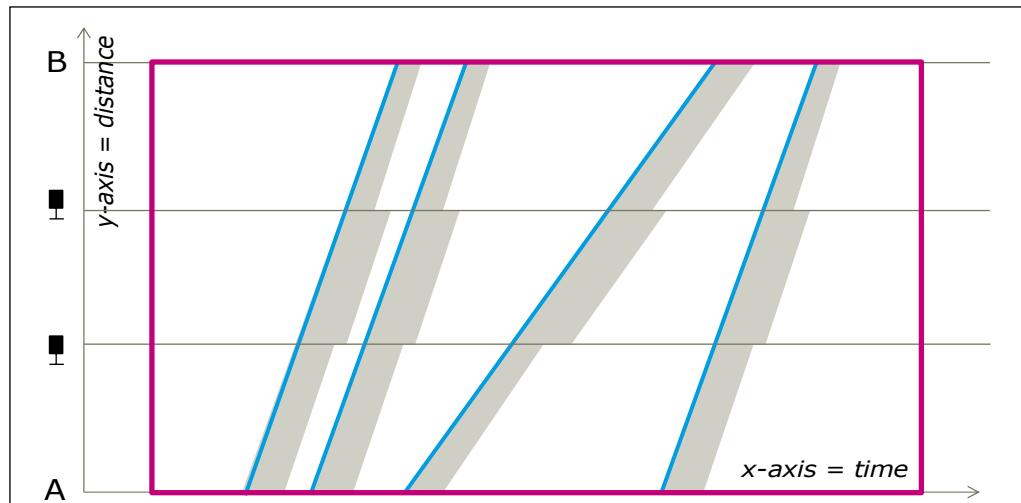


Figure 10. Example with no partial trains.

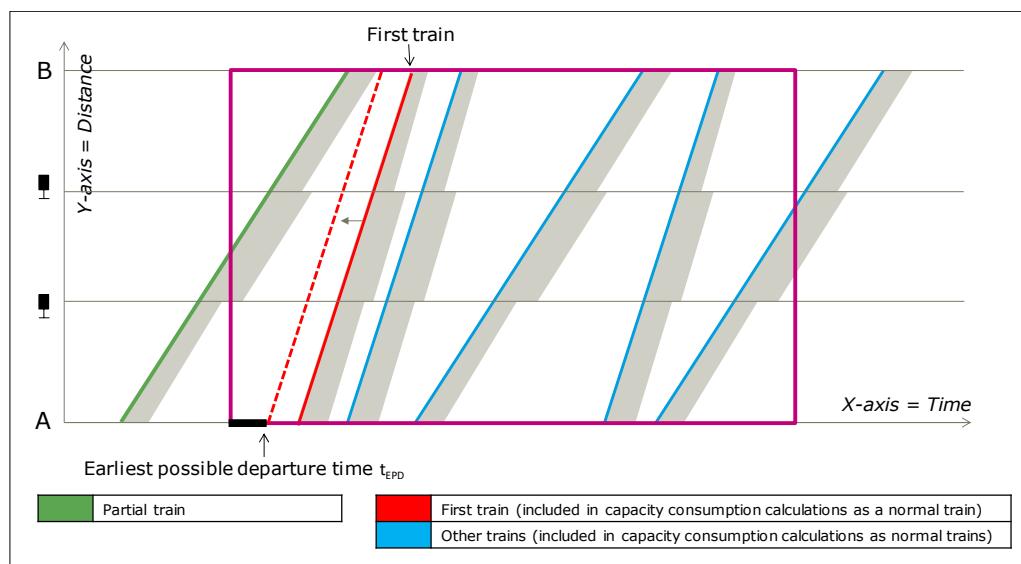


Figure 11. Example with one partial train.

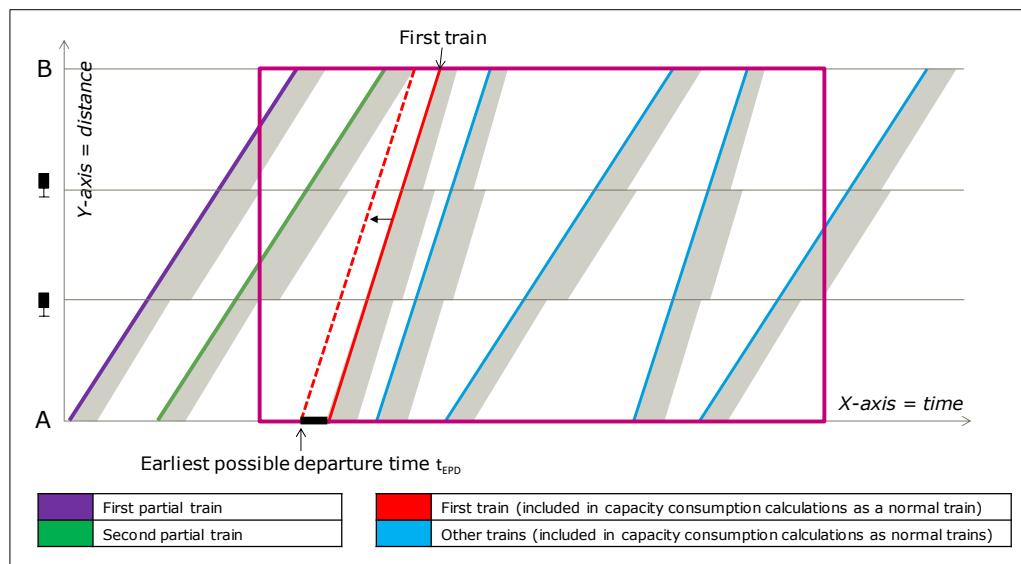


Figure 12. Example with two partial trains.

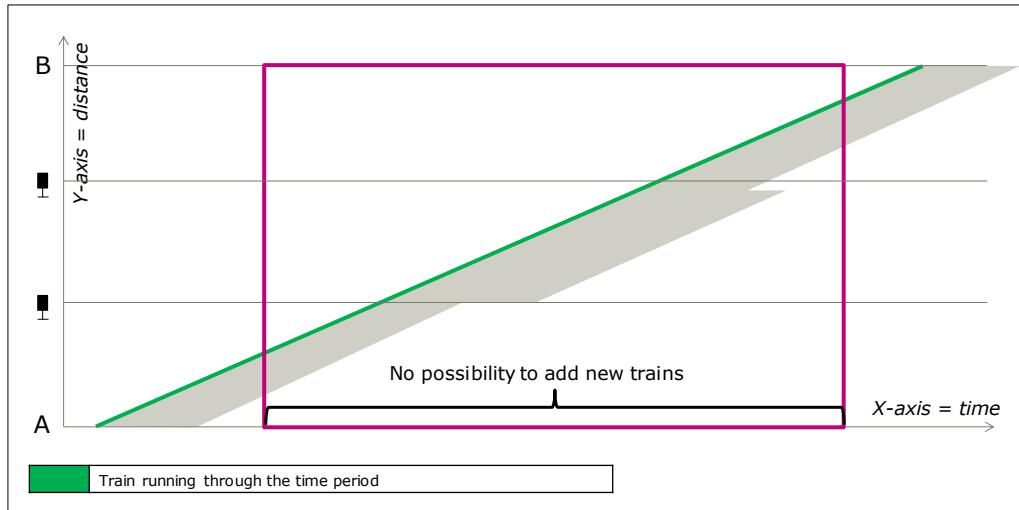


Figure 13. Example with one partial train running through the period.

Depending on the operations, the formula for adding Earliest possible departure time can give values below 0 (Figure 14). In that case, earliest departure time will be set to 0.

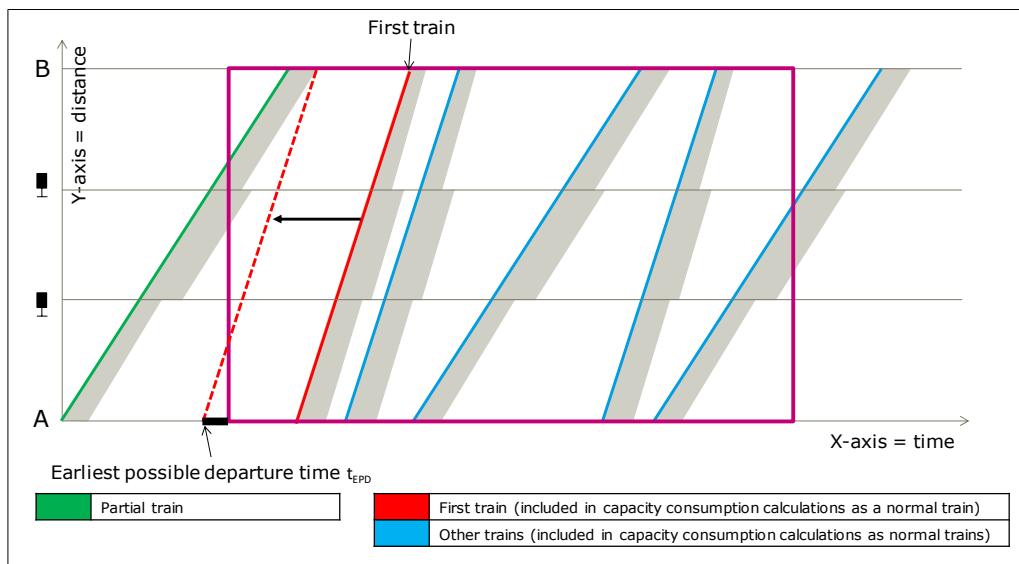


Figure 14. Explanation on a graphical time of why the earliest possible departure time can be negative.

1.3.4 Definition of maintenance work and shuntings t_M

A timetable may or may not include planned capacity reservations for maintenance work or shunting. In case these are included, they will be analysed as virtual trains similarly as described earlier. If these operations aren't included in the analyses, but they are planned and known, they can be added in the timetable by simply adding a requisite number of minutes.

$$t_M = \text{Duration of planned maintenance work or shuntings}$$

1.3.5 Definition of station and crossing times t_s

Depending on the infrastructure and interlocking, in some cases two trains cannot arrive to a same station simultaneously. In these cases, the second arriving train must wait before it can reserve an itinerary. Station and crossing times are location-specific and must be analysed from a Signalling plan or by consulting a signalling specialist. However, without detailed information, a default value of 60 seconds can be used.

Station crossing time will be added whenever two trains are meeting in passing loop (single track lines). Junction crossing time will be added whenever the study area covers a junction that is being used (double track lines). Unintuitively, junction crossing time will be added into the capacity consumption calculation on the opposite track (an explanation is visualized in Figure 15, right side, with a blue circle).

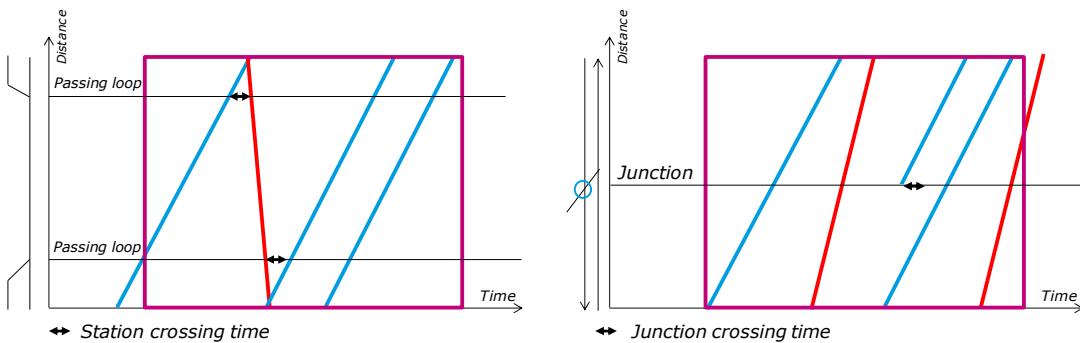


Figure 15. Left: Station crossing time visualised on a graphical timetable. Right: Junction crossing time visualised on a graphical timetable.

Both occupation types can be included in the analysis by simply adding a requisite number of minutes.

t_s = Sum of occupation time needed for stations and junctions.

1.3.6 Definition of capacity consumption for the partial calculation

Once all terms reviewed are defined, the terms can be added into the final capacity consumption formula:

$$K = \frac{h_A + t_D + t_{EPD} + t_M + t_s}{T}, \text{ where}$$

K	Capacity consumption [%]	t_D	Driving time difference [min]
T	Time period [min]	t_{EPD}	Earliest possible departure time [min]
h_A	Total minimum headway [min]	t_M	Maintenance and shuntings [min]
		t_s	Station and crossing time [min]

The value for capacity consumption describes the percental amount of reserved capacity during the study period. The next chapter reviews how results should be interpreted and compared between study areas and time periods.

1.4 Result interpretation and conclusions

1.4.1 Capacity consumption dependence on study area

Once the capacity consumption values are defined for all necessary locations, the consumption value for the whole railway line can be determined. For **single track lines**, defining the total capacity consumption for the railway line is simple; the definition is made based on the highest value during certain time, as explained in the Figure 6 (left). For **double track sections** the highest calculated capacity consumption value defines again the significant value for the whole case study area. Both directions are analysed separately.

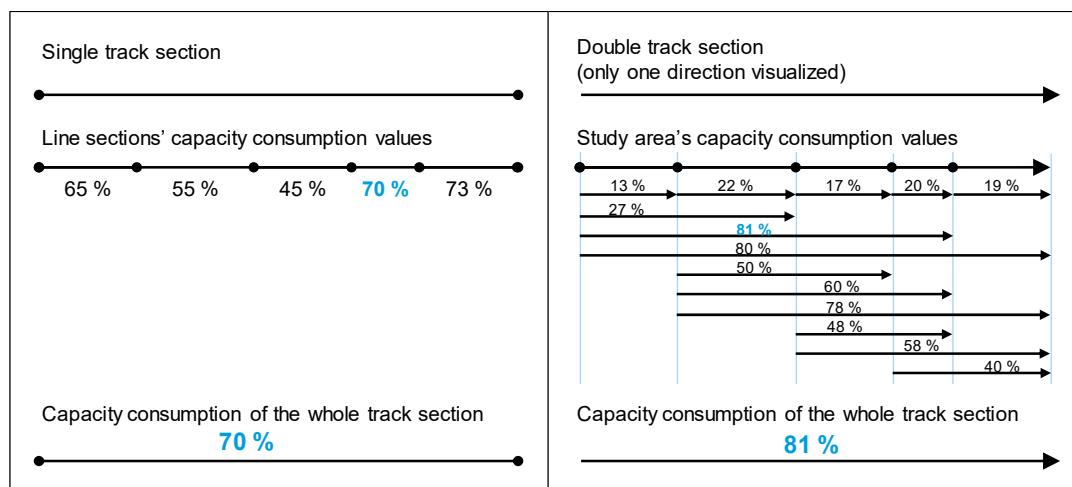


Figure 16. Illustration on how capacity consumption for the whole track section is interpreted based on partial calculations' capacity consumption values.

1.4.2 Capacity consumption variability over time

Once the capacity consumption results are defined for all time periods and separately for with and without running time margins, they can be combined to see the consumption variability over time. If the capacity consumption values are calculated for the whole 24-hour period, typically some peak times can stand out. The sharpness of these peaks can then give important information on the track sections tendency for consecutive delays.

For track sections having both passenger and freight trains, UIC (2013) has set threshold values of 75% for maximum suggested capacity consumption value during peak hour and 60% for mixed traffic line operations.

Type of line	Peak hour	Daily average
Dedicated suburban passenger line	85 %	70 %
Dedicated high speed line	75 %	60 %
Mixed-traffic lines	75 %	60 %

Figure 17 illustrates example results on a single track line that has mixed operations. The calculations have been done for the whole day and the time period was one hour. The capacity consumption for each analysed line section is shown in red lines and the maximum value is shown with a black line. The threshold values for mixed-traffic lines are shown with red lines. In this case example, capacity consumption rises above 75 % three times, but the daily average remains below 60 %. These capacity consumption peaks increase the risk of punctuality issues, especially during the first peak which lasts for three hours. From a punctuality point of view, it is suggested the timetable is planned to be smoothed to remove these peaks.

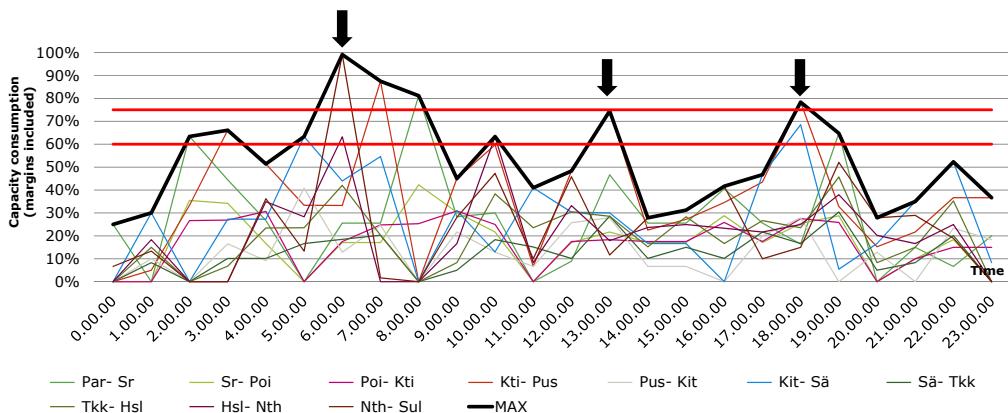


Figure 17. Capacity consumption variability over time - example results on Parikkala-Joensuu Sulkulahti -single track line.

Figure 17 illustrates the capacity consumption results only including running time margins. The results without the margins would decrease the results by 0 to 10 percentage points (Figure 18). For simplicity, only the maximum values are illustrated in Figure 18.

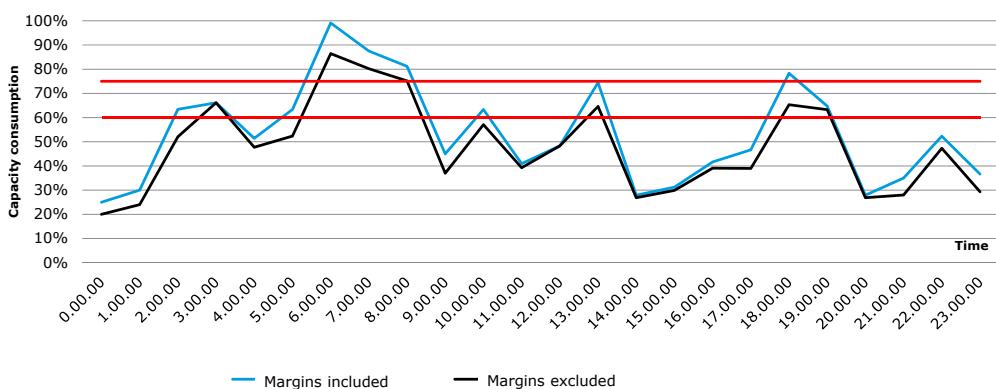


Figure 18. The impact of running time margins for capacity consumption.

Sources

Landex, A., 2008. *Methods to estimate railway capacity and passenger delays*, Copenhagen: Technical University of Denmark.

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User's manual: delay estimation

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1.1 General overview

Description of delay evaluation tools and input data requirements

As part of socio-economical assessments of railway infrastructure investments, impacts on punctuality are evaluated through the average delay. Delay means how much on average a train is delayed when it exits the investment area. Delay is given in seconds per train per day.

Depending on the number of tracks, trains are delayed for different reasons. Statistically, in single track sections most delays are due to train crossing events. This means that operations in opposite directions interact. The amount of delays experienced by trains exiting the investment area (later to be called output delay) is also dependent on the amount of delays that they are already experiencing on entering the area (input delay).

In double track lines all trains are running towards the same direction, and statistically the majority of delays occur when trains are planned to operate within only a small headway. In double track sections, the amount of margin time included in the timetable affects the output delay. The more margin is included in the timetable, the more easily trains can recover from minor delays. Similarly to single track sections, for double track sections the output delay is dependent on the input delay.

Due to the differences in delay evaluation for single and double track lines, two separate calculation methods for delay evaluation have been developed. The input data requirements for both methods are listed in Table 1 and the calculation guidelines are described in chapters 1.2 and 1.3.

Table 1. *Input data requirements and descriptions for delay calculations in single and double track lines.*

Input	Details	Input data requirement	
		Single track	Double track
Timetable	Timetable describing arrival, departure, driving and dwell times for each station and line section.	X	X
Graphical timetable	The graphical timetable (produced by Viriato or any other tool) can be used to count the crossings on single track lines.	X	
Signalling	Number of signals influences the minimum headway		X
Input delays	The average input delays for the studied track section given in [second/train/day]. The average input is estimated based on track history data or similar track section.	X	X

Method applicability and limitations in socio-economic assessment cases

As the delays defined using the calculation methods for both single and double track sections are dependent on the planned timetables, both methods are only applicable for cases that have an influence on the planned timetable. Otherwise no change in the estimated delays are noticed. Such impacts can relate, for example, to driving speeds, number of trains or number of crossings. In cases where the investment has a clear impact on the punctuality of arriving trains, for example when a single track line is upgraded into a double track line (punctuality issues from passing events are removed), also the input delays may change.

Thus, both calculation methods are applicable for socio-economic assessment cases, where the speed restriction or number of blocking sections is increased. However, applicability for cases where new passing loops is increased is not unambiguous: in case these new passing loops are designed to be used in planned timetable, and their impact can be seen in the planned timetable, the methods are applicable. If the new passing loops are planned to be used only in disruption events, and they won't be seen in the planned timetable, the methods are not applicable.

Other notes

Calculation method choice when the track is partially single and partially double track

In case the studied track section is partially single and partially double track, the calculation shall be performed in two parts. It must be noted though, that the methods are not applicable for short track sections (few stations or other node points only). Especially in double track sections the delays are developed from the interaction of consecutive trains, and thus the method is not able to notice

punctuality impacts when the study track section is short (less than four stations or other node points).

Due to this restriction, for case areas consisting of mostly single track and only partially double track, it is recommended that the whole case area is analyzed using the single track delay method. One of the input requirements for single track sections is the number of crossings, as will be discussed in more detail in chapter 1.2, and in these cases the passing events are simply ignored if they occur at the double track area.

Impact of the delay evaluation method development process

As part of the delay evaluation development process, TRENTO-software developed by Trenolab was utilized for analyzing train operations and timetabling. This can be seen especially from the method for double tracks. However, the developed methods are not dependent on the TRENTO-tool and all calculation steps can be performed using any spreadsheet program.

1.2 Delay evaluation on single track lines

The average delay (output delay) describes the punctuality of a train leaving from the studied area. On single-track lines, the estimation is based on two inputs: the planned timetable and the average punctuality (input delays) of trains arriving into the study area.

Output delay is calculated adding variables $t_{d+,e}$ and N_x into the following formula:

$$t_{d+,e} = 0.917 \cdot t_{d+,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x, \text{ where}$$

- $t_{d+,e}$ is the average delay (output delay) of trains when they leave the study area [sec/train/day],
- $t_{d+,i}$ is the average delay (input delay) of trains when they enter the study area [sec/train/day] and
- N_x is the average number of crossing events at the study area per one train.

As an output, the formula gives an average delay of all trains leaving the study area in unit second per train per day.

The calculation steps are illustrated in a chart in Figure 1.

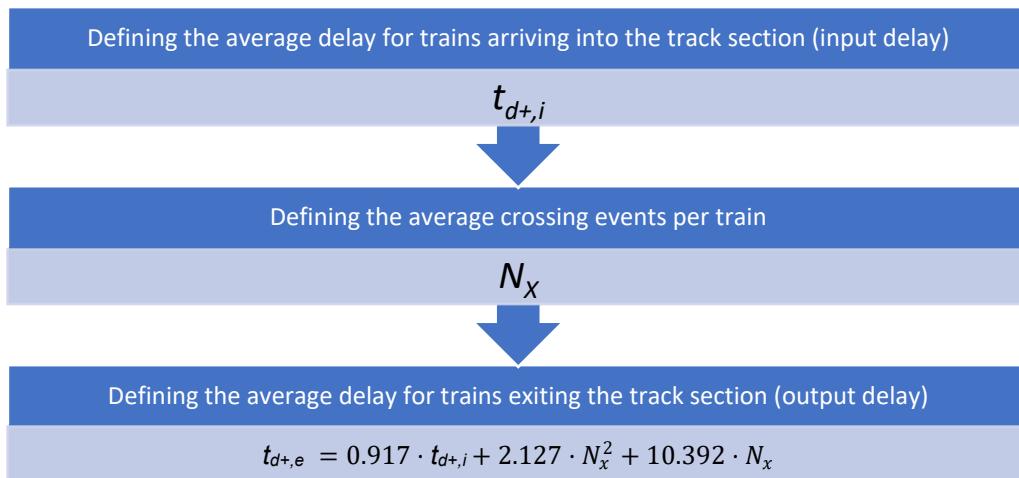


Figure 1. The calculation steps of delay evaluation on single track lines.

The delay calculation formula considers both driving directions simultaneously, and thus only one calculation process is required (compared to double track sections, where both directions form independent unities).

Defining the input delay $t_{d+,i}$

The input delay is defined based on the history data of the studied track section or, in case of a new rail connection, a similar track section's history data. The input delay is defined based only on delayed trains – in other words, early trains are ignored from the analysis. The input delay is first defined separately for passenger and freight trains. In case no history data is available, the input delay can be estimated using the example numbers given in Table 2. The example numbers describe real delays during Spring 2018.

Table 2. Example input delay values for a few single track sections in Finland (Spring 2018).

Line	Input delay $t_{d+,i}$ [sec/train/day]	
	Passenger trains	Freight trains
Kirkkonummi–Turku	112	-
Turku–Toijala	184	165
Luumäki–Imatra	367	607
Kouvola–Pieksämäki	313	746
Lielahdi–Pohjois-Louko	234	556
Seinäjoki–Vaasa	181	-
Ylivieska–Iisalmi	267	509
Parikkala–Joensuu	211	560
Oulu–Kontiomäki	312	722

The average input delay of all trains is submitted in the delay formula. It is defined based on weighted average of passenger and freight trains unique input delays:

$$t_{d+,i}$$

$$= \frac{\text{No. of passenger trains} * t_{d+,i}(\text{passenger trains}) + \text{No. of freight trains} * t_{d+,i}(\text{freight trains})}{\text{Number of all trains}}$$

By default, input delay defined with the above formula is inserted to all scenarios that are studied in the socio-economic assessments. This means that the value for input delay remains the same for all scenarios and punctuality is affected only through the other parameter (number of crossing events N_x). However, in some cases, investments may have a clear impact on punctuality issues occurring outside the study area, and the value for input delay must be modified accordingly. Notable special cases are:

- As part of the investment, a whole single track line is upgraded into a double track line. For the reference scenario, input delay will be calculated using the above formula, but no information about the level of input delay for double track exists. It is known, however, that the input delay is decreasing due to the fact that on double track lines delays are not caused by train crossings.

A solution for defining input delay in the investment scenario: the relative amount of delays due to train crossings can be calculated using the delay code data. Input delays are decreased by the same relative level. The delay code data is publicly available in the Finnish Transport Infrastructure Agency's website.

- After the investment, all freight trains are re-routed and will no longer operate in the study area. In this case the relative amounts of passenger and freight trains change. On average the freight trains are less punctual than passenger trains, and thus re-routing the freight trains decreases the average input delay.

A solution for defining input delay in the investment scenario: Input delay is re-estimated separately for all scenarios.

Defining the average number of train crossing events N_x

The average number of train crossing events N_x can be calculated from a graphical timetable. Crossing events are calculated by hand from both middle and the end stations or other node points. Where one train is crossed by two trains, both crossings are included in the calculations. An example of calculating number of crossings from a graphical timetable is illustrated with orange circles in Figure 2.

The total number of trains can be calculated either from a graphical or a tabular timetable. Operations in both directions are included in the calculations, as well as operations that are not operating at all of the line sections of the studied area.

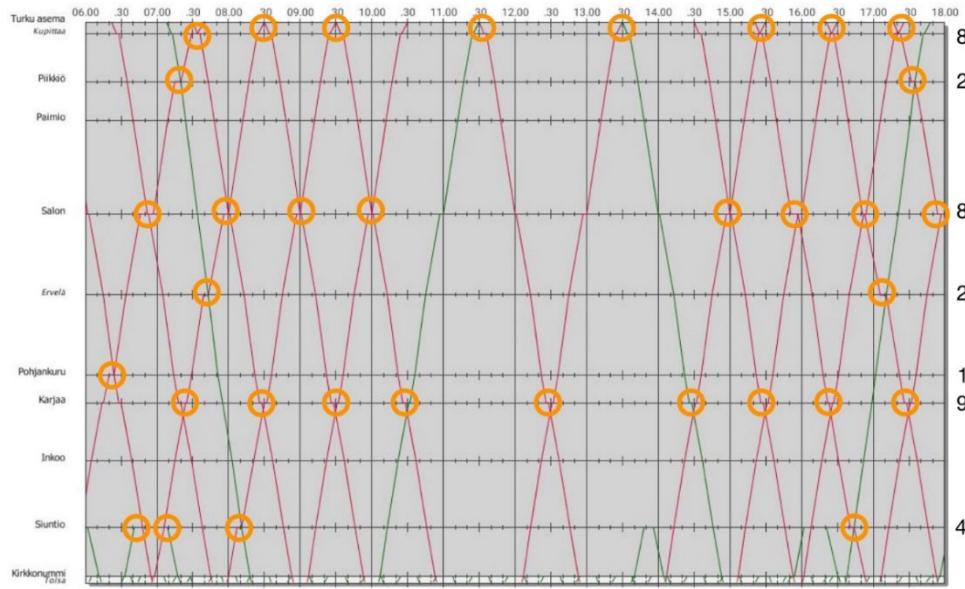


Figure 2. Defining the number of trains and train crossing events from a graphical timetable.

The average number of train crossing events N_x is calculated as the ratio of crossing events and total number of trains:

$$N_x = \frac{\text{No. of train crossing events during one day}}{\text{No. of trains during one day}}$$

Average number of train crossing events N_x does not have any unit.

Defining output delay

After defining terms N_x and $t_{d+,i}$, they can be inserted in the delay evaluation formula:

$$t_{d+,e} = 0.917 \cdot t_{d+,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x$$

The formula gives as a result the average number of delay of trains exiting the study area in unit [sec/train/day].

1.3 Delay evaluation on double track lines

For delay evaluation on double track lines, four variables are defined. The terms describe the sensitivity for punctuality issues and margin time as well as the input delays. Conversely to single track lines: input delays are separated into two: positive input delay describes how much the delayed trains are delayed on average when they enter the study area and negative input delay describes how much early trains are early, on average, when they enter the study area. Delay evaluation for double track lines is more complicated than for single track lines. Therefore, a separate calculation program has been developed to perform the most laborious work phases automatically.

Delay is calculated by inserting terms $\sum_{b \in B} (w(b) \cdot b f_g^b)$ and $t_{mr,g}$ (defined by the calculation program) and terms $t_{d+,i}$ ja $t_{d-,i}$ (defined by the user) into the following formula:

$$t_{d+,e} = 22.443 \cdot \sum_{b \in B} (w(b) \cdot b f_g^b) - 0.033 \cdot t_{mr,g} + 1.029 \cdot t_{d+,i} - 0.001 \cdot t_{d-,i}$$

where

- $\sum_{b \in B} (w(b) \cdot b f_g^b)$ describes the sensitivity of a planned timetable
- $t_{mr,g}$ defines the number of margin on a planned timetable
- $t_{d+,i}$ defines, how much delayed trains are on average delayed when they enter the study area [sec/train/day] and
- $t_{d-,i}$ defines, how much early trains are on average early when they enter the study area [sec/train/day].

The result describes the average delay of trains exiting the study area in unit [sec/train/day].

The calculation process starts with creating four input files, that are inserted into the calculation tool by the Finnish Transport Infrastructure Agency (FTIA). These four files describe the planned timetable in different ways: the studied track section, planned timetable, planned margins and minimum headway times are stored in the input files. After using the calculation tool, the output delay is calculated using the above formula. All calculation steps are illustrated in Figure 3.

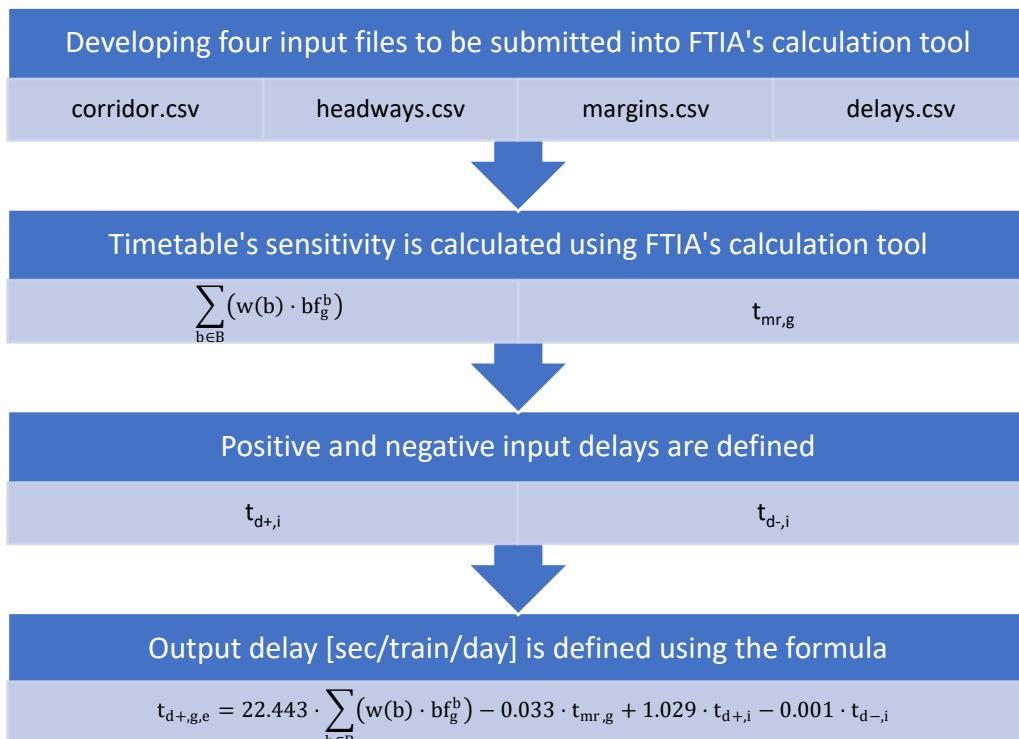


Figure 3. Calculation steps for delay evaluation in double track lines.

The following chapter reviews the steps for creating the four input files. The files are submitted into the calculation program in csv-form, however it is possible to create them using any spreadsheet program.

Due to the fact that on double track sections, each line is independent without any interaction, both directions must be analysed separately.

Creation of input files

corridor.csv

Features of the analysed track section are described in Corridor.csv file. The file's form is illustrated in Table 3. The first row always consists of the words similar to the example: *Corr / Prog / Orig / Dest*. The rows below describe the line sections and stations in the studied direction (one line section is described in each row). Note that the numbers 1–4 in first row are for illustration purposes only, and they won't be added to the actual corridor file.

Table 3. Format of corridor.csv

1	2	3	4
Corr	Prog	Orig	Dest
Helsinki-Kerava	1	Helsinki asema	Pasila asema
Helsinki-Kerava	2	Pasila asema	Pasila autojuna- asema
...

Contents of columns 1–4:

1. Name of the track section. The same name is repeated on all rows.
2. A cumulative number to illustrate the line sections
(always starts with number 1)
3. Name of the first node point on the particular line section
4. Name of the last node point on the particular line section

delays.csv

Planned timetable is described in file delays.csv. The file's form is illustrated in Table 4. The first row always consists of the words similar to the example: *Train number / Date / Pass / Station / Arrival difference / Departure difference / Arrival planned / Departure planned / Actual arrival / Actual departure*. Each train's arrival and departure times at all stations are included in the file. Note that the numbers 1–10 in first row are for illustration purposes only, and they won't be added to the actual corridor file.

Table 4. Format of delays.csv.

1	2	3	4	5	6	7	8	9	10
Train number	Date	Pass	Station	Arrival difference	Departure difference	Arrival planned	Departure planned	Actual arrival	Actual departure
9041	14/09/2016	5	Käpylä			30402	30420	30402	30420
9041	14/09/2016	6	Oulunkylä			30516	30540	30516	30540
...

Contents of columns 1–10:

1. Train number. A unique train number to separate that particular train from other trains.
2. Date. Date of the reference day. As part of socio-economic assessments, this date can be chosen freely. However, it must be carefully follow the same format as in the example.
3. Node point ordinal number (pass). All stations are given a station number. The first node point always receives number 1.
4. Node point. Given in the exact same format as in corridor file.
5. Arrival difference. Column is left unfilled as part of socio-economic assessments.
6. Departure difference. Column is left unfilled as part of socio-economic assessments.
7. Planned arrival time. Arrival time to the node point is given in seconds after midnight. For example, time 00:01:00 receives number 60 (seconds).
8. Planned departure time. Departure time from the node point, given in seconds after midnight. For example, time 01:00:00 receives number 3600 (seconds).
9. Actual arrival time. As part of socio-economic assessments, this column receives the same input as for column 7.
10. Actual departure time. As part of socio-economic assessments, this column receives the same input as for column 8.

The cells in columns 7–10 can be left unfilled in cases when that particular row describes a train's departure time from the first station (no need to define the arrival time) or the arrival time to the last station (no need to define the departure time).

margins.csv

The number of margins for all trains is collected in file *margins.csv*. The number of margin is given separately for each line section. The file's form is illustrated in Table 5. The first row always consists of the words similar to the example: *Pass / Train number / Margin*. Note, that the numbers 1–3 in first row are for illustration purposes only, and they won't be added to the actual margins file.

Table 5. Format of margins.csv.

1	2	3
Pass	Train number	Margin
8	9064	18
9	9064	12
...

Contents of columns 1–3:

1. Line section, numbered similarly to the delays file. The first line section on the analysed direction receives number 1.
2. Train number. Trains are numbered similarly to other files.
3. Margin. The number of margin time included in the timetable for the particular line section, given in seconds. The amount of margin time is decided in the timetabling process, however, if more detailed information is not known, the following numbers can also be used:
 - 5 % of commuter train planned driving time is margin
 - 10% of long distance passenger train planned driving time is margin
 - 12 % of freight train planned driving times is margin.

headways.csv

Unlike the other input files, defining the values for headway files requires initial calculation. The file describes the technical minimum headway times, that is depending on the average travel speed as well as the signalling along the line.

The minimum headway time is calculated for each line section separately with the following formula:

$$h_i = \frac{n * d * 3600}{s} \quad \text{, where}$$

h_i	[sec]	The technical minimum headway time for line section i
n		Multiplication factor depending on the number of block sections on line section i. $n = 1$, if there is only one block section on the line section $n = 2$, if there are multiple block sections on the line section
d	[km]	Average length of block sections on the line section
s	[km/hour]	Average travel speed on the line section

The average travel speed is calculated as follows:

$$s = \frac{\text{length of line section [km]}}{\text{average travel time [h]}}$$

The headway times for each line section is collected in headways.csv file. The format of the file is illustrated in Table 6. Headway file does not have any header row. Note, that the numbers 1–3 in first row are for illustration purposes only, and they won't be added to the actual headways file.

Table 6. Format of headways.csv.

1	2	3
Pasila asema	Käpylä	192
Käpylä	Oulunkylä	432
...

Contents of columns 1–3:

1. Name of the first node point
2. Name of the last node point
3. The technical minimum headway time on the studied operation direction, given in seconds.

Calculating timetable's sensitivity using the calculation tool of the Finnish Transport Infrastructure Agency

Taking input files into same folder

After creating the four input files, it must be re-checked that they are saved in csv-format and that they are named as in the Figure 4 below. The four input files should be stored in the same working folder.

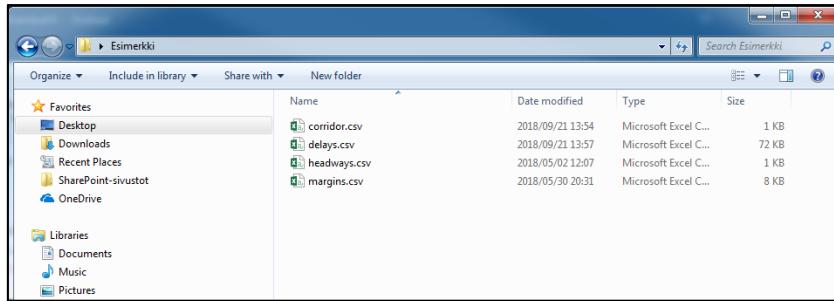


Figure 4. Four input files stored in the same folder.

Using the calculation tool

Finnish Transport Infrastructure Agency's delay calculation tool ("Data analyzer for regression") is a file in a jar-format, and it is publicly available in FTIA's website:

<https://vayla.fi/documents/20473/572646/tasmallisyyden-laskentatyokalu.jar/4ef5b258-4c33-4dba-b9b4-92fdbd7249197>

The delay calculation tool is designed for either data analysis or delay calculation as part of socio-economic assessment. This user's manual reviews only functionalities that are required for delay calculation.

The front panel is divided into seven sections as illustrated in Figure 5.

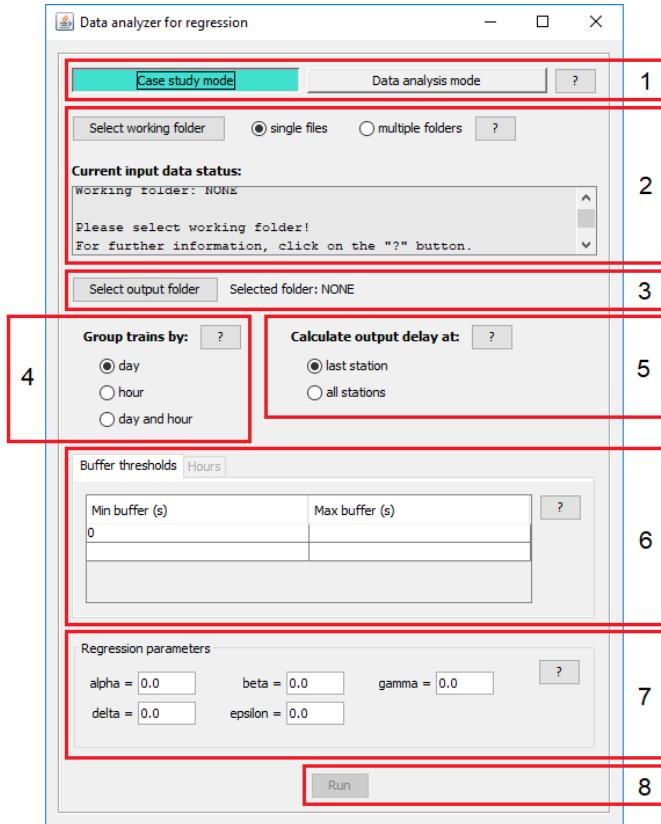


Figure 5. Calculation tool outlook.

1. Select "Case study mode". The selected button is highlighted in turquoise colour.
2. Select "Select working folder" and find the folder where the input files are stored. Select "single files".
If the input files are found and named correctly, a text "input data are valid" appears in the window named "current input data status".
3. Select "Select output folder" and find a folder, where the result file is to be printed.
4. Select "day".
5. Select "last station".
6. Write the following numbers in the table:

0	60
60	120
120	180
180	240
240	300
300	

7. As part of delay calculations, all parts of section 7 gets a value of 0.
8. Select "run" to run the calculations. A window appears describing the current state of the calculations (Figure 6).

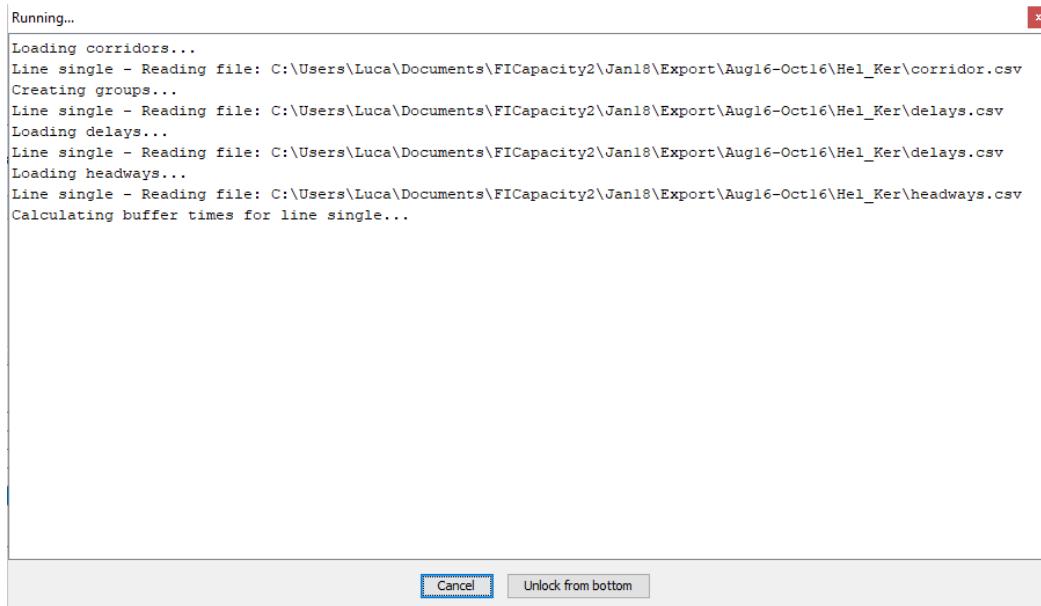


Figure 6. A window telling the current state of the calculations.

Finding terms $\sum_{b \in B} (w(b) \cdot bf_g^b)$ and $t_{mr,g}$ out of a results file

The analysis resulting from the calculation process is written in a file named *RegressionData_day_last.csv*. Figure 7 illustrates the form of the results file. Information needed as part of the delay calculation are written in columns J and K. Column J stores the value for term $\sum_{b \in B} (w(b) \cdot bf_g^b)$, which describes the sensitivity of a timetable. Column K stores the value for timetable's average margin $t_{mr,g}$. Both terms are inserted in the delay formula without further calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Group	Line	Trains	buff_0	buff_60	buff_120	buff_180	buff_240	buff_300	buffWeight	marg	Din+	Din-	Dout+	ED+
2	TG_single	single	66	0	0	9	21	35	773	0.053504	68.39394	0	0	0	0

Figure 7. Form of results file.

Before further calculation steps, the number of trains in column C is compared with the planned number of trains in the studied direction.

Defining positive input delay $t_{d+,i}$ and negative input delay $t_{d-,i}$

While delay calculations for single track sections require only the positive input delay as an input, delay calculations for double track sections consider both negative and positive input delays. Positive input delay $t_{d+,i}$ describes, how much on average trains are delayed when they enter the study area and negative input delay $t_{d-,i}$ describes how much on average trains are early when they enter the study area.

The input delay is defined based on the history data of the studied track section or, in case of a new rail connection, estimated based on a similar track section's history data. The input delay is first defined separately for long distance passenger trains, commuter trains and freight trains. If no history data is available, input delay can be estimated using the example numbers given in table 7. The example numbers describe real delays during Spring 2018.

Table 7. Example numbers for input delays.

Track section	Input delay [sec/train/day]					
	Long distance passenger trains		Commuter trains		Freight trains	
	Positive delay $t_{d+,i}$	Negative delay $t_{d-,g,i}$	Positive delay $t_{d+,i}$	Negative delay $t_{d-,g,i}$	Positive delay $t_{d+,i}$	Negative delay $t_{d-,g,i}$
Helsinki-Kirkkonummi	106	21	37	9		
Helsinki-Kerava	158	67	76	9		
Kerava-Lahti	337	32	111	14	439	861
Lahti-Riihimäki	421	39	122	27	577	566
Riihimäki-Tampere	209	59	118	70	418	964
Tampere-Orivesi	165	25			446	732
Lahti-Kouvola	339	4	194	2	482	445
Kouvola-Luumäki	314	25			880	556

The weighted average input delays $t_{d+,i}$ and $t_{d-,i}$ are inserted in the final formula as follows:

$$t_{d+,i} = \frac{\text{No. long distance} * t_{d+,i}(\text{long distance}) + \text{No. commuter} * t_{d+,i}(\text{commuter}) + \text{No. freight} * t_{d+,i}(\text{freight})}{\text{No. all trains}}$$

and

$$t_{d-,i} = \frac{\text{No. long distance} * t_{d-,i}(\text{long distance}) + \text{No. commuter} * t_{d-,i}(\text{commuter}) + \text{No. freight} * t_{d-,i}(\text{freight})}{\text{No. all trains}}$$

Defining output delay

After defining terms $\sum_{b \in B} (w(b) \cdot bf_g^b)$ and $t_{mr,g}$ using Finnish Transport Infrastructure Agency's calculation tool and the input delays terms $t_{d+,i}$ and $t_{d-,i}$, all terms are inserted into the delay calculation formula:

$$t_{d+,g,e} = 22.443 \cdot \sum_{b \in B} (w(b) \cdot bf_g^b) - 0.033 \cdot t_{mr,g} + 1.029 \cdot t_{d+,i} - 0.001 \cdot t_{d-,i}$$

The formula gives as a result the average number of delay of trains exiting the study area in unit [sec/train/day].

Laskentaohjeistus kapasiteetin käyttöasteen arviointiin hankearvioinnissa

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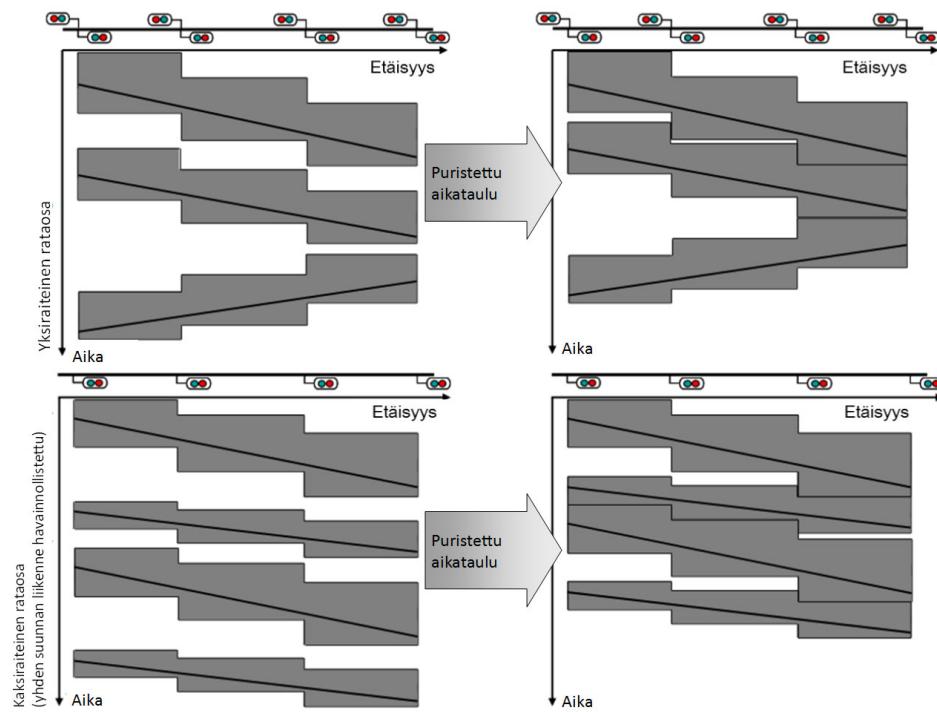
1.1 Yleistä laskentamenetelmästä

1.1.1 Laskentamenetelmän kuvaus

Kansainvälinen rautatieliitto UIC määrittää kapasiteetin käyttöasteen tunnuslukuna, joka kuvaaa rataosien ja liikenepaikkojen kuormittuneisuutta (UIC 2013). Kuormittuneuteen vaikuttaa liikennöivien junien lukumäärä ja aikataulu, kaluston ominaisuudet sekä infrastruktuuri ja turvalaitteet.

Kapasiteetin käyttöasteen avulla voidaan arvioda suunnitellun aikataulun toteutettavuutta. Korkea käyttöaste indikoi tarvetta joko parantaa infrastruktuuria tai muokata aikataulua esimerkiksi poistamalla osa suunnitellusta junista, tai vaihtoehtoisesti yhtenäistää junien aikataulua esimerkiksi hidastamalla nopeimpia junia tai lisäämällä niille ylimääräisiä pysähdyksiä.

Kapasiteetin käyttöasteen käsitettä voidaan havainnollistaa yksinkertaisimmin graafisesta aikataulusta (Kuva 1). Kun tarkasteltavien junien aikatauluviivoja siirretään niin lähelle toisiaan kuin mahdollista, ensimmäisen ja viimeisen junan välinen aika kuvaaa sitä ajanjaksoa, jolloin rataosa on varattu, ja jäljelle jäävä osa kuvaaa vapaata kapasiteettia. Aikatauluviivojen siirtämisesessä junien järjestystä, ajoaikoja tai pysähdyksia ei lähtökohtaisesti saa muuttaa. Mitä homogeenisempi aikataulu on, sitä lähemmäs toisiaan junat voidaan siirtää ja sitä pienemän arvon kapasiteetin käyttöaste saa.



Kuva 1. Graafisen aikataulun puristaminen havainnollistettuna yksi- ja kaksiraitaisella rataosalla (Kuva suomennettu lähteestä Landex, 2008). Harmaita laatikoita kuvitteellisesti "siirretään" lähemmäs toisiaan, kunnes jokin opastinvälien laatikosta koskee edellisen junan harmaata laatikkoa. Mitä enemmän aikataulua on mahdollista puristaa, sitä pienemmän kapasiteetin käyttöasteen arvon se saa.

Kapasiteetin käyttöaste on kansainvälisesti yleisesti käytetty laskentamenetelmä, joka perustuu UIC:n karkeaan ohjeistukseen. UIC:n ohjeistuksen tarkkuus-tason johdosta menetelmästä on kehitetty maakohtaisia tulkintoja. Tätä ohjeistusta laadittaessa menetelmää muokattiin Suomen olosuhteisiin paremmin so-veltuvaksi ja laskentamenetelmän peruskaava muodostui seuraavanlaiseksi:

$$K = \frac{h_A + t_D + t_{EPD} + t_M + t_S}{T}, \text{ missä}$$

Termi	Kuvaus ja yksikkö	Selite
K	Kapasiteetin käyttöaste [%]	Termi kuvaaa, kuinka suuri osuus tarkastelualueen kapasiteetista on käytössä tietyllä aikataululla ja infrastruktuurilla
T	Tarkasteluaajanjakso [min]	Analyysiin sisällytettävä ajankohta. Tyypillisesti tarkastelu tehdään yhden tunnin ajanjaksoille kerrallaan, muita yleisesti käytettyjä vaihto-ehtoja ovat 20 h tai 24 h
h_A	Kokonaisminimijunaväli [min]	Tarkasteluaajanjaksona tarkastelualueella samaan suuntaan kulkeville junille lisättävien minimijunaväli-termien summa. Minimijunaväli kuvaaa turvalaitejärjestelmän mahdollistamaa pienintä mahdollista junien etäisyyttä minuutteina.
t_D	Ajoaikojen kokonaisero [min]	Tarkasteluaajanjaksona tarkastelualueella samaan suuntaan kulkeville, mutta eri nopeuksilla eteneville junille lisättävien ajoaikojen ero -termien summa. Ajoaikojen ero kuvaaa ajanjaksoa, joka nopean seuraavan junan pitää odottaa, jotta se ei joudu linjaosuudella hidastamaan edeltävän itseään hitaanman junan perässä.
t_{EPD}	Ensimmäinen mahdollinen lähtöaika verrattuna tarkasteluaajanjakson alkuun kaksiraiteisilla rataosilla [min]	<u>Vain kaksiraiteisilla rataosilla huomioitava</u> termi, joka ottaa huomioon tarkasteluaajan-kohtaa edeltävien junien vaikutuksen tarkastelujankohdan ensimmäisen junan liiken-nöintiin
t_M	Ratatyövaraaus [min]	Radan huollolle ja mahdollisille muille toimenpiteille varattava aikajakso, jolloin rata ei ole normaalille liikennöinnille käytettävissä
t_S	Turva-ajat kulku- teiden vapautumi- selle [min]	Liikennepaikkojen turva-aikoihin ja vaihteiden käänymisiin tarvittavien turva-aikojen summa

Kaavan termit, niihin vaadittavat lähtötiedot ja laskentaohjeistukset on kuvattu tässä ohjeessa. Laskennan vaiheet on kuvattu seuraavassa:



Kuva 2. *Kapasiteetin käyttöasteen laskentavaiheet.*

1.1.2 Laskentamenetelmän lähtötiedot

Rataosan suunniteltu aikataulu tarkastelupäivältä

Käyttöästetarkastelut tarvitsevat laskennan pohjaksi aikataulun koko tarkastelupäivältä rataosalle ja ajanjaksonalle. Osana hankearvioinnin käyttöästelaskentaa aikatauluksi on valittava sellaisen yksittäisen päivän aikataulu, joka edustaa tarkastelalueelle tyypillistä liikennöintimääräätä. Tämä on erityisen tärkeää, jos rataosalla kulkee epäsäännöllistä liikennettä (tämä on tyypillistä tavarajunien osalta). Suurimmalla osalla Suomen rataosista kapasiteetin käyttöaste saa suurimman arvon arkipäivinä, kuitenkin on huomioitava, että joillakin rataosilla liikennöintimäärä on suurempi viikonloppuna. Kapasiteetin käyttöaste lasketaan aina liikennemääärän kannalta vilkkaimmalta päivältä.

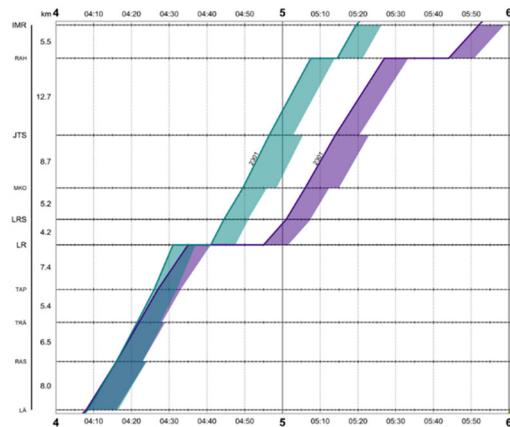
Lisäksi on huomioitava, että Suomessa tyypillisesti tavarajunien liikennöinnin tarve vaihtelee päivästä säästä ja päätös junien liikennöinnistä tehdään lyhyellä varoitusajalla. Koska kapasiteettivarauksen peruminen on yksinkertaisempaa kuin nopean varoitusajan kapasiteettivarauksen tekeminen, osalla tavarajunista kapasiteettia on yliverattu. Tämä on selkeästi nähtävissä vertaamalla todellista ja suunnitelua liikennöintimääräätä. Käytännössä kapasiteetin käyttöasteen laskeminen aikataulusta, jossa on suuri osa tavarajunia, johtaisi todennäköisesti todellisuutta korkeampaan kapasiteetin käyttöasteeseen. Osana hankearvointia kuitenkin suositellaan valitsemaan aikatauluun todellista yksittäistä päivää kuvaava liikennemäärä jättämällä valikoidut tavarajunat pois.

Pelivarat

Ajoaikojen pelivaraa kuvaava rataosan nopeimman mahdollisen ajoajan ja suunnittelun ajoajan eroa. Nopeinta mahdollista ajoaikaa kutsutaan minimiajoajaksi ja sitä käytetään aikataulusuunnittelun lähtötietona. Koska todelliseen liikennöintiin sisältyy aina pieniä poikkeustekijöitä, ajoaikoihin lisätään aina jonkin verran lisääikaa eli pelivaraa, jonka avulla junat voivat kulkea aikataulussaan pienistä poikkeamista huolimatta.

Kapasiteetin käyttöaste voidaan laskea joko pelivarojen kanssa tai ilman niitä. Pelivarojen huomioiminen laskennassa kertoo rataosan todellisen käyttöasteen, ja se on tiedettävä, kun tarkastellaan olemassa olevan aikataulurakenteen täsmällisyyttä, vaihtoyhteysmahdollisuksia tai vakiominuuttiaikataulurakenteita. Toisaalta ilman pelivaroja laskeminen tuo toisenlaista tietoa rataosan kuormitustuneisuudesta: sen avulla kuvataan teoreettista radan kuormittuneisuutta. Tämä on tärkeää esimerkiksi uudella rataosalla, jolloin on tiedettävä, kuinka monta junaa rataosalla voidaan liikennöidä erilaisilla oletusarvoilla (esimerkiksi erilaisilla pelivaroilla). Yleisesti suositellaan, että käyttöästelaskennat suoriteitaan erikseen pelivarojen kanssa ja ilman niitä, jotta voidaan arvioida, kuinka paljon pelivarojen olemassaolo vähentää kapasiteettia (Kuva 3).

Ajoaikoihin lisätyn pelivararen lisäksi myös asemapysähdyksien ajoaikoihin lisätään pelivaraa (kuva 3). Sen arvioiminen valmiista aikataulusta on kuitenkin usein haasteellista. Esimerkiksi tavarajunien vaihtotöiden minimipysähdyksajat voivat vaatia kyseisen operaattorin haastattelua. Jotta laskenta voidaan tehdä luotettavasti, asemapysähdyksien pelivaroja ei suositella huomioitavan osana hankearvointien käyttöästelaskentoja.



Kuva 3. Violettin aikatauluviiva kuvailee junan suunniteltua aikataulua. Vihreä alue kuvaa vastaavan junan aikatauluviivaa ilman ajoaikojen ja asemapysähdyksien pelivaroja. Junan matka-aika ensimmäiseltä liikennepaikalta viimeiseen liikennepaikkaan on merkittävästi lyhentynyt.

Pelivarojen suuruutta arvioidaan aikataulusuunnitteluvaiheessa ja ne voi tarkistaa esimerkiksi Viriato-aikataulusuunnitteluoohjelman junakohtaisista tiedoista. Jos minimiajoajat eivät ole tiedossa, niitä voidaan arvioida seuraavan kaavan avulla:

$$\text{Minimiajoaika} = \text{Suunniteltu ajoaika} * (1 - \text{pelivara} [\%])$$

Pelivarojen määrä voi vaihdella merkittävästi eri rataosilla ja junatyypeillä, mutta tarkemman tiedon puuttuessa laskennassa voidaan käyttää seuraavia oletuslukuarvoja:

- Lähijunat: 5 %
- Kaukojunat: 10 %
- Tavarajunat: 12 %

Kun kapasiteetin käyttöaste lasketaan ilman pelivaroja, laskennan pohjana käytetään sellaista aikataulua, josta pelivararat on etukäteen otettu pois yllä olevan kaavan avulla.

Turvalaitteet

Junien pienin mahdollinen väli vaikuttaa siihen, kuinka lähelle toisiaan aikatauluviivat voidaan puristaa. Pienintä mahdollista väliä kutsutaan minimijunaväliksi, ja se riippuu kyseisen liikennepaikkavälin opastinvälien määrästä. Yhdellä opastinvälillä voi olla kerrallaan yksi junta. Opastintiedot voi tarkistaa esimerkiksi rataosien linjakaavioista.

Asemien turva-ajat

Raiteistokaaviosta, käytettävistä turvalaitteista ja asetinlaitteesta riippuen joillain asemilla kaksoisjunaa ei voi saapua asemalle samanaikaisesti. Tällaisissa tapauksissa ensimmäinen junta saattaa joutua olemaan paikallaan määrätyn ajan ennen kuin toinen kulkutie voidaan varmistaa. Nämä ajat tulee ottaa huomioon laskennassa, ja viimeisimmän tiedon aikojen suuruudesta eri asemilla kannattaa varmistaa liikenteenohjauksesta. Turva-ajat voivat vaihdella myös aseman sisällä riippuen mm. junien tulosuunnista, käytettävistä raiteista ja kulkuteistä.

Infrastruktuurin ja asetinlaitteen rajoitukset

Joissain tapauksissa infrastruktuurilla ja asetinlaitteella on vaikutusta siihen, minkälainen aikataulu voidaan suunnitella. Esimerkiksi Suomessa osa kohtauspaikoista ovat niin lyhyitä, ettei pisimmat tavarajunat voi kohdata niissä, tarkoittaa, etteivät kaikki junat voi kohdata kaikilla liikennepaikoilla. Nämä rajoitukset on otettava huomioon aikataulusuunnitteluvaiheessa ja on siten huomioitu valmiiksi aikatauluun. Käyttöasteen laskennassa tällaisia rajoituksia ei tarvitse huomioida uudelleen.

1.2 Tarkastelalueiden ja -ajankohtien määrittäminen

1.2.1 Rataosuuden jako tarkastelalueisiin

Tarvittavien laskentaskenaarioiden määrä riippuu tarkastelalueesta. Yksiraitaisilla rataosilla junajärjestys voi muuttua ainoastaan liikennepaikoilla, esimerkiksi kohtauspaikoilla. Kaksiraitaisilla rataosilla junat voivat kohdata ja ohittaa toisensa myös linjaosuuksilla, mikä tekee käyttöästelaskennoinsta hieman työlämpää. Sekä yksi- että kaksiraitaiset rataosat jaetaan liikennepaikkavaleihin, jotka rajautuvat erityyppisiin solmupisteisiin (usein liikennepaikoihin). Erikoisia liikennepaikkoja on kuvattu kuvassa 4.



Kuva 4. Rataosan jako liikennepaikkavaleihin.

Kaksiraiteisilla rataosilla suositellaan, että kaikki mahdolliset liikennepaikka-väliyhdistelmät lasketaan ensin erikseen. Laskennat tulee suorittaa lisäksi eri suuntien junille erikseen, koska eri suuntien junat eivät ole vuorovaikutuksessa keskenään ja muodostavat siten itsenäiset kokonaisuutensa. Tämä nostaa laskettavien skenaarioiden määärää merkittävästi. Kuvassa 5 (vasen puoli) asemat on numeroitu (1-N), ja laskettavat kombinaatiot on merkitty ✓-symbolilla.

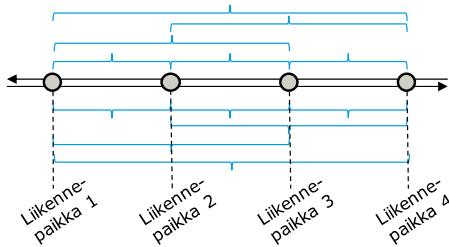
Yksiraiteisilla rataosilla riittää, että käyttöästelaskennat tehdään vain yksittäisille liikennepaikkaväleille. Eri suuntien liikenne otetaan samassa laskennassa huomioon. Kuvassa 4 (oikea puoli) asemat on numeroitu välillä 1-N ja tarvittavat laskentakombinaatiot merkitty ✓-symbolilla.

Jos on kuitenkin tiedossa, ettei **yksi- tai kaksiraiteisilla** rataosilla olevilla liikennepaikoilla liikenteen koostumus (junamäärä tai järjestys) voi muuttua, kyseestä liikennepaikkaväliä ei tarvitse jakaa osiin.

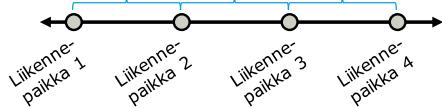
Analysoitavat tarkastelualueet kaksiraiteisella rataosalla		Tarkastelualueen ensimmäinen liikennepaikka				
		1	2	...	N-1	N
Tarkastelualueen viimeinen liikennepaikka	1	✓	✓	✓	✓	✓
	2	✓		✓	✓	✓
	...	✓	✓		✓	✓
	N-1	✓	✓	✓		✓
	N	✓	✓	✓	✓	

Analysoitavat tarkastelualueet yksiraiteisella rataosalla		Tarkastelualueen ensimmäinen liikennepaikka				
		1	2	...	N-1	N
Tarkastelualueen viimeinen liikennepaikka	1	✓				
	2	✓				
	...		✓			
	N-1			✓		
	N				✓	

Tarkastelualueet havainnollistettu kaksiraiteisella rataosalla, jolla on neljä liikennepaikkaa:



Tarkastelualueet havainnollistettu yksiraiteisella rataosalla, jolla on neljä liikennepaikkaa:



Kuva 5. Yksitellen analysoitavat tarkastelualueet havainnollistettuna yksi- ja kaksiraiteisilla rataosilla. Yksiraiteisella rataosalla molempien suuntien liikennöinti huomioidaan yhtäaikaisesti.

1.2.2 Aikataulun jako tarkastelujankohdeihin

Kapasiteetin käyttöaste vaihtelee kellonajasta riippuen. Tyypillisesti matkustajajunapainotteisilla rataosilla liikenteen määrä on suurin aamu- ja iltahuipputuntien aikana. Suuren vaihtelon vuoksi yhdessä laskennassa ei voida arvioida koko vuorokauden keskimääräistä käyttöästettä, vaan se suositellaan laskettavan jokaiselle tunnille (esimerkiksi klo 0–1, 1–2 jne.) erikseen. Tämä antaa aikataulusuunnittelijoille tarkempaa tietoa aikataulun kapasiteettirajoitteista ja mahdollista pullonaula- ja täsmällisyysongelmakohdista.

1.2.3 Yhteenveto tarkastelalueista ja -ajankohdista (osalaskennat)

Osana käyttöästelaskentoja aikataulu ja ratainfra jaetaan tarkastelalueisiin ja -ajankohdiin. Jaon seurausena syntyy ns. osalaskentoja, joille käyttöaste laskeetaan vuorotellen toistamalla seuraavissa kappaleissa esitettyjä laskentavaiheita. Osalaskentojen käyttöasteita vertailemalla saadaan tietoa koko tarkastelalueen käyttöasteen vaihtelevuudesta vuorokauden eri aikoina.

1.3 Laskentavaiheet

1.3.1 Kokonaisminimijunavälin h_A määrittäminen

Rataosan minimijunavälien määrittäminen

Lasketaan aloitetaan määrittämällä rataosan jokaiselle liikenepaikkavälille tunnusomainen minimijunaväli. Minimijunavälin arvo riippuu radan turvalaitteista ja keskimääräisestä liikenteestä. Liikenepaikkavälin i minimijunaväli lasketaan seuraavalla kaavalla:

$$h_i = \frac{n * d * 60 \text{ min/h}}{s}, \text{ missä}$$

h_i [min] liikenepaikkavälin i minimijunaväli

n vakio, joka riippuu liikenepaikkavälillä olevien opastinvälien määristä:

$n = 1$, jos liikenepaikkavälillä on yksi opastinväli

$n = 2$, jos liikenepaikkavälillä on useampi kuin yksi opastinväli

d [km] opastinvälien keskimääräinen pituus liikenepaikkavälillä, joka lasketaan seuraavasti:

$$d = \frac{\text{liikenepaikkavälin i pituus [km]}}{\text{opastinvälien lukumäärä liikenepaikkavälillä } i}$$

s [km/h] liikenepaikkavälin painotettu matkanopeus, joka lasketaan seuraavasti

$$s = \frac{\text{liikenepaikkavälin pituus [km]}}{\text{keskimääräinen matka- aika [h]}}$$

On huomioitava, että jos analysoitavan aikataulun tarkkuustaso on karkea (1 minuutti), laskenta voi johtaa epäluotettaviin tuloksiin silloin, kun liikenepaikkavälit ovat lyhyitä.

Minimijunavälin arvon lisääminen yksittäisille junille

Osana hankearvointia käyttöaste suositellaan laskettavan jokaiselle tunnille erikseen. Kun tarkasteluajankohta on lyhyt, aikataulusta on määritettävä ne junat, jotka kullakin tarkasteluajankohtana analysoidaan. Junien jakaminen eri tarkasteluajankohtiin on erityisen tärkeää silloin, kun tarkasteluaika on lyhyt, jolloin on suuri todennäköisyys, että junat liikennöivät tarkastelalueella vain osittain tarkasteluajankohdan aikana.

Tarkasteltavaksi valitaan jokaisessa osalaskennassa ne junat, jotka lähtevät tarkastelalueella olevalta ensimmäiseltä liikennepaikaltaan tarkasteluajankohdan aikana. Huomaa, että kaksiraiteisilla rataosilla "yksittäisen junan ensimmäinen liikennepaikka" ei tarkoita koko tarkastelalueen ensimmäistä liikennepaikkaa, jos junta ei liikennöi koko tarkastelalueella.

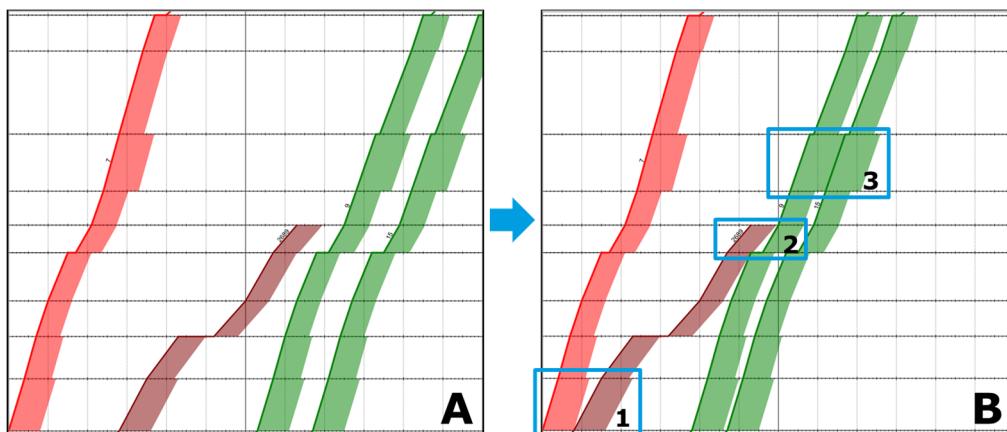
Kun on tunnistettu, mitkä junat analysoidaan kussakin osalaskennassa, jokainen niistä käydään läpi ja tarkistetaan, lisääänkö niille minimijunavälin arvo. Lisääminen riippuu siitä, onko tarkastelalue yksi- vai kaksiraiteinen.

Kaksiraiteisilla rataosilla minimijunavälin arvon lisääminen riippuu tarkasteltavaa junaa seuraavasta junasta. Tarkastelussa kahta peräkkäistä junaa vertailulla etsitään kriittinen liikennepaikkaväli i , jonka tunnusomainen minimi-7 junaväli h_i lisäään laskelmaan tarvittaessa.

Tapaus	Kriittinen liikennepaikkaväli i
Tarkasteltavaa junaa i seuraa itseään hitaampi juna $i+1$ $Ajoaika(juna i) - Ajoaika(juna i + 1) < 0$	Se liikennepaikkaväli, jolla tarkasteltava juna kulkee ensimmäiseksi, muodostuu kriittiseksi
Tarkasteltavaa junaa i seuraa itseään nopeampi juna $i+1$ $Ajoaika(juna i) - Ajoaika(juna i + 1) > 0$	Se liikennepaikkaväli, jolla tarkasteltava juna kulkee viimeiseksi, muodostuu kriittiseksi
Tarkasteltavaa junaa i seuraa vastaavalla nopeudella etenevä juna $i+1$ $Ajoaika(juna i) - Ajoaika(juna i + 1) = 0$	Se liikennepaikkaväli, jonka tunnusomainen minimijunavälin arvo on suurin, muodostuu kriittiseksi

Taulukossa ajoaika kuvailee koko tarkastelalueen läpi kuljemiseen ja väliasemilla pysähdyksiin varattavaa aikaa. Mikäli jompikumpi vertailtavista junista (tarkasteltava juna tai sitä seuraava juna) ei liikennöi koko tarkasteltavan osuuden läpi, ajoaika lasketaan molemmilta junilta vain siltä osuudelta, jonka läpi molemmat junat kulkevat.

Kriittistä liikennepaikkaväliä ja sitä vastaavan minimijunavälin lisäämisen periaate voidaan havainnollistaa graafisesta aikataulusta. Koska käyttöasteen laskenta perustuu aikataulun puristamiseen, ensimmäinen kohta, josta aikatauluviivat koskevat toisiaan, riippuu junaviivojen kulmakertoimien jyrkkyydestä eli junien nopeudesta (kuva 5). Kuvassa vaakaviivat kuvaavat liikennepaikkojen sijainteja.



Kuva 6. Kriittisen liikennepaikkavälin tunnistaminen ja sitä vastaavan minimijunavälin määrittäminen kaksiraiteisella rataosalla havainnollistettuna graafisessa aikataulussa.

Kuvassa 6 graafinen aikataulu A kuvailee tilannetta, jossa on kolme nopeaa matkustajajunaa ja yksi hitaampi tavarajuna. Sama aikataulu on esitetty puristetussa muodossa graafisessa aikataulussa B. Punaista junaa seuraa hitaampi ruskea junta, joten puristettaessa aikatauluviivat koskevat ensin ensimmäisellä asemalla. Siten ensimmäinen liikennepaikkaväli muodostuu kriittiseksi ja sitä vastaava minimijunaväli lisätään laskelmaan. Ruskeaa junaa seuraa nopeampi vihreä junta, ja viimeisestä liikennepaikkavälistä, jolla ruskea junta kulkee, muodostuu kriittinen. Vihreää junaa seuraa vastaanlainen, yhtä nopea toinen vihreä junta. Näitä puristettaessa se liikennepaikkaväli, jolla on suurin minimijunavälin arvo, muodostuu kriittiseksi.

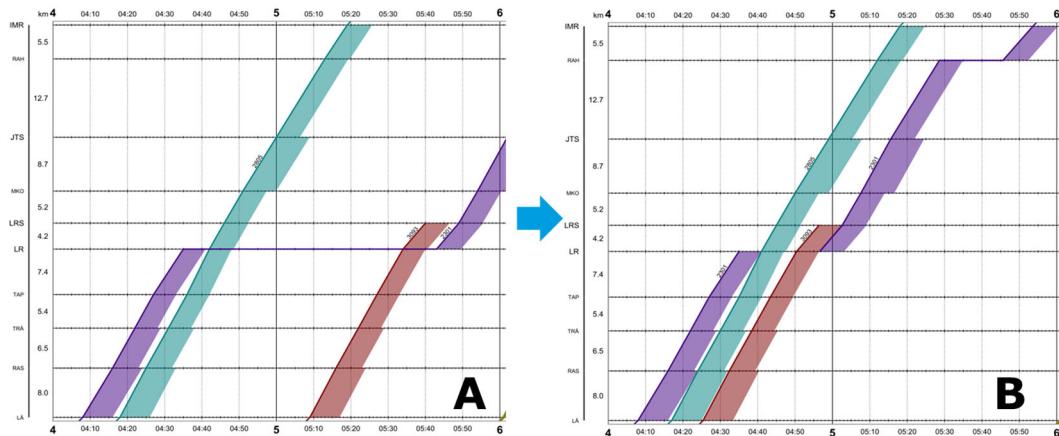
Kaksiraiteilla rataosilla kaikki junat liikennöivät samaan suuntaan ja jokaiselle junalle lisätään minimijunavälin arvo. **Yksiraiteisilla rataosilla** vain samaan suuntaan kulkeville junille lisätään minimijunaväli. Koska yksiraiteiset rataosat analysoidaan yksi liikennepaikkaväli kerrallaan, valitaan aina kyseiselle liikennepaikkavälille määritetty minimijunaväli.

Tapaus	Lisättävä minimijunavälin h_i arvo
Tarkasteltavaa junaa seuraa samaan suuntaan kulkeva junta $i+1$ Suunta(juna i) = Suunta(juna $i + 1$)	Tarkasteltava junta saa kyseisen liikennepaikkavälin minimijunavälin h_i arvon
Tarkasteltavaa junaa seuraa eri suuntaan kulkeva junta $i+1$ Suunta(juna i) ≠ Suunta(juna $i + 1$)	Tarkasteltava junta saa minimijunavälin arvon 0

Sekä yksi- että kaksiraiteilla rataosilla minimijunavälin arvo perustuu tarkasteltavan junan vertailuun sitä seuraavan junan kanssa. Kun tarkastelualueen viimeistä junaa analysoidaan, sitä verrataan seuraavaan junaan, vaikka se ei liikennoisikään tarkasteluajanjaksona. Kun analysoidaan päivän viimeistä junaa, jolle ei ole selkeää seuraavaa junaa, sitä verrataan identtiseen junaan itsensä kanssa.

Kaksiraiteisten rataosien erikoistapaus: ohitustilanteiden huomioiminen

Kun kaksiraiteisilla rataosilla tapahtuu junien ohitustilanne, junia ei voida verrata seuraavaan junaan yhtä yksiselitteisesti. Ohitettu juna jaetaan kahtia ja osia käsitellään itsenäisinä junina. Nopeammat junat analysoidaan normaalisti. Kuvaan 7 on havainnollistettu ohitustilanne, jossa kaksi junaa ohittavat violetin junan. Kuvan mukaisen violetin junan puristaminen voidaan tehdä vain silloin, jos tiedetään, ettei violetti juna tarvitse pitkää pysähdyssaihkaa esimerkiksi vaihtotöiden takia.



Kuva 7. Kaksiraiteisilla rataosilla ohitustilanteiden huomioiminen.

Kokonaisminimijunavälin h_A määrittäminen

Kun kaikille junille on tunnistettu kriittinen liikennepaikkaväli ja sitä vastaava minimijunaväli, kokonaisminimijunaväli voidaan määrittää lisäämällä kaikkien tarkasteltujen junien minimijunavälit yhteen:

$$h_A = \sum_i h_i, \text{ missä}$$

h_A kuvaa skenaarion kokonaisminimiunaväliä. Tämä luku lisätään sellaisenaan kapasiteetin käytöasteen laskentakaavaan. h_i kuvaa yksittäisille junille i määritettyjä minimijunavälin arvoja.

1.3.2 Ajoaikojen eron määrittäminen (t_D)

Ajoaikojen ero yleisesti

Ajoaikojen ero on termi, joka kuvaa lisääikaa, joka tarvitaan, kun hidasta junaa seuraa nopeampi juna. Tällöin nopeampi juna ei voi liikennöidä liikennepaikkaväliä tavoitenopeuttaan. Homogeeninen aikataulu, jossa junat liikennöivät samaan suuntaan yhtäläisellä nopeudella, on vähemmän kuormitetumpi kuin vastaava aikataulu, jossa junat liikennöivät eri nopeuksilla.

Ajoaikojen eron lisääminen yksittäisille junille

Ajoaikojen ero perustuu peräkkäisien junien vertailuun samankaltaisesti kuin minimijunavälien arvoja määritettäessä. Myös vastaavat junat valitaan tarkasteluun: Tarkasteltaviksi juniksi valitaan jokaisessa laskentaskenaariossa ne junat, jotka lähtevät tarkastelualueella olevalta ensimmäiseltä liikennepaikaltaan tarkasteluajankohdan aikana.

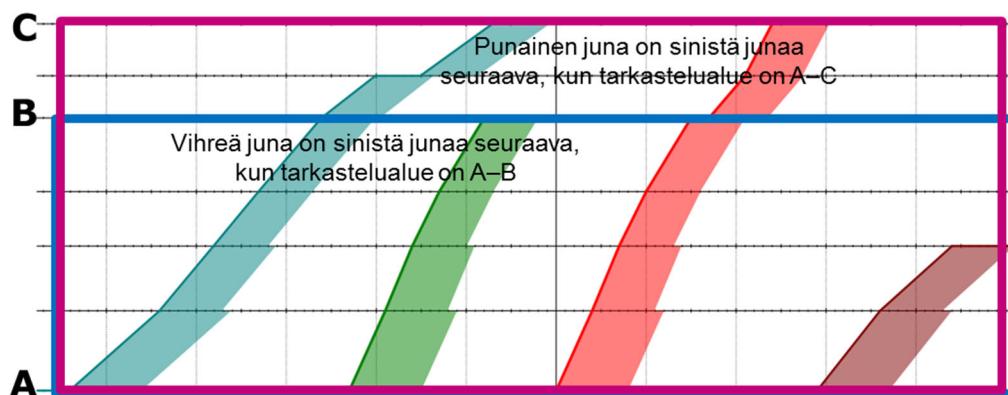
Tarkasteltavat junat käydään yksitellen läpi ja seuraavassa taulukossa esitetyn perusteella niille lisätään tarvittaessa ajoaikojen ero.

Tapaus	Lisättävä ajoaikojen eron arvo
Tarkasteltavaa junaa i seuraa itseään hitaampi tai samalla nopeudella etenevä juna i+1, joka kulkee samaan kulkusuuntaan: Kulkusuunta(juna i) = Kulkusuunta(juna i + 1); Ajoaika(juna i) – Ajoaika(juna i + 1) ≤ 0	0
Tarkasteltavaa junaa i seuraa itseään nopeampi juna i+1, joka kulkee samaan kulkusuuntaan: Kulkusuunta(juna i) = Kulkusuunta(juna i + 1); Ajoaika(juna i) – Ajoaika (juna i + 1) > 0	Tarkasteltavalle junalle lisätään vertailtavien junien ajoaikojen ero: Ajoaika(juna i) – Ajoaika(juna i + 1)
Tarkasteltavaa junaa i seuraa juna, joka etenee eri kulkusuuntaan (tapaus mahdollinen vain yksiraiteisilla rataosilla): Kulkusuunta(juna i) ≠ Kulkusuunta(juna i + 1)	Se osuuus ajoajasta (juna i), jonka juna i viettää tarkasteltavalla liikennepaikkavälillä. *

*) Tarkastelusta riippuen ajoajat joko sisältävät tai eivät sisällä ajoaikojen pelivarjoa

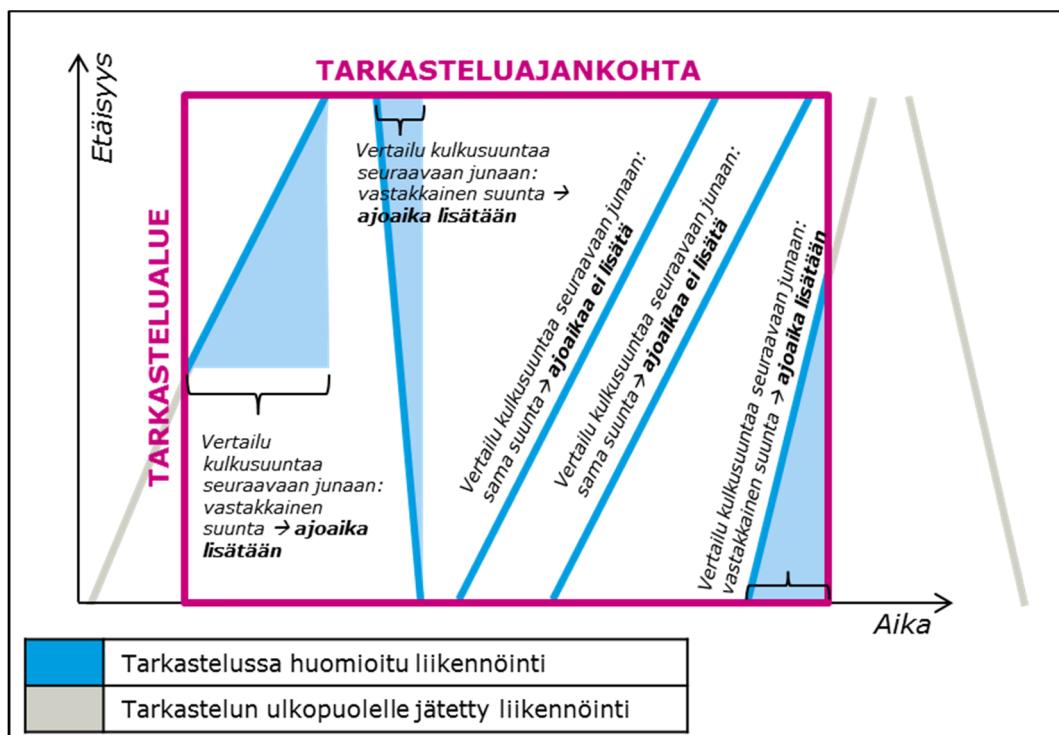
Kun tarkastellaan tarkasteluajanjakson viimeistä junaa, sitä verrataan ensimmäiseen seuraavaan junaan, joka on tarkastelujakson ulkopuolella. Kun analysoidaan päivän viimeistä junaa, jolle ei ole selkeää seuraavaa junaa, sitä verrataan identtiseen junaan itsensä kanssa.

Kaksiraiteisten rataosien laskennassa, jossa tarkastelualue voi kattaa useamman liikennepaikkavälin, on tyypillistä, etteivät kaikki tarkasteltavat junat liikenöi koko tarkastelualueen läpi. Näissä tapauksissa seuraavalla junalla tarkoitetaan tarkastelualueen viimeisellä välillä seuraavaa junaa. Kuvassa 8 on havainnollistettu esimerkki, jossa sinistä junaa seuraa vihreä juna liikennepaikkavälillä A-B ja punainen juna liikennepaikkavälillä B-C. Tarkasteltavasta skenaariosta riippuen molemmat (punainen ja vihreä) voivat olla "seuraavia junia": jos tarkastellaan käyttöästetä tarkastelualueella A-B, vihreä juna luetaan "seuraavaksi junaksi". Toisaalta, jos skenaario kattaa koko rataosan A-C, sinistä junaa on verrattava punaiseen junaan.



Kuva 8. Ajoaikoja lisättääessä tarkasteltavaa junaa verrataan seuraavaan junaan.

Eri suuntiin kulkevien junien tapauksessa lisättävää aikaa on havainnollistettu kuvassa 9.



Kuva 9. Yksiraiteisella rataosalla kulkuteiden vapautumisiin kuluvan ajan lisäämisen periaate havainnollistettuna graafisessa aikataulussa.

Ajoaikojen kokonaiseron t_D määrittäminen

Kun kaikille junille on määritetty ajoaikojen ero, ajoaikojen kokonaisero voidaan määrittää summaamalla arvot yhteen:

$$t_D = \sum_i t_i, \text{ missä}$$

t_D kuvailee ajoaikojen kokonaiseroa ja t_i kuvailee tarkasteltaville junille lisättyjä ajoaikojen eroja. Ajoaikojen kokonaiseron arvo lisätään sellaisenaan kapasiteetin käyttöasteen kaavaan.

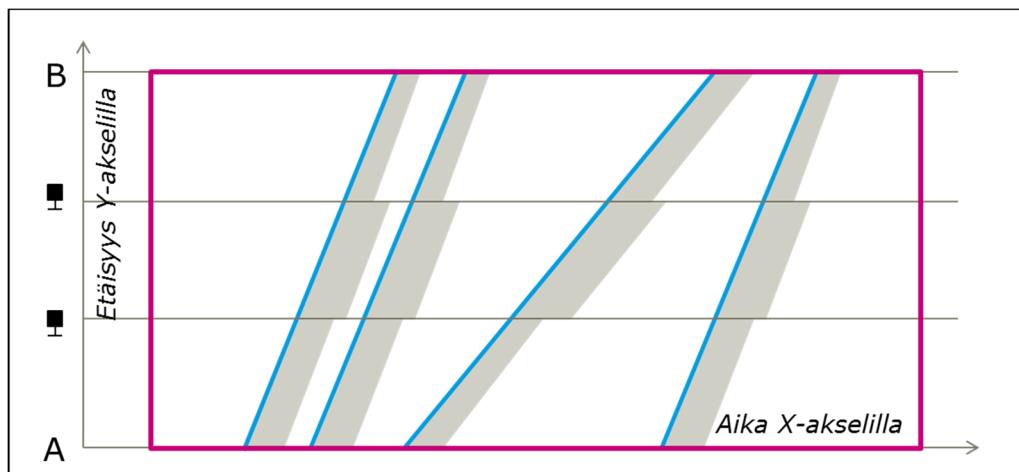
1.3.3 Ensimmäisen mahdollisen lähtöajan t_{EPD} määrittäminen

Ensimmäinen mahdollinen lähtöaika on kaksiraiteisilla rataosilla lisättävä termi, joka kuvailee vain osittain tarkasteltavalla rataosalla liikennöivien junien vaikuttusta tarkasteluajankohdan käyttöoesteeseen. Nämä "osittaiset junat" liikennöivät tarkastelalueella ennen tarkasteluajankohdan alkua ja pääsevät perille tarkasteluajankohdan aikana. Niille ei lisätä minimijunavälin tai ajoaikojen eroa muiden junien kaltaisesti.

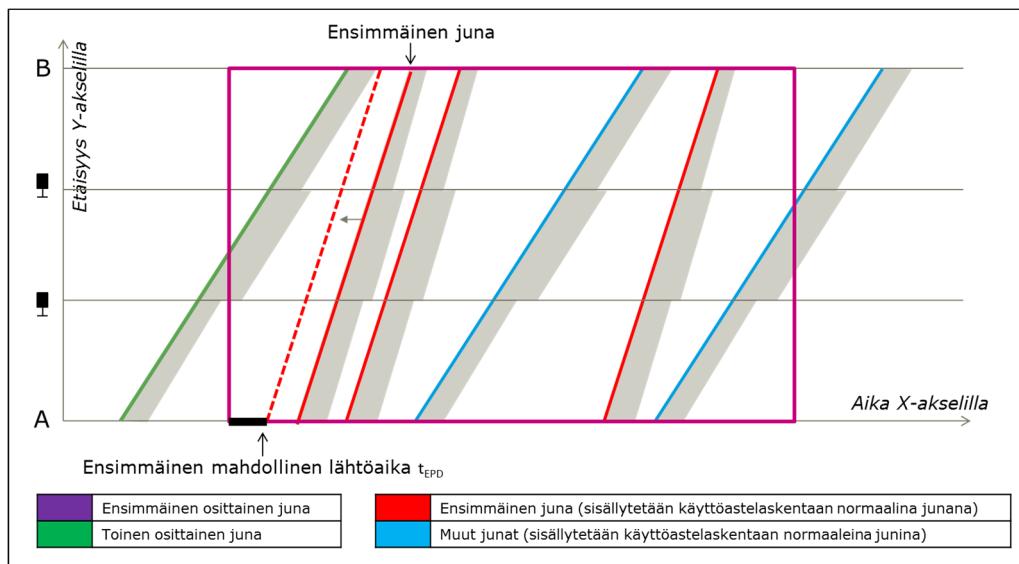
Ensimmäisen mahdollisen lähtöajan lisääminen riippuu siitä, miten junat on suunniteltu liikennöivän tarkasteluajankohdan aikana:

Tapaus	Tapauksen kuvaus ja lisättävä ensimmäisen mahdollisen lähtöajan arvo
Kaksiraiteinen rataosa, ei osittaisia junia (kuva 10)	Kaikki junat lähtevät ensimmäiseltä asemaltaan vasta tarkasteluajankohtana tai pääsevät perille viimeiselle asemalleen ennen tarkasteluajankohdan alkua $t_{EPD} = 0$
Kaksiraiteinen rataosa, yksi osittainen junta (kuva 11)	Tarkasteluajankohtana on yksi sellainen junta, joka lähtee ensimmäiseltä asemaltaan ennen tarkasteluajankohdan alkamista, mutta saapuu viimeiselle asemalleen vasta tarkasteluajankohdan alettua $t_{EPD} =$ osittaisen junan saapumisaika viimeiselle asemalle + minimijunaväli viimeiseltä liikenepaikkaväliltä – ensimmäisen tarkasteluajankohtana lähtevän junan ajoaika – tarkasteluajankohdan alkamisen ajankohta jos t_{EPD} saa negatiivisen arvon, sille annetaan lukuarvoksi 0.
Kaksiraiteinen rataosa, kaksi tai useampi osittainen junta (kuva 12)	Tarkasteluajankohtana on kaksi tai enemmän sellaista junaa, jotka lähtevät ensimmäiseltä asemaltaan ennen tarkasteluajankohdan alkamista, mutta saapuvat viimeiselle asemalleen vasta tarkasteluajankohdan alettua. Vain viimeisen osittaisista junista huomioidaan. Junalle lisätään ensimmäisen mahdollisen lähtöajan arvo kuten yllä.
Kaksiraiteinen rataosa, yksi tai useampi osittainen junta liikennöi koko tarkastelalueen läpi (kuva 13)	Tarkasteluajankohtana on yksi tai useampi sellainen junta, jotka lähtevät ensimmäiseltä asemaltaan ennen tarkasteluajankohdan alkamista, mutta saapuvat viimeiselle asemalleen vasta tarkasteluajankohdan päätyttyä $t_{EPD} =$ tarkasteluajankohdan pituus (tyypillisesti 60 min). Näissä tapauksissa kapasiteetin käyttöaste on kyseiselle tarkastelualulle aina 100%.
Yksiraiteinen rataosa	$t_{EPD} = 0$

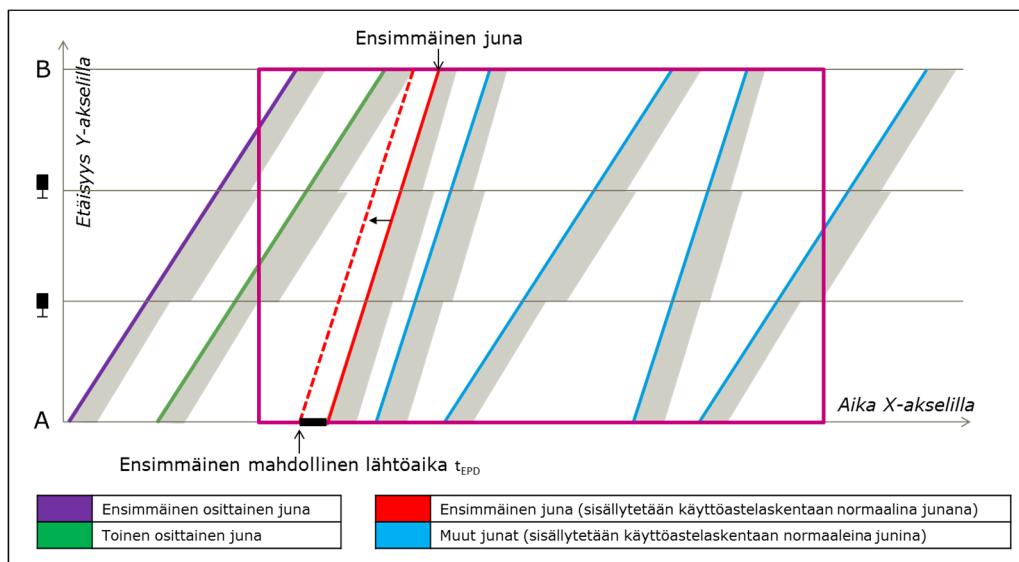
Jokaisen taulukossa kuvatun tapauksen esimerkit on havainnollistettu kuvissa 10–13.



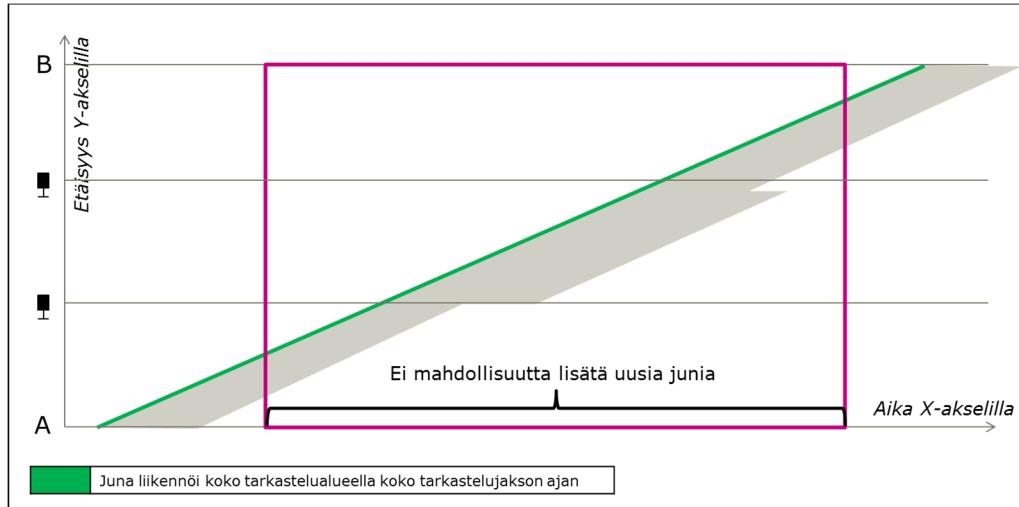
Kuva 10. Esimerkki graafisesta tarkasteluajankohdasta ja -alueesta, jossa ei ole yhtään osittaista junaa.



Kuva 11. Esimerkki graafisesta tarkasteluajankohdasta ja -alueesta, jossa on yksi osittainen junta.

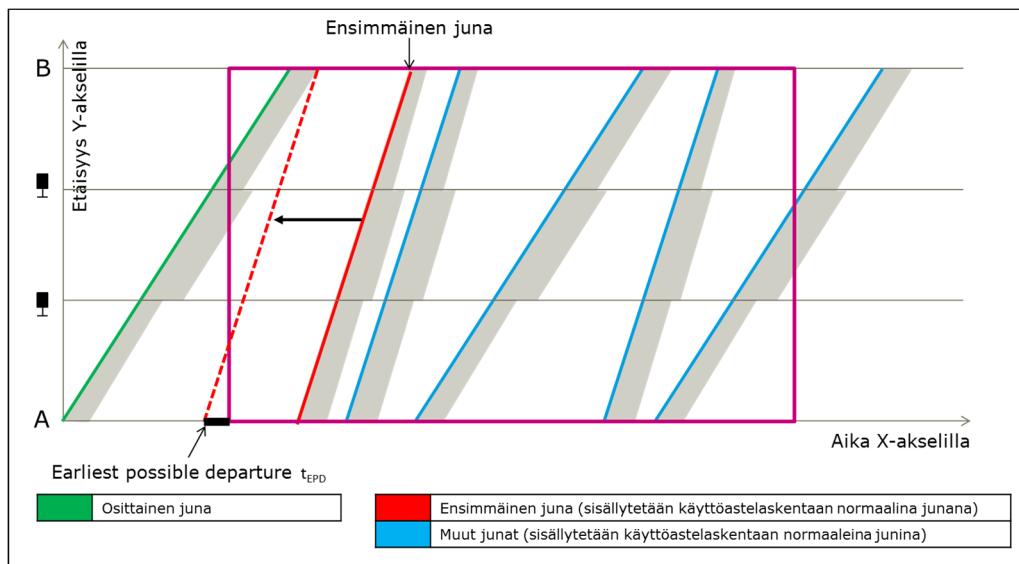


Kuva 12. Esimerkki graafisesta tarkasteluajankohdasta ja -alueesta, jossa on kaksi osittaista junaa.



Kuva 13. Esimerkki graafisesta tarkasteluajankohdasta ja -alueesta, jossa osittainen junan liikennöi koko tarkasteluajankohdan läpi.

Liikennöinnistä riippuen ensimmäinen mahdollinen lähtöaika voi saada myös negatiivisen arvon (kuva 14). Näissä tapauksissa arvoksi annetaan 0.



Kuva 14. Esimerkki graafisesta tarkasteluajankohdasta ja -alueesta, jossa ensimmäinen mahdollinen lähtöaika saa negatiivisen arvon.

1.3.4 Ratatyövarausten t_M määrittäminen

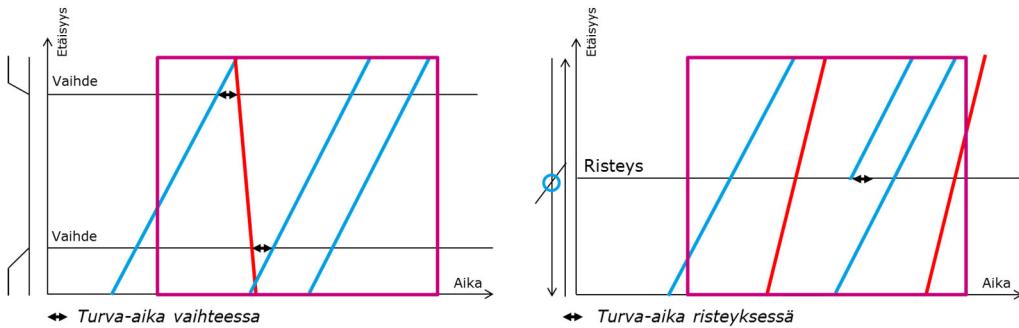
Osaan aikatauluista on voitu erikseen määrittää ratatyövaraukset tai vaihtotyöhön kuluva aika. Näissä tapauksissa varaukset otetaan huomioon samalla ohjeilla kuin muutkin junat. Jos aikatauluun ei ole erikseen kirjattu ratatyövaraauksia tai vaihtotyötä, mutta niiden vaatima aika on tiedossa, ne voidaan huomioida tarkastelussa yksinkertaisesti lisäämällä vaadittu määrä minuutteja:

$$t_M = \text{Ratatyöihin tai vaihtotyöihin varattu minuuttimäärä tarkasteluajankohtana}$$

1.3.5 Kulkuteiden vapautumisten turva-aikojen määrittäminen t_s

Raiteistosta, käytettävistä turvalitteista ja asetinlaitteesta riippuen joillain asemilla kaksi junaa ei voi saapua asemalle samanaikaisesti. Tällaisissa tapauksissa ensimmäinen junta saattaa joutua odottamaan ennen kuin toinen kulkutie voidaan varmistaa. Joidenkin liikenepaikkojen osalta turva-ajat on ilmoitettu Väyläviraston ylläpitämässä Viriato-master data -tietokannassa¹. Jos tarkkaa tietoa ei ole saatavissa, turva-aikojen vakioarvona voidaan käyttää 60 sekuntia.

Vaihteiden turva-ajat on lisättävä yksiraiteisilla rataosilla silloin, kun kaksi junaa kohtaa kohtauspaikalla tai kaksiraiteisilla rataosilla ohittavat toisensa (kuva 15, vasen puoli). Junaristeystilanteissa turva-aika lisätään vastakkaisen raiteen käyttöästeeseen (kuva 15, oikea puoli, havainnollistettu sinisellä ympyrällä).



Kuva 15. Vasen: vaihteen turva-ajan lisäämisen tarve havainnollistettu graafisessa aikataulussa. Oikea: risteyksen turva-ajan lisäämisen tarve havainnollistettu graafisessa aikataulussa.

Turva-ajan lisäämisen tarve tarkistetaan jokaisen junan osalta yksitellen. Kapasiteetin käyttöästeen kaavaan lisätään tarvittavien turva-aikojen summa:

$$t_s = \text{vaihteiden ja risteysten turva-aikojen summa tarkasteluajankohdan aikana}$$

1.3.6 Osalaskennan kapasiteetin käyttöästeen määrittäminen

Kun kappaleissa 1.3.1–1.3.6 esitettyt termit on määritetty, ne lisätään kapasiteetin käyttöästeen laskentakaavaan:

$$K = \frac{h_A + t_D + t_{EPD} + t_M + t_s}{T}, \text{ missä}$$

K Kapasiteetin käyttöäste [%]

T Tarkasteluajanjakso [min]

h_A Kokonaisminimijunaväli [min]

t_D Ajoaikojen kokonaisero [min]

t_{EPD} Ensimmäinen mahdollinen lähtöaika verrattuna tarkasteluajanjakson alkuun kaksiraiteisilla rataosilla [min]

t_M Ratatyövaraus [min]

t_s Turva-ajat kulkuteiden vapautumiselle [min]

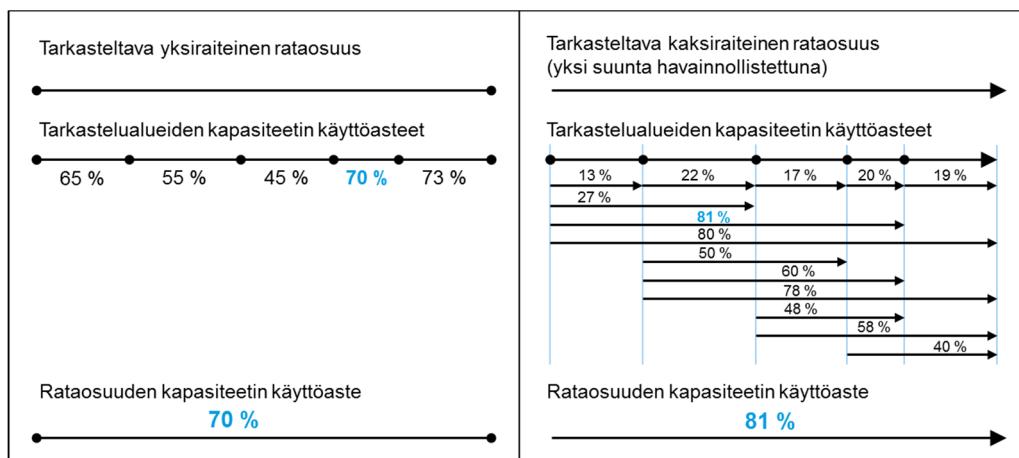
¹ Viriato on Suomessa yleisesti käytetty raideliikenteen aikataulujen suunnitteluhjelmisto.

Laskentakaava antaa tulokseksi, kuinka suuri prosentuaalinen osuuus tarkastelualueen kapasiteetista on käytössä tarkasteluajankohdalla. Seuraavassa kappaleessa kuvataan, miten tuloksia voidaan tulkita verrattaessa eri tarkasteluajankojen ja -kohtien käyttöasteita.

1.4 Laskentatulosten tulkinta ja johtopäätökset

1.4.1 Tarkastelalueiden kuormitusten vaikutus koko rataosan käyttöasteeseen

Koko rataosuuden kuormittuneisuutta voidaan arvioida eri tarkastelalueiden käyttöästelukujen perusteella. Yksiraiteisilla rataosilla koko rataosan käyttöaste on sama kuin kuormitetuimman tarkastelalueen (liennepaikkavälin) käyttöaste (kuva 16, vasen). Kaksiraiteisilla rataosilla koko rataosan käyttöaste on sama kuin kuormitetuimman liennepaikkavälin käyttöaste (kuva 16, oikea). Kaksiraiteisilla rataosilla eri kulkusuunnat tarkastellaan erillisinä kokonaisuksinaan.



Kuva 16. Tarkasteltavan rataosuuden kapasiteetin käyttöasteen määrittäminen liennepaikkavälien ja liennepaikkaväliyhdistelmien käyttöästelukujen perusteella.

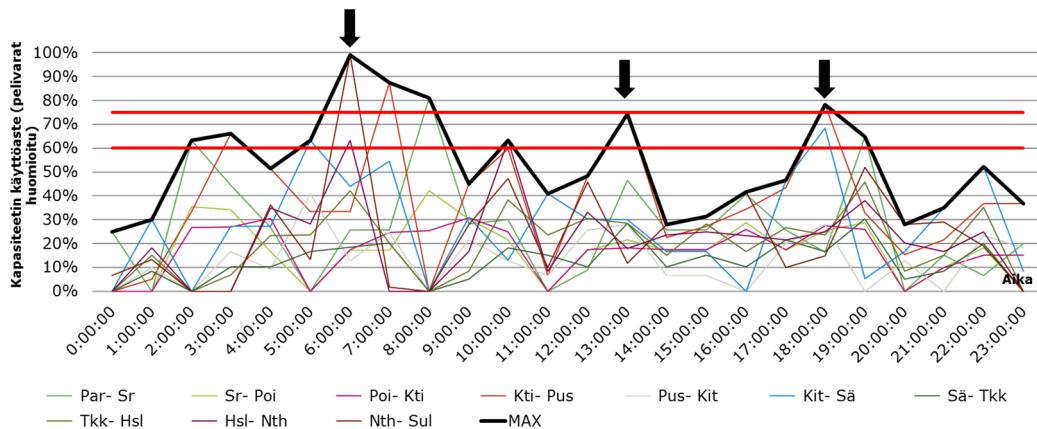
1.4.2 Kapasiteetin käyttöasteen vaihtelu eri vuorokaudenaikoina

Kun kapasiteetin käyttöasteen luvut on määritetty pelivaroineen ja ilman pelivaroja kaikille tarkasteluajankohdille, voidaan muodostaa kokonaiskäsitys käyttöasteen vaihtelevuudesta eri vuorokaudenaikoina. On tyypillistä, että käyttöasteessa on esimerkiksi aamu- ja iltahuipputunnin aikana kuormitushuippuja.

UIC on määrittänyt kapasiteetin raja-arvoiksi seuraavassa taulukossa esitetyt luvut (UIC 2013):

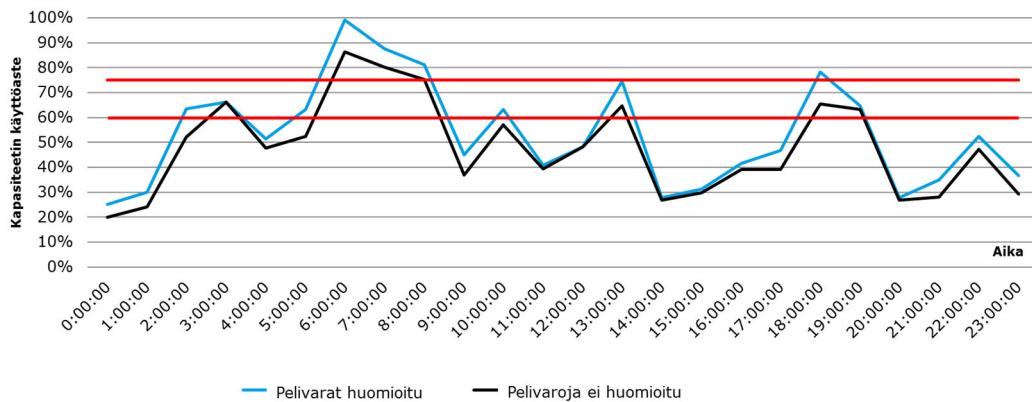
Rataosuuden typpi	Ruuhkahuippu	Vuorokauden kesiarvo
Kaupunkirata (valtaosa lähijunia)	85 %	70 %
Suurnopeusrata	75 %	60 %
Sekaliikennerata	75 %	60 %

Eri ajankohtien kapasiteetin käyttöästeluvut voidaan havainnollistaa esimerkiksi kuvan 17 mukaisessa kaaviossa. Kuvassa havainnollistetaan käyttöasteen vaihtelevuutta yhden vuorokauden aikana Joensuu–Parikkala Sulkulahti -rataosalla. Värilliset viivat kuvaavat jokaisen tarkastelualueen liikennepaikkavälin käyttöästettä ja musta viiva kuvailee suurinta havaittua käyttöästettä. Rataosalla käyttöaste kohoa kolme kertaa 75 % rajan ylitse, mutta koko päivän keskiarvo pysyy kuitenkin 60 % alapuolella. Kuormituspiikit lisäävät viiveiden todennäköisyyttä etenkin ensimmäisessä piikissä, joka kestää kolme tuntia. Jos liikenteen näkökulmasta on mahdollista, aikataulua suunnitellaan tasoittamaan siten, että kuormituspiikit tasoittuvat.



Kuva 17. Kapasiteetin käyttöästeen vaihtelevuus eri vuorokaudenaikoina.

Kuvassa 17 kuvattiin kapasiteetin käyttöaste vain tilanteessa, jossa pelivarat on sisällytetty. Kun pelivarajoja ei huomioida, käyttöaste laskee 0–10 prosenttiyksikön verran (kuva 18, havainnollistamisen vuoksi vain suurimmat havaitut käyttöästeluvut ilmoitettu).



Kuva 18. Pelivarojen vaikutus kapasiteetin käyttöästeeseen.

Lähteet

Landex, A., 2008. *Methods to estimate railway capacity and passenger delays*, Copenhagen: Technical University of Denmark.

UIC, 2013. *UIC Code 406*, Paris: International Union of Railways.

Laskentaohjeistus täsmällisyden arvointiin hankearvioinnissa

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1.1 Yleistä laskentamenetelmistä

Laskentamenetelmien kuvaus ja lähtötiedot

Ratahankkeiden hankearvioinneissa hankkeiden vaikutukset täsmällisyteen arvioidaan junien keskimääräisen viivästymisen avulla. Viive tarkoittaa keskimääräistä myöhästymistä, jolla junat poistuvat tarkasteltavalta rataosalta. Viive ilmoitetaan yksikössä sekuntia/juna/vuorokausi.

Rataosalla liikennöivien junien viiveisiin vaikuttavat eri asiat riippuen raiteiden määrästä. Yksiraiteisella rataosalla suurin viiveitä aiheuttava tekijä on junakohtaukset. Eri suuntiin liikennöivät junat ovat siten vuorovaikutuksessa keskenään. Rataosalta poistuvien junien viivästymisen määrään vaikuttaa lisäksi se viive, jolla junat ovat alun perin saapuneet tarkasteltavalalle rataosuudelle.

Kaksiraiteisella rataosalla eri suuntien junat eivät pääsääntöisesti ole vuorovaiatuksessa keskenään, joen niitä pitää tarkastella omina kokonaisuuksinaan. Kaksiraiteisella rataosalla viiveitä syntyy tilastollisesti eniten silloin kuin peräkkäisillä junilla on lyhyt junaväli. Kaksiraiteisilla rataosilla aikatauluihin suunniteltujen pelivarojen suuruudella on suuri vaikutus: suuri pelivara vaikuttaa myönteisesti viiveiden kehitykseen rataosalla. Kuten yksiraiteisilla, myös kaksiraiteisilla junien saapumisviiveet tarkastelualueelle vaikuttavat myöhästymisen määrään. Kaksiraiteisilla rataosilla myös etuajassa liikennöivät junat vaikuttavat täsmällisyteen.

Mainituista eroista johtuen viiveiden arvioiminen yksi- ja kaksiraiteisilla rataosilla vaatii kaksi erillistä laskentamenetelmää. Molempien menetelmien vaativat lähtötiedot on kuvattu seuraavassa taulukossa 1 ja laskentaohjeistukset reportin seuraavissa kappaleissa 1.2 ja 1.3.

Taulukko 1. Viivelaskennan lähtötietovaatimukset ja lähtötietojen kuvaukset yksi- ja kaksiraiteisten rataosien viivelaskennassa.

Lähtötieto	Lähtötiedon kuvaus	Lähtötietovaade	
		Yksiraiteinen rataosa	Kaksiraiteinen rataosa
Suunniteltu aikataulu	Aikataulu, jossa kuvataan lähtö-, saapimus-, ajo- ja pysähdyssajat liikennepaikkaleittäin.	X	X
Suunniteltu aikataulu graafisessa muodossa	Graafista aikataulua tarvitaan junakohtausten määrän määrittämiseen yksiraiteisilla rataosilla. Aikataulun voi tuottaa esimerkiksi Viriato-aikataulusuunnitteluohejelmalla.	X	
Opastinvälien määrät	Opastinvälien lukumäärä vaikuttaa junien minimijunaväliin saaman suuntaan kulkeville junilla.		X
Saapumisviive	Tutkitulle rataosalle määritetyt keskimääräiset saapumisviiveet yksikössä sekuntia/juna/vuorokausi arviodaan tutkitun rataosan historiatietojen tai vastaan rataosan mitatun datan perusteella.	X	X

Laskentamenetelmien soveltuvuus ja rajoitteet eri hankearvointitapauksissa

Sekä yksi- että kaksiraiteisten rataosien laskentamenetelmien avulla määritetyt viiveet riippuvat suunnitellusta aikataulusta, minkä takia menetelmät soveltuват vain sellaisiin hankearvointitapauksiin, joilla on vaikutusta rataosan aikatauluun. Vaikutukset voivat liittyä esimerkiksi junien ajonopeuksiin tai junien ja junakohtausten lukumäärään. Jos investoinilla on selkeä vaikutus rataosille saapuvien junien viiveisiin, esimerkiksi yksiraiteisen rataosan muuttuessa kaksiraiteiseksi, jolloin junakohtauksista aiheutuvat viiveet poistuvat, myös saapumisviiveet voivat muuttua.

Laskentamenetelmät soveltuват hankearvointitapauksiin, joissa nostetaan nopeusrajoitusta tai lisätään välisuojastuspisteiden määrää. Toisaalta menetelmien soveltuvuus kohtauspaikkojen vaikutusten arvointiin ei ole yksiselitteistä: jos uusia kohtauspaikkoja suunnitellaan käytettävän perusliikenteessä, jolloin ne vaikuttavat aikatauluun, menetelmiä voidaan hyödyntää. Toisaalta jos uusia kohtauspaikkoja suunnitellaan käytettävän vain häiriötilanteissa, jolloin ne eivät vaikuta suunniteltuun aikatauluun, laskentamenetelmiä ei voida hyödyntää.

Laskentamenetelmien muut huomiot

Laskentamenetelmän valinta, jos rataosa on osittain yksi- ja osittain kaksiraiteinen

Jos osana hankearvointia halutaan tarkastella tilannetta, jossa osa rataosasta on yksiraiteinen ja osa kaksiraiteinen, laskenta tulee tehdä kahdessa osassa. On kuitenkin huomioitava, että menetelmät on sovellettu suppeisiin tarkastelualueisiin (vain muutama asema/kohtauspaikka). Etenkin kaksiraiteisten menetelmä, joka perustuu peräkkäin kulkevien junien vuorovaikutukseen, ei kykene havaitsemaan täsmällisyyden vaikutusta, jos tarkasteltava rataosa on lyhyt (alle 4 liikenepaikkaa).

Rajoitteen takia sellaiset tarkastelalueet, jotka koostuvat suurimmaksi osaksi yhdestä raiteesta ja vain lyhyeltä matkalta kahdesta raiteesta, suositellaan analysoitavan kokonaan yksiraiteisella menetelmällä. Yksiraiteisen menetelmän yksi lähtötiedoista on junakohtausten määrä, kuten kappaleessa 1.2 esitetään tarkemmin, ja tällöin yksinkertaisesti jätetään junakohtaukset kaksiraiteiselta osalta analysoimatta.

Laskentamenetelmien kehitystyössä käytettyjen työkalujen vaikutus

Laskentamenetelmien kehitystyössä on hyödynnetty vahvasti Trenolabin kehitämää TRENO-ohjelmistoa, joka soveltuu junien liikennöintidatan analysoimiseen ja aikataulusuunnitteluun. Etenkin kaksiraiteisten rataosien laskentamenetelmässä TRENO-ohjelman vaikutus on kuitenkin havaittavissa laadittavien lähtötiedostojen ulkoasussa. Kehitetyt menetelmät eivät ole riippuvaisia ohjelmistosta, ja kaikki laskentavaiheet voidaan suorittaa taulukkolaskentaohjelman avulla.

1.2 Yksiraiteisten rataosien viivelaskenta

Tarkastelalueen keskimääräinen viive kuvailee, kuinka paljon rataosalta lähtevä junta on keskimäärin myöhässä. Yksiraiteilla rataosilla viiveiden laskemiseen tarvitaan vain kaksi lähtötietoa: tarkasteltavan rataosan suunniteltu aikataulu ja tarkastelalueelle saapuvien junien keskimääräinen myöhästyminen.

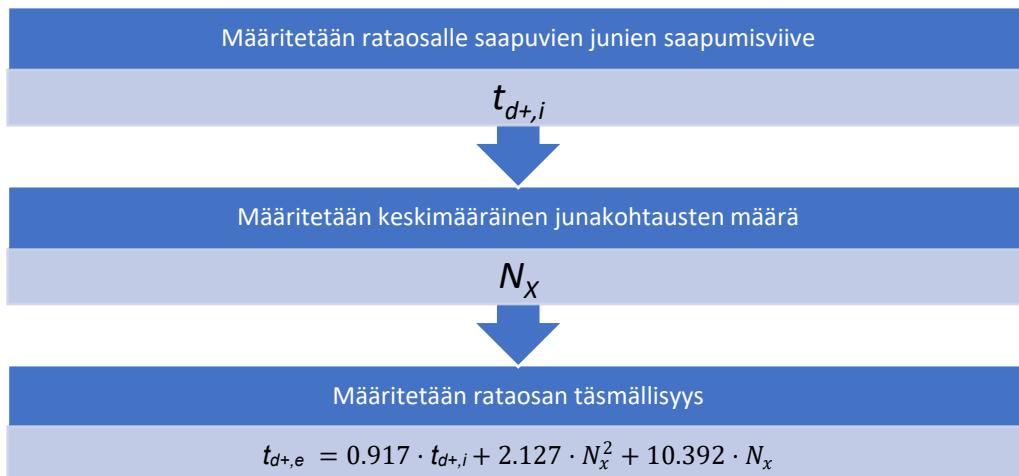
Viive lasketaan lisäämällä termit $t_{d+,i}$ ja N_x seuraavaan kaavaan:

$$t_{d+,e} = 0.917 \cdot t_{d+,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x, \text{ missä}$$

$t_{d+,e}$	kuvailee junien täsmällisyyttä niiden lähtiessä pois tarkastelalueelta [s/juna/vrk],
$t_{d+,i}$	kuvailee myöhästyneiden junien täsmällisyyttä niiden saapuessa tarkastelalueelle [s/juna/vrk] ja
N_x	kuvailee, kuinka monta junakohtausta keskimäärin rataosalla koetaan.

Kaava antaa tulokseksi kaikkien junien keskimääräisen myöhästymisen määrän yksikössä sekuntia/juna/vuorokausi.

Laskennan vaiheet on esitetty kaaviomuodossa kuvassa 1.



Kuva 1. Yksiraiteisen rataosan viivelaskennan työvaiheet.

Viivelaskenta yksiraiteisilla rataosilla ottaa molempien kulkusuuntien junat huomioon, eli yksittäisen rataosan tarkastelu vaatii vain yhden laskutoimituksen (vrt. kaksiraiteinen rataosa, jonka molemmat kulkusuunnat ovat omia kokonaisuuksia).

Saapumisviiveen $t_{d+,i}$ määrittäminen

Saapumisviiveet määritetään kyseisen rataosan historiadataan tai arviodun tullevan täsmällisyystiedon perusteella. Saapumisviiveen määrittämisessä huomioidaan vain myöhässä olevat junat. Jos historiadataa ei ole saatavilla, saapumisviivettä voidaan arvioida alla olevassa taulukossa ilmoitettujen lukujen avulla. Taulukon luvut kuvavat kevään 2018 toteutuneita täsmällisyyksiä.

Taulukko 2. Esimerkkilukuja saapumisviiveistä valikoiduilla suomalaisilla rataosilla (kevät 2018).

Rataosa	Saapumistäsmällisyys $t_{d+,i}$ [s/juna/vrk]	
	Matkustajajunat	Tavarajunat
Kirkkonummi-Turku	112	-
Turku-Toijala	184	165
Luumäki-Imatra	367	607
Kouvola-Pieksämäki	313	746
Lielahdi-Pohjois-Louko	234	556
Seinäjoki-Vaasa	181	-
Ylivieska-Iisalmi	267	509
Parikkala-Joensuu	211	560
Oulu-Kontiomäki	312	722

Viivelaskennassa otetaan huomioon kaikkien junien keskimääräinen viive. Se määritetään matkustaja- ja tavarajunien viiveiden painotettuna keskiarvona:

$$\frac{t_{d+i}}{\text{Kaikkien junien lkm}} = \frac{\text{matkustajajunien lkm} * t_{d+i}(\text{matkustajajunat}) + \text{tavarajunien lkm} * t_{d+i}(\text{tavarajunat})}{\text{Kaikkien junien lkm}}$$

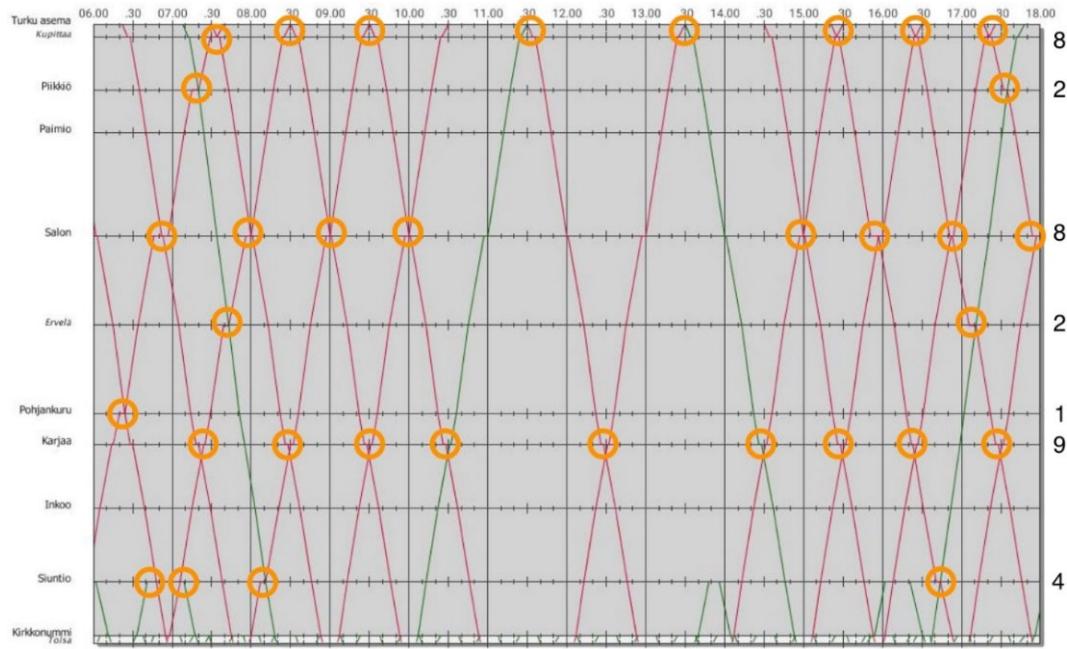
Lähtöoletuksena on, että yllä olevalla kaavalla määritetty saapumisviive syöttääni sellaisenaan sekä vertailu- että hankearvioinnin vaihtoehtojen laskelmiin. Tällöin saapumisviive on yhtäläinen kaikissa vaihtoehdissa ja hankearvioinnin myötä täsmällisyyteen vaikutetaan vain muuttuneen junakohtausten määrän avulla. Joissain tapauksissa voidaan kuitenkin selkeästi todeta, että investoinnilla on vaikutusta myös sen ulkopuolella tapahtuviin täsmällisyyspoikkeamiin. Näissä tilanteissa saapumistäsmällisyyttä voidaan muokata arviontujen vaikuttosten mukaisesti. Kuvattuja erikoistapauksia ovat esimerkiksi seuraavat hankearvointitapaukset:

- Hankearvioinnissa yksiraiteinen rataosa rakennetaan kokonaan kaksiraitiseksi. Hankearvioinnin vertailuvaihtoehdossa lähtötiedoksi valitaan ylläolevan taulukon mukainen saapumisviive, mutta kaksiraiteisen rataosan tilanteesta ei ole etukäteen tietoa. On kuitenkin tiedossa, että saapumistäsmällisyys paranee ainakin siksi, että kaksiraiteisilla rataosilla ei synny junakohtauksista aiheutuvia viiveitä.
Saapumisviiveen arvioiminen hankevaihtoehdossa: Nykytilan junakohtauksista aiheutuvien viiveiden suhteellinen määrä voidaan selvittää sykoodidatan avulla, ja vähentää vastaava suhteellinen määrä saapumistäsmällisydestä.
- Hankkeen seurauksena rataosan tavarajunat liikennöidään muita reittejä pitkin. Tässä tapauksessa muuttunut liikenekoostumus vaikuttaa keskimääräiseen saapumisviiveeseen. Keskimäärin tavarajunat liikennöivät matkustajajunia epätäsmällisemmin, jolloin tavarajunien määrän vähentyminen vähentää keskimääräistä saapumisviivettä.
Saapumisviiveen arvioiminen hankevaihtoehdossa: Saapumisviive määritetään yllä olevan kaavan avulla erikseen jokaiselle vaihtoehdolle.

Keskimääräisen junakohtausten määrän N_x määrittäminen

Keskimääräinen junakohtausten lukumäärä tarkoittaa, kuinka monta kertaa tar- kasteltavalla rataosalla keskimääräisesti yksittäinen juna risteää muiden junien kanssa. Junakohtausten lukumäärä voidaan määrittää graafisesta aikataulusta, joka voidaan tuottaa esimerkiksi Viriato-aikataulusuunnitteluoohjelmalla. Junakohtaukset lasketaan sekä tarkasteltavan rataosan pääteasemilta että väliasemilta. Jos junta ohitetaan kohtauspaikalla kahdesti, molemmat kohtaukset lasketaan. Kuvan 2 graafisessa aikataulussa on yhteensä 34 junakohtausta (havainnollistettu oransseilla ympyröillä).

Junien kokonaismäärä voidaan laskea joko graafisesta tai numeerisesta aikataulusta. Junien lukumäärään lasketaan kaikki junat molempiin kulkusuuntiin, myös ne, jotka liikennöivät vain osalla tarkasteltavan rataosan liikennepaikkaväleistä.



Kuva 2. Junien ja junakohtausten määrittäminen graafisesta aikataulusta.

Keskimääräinen junakohtausten määrä N_x voidaan laskea junakohtausten ja junien kokonaismäärän suhteessa seuraavasti

$$N_x = \frac{\text{junakohtausten lkm yhden vuorokauden aikana}}{\text{junien lkm yhden vuorokauden aikana}}$$

Junakohtausten määrällä N_x ei ole yksikköä.

Keskimääräisen viiveen määrittäminen

Termien N_x ja $t_{d+,i}$ määrittämisen jälkeen ne voidaan syöttää yksiraiteisen rataosan viiveiden laskentakaavaan:

$$t_{d+,e} = 0.917 \cdot t_{d+,i} + 2.127 \cdot N_x^2 + 10.392 \cdot N_x$$

Kaava antaa tulokseksi kaikkien junien keskimääräisen myöhästymisen määrän yksikössä s/juna/vuorokausi.

1.3 Kaksiraiteisten rataosien viivelaskenta

Kaksiraiteisilla rataosilla viiveiden laskemiseen tarvitaan neljä tekijää, jotka kuvaavat suunnitellun aikataulun häiriöherkkyyttä ja pelivaraa sekä rataosalle saapuvien junien keskimääräistä viivettä ja etuajassa oloa. Viiveiden laskenta kaksiraiteisilla rataosilla vaatii monimutkaisempien laskentatoimitusten laatimista kuin yksiraiteisilla rataosilla. Tämän takia laskennan tueksi on laadittu laskentaohjelma, johon syötetyt lähtötiedot tekevät monimutkaisimmat laskentavaiheet automaattisesti.

Viive lasketaan syöttämällä laskentaohjelman laatimat termit $\sum_{b \in B} (w(b) \cdot b f_g^b)$ ja $t_{mr,g}$, sekä käyttäjän määrittämät termit $t_{d+,i}$ ja $t_{d-,i}$ seuraavaan kaavaan:

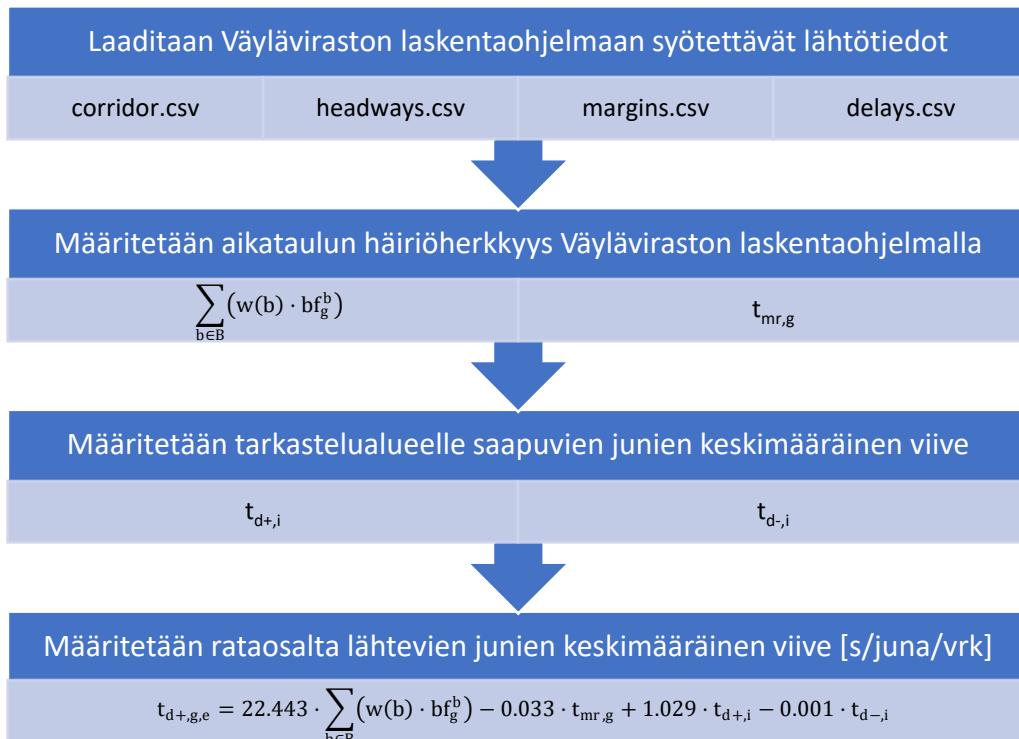
$$t_{d+,g,e} = 22.443 \cdot \sum_{b \in B} (w(b) \cdot b f_g^b) - 0.033 \cdot t_{mr,g} + 1.029 \cdot t_{d+,i} - 0.001 \cdot t_{d-,i}$$

missä

- $\sum_{b \in B} (w(b) \cdot b f_g^b)$ kuvaa suunnitellun aikataulun häiriöherkkyyttä,
- $t_{mr,g}$ kuvaa aikatauluun sisällytettyä pelivaraa,
- $t_{d+,i}$ kuvaa rataosalle myöhässä saapuvien junien keskimääräistä myöhästymistä [s/juna/vrk] ja
- $t_{d-,i}$ kuvaa rataosalle etuajassa saapuvien junien keskimääräistä etuajassa olon määrää [s/juna/vrk].

Kaava antaa tulokseksi kaikkien rataosalta poistuvien junien keskimääräisen myöhästymisen määrän yksikössä s/juna/vuorokausi.

Laskenta aloitetaan laatimalla neljä lähtötietoa, jotka syötetään Väyläviraston laskentaohjelmaan. Lähtötiedot kuvaavat suunniteltua aikataulua eri tavoilla: niihin syötetään tiedot tarkasteltavasta rataosasta, junien aikataulusta ja suunnitelluista pelivaroista, sekä rataosan teknisistä minimijunaväleistä. Laskentaohjelman käytön jälkeen määritetään tarkastelalueelle saapuvien junien täsmällisyys. Lopuksi kaikki määritetyt termit syötetään kaksiraiteisten rataosien viivelaskennan kaavaan. Kaikki laskentavaiheet on esitetty seuraavassa kuvassa 3.



Kuva 3. Kaksiraiteisen rataosan viivelaskennan työvaiheet.

Seuraavassa kappaleessa kuvataan neljän lähtötiedon laatimin. Tiedostot syötetään csv-muodossa laskentaohjelmaan, ja niiden laatiminen on helpointa excel- tai muun taulukkolaskentaohjelman avulla.

Kaksiraiteisen rataosan raiteet muodostavat omat kokonaisuutensa, jotka eivät ole vuorovaikutuksessa keskenään. Siten eri kulkusuunnat pitää tarkastella omina kokonaisuksinaan ja tässä ohjeessa esitetyt laskentavaheet pitää tois- taa eri kulkusuunnille erikseen.

Lähtötietojen laadinta

corridor.csv

Corridor.csv-tiedostoon kuvataan tarkasteltava rataosa. Tiedoston rakenne on kuvattu taulukossa 2. Ensimmäiselle riville kirjataan aina esimerkissä kuvatut sanat: *Corr / Prog / Orig / Dest*. Seuraavat rivit kuvaavat liikennepaikkavälejä rataosan tarkastelusuunnassa (yhdellä rivillä kuvataan yksi liikennepaikkaväli). Alla olevassa esimerkissä on kuvattu rivien tarkempi sisältö. Huomaa, että ensimmäisellä rivillä olevat luvut 1–4 ovat havainnollistamista varten, niitä ei tule kirjata varsinaiseen corridor-tiedostoon.

Taulukko 3. Tiedoston corridor.csv muoto.

1	2	3	4
Corr	Prog	Orig	Dest
Helsinki-Kerava	1	Helsinki asema	Pasila asema
Helsinki-Kerava	2	Pasila asema	Pasila autojunaa sema
...

Sarakkeissa 1–4 kuvatut asiat:

1. Tarkasteltavan rataosan nimi. Sama nimi toistetaan jokaisella rivillä.
2. Kumulatiivinen luku kuvaamaan liikennepaikkavälejä (alkaa aina luvusta 1)
3. Ensimmäisen liikennepaikkavälin ensimmäinen asema.
4. Ensimmäisen liikennepaikkavälin viimeinen asema.

delays.csv

Suunniteltu aikataulu kuvataan tiedostoon delays.csv. Ensimmäiselle riville kirjataan aina esimerkissä kuvatut sanat: Train number / Date / Pass / Statio / Arrival difference / Departure difference / Arrival planned / Departure planned / Actual arrival / Actual departure. Tiedoston muoto on kuvattu taulukkoon 4. Tiedostossa kuvataan jokaisen referenssipäivänä liikennöivän junan saapumis- ja lähtöajat jokaiselle asemalle. Huomaa, että ensimmäisellä rivillä olevat luvut 1–10 ovat havainnollistamista varten, eikä niitä tule kirjata varsinaiseen delays-tiedostoon.

Taulukko 4. Tiedoston delays.csv muoto.

1	2	3	4	5	6	7	8	9	10
Train number	Date	Pass	Station	Arrival difference	Departure difference	Arrival planned	Departure planned	Actual arrival	Actual departure
9041	14/09/2016	5	Käpylä			30402	30420	30402	30420
9041	14/09/2016	6	Oulun kylä			30516	30540	30516	30540
...

Sarakkeissa 1–10 kuvatut asiat:

1. Junanumero (*Train number*): Mikä tahansa numeerinen arvo kuvaamaan tar- kasteltavaa junaa. Eri junille on annettava yksilölliset numerot, joiden avulla ne erotetaan toisistaan.
2. Päivämäärä (*Date*): Referenssipäivän päivämäärä, osana hankearvointilas- kentaa tämä päivämäärä voi olla mikä tahansa, mutta on pidettävä huoli, että se on sama kaikissa tiedoston riveissä. Päivämäärä on ilmoitettava muo- dossa pp/kk/vvvv.
3. Aseman järjestysnumero (*pass*): Tarkastelualueen ja tarkasteltavan suun- nan ensimmäinen asema saa arvon 1. Huomaa, että jos tarkasteltava junta ei kulje koko tarkastelualueen läpi, sen ensimmäinen asema ei ala numerosta 1.
4. Aseman nimi (*Station*): Aseman nimi kuvataan täsmälleen kuten corridor-tie- dostossa.
5. Saapumistäsmällisyys (*Arrival difference*): Sarake jätetään tyhjäksi han- kearvointilaskennassa.
6. Lähtötäsmällisyys (*Departure difference*): Sarake jätetään tyhjäksi hanke- arvointilaskennassa.
7. Suunniteltu saapumisaika (*Arrival planned*): Saapumisaika asemalle kuva- taan sekuntteina alkaen puoliyöstä, esimerkiksi klo 00:01:00 saa arvon 60 (sekuntia).
8. Suunniteltu lähtöaika (*Departure planned*): Lähtöaika asemalta kuvataan se- kunteina alkaen puoliyöstä, esimerkiksi klo 01:00:00 saa arvon 3600 (sekun- tia).
9. Todellinen saapumisaika (*Actual arrival*): Osana hankearvointilaskentaa sa- rakkeeseen kopioidaan samat tiedot kuin sarakkeessa 7.
10. Todellinen lähtöaika (*Actual departure*): Osana hankearvointilaskentaa sa- rakkeeseen kopioidaan samat tiedot kuin sarakkeessa 8.

Sarakkeiden 7–10 luvut voidaan jättää tyhjiksi silloin, kun kyseisellä rivillä kuva- taan junan lähtöaika ensimmäiseltä asemalta (jolloin ei tarvita saapumisaikaa) tai kuvataan junan saapumisaika viimeiselle asemalle (ei tarvita lähtöaikaa).

margins.csv

Margins.csv-tiedostossa kuvataan jokaisen junan aikatauluihin syötettyjen pelivarojen määrä eri liikennepaikkaväleillä. Ensimmäiselle riville kuvataan aina taulukossa 4 kuvatut sanat: Pass / Train number / Margin. Tiedostossa kuvataan jokaisen junan aikatauluun syötetyn pelivararen määrä eri liikennepaikkaväleillä. Huomaa, että ensimmäisellä rivillä olevat luvut 1–3 ovat havainnollistamista varten, niitä ei tule kirjata varsinaiseen margins-tiedostoon.

Taulukko 5. Tiedoston margins.csv muoto.

1	2	3
Pass	Train number	Margin
8	9064	18
9	9064	12
...

Sarakkeissa 1–3 kuvatut asiat:

1. Liikennepaikkaväli (Pass): Liikennepaikkavälit numeroidaan yhtäläisesti de-lays-tiedoston kanssa siten, että tarkastelualueen ensimmäisen ja toisen aseman väli saa lukuarvon 1. Esimerkiksi lähijunia tarkasteltaessa Helsingistä pohjoiseen lähdettäessä Helsinki–Pasila saa pass-arvon 1 ja Pasila–Käpylä saa pass-arvon 2.
2. Junanumero (Train number): Junat numeroidaan yhtäläisesti muiden tiedostojen kanssa.
3. Pelivara (Margin): Tarkasteltavan liikennepaikkavälin suunniteltuun ajoai-kaan sisällytetyn pelivararen määrä sekunteina. Pelivarojen määrä suunnitel-laan aikataulusuunnitteluvaiheessa ja ensisijaisesti tarkastelussa tulee hyödyntää tarkkaa pelivararen määrää. Tarkemman tiedon puuttuessa las-kennassa voidaan myös käyttää seuraavia arvoja:
 - a. Lähijunien ajoajasta 5 % on pelivaraa
 - b. Henkilökaukojunien ajoajoista 10 % on pelivaraa
 - c. Tavarajunien ajoajoista 12 % on pelivaraa.

headways.csv

Headways-tiedostoon syötettävien lukuarvojen määrittäminen vaatii muista tiedostoista poiketen ennakkolaskentaa. Tiedostossa kuvataan jokaisen liiken-nepaikkavälin minimijunaväli, joka riippuu rataosalla liikennöivien junien keski-määräisestä matkanopeudesta sekä liikennepaikkaväillä olevien/suunniteltu-jen opastinvälien lukumäärästä ja pituudesta.

Minimijunavälit lasketaan jokaiselle liikennepaikkavälille erikseen seuraavalla kaavalla:

$$h_i = \frac{n * d * 3600}{s} , \text{ missä}$$

h_i [s]	Liikennepaikkavälin i minimijunaväli
n	Kerrointermi, joka riippuu liikennepaikkavälillä olevien opastinvälien määrästä: n = 1, jos liikennepaikkavälillä on yksi opastinväli n = 2, jos liikennepaikkavälillä on useampi kuin yksi opastinväli
d [km]	Opastinvälien keskimääräinen pituus liikennepaikkavälillä
s [km/h]	Liikennepaikkavälin painotettu matkanopeus

Liikennepaikkavälin painotettu matkanopeus s lasketaan seuraavasti:

$$s = \frac{\text{liikennepaikkavälin pituus [km]}}{\text{keskimääräinen matka- aika [h]}}$$

Jokaiselle liikennepaikkavälille määritetyt minimijunavälit kootaan headways.csv-taulukkoon, jonka muoto on kuvattu taulukossa 6. Huomaa, että ensimmäisellä rivillä olevat luvut 1–3 ovat havainnollistamista varten, niitä ei tule kirjata varsinaiseen headways-tiedostoon. Headways-tiedostoon ei tehdä varsinista otsikkoriviä.

Taulukko 6. Tiedoston headways.csv muoto

1	2	3
Pasila asema	Käpylä ☰	192
Käpylä ☰	Oulunkylä ☰	432
...

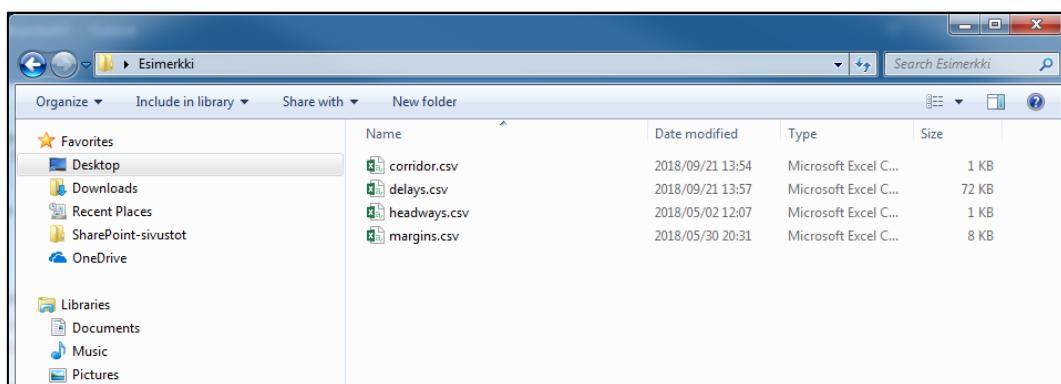
Sarakkeissa 1–3 kuvatut asiat:

1. Ensimmäisen aseman nimi
2. Toisen aseman nimi
3. Ensimmäisen ja toisen aseman välisen rataosan minimijunaväli tarkastelusuuntaan. Minimijunaväli ilmoitetaan sekunneissa.

Aikataulun häiriöherkkyyden määrittäminen Väyläviraston laskentaohjelman avulla

Lähtötieto-tiedostojen vieminen yhteiseen kansioon

Neljän lähtötieto-tiedoston laatimisen jälkeen varmistetaan, että ne on tallennettu csv-muotoon. Huomaa, että excel-ohjelman oletusarvoinen päivämäärän muoto ei ole sama, kuin delays-tiedostossa ilmoitettiin. Sen takia varmista, että csv-muotoon tallentaminen ei muuttanut päivämäärän muotoa tallennusmuodon vaihtuessa. Lopuksi varmistetaan, että tiedostot on nimetty, kuten kuvan 4 esimerkissä.



Kuva 4. Neljä lähtötietoa tallennettuna yhteiseen kansioon.

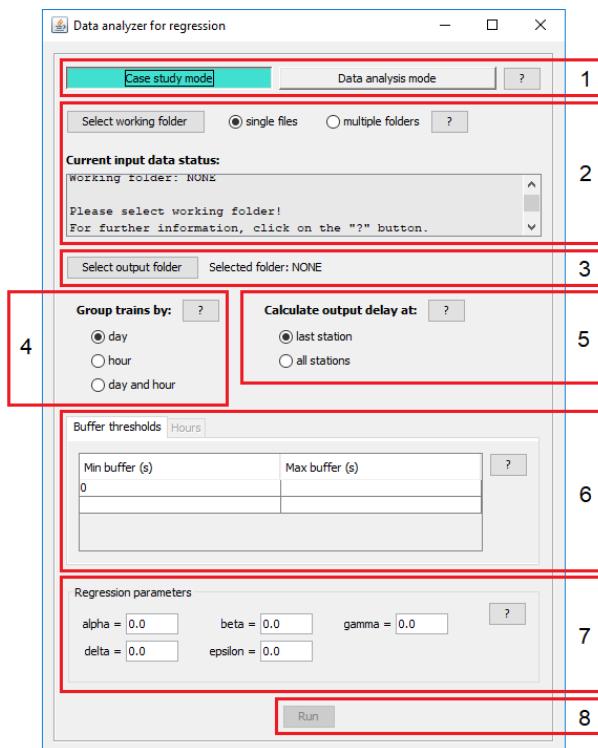
Laskentaohjelman käyttö

Väyläviraston junaviiveiden laskentatyökalu ("Data analyzer for regression") on jar-tiedosto, joka on ladattavissa Väyläviraston internet-sivuilta:

<https://vayla.fi/documents/20473/572646/tasmallisyyden-laskentatyokalu.jar/4ef5b258-4c33-4dba-b9b4-92fb7249197>

Laskentatyökalu mahdollistaa joko datan analysoimisen tai viiveiden laskemisen osana hankearvointilaskentaa. Tässä laskentaohjeessa esitellään vain toiminnot, joita tarvitaan osana viivelaskentaa. Työkalun kaikki toiminnot on esitetty laskentaohjelman englanninkielisessä käyttöohjeessa (Liite 3).

Laskentaohjelman etupaneeli on jaettu kuvassa 5 havainnollistettuun seitsemään osaan, johon syötettäväät asetukset on esitetty seuraavaksi.



Kuva 5. Laskentaohjelman etupaneelin ulkoasu.

1. Valitaan "Case study mode". Valittu painike on korostettuna turkoosilla värellä.
2. Painetaan "Select working folder" ja tiedostoista haetaan kansio, johon lähtötieto-tiedostot on tallennettu.

Painetaan "Single files".

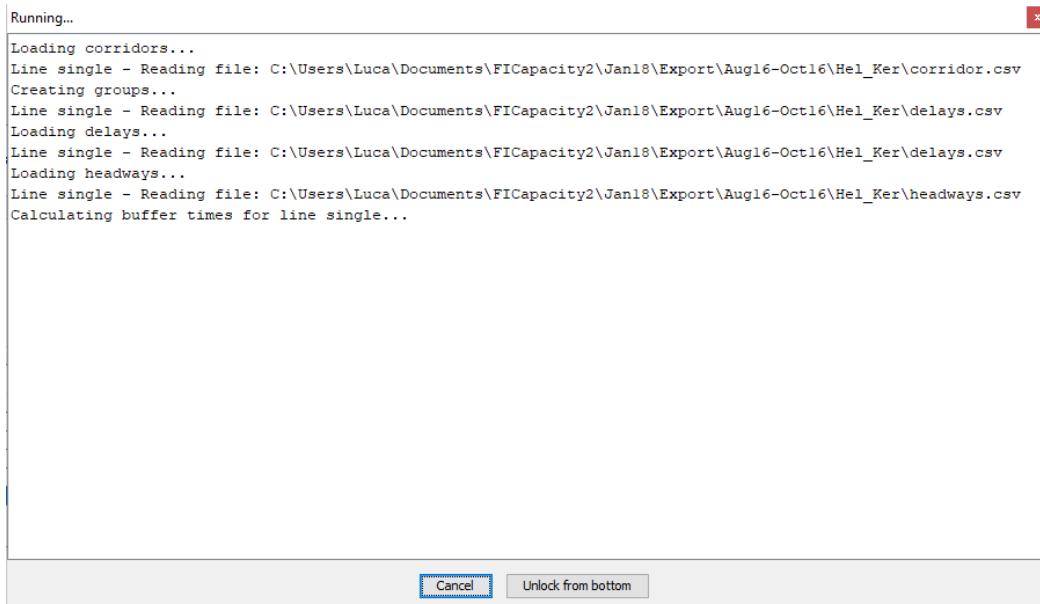
Jos lähtötietojen hakeminen on mennyt oikein, laatikkoon "Current input data status" ilmestyy teksti "Input data are valid!". Jos tekstiä ei ilmesty, lähtötietoja ei ole nimetty oikein tai niitä ei ole tallennettu oikeaan kansioon.

3. Painetaan "Select output folder" ja tiedostoista haetaan kansio, johon laskentaohjelman tulostiedostot halutaan tulostettavan.
4. Valitaan "day".
5. Painetaan "last station".
6. Kirjataan taulukkoon seuraavat luvut:

0	60
60	120
120	180
180	240
240	300
300	

7. Osana hankearviointilaskentaa kohdan 7 jokainen luku saa arvon 0.
8. Painetaan "run". Laskentatyökalu prosessoi lähtötieto-tiedostojen datan.

Näytölle ilmestyy ikkuna, joka kertoo laskennan edistymisestä (kuva 6).



Kuva 6. Laskennan edistymisestä kertova ikkuna.

Termien $\sum_{b \in B} (w(b) \cdot bf_g^b)$ ja $t_{mr,g}$ hakeminen laskentaohjelman tulostiedostosta

Laskentaohjelman laskentatulokset tallennetaan tulostiedostoon, jonka nimi on *RegressionData_day_last.csv*. Kuvassa 7 havainnollistetaan tulostiedoston rakenne. Tulostiedoston luvut, joita tarvitaan osana hankearviointilaskentaa, löytyvät sarakkeista J ja K. Sarakkeessa J ilmoitetaan aikataulun junavälien häiriöherkkyyttä kuvaava painotettu termi $\sum_{b \in B} (w(b) \cdot bf_g^b)$ ja sarakkeessa K ilmoitetaan aikataulun keskimääräinen pelivara $t_{mr,g}$. Molemmat termit syötetään viiveiden laskentakaavaan sellaisenaan.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Group	Line	Trains	buff_0	buff_60	buff_120	buff_180	buff_240	buff_300	buffWeight	marg	Din+	Din-	Dout+	ED+
2	TG_single	single		66	0	0	9	21	35	773	0.053504	68.39394	0	0	0

Kuva 7. Esimerkki viivelaskentaohjelman tulostiedostosta.

Ennen seuraavia laskentavaiheita tarkistetaan, että sarakkeessa C ilmoitettu junamäärä (*Trains*) vastaa aikatauluun suunniteltua junamääriä tarkastelusuunnassa.

Tarkastelalueelle saapuvien junien viiveen $t_{d+,i}$ ja etuajassa olon $t_{d-,i}$ määrittäminen

Toisin kuin yksiraiteisten rataosien viivelaskennassa, jossa huomioitiin ainoastaan myöhästyneiden junien keskimääräinen myöhästyminen ("positiivinen viive $t_{d+,i}$ "), kaksiraiteisten rataosien viivelaskennassa huomioidaan lisäksi etuajassa saapuneiden junien etuajassa olon määrä ("negatiivinen viive $t_{d-,i}$ ").

Saapumisviiveet määritetään kyseisen rataosan historiadataan tai arviodun tullevan täsmällisyystiedon perusteella. Jos historiadataa ei ole saatavilla, saapumisviivettä voidaan arvioida alla olevassa taulukossa 7 ilmoitettujen lukujen avulla. Taulukon luvut kuvaavat kevään 2018 toteutuneita täsmällisyyskäsiä.

Taulukko 7. Toteutuneesta datasta määritettyjä saapumistäsmällisyyksiä.

Rataosa	Saapumistäsmällisyys [s/juna/vrk]					
	Kaukojunat		Lähijunat		Tavarajunat	
	Positiivinen viive $t_{d+,i}$	Negatiivinen viive $t_{d-,i}$	Positiivinen viive $t_{d+,i}$	Negatiivinen viive $t_{d-,g,i}$	Positiivinen viive $t_{d+,i}$	Negatiivinen viive $t_{d-,i}$
Helsinki-Kirkkonummi	106	21	37	9		
Helsinki-Kerava	158	67	76	9		
Kerava-Lahti	337	32	111	14	439	861
Lahti-Riihimäki	421	39	122	27	577	566
Riihimäki-Tampere	209	59	118	70	418	964
Tampere-Orivesi	165	25			446	732
Lahti-Kouvola	339	4	194	2	482	445
Kouvola-Luumäki	314	25			880	556

Viivelaskennassa otetaan huomioon kaikkien junien keskimääräinen viive. Se määritetään eri junatyyppien tilastollisten viiveiden painotettuna keskiarvona:

$$\bar{t}_{d+,i} = \frac{\text{kaukojunien lkm} * t_{d+,i}(\text{kaukojunat}) + \text{lähijunien lkm} * t_{d+,i}(\text{lähijunat}) + \text{tavarajunien lkm} * t_{d+,i}(\text{tavarajunat})}{\text{Kaikkien junien lkm}}$$

ja

$$\bar{t}_{d-,i} = \frac{\text{kaukojunien lkm} * t_{d-,i}(\text{kaukojunat}) + \text{lähijunien lkm} * t_{d-,i}(\text{lähijunat}) + \text{tavarajunien lkm} * t_{d-,i}(\text{tavarajunat})}{\text{Kaikkien junien lkm}}$$

Lähtöletuksena on, että yllä olevilla kaavoilla määritetyt viiveet syötetään sellaisenaan sekä vertailu- että hankearvioinnin vaihtoehtojen laskelmiin. Tällöin saapumisviive on yhtäläinen kaikissa vaihtoehdissa ja hankearvioinnin myötä täsmällisyyteen vaikutetaan muuttuneen aikataulurakenteen kautta. Joissain tapauksissa voidaan kuitenkin selkeästi todeta, että investoinilla on vaikutusta myös sen ulkopuolella tapahtuviin täsmällisyyspoikkeamiin. Näissä tilanteissa saapumistäsmällisyyttä voidaan muokata arvioitujen vaikutusten mukaisesti. Esimerkiksi niissä hankearvioinneissa, joissa eri junatyyppien määrät muuttuvat merkittävästi, voidaan saapumisviiveet (positiivinen ja negatiivinen) määrittää yllä olevien kaavojen avulla erikseen jokaiselle vaihtoehdolle.

Keskimääräisen viiveen määrittäminen

Viiveiden laskentatyökalun käytön (termit $\sum_{b \in B} (w(b) \cdot bf_g^b)$ ja $t_{mr,g}$) ja saapumisviiveiden määrittämisen (termit $t_{d+,i}$ ja $t_{d-,i}$) jälkeen kaikki termit syötetään kaksiraiteisten rataosien viiveiden laskentakaavaan:

$$t_{d+,g,e} = 22.443 \cdot \sum_{b \in B} (w(b) \cdot bf_g^b) - 0.033 \cdot t_{mr,g} + 1.029 \cdot t_{d+,i} - 0.001 \cdot t_{d-,i}$$

Kaava antaa tulokseksi kaikkien junien keskimääräisen myöhästymisen määrän yksikössä s/juna/vuorokausi.



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