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Finnish Transport Infrastructure Agency

Nelli Nokkonen

The consideration of crosswinds in railway design

Application to the Finnish railway network

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Abstract

To reach the transport climate goals, there is a need to reduce vehicle kilometres travelled and increase the use of sustainable mode of transportation. As far as long-distance transport is concerned, great growth potential has been identified in speeding up transport. In rail transport, in addition to speed, operational reliability and ensuring adherence to schedules are important issues. With climate change, extreme weather events are predicted to increase, which affects the safety of rail traffic, and there may be more wind-critical points along the tracks. This will affect the functionality and reliability of rail traffic in Finland.

The influence of wind on rail traffic has not been studied much on the Finnish railway network. In the coming years, train speeds will increase, and locomotives will be made lighter. Previous international studies have found that increasing speeds and lightening the locomotive increase the risk of train overturning caused by crosswinds. International examples of wind-caused accidents and risk mitigation methods can be found both in Europe and outside of it. In Europe, the effect of winds has been considered in the operation of rail traffic with separate speed limits and in the design phase of the track with structural design such as separate wind barriers.

The aim of the thesis was to find out the effect of crosswinds on trains, to find conditions prone to derailment and mitigation measures for crosswinds. The study deals with international methods used to assess the effect of crosswind in rail transport. The European Union standard EN 14067-6:2018, which deals with crosswinds, divides the different requirements according to train speeds. This thesis deals with speeds between 140 km/h < V < 250 km/h, which are significant considering the near future of Finnish rail traffic. Thesis is limited to passenger trains and therefore does not take freight trains into account.

In this research, qualitative interviews were conducted with experts and designers. Based on the interviews, a crosswind analysis procedure was carried out. The goal of the procedure is to help ensure the safety of rail traffic in the future, even after the increase in train and wind speeds. The results of the thesis are based on out-come of the case study about the functionality of the model. The thesis brings up factors predisposing a train to overturn due to crosswind, the observation of these on the Finnish railway network is tested with the model. In the future, the model can be used as a draft version for crosswind analysis. The study showed that more information should be gathered about the implementation of the crosswind analysis and the costs and functionality of the mitigation measures. For this, in the future the model and crosswind mitigation measures should be tested on a rail-way project.

Nelli Nokkonen: Sivutuulen huomiointi ratasuunnittelussa Suomen rataverkolla. Väylävirasto Helsinki 2023. Opinnäytetyö 4/2023. 74 sivua ja 1 liite. ISSN 2490-1202, ISBN 978-952-317-070-8.

Avainsanat: sivutuuli, ilmastonmuutokset, ratasuunnittelu, raideturvallisuus

Tiivistelmä

Liikenteen ilmastotavoitteisiin pääsemiseksi on tarve vähentää henkilöautoliikennettä ja lisätä kestävien kulkutapojen käyttöastetta. Kaukoliikenteen osalta suurta kasvupotentiaalia on tunnistettu liikenteen nopeuttamisessa. Raideliikenteessä nopeuden lisäksi toimintavarmuus ja aikataulujen pitävyyden turvaaminen ovat tärkeitä asioita. Ilmastonmuutoksen myötä sään ääri-ilmiöiden ennustetaan kasvavan, mikä vaikuttaa paikoittain raideliikenteen turvallisuuteen ja tuulelle kriittisiä kohtia voi esiintyä ratojen varrella enemmän. Tämä tulee vaikuttamaan raideliikenteen toimivuuteen ja toimintavarmuuteen Suomessa.

Tuulen vaikutusta raideliikenteeseen ei olla juurikaan tutkittu Suomen rataverkolla. Tulevina vuosina junien nopeudet tulevat kasvamaan ja vetureita tehdään kevyemmiksi. Aikaisemmat kansainväliset tutkimukset ovat todenneet nopeuksien kasvamisen ja veturin kevennyksen suurentavan sivutuulesta aiheutuvan junan kaatumisen riskiä. Kansainvälisiä esimerkkejä tuulten aiheuttamista onnettomuuksista ja riskin lieventämismenetelmistä löytyy sekä Euroopasta että sen ulkopuolelta. Euroopassa tuulten vaikutusta on huomioitu raideliikenteen operoinnissa erillisillä nopeusrajoituksilla sekä radan suunnitteluvaiheessa rakennesuunnittelulla kuten erillisillä tuuliesteillä.

Tutkimuksen tavoitteena oli tutkia sivutuulen vaikutusta juniin, löytää suistumiselle alttiita olosuhteita ja tutkia mahdollisia menetelmiä sivutuulen vaikutuksen vähentämiseksi. Tutkimus käsittelee kansainvälisiä menetelmiä, joilla sivutuulen vaikutusta arvioidaan raideliikenteessä. Sivutuulta käsittelevä Euroopan Unionin standardi EN 14067-6:2018 jaottelee eri vaatimukset junien nopeuksien mukaan. Suomen osalta tutkimus käsittelee nopeuksia väliltä 140 km/h < V < 250 km/h, jotka ovat Suomen raideliikenteen lähitulevaisuutta ajatellen merkittäviä. Tutkimus rajautuu matkustajajuniin eikä ota siis huomioon tavarajunia.

Tutkimuksessa tehtiin laadullisia haastatteluja asiantuntijoilla, joiden perusteella luotiin menetelmä sivutuulen huomioimiseksi ratasuunnittelussa. Mallin tavoitteena on toimia apuna raideliikenteen turvallisuuden takaamisessa tulevaisuudessa junien ja tuulten nopeuksien kasvamisen jälkeenkin. Tutkimuksen tulokset perustuvat tapaustutkimuksessa tehtyihin havaintoihin mallin toiminnallisuudesta. Tutkimus tuo esille junan kaatumiselle altistavia olosuhteita, joiden havainnointia Suomen rataverkolta testataan mallin avulla. Tulevaisuudessa mallia voidaan käyttää luonnoksena sivutuulianalyysin tekemiseen. Tutkimus osoitti, että sivutuulianalyysin toteutuksen, että lieventämismenetelmien kustannuksista sekä toimivuudesta tulisi kerätä lisää tietoa käytännöstä. Tätä varten tulevaisuudessa mallia ja lieventämismenetelmiä tulisi testata ratahankkeilla.

Nelli Nokkonen: Beaktande av sidovind i banplaneringen på Finlands bannät. Trafikledsverket. Helsingfors 2023. Lärdomsprov 4/2023. 74 sidor och 1 bilagor. ISSN 2490-1202, ISBN 978-952-317-070-8.

Sammanfattning

För att uppnå klimatmålen för trafiken finns det ett behov av att minska personbilstrafiken och öka användningen av hållbara färdsätt. När det gäller fjärrtrafiken har man identifierat en stor tillväxtpotential för att göra trafiken snabbare. Utöver snabbheten i spårtrafiken är det viktigt att trygga driftsäkerheten och tidtabellerna. I och med klimatförändringen förutspås extrema väderfenomen öka, vilket ställvis påverkar spårtrafikens säkerhet och ställen som är kritiska för vind kan förekomma i större utsträckning längs spåren. Detta kommer att påverka spårtrafikens funktion och driftsäkerhet i Finland.

Vindens inverkan på spårtrafiken har knappt alls undersökts på Finlands bannät. Under de kommande åren kommer tågens hastigheter att öka och loken blir lättare. Tidigare internationella undersökningar har konstaterat att risken för att tåget kantrar på grund av sidovind ökar när hastigheterna ökar och loket blir lättare. Internationella exempel på olyckor som orsakats av vind, och metoder för att minska risken finns både i och utanför Europa. I Europa har vindens inverkan beaktats i driften av spårtrafiken med separata hastighetsbegränsningar samt i planeringsskedet av banan med konstruktionsplanering såsom separata vindskydd.

Syftet med undersökningen var att undersöka sidovindens inverkan på tågen, hitta förhållanden som är utsatta för urspårning och undersöka eventuella metoder för att minska sidovindens inverkan. Undersökningen behandlar internationella metoder med vilka sidovindens inverkan på spårtrafiken bedöms. Europeiska unionens standard EN 14067-6:2018 som behandlar sidovind delar in olika krav enligt tågens hastigheter. För Finlands del behandlar undersökningen hastigheter mellan 140 km/h och < V < 250 km/h, som är betydande med tanke på den närmaste framtiden för Finlands spårtrafik. Undersökningen begränsas till passagerartåg och beaktar alltså inte godståg.

I undersökningen gjordes kvalitativa intervjuer med experter, utifrån vilka man skapade en metod för att beakta sidovinden i järnvägsplaneringen. Modellens mål är att bidra till att trygga spårtrafikens säkerhet i framtiden även efter att tågens och vindarnas hastigheter har ökat. Resultaten av undersökningen grundar sig på de observationer som gjorts i fallstudien om modellens funktionalitet. Undersökningen lyfter fram förhållanden som ökar risken för att tåg kantrar och observationen av dessa på Finlands bannät testas med hjälp av en modell. I framtiden kan modellen användas som utkast till sidovindsanalys. Undersökningen visade att mer praktisk information borde samlas i om genomförandet av sidovindsanalysen, funktionaliteten och kostnaderna för lindringsmetoderna. För detta ändamål bör modellen och lindringsmetoderna testas i banprojekt i framtiden.

Foreword

The effect of crosswind on rail transport has not been studied much on the Finnish railway network. In the coming years, train speeds will increase, and locomotives will be made lighter. International studies have found that increasing speeds and lightening the locomotives increase the risk of train overturning caused by crosswinds. The aim of this thesis was to find out the effect of crosswinds on trains in Finland. Find out conditions prone to derailment and mitigation measures for crosswinds.

This master's thesis was written by Nelli Nokkonen at Aalto University School of Engineering, Department of Built Environment. The thesis was advised and guided by Outi Leuhtonen from Finnish Transport Infrastructure Agency and Pekka Saarinen from AFRY Finland Oy. In addition, expert Hannu Heikkilä from Finnish Transport Infrastructure Agency has participated in the guidance. The thesis was supervised by professor Miloš Mladenović from Aalto University.

In Helsinki, May 2023

Finnish Transport Infrastructure Agency
Infrastructure Planning

Contents

1 Introduction

1.1 Background

Several problems have emerged with the growth in demand for transport. These problems include traffic congestion, urban sprawl, traffic safety, and environmental problems, such as noise, air pollution, ecosystems impacts, and greenhouse gas (GHG) emissions (Scholl et al. 1996). Transport is the only major sector where emissions continue to grow, with car use, road and maritime freight, and aviation being the principal contributors to GHG emissions (Chapman 2007).

In rail traffic, the vulnerability to disruptions caused by weather conditions can be affected by the amount of passenger and freight traffic, the capacity of the tracks, technologies, and electricity networks (Saarelainen & Makkonen 2008). In addition, according to a study con-ducted in Sweden, factors affecting vulnerability are also the type of tracks, the lack of alternative routes, and the awareness of railway professionals about the effects of weather and climate change and the connection between them (Lindgren et al. 2009).

Climate change increases the amount of damage caused by storm winds and the intensity of heavy rains. In Finland the average estimate of wind speed changes is close to zero, but the estimates of climate models differ significantly (Tuomenvirta et al. 2018). Also, there is not enough knowledge about the effects of climate change on strong low-pressure areas or small-scale phenomena, such as strong thunderclouds. Strong winds are associated with uncertainties, and the characteristic variability of the wind is significant.

A dense rail network creates opportunities to build a dense community structure in an eco-efficient way. A community structure based on rail traffic reduces car dependency and is economically efficient. Internationally, it can also be seen that sustainable mobility is based specifically on the rail transport network, which creates sustainability and development opportunities more efficiently than bus transport (Manninen 2012).

To achieve climate targets in transport, there is a need to reduce passenger car traffic and increase sustainable transport rate of occupancy (Kenworthy 2006). For long-distance transport, great growth potential has been identified in terms of speeding up the traffic. In rail transport, in addition to speed, operational reliability and safeguarding the keeping of schedules are important factors. Lack of these factors affects the image and attractiveness of rail transport, which may lead to a decrease in passenger numbers.

Weather conditions affect the safety and smoothness of train traffic (Laapas & Latikka 2022). In addition to the general weather situation, the local windiness is affected by the surrounding terrain. In particular, the distribution of water bodies or the quality of the ground surface and surface elevation changes influence wind speed and direction. Windiness is a very local variable, which is why wind conditions can change along the track section. Also, the climate change has effect on the wind. Extreme weather events are predicted to increase, affecting the safety of rail traffic locally, and more wind critical points may occur along the lines. This will affect the operation and reliability of rail transport.

The strong winds can blow the train off tracks and cause overturning accidents. The critical wind speed for the train to overturn varies from the natural wind direction and the speed of the train (Fujii et al. 1999). Previous international studies have identified increasing speeds, and lighter locomotive increase the risk of train overturning caused by crosswinds. The effects of crosswinds on rail traffic have been studied in Japan, Germany, and France, among others. International examples of risk mitigation methods and mitigation measures can be found both in and outside Europe.

Accidents caused by strong wind have occurred in Japan, China, Denmark, Austria, and Germany. Compared to Europe, there have been many train accidents caused by wind in Asia. There have already been 30 wind-caused accidents in Japan and in China crosswinds cause most accidents on high-speed trains and ordinary trains. In 2007, a strong wind overturned a train in China near Turpan, 4 people died and 30 were injured in the accident. There is a high risk of losing human lives in overturning derailment accidents (Fujii et al. 1999).

In Europe, there have also been train accidents that claimed human lives, in which the wind has played a part. Denmark, 8 people died and 16 were injured in the bridge accident (Vainio & Hannula 2019). Where the crosswind did not overturn the train, but the wind influenced the accident, which proves that overturning is not the only risk of strong wind. Figure 1. shows wind related accident from Austria in 2002. Accidents show that crosswinds can have serious consequences. Several countries are already researching crosswinds nationally, and the European Union has also taken a position on taking crosswinds into account in rail traffic, especially for high-speed trains.

Figure 1. Wind-related accident from Austria in 2002 (Ezoji & Talaee 2022).

1.2 Aims and scope

The main aim of the thesis is to guarantee track safety during strong winds. The need for research has been increased by numerous train accidents caused by strong winds. In Europe, the mitigation measures have been considered in the operation of the rail traffic and in the design phase of the railway line.

This thesis focuses on the effect of crosswind on trains running on the Finnish railway network, with a speed of 140 - 250 km/h. Thesis explores current international ways of studying crosswind effects, crosswind risk target values, and current mitigation measures. These are considered in terms of current railway network planning and operating system in Finland. The outcome of the study is to suggest and test a crosswind analyses procedure which would be possible to implement in Finland's railway planning and operation system.

The aim for the thesis is to identify the current methods in use and determine the method suitable for the Finnish system. For this it is necessary to understand the crosswind risk value calculation methods in different countries and compare their pros and cons. Determining the risk value and the calculation method is necessary for guiding the effects of crosswinds and implementing mitigation methods. The risk value indicates when the track is too vulnerable to the danger of falling due to the wind and measures must be taken. For this reason, a risk value and calculation method should be determined for Finland to secure rail transport even at higher speeds during extreme conditions.

The central questions of the thesis are:

- Why should the effect of crosswind be studied in track design?
- How and when crosswind could be considered in track design?
- By what methods the effects of crosswinds can be mitigated in track design?

2 Literature review

This chapter reviews the thesis literature review. The first chapter deals with railway technology and planning in Finland. Here, the national standards of railways and Finland's planning stages are discussed. After this, the thesis deals with railway safety and risk evaluation at the international and national level. At the end of the chapter, the thesis brings up wind studies done in Finland from different track sections and crosswind studies from different countries. Finally, the thesis discusses the mitigation methods identified in previous publications.

2.1 Railway technology and planning in Finland

2.1.1 Railway Network

The railway system includes the rail network and all related buildings, equipment, and systems that are needed to manage and secure traffic, as well as rolling stock on the rail network. Figure 2 shows the Finnish railway network, where the blue line shows the tracks used by passenger traffic and the orange only tracks for freight traffic, the orange dashed lines are tracks closed to traffic. The life cycle of railway infrastructure refers to the service life of track structures, equipment, and systems (Tuominen 2004). This includes planning, construction, commissioning, inspection, and maintenance. Railway safety must be maintained throughout its entire life cycle and railway regulations and laws must be guaranteed.

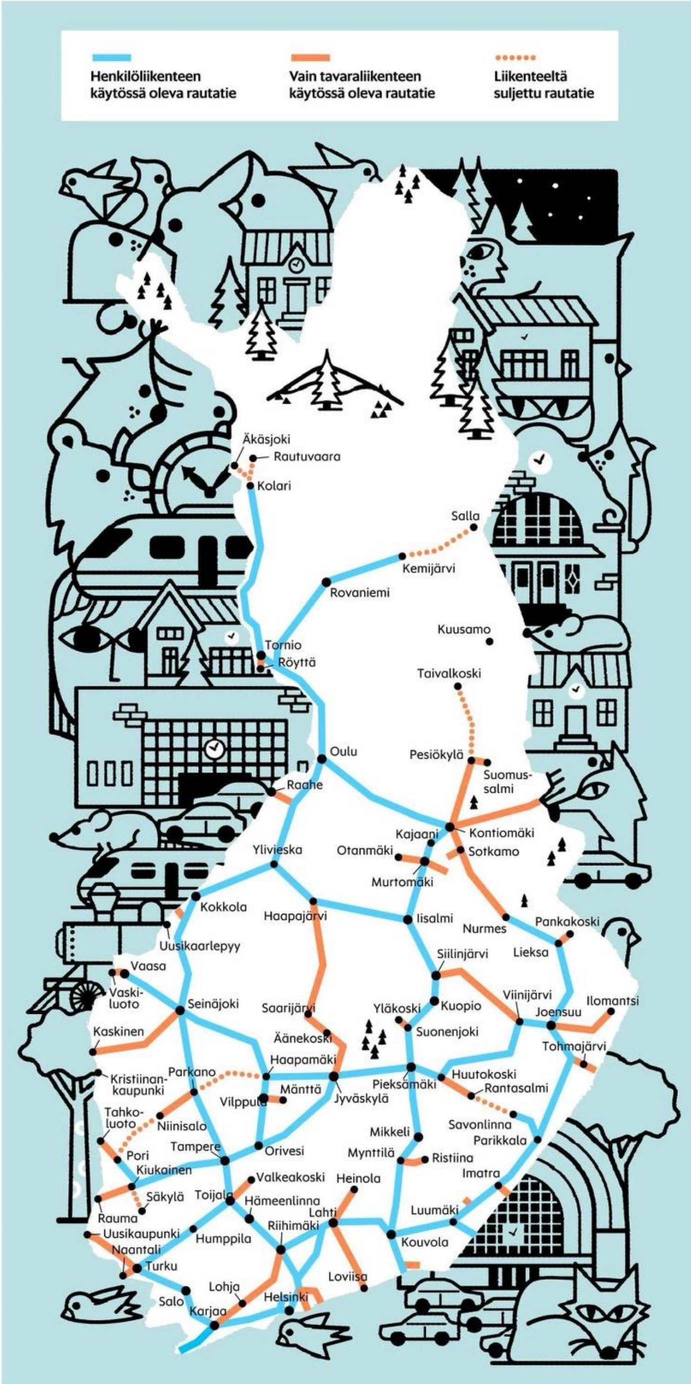

Figure 2. Finland's railway network on the map (Pylväs & Tuominen 2021).

International and national laws and regulations are at the top of the documents that determine and guide the railway system. These include the *Technical Specifications for Interoperability (TSI)* based on the regulations of the European Commission. The TSI defines the basic parameters and minimum values that must be followed to meet the essential requirements. TSI is not a design guide, but the design values should be following the TSI (European Railway Agency 2015). Figure 3 represent a framework how international laws and regulations are implemented practice in Finland. The infrastructure manager shall have an up-to-date safety management system for railway operations and compliance with the procedures of the safety management system. In Finland, the safety permit is issued by Traficom, the Finnish Transport and Communications Agency. The safety permit is granted only for five years.

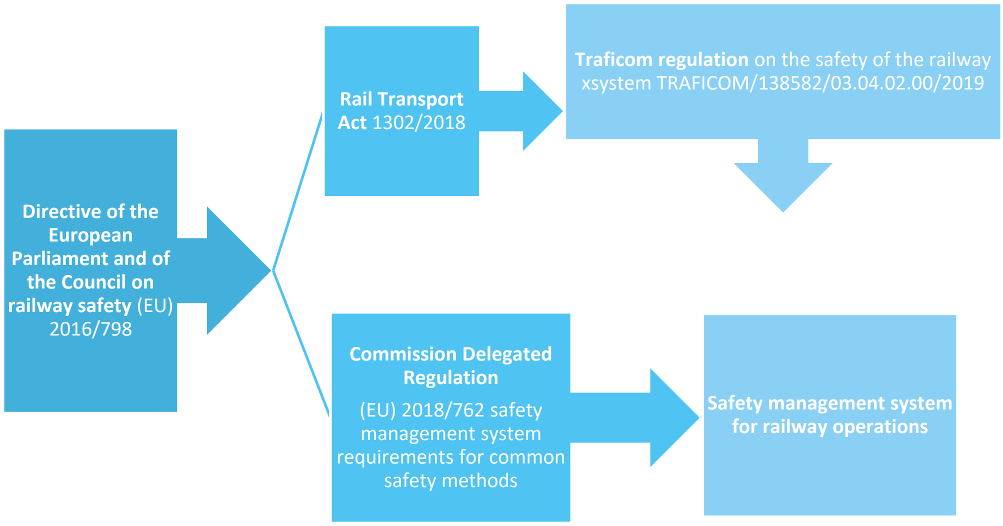

Figure 3. Regulatory framework for railway safety management for infrastructure managers (Ranttila 2022).

The Finnish Transport Infrastructure Agency (FTIA) is the manager of the government railway network and must ensure the reliability, safety, and maintainability of the railway system, as well as the safety of the people, moving, operating, and working there. FTIA's responsibility includes the maintenance, development, and maintenance of the railway network, as well as tasks related to traffic control of the railway network, monitoring, and management of traffic and electrified railways. The government railway network includes several private railways that are not managed by the FTIA. The owner of the private railway network has the same responsibilities and obligations as the FTIA (Salokangas et al. 2018).

In Finland, railway design standards are defined in the FTIA's Rail Technical Guidelines (RATO), which consists of 21 parts. These parts contain requirements and instructions for various entities related to the railway system. RATO contains information for the design, construction, inspection, and maintenance of the track and track equipment belonging to the government railway network. These instructions must be followed in the design, construction, inspection, and maintenance of railways. The highest of the internal hierarchy of the FTIA's instructions are RATO, the safety regulations for rail transport and shift work (Jt), and the safety instructions for railway maintenance (TURO). After this, other instructions drawn up by the Finnish Transport Agency must be followed (Ranttila 2022).

2.1.2 Rolling stock

In Finland, train units moving only on the railway network have a width of 3.2 m and a platform height of 550 mm. The driving force of the fleet is mainly electricity obtained from the catenary. The maximum speed of motor trains intended for regional train traffic is usually 160 km/h, but even higher speeds are possible if necessary. In Finland, the maximum permitted speed for passenger trains is 220 kilometres per hour and for freight trains 120 kilometres per hour. Thus, there are no high-speed lines in Finland with train speeds of at least 250 km/h. (Väylävirasto 2022/b)

According to the International Union of Railways, high-speed railways are classified as new railways with speeds of at least 250 km/h and old renovated railways with speeds of at least 200 km/h. High-speed lines are also assumed to have technically higher-level infrastructure, in addition to high-speed trains, this can mean better safety devices, communication, and track structure components. When these risks occur, the damage it produces often increases because of the higher speed. High-speed railway projects are usually much more expensive investments than regular railway projects not only because of the technology but also because of safety requirements (UIC 2022).

2.1.3 Track geometry in general

The position of the track describes its geometric shape in terms of rolling stock, i.e., the change of the track when moving along the track. Forces are applied to the track because of the position of the track, which affects safety, stress on the structures, and travel comfort. The position of the track is determined by the direction of the track and changes in a direction vertically and horizontally with track inclination. Track geometry binds all track infrastructure either indirectly or directly and all track technology can be in the track geometry with the help of piling.

Elements of horizontal geometry include straight lines, clothoids, circles, and gears. The circle and the clothoids together form the basic structure of the curve. The curve can also consist of only a circle or several circles and a clothoids. The clothoid is used for a smooth transition between a straight line and a circle. When using a clothoid, the change in curve takes place over a longer distance, which improves travel comfort and reduces the forces on the track. Also, the cant deficiency and the transverse acceleration on the train changes more.

2.1.4 Cant deficiency

According to need, track cant is planned for track curves to achieve the desired speed and to reduce the adverse effects of transverse acceleration. Cant deficiency can acquire a positive or negative value. When the rail on the outer curve side is higher than the inner curve rail, the cant deficiency value is positive. Whereas the outer curve side rail is lower than the inner curve rail, the cant deficiency value is negative. Negative cant deficiency is not recommended except for exceptional cases The purpose of the balance cant is the theoretical zeroing of the transverse acceleration in the track at a specified speed. Figure 4 shows a cross-section of the cant deficiency (Väyläviraston ohjeita 22/2021).

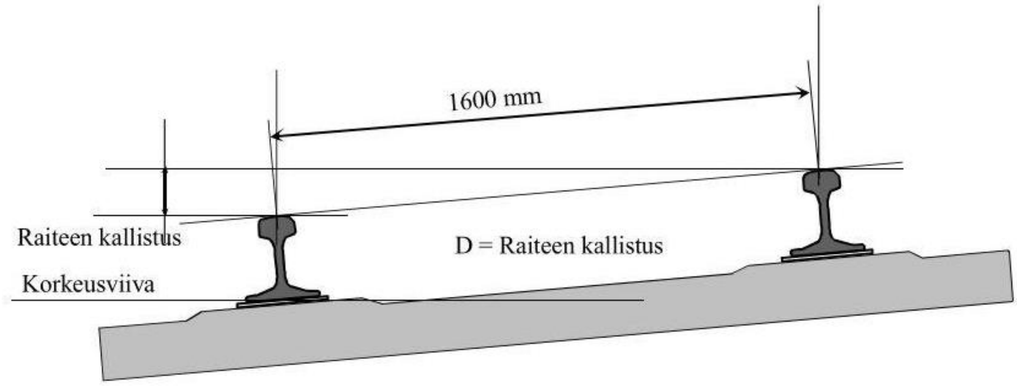

Figure 4. Measure of cant deficiency D (Taimela 2011).

Determining the cant deficiency is more complicated for mixed tracks that operate both passenger traffic and freight traffic. The speed differences of the rolling stock on these tracks may be large, and the stabilization must consider both speeds. Perfect cant deficiency for faster passenger trains is too much for freight trains traveling at lower speeds, which causes track and stock compatibility problems. In Finland, this problem is very present, as all Finnish tracks are in mixed track use. This can cause more abrasion than normal on the rails.

The dimensioning of the track geometry is based on a method using either the cant deficiency or the lateral acceleration. The cant deficiency is a consequence of the lateral acceleration and describes the magnitude of the lateral acceleration. Cant deficiency corresponds to the same phenomenon as the lateral acceleration, but it is expressed by a different name and unit of measure. The cant deficiency and the lateral acceleration have the following equivalence:

$$a_q = \frac{g \times I}{1600} = \frac{I}{163}$$

(2.3.5.1)

a_q = uncompensated lateral acceleration [m/s2]
g = gravity of Earth [m/s2]
I = cant [mm]
(Väyläviraston ohjeita 22/2021)

Lateral acceleration can be calculated at the level of the back of the rail using following formula:

$$a_q = \frac{V^2}{12{,}96R} - \frac{D}{163}$$

(2.3.5.2)

a_q = uncompensated lateral acceleration [m/s2]
V = speed [km/h]
R = radius of curve [m]
D = cant deficiency [mm]
(Väyläviraston ohjeita 22/2021)

2.1.5 Track gauge

A rolling stock (e.g., locomotive, wagon) may use the government rail network when it has completed the legal requirements for operation. Compatibility of the rolling stock with the rail network is a basic requirement for movement. The track gauge of the Finnish railway network, i.e., the inside dimension of rails, is 1,524 mm. In the world and in Europe, the most common track gauge is 1,435 mm and this is often called the standard gauge (Shi et al. 2021). The broad-gauge track refers to all tracks with a track gauge greater than the international standard gauge of 1,435 mm. Different track gauges are shown in Figure 5. When reaching high speeds, broad gauge track is more used than the narrow-gauge track. The track gauge affects the balance position of the train and the capacity of the train, of course both depend also on the shape of the fleet. However broad gauge is better in terms of faster trains, which is a good thing for Finland.

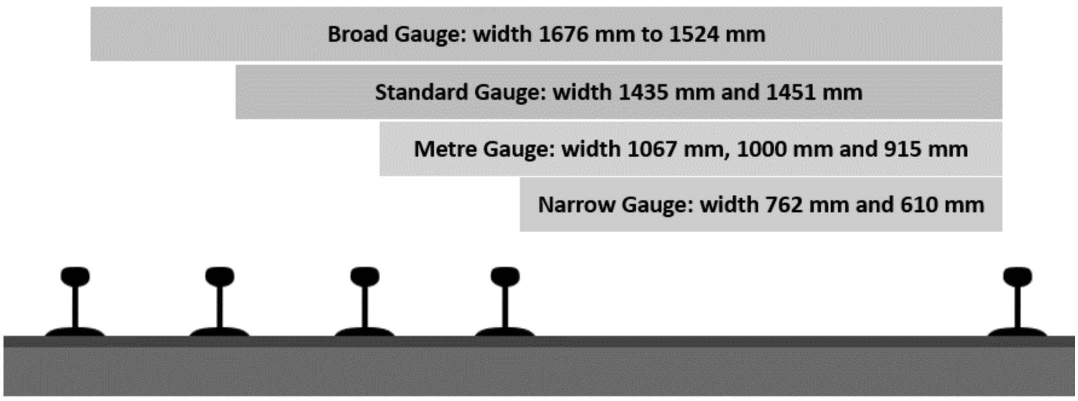

Figure 5. The different type of gauges (Railsystem 2022).

2.1.6 Railway Project Planning Phases

Railway project is a phased continuous process. Planning accuracy and decision-making for each phase are coordinated with land-use planning. All phases of the railway design also clarify environmental issues. Significant projects will provide a statutory environmental impact assessment if necessary. Railway projects are typically long-lasting, expensive investments, and have significant habitat-altering impacts, which affects people.

The phases of track design vary slightly depending on the rail project. Generally, rail design phases have four preliminary study, general plan, basic design, and detailed design. Figure 6 shows the different phases and the planning arrangement. First, a preliminary study is carried out, here the need and timing of rail projects are investigated. This should be done at the approximate level of accuracy of the provincial plan and general plan. In the preliminary study, there may be many different alternate alignments of the rail location. With a more precise design, the number of options is reduced. In smaller projects, some design phases may be skipped or combined with other stages.

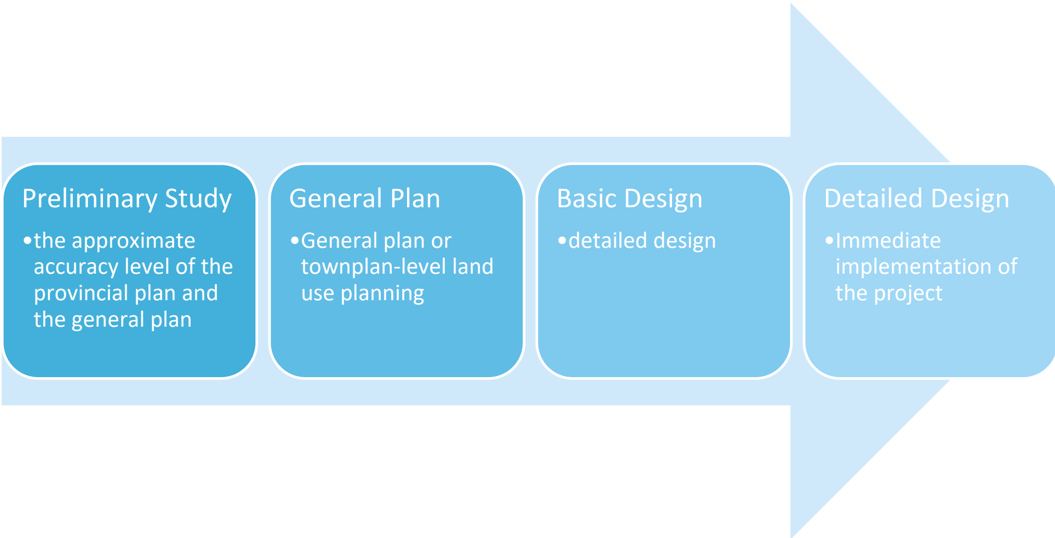

Figure 6. Different planning phase of the rail project.

After preliminary study follow a general plan phase. In this phase the approximate location and space requirement of the railway and the relationship to surrounding land use will be determined. After this follow the basic design phase, which is a more specific design of the rail and planning aims to implement the project. Based on a lawful rail plan, the necessary railway area will be taken for the construction of the railway. The final stage becomes the detailed design, which is associated with the immediate implementation of the project. Detailed design is often included in the work and is done only when funding for the project is arranged.

Regulations and laws must be considered in the different planning phase with appropriate precision. The old planning phase serves as initial information and a basis for the new planning area, so the solutions of the planning phase should consider the criteria of the future planning phases. The outcome of the planning phase should be realistic and feasible in terms of regulations but also for the costs of the project.

2.2 Railway safety and risk evaluation

The European Union determines the common safety objectives and common safety indicators of the European railway system, as well as other harmonization measures, and monitors the development of common railway safety.

Risk management refers to all activities carried out in the company to reduce risks and the resulting damages. FTIA's risk management follows the TSI regulations of which is Figure 7. These regulations are a common safety method for risk management, which was issued in regulation (EU) 402/2013. The TSI regulation applies only to railway risk management. The goal of risk management according to the TSI regulation is to ensure that the changes made to the railway system do not weaken its safety and to enable an open market by unifying certain practices / processes at the European level. The TSI regulation is followed in all changes to the railway system, which are significant from a safety point of view. The changes in question may be related to the technology, operation, use and/or maintenance or organization of the system (Väylävirasto 2020).

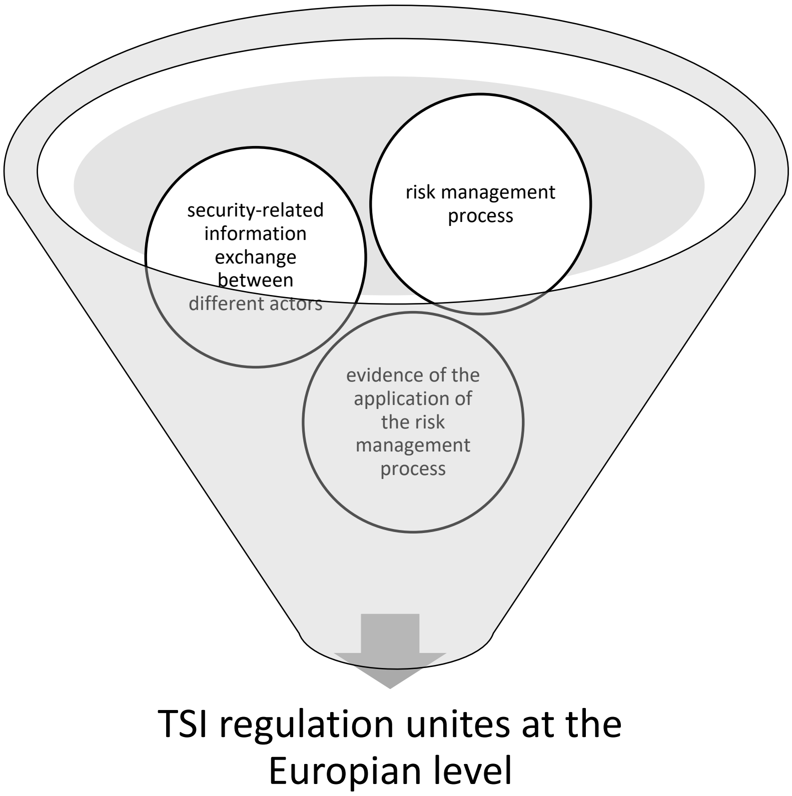

Figure 7. The Technical Specifications for Interoperability.

According to the TSI regulation, measures are needed to manage risks that have been identified. These measures can be accepted as sufficient with three criteria: operating instructions, a comparison system or risk estimation, where the assessment of the magnitude of the risk and possible consequences is presented and visible. The content and requirements of three different criteria are presented as follows:

Risk analysis and risk evaluation must be done with the help of a working group consisting of experts from different fields, for example in workshops. The number of workshops depends on the scope and length of the project and the change.

The reference system means a previously approved system or change that is like the system that is the subject of a significant change to be evaluated, for which there are sufficient usage and interference statistics to demonstrate sufficient safety. The comparison system must meet the following requirements:

- It has already been found in use to lead to an acceptable level of safety, and it could still be accepted for use in Finland
- It has similar functionality and interfaces to the system under evaluation
- It is used under similar operating conditions as the system under evaluation
- It is used in similar environmental conditions as the usual system.

Risk estimation is used when it is not possible to be convinced that the risks are at an acceptable level in all respects with operating instructions or reference to comparison systems. For example, when the system to be evaluated is completely new, or when there are deviations from existing operational guidelines or reference systems. If the estimated risk is not at an acceptable level, safety measures must be defined and implemented to reduce the risk to an acceptable level.

According to the TSI regulation risks are at an acceptable level when the measures required by comparison systems or operating instructions are used to manage the risks in question. In some cases, the acceptable risk level for technical systems can be defined numerically. If a malfunction of the technical systems can plausibly cause immediate destructive consequences, the reliability requirement is applied to them: the frequency of occurrence of the malfunction must not exceed 10^{-9} malfunctions per hour of operation (Väylävirasto 2020).

The independent safety assessment institution, ISA, evaluates compliance with the risk assessment process according to the TSI regulation. The assessment includes the risk assessment process, starting with the definition of the system and its safety goals and including the phase of hazard identification, risk analysis and demonstration of compliance with the safety measures based on it.

Climate change affects people, society, economy, and nature in direct and indirect ways. It increases the risks posed by extreme and unusual weather phenomena by changing the frequency and intensity of these phenomena and their typical time. It brings new, gradually increasing direct risks, especially to ecosystems and infrastructure. Climate risks involve impacts that can be both direct and indirect. Risk-related components are divided into three categories:

- **Hazard factor** means a physical phenomenon caused by nature or human activity and its development that may cause damage or danger.
- **Exposure factor** refers to the location of people, businesses, ecosystems and natural resources, infrastructure or economic, social, or cultural capital in a place where they may suffer damage or danger.
- **Vulnerability factor** means sensitivity to a phenomenon that potentially causes damage or danger. The concept of vulnerability applies to infrastructure, individuals, and societies.

Harm reduction involves anticipating and reducing risk by better understanding natural hazards and reducing people's vulnerability, rather than helping people when they have already faced the damage (Tostevin 2014). Figure 8 shows how to reduce the risk in terms of different categories:

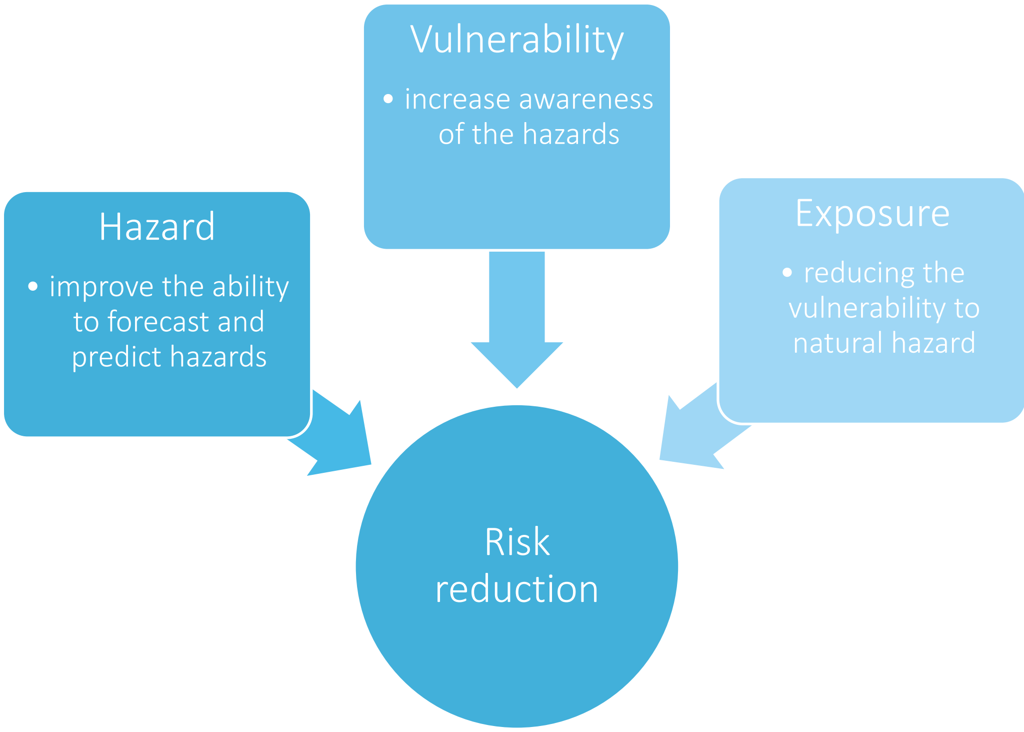

Figure 8. Reduce the risks by the risk-related components.

Risk management capability refers to the assets, characteristics and resources of organizations, communities, and societies. It can be used to reduce risk and react to actual impacts and recover from them. The risk management ability of different actors has a significant impact on the formation of risk. There are numerous ways of managing and adapting weather risks in infrastructure, such as protection planning, improving structures, checking guidelines, and adapting maintenance.

2.3 Wind studies in Finland

Previous research on the effect of wind on railways has mainly dealt with falling leaves and falling trees. Case of falling leaves, the danger is the reduction of surface friction from the leaves being thrown onto the tracks and when they slide under the wheels of the train (Tuomenvirta et al. 2018). This affects the driving conditions of track. Falling trees on the track, power lines or overhead wires may affect operation of trains for a long time. Therefore, the railway owner should try to cut down risky trees near the track (Saarelainen & Makkonen 2008). However, there is not much research in Finland on the effect of crosswind on the railways. The following sections discuss a few wind studies on the Finnish railway network.

In 1998, the Rail Administration Center, or the current FTIA, ordered the wind observations of the "Kiteen Syrjäsalmi" and Vaajakoski Leppävesi measurement stations from the Meteorological Institute. The purpose of the measurement result report was to find out the wind conditions of the track sections exposed to the wind. April 1–December 31, 1998 was chosen as the period when average wind speed distributions and the highest 3-second gust speeds were examined. Based on the findings from the study, the new possible measurement sites should be placed in places where water crossings are as open as possible. (Ratahallintokeskus 1998)

Recently The Finnish Meteorological Institute (FMI) has studied wind surveys on the Finnish rail network. The locations of the survey have been the coastal line in the Karjaa-Turku section and the main line in the Tampere-Oulu section. FTIA commissioned the studies, where the FMI identified the risky wind locations from the designated track section. The outcome of the study can be used by FTIA to examine the current driving speeds and potential safety risks caused by wind gusts. The study used gust speed threshold values of 21 m/s or 23 m/s for the double-decker wagons and a lower threshold value of 18 m/s was used in the curves (Laapas 2021; Laapas 2022).

FMI's research showed that all wind-sensitive places have open terrain, where there is a field, swamp, clear-cut area, or water body near the rail. In the curves, the lower threshold value of 18 m/s was also exceeded in other locations than open terrain. These wind-sensitive places can help plan the placement of wind sensors. Wind sensors can be used to help control train traffic, especially in longer-lasting situations of strong gusts. According to the study when placing sensors, it is important to consider the openness of the environment to the considered wind direction, the measurement height, and the effect of train traffic on the measurement results (Laapas 2021; Laapas 2022).

2.4 International crosswind studies

The effect of crosswind has been studied internationally since 1970, especially in Germany, England, and Japan (Matschke 2001). Other countries also started to join the research in the 1990s when high-speed railways started to be built and train speeds increased to 300 km/h. For example, the South of France TVG-Mediterranean Line includes vulnerable points to crosswinds, where various methods are used to minimize the risk of overturning. Also, European new train models with lighter carriages, such as the high-speed trains ICE2 and ICE3 make the transport system more sensitive to strong winds (UIC SAFIRST 2017).

The European standard EN 14067-6:2018 defines certain frameworks for guaranteeing the safety of trains regarding crosswinds. However, each country can apply the standard as a national standard. The standard divides the different requirements according to the train speeds. Trains traveling at 140 km/h < V < 250 km/h have different crosswind requirements than trains over 250 km/h. Regarding lower speeds, the national practices of different countries may differ more from each other, or the countries do not have a practice for assessing crosswinds. This is, for example, the case of Finland. Differences can also occur in the distribution of speed categories, i.e., when more precise safety criteria must be followed. For example, in Germany, the speed limit for separation is 230 km/h.

One of the most critical points in crosswind safety is the method of determining the limit values, i.e., the way in which different countries have determined the limit value of the risk. In some countries such as Sweden and Germany, certain risk value or level is in use, which describes the probability value of an accident, loss of life or other similar incident caused by crosswind. The value is connected to the countries previously determined value or an assumption about acceptable probability for a person to die.

In some countries, such as France and Spain, the methods are based on the probability of when a train may overturn because of crosswind (UIC SAFIRST 2021). And these methods do not consider the magnitude of the consequence of the accident, such as how many lives are lost or injured. In the following subsections, the methods of different countries are reviewed in more detail.

2.4.1 France

France use the RM002 system, where every new or side system or modification must be designed and built so that the security level is at least equal to the existing system. There are no defined precise instructions on how to perform risk calculations or which forecasting methods should be used. According to RM002 the safety can be demonstrated by using a quantified target, where the probability of an operating train being overturned by a wind gust should be less than 10^{-9} per train operating hour, which is the same as the TSI definition in section 2.1.1 (UIC SAFIRST 2021)

2.4.2 Germany

In Germany, track sections are divided according to the speed between those traveling at or equal to 230 km/h and those traveling at more than 250 km/h. In this way, the security definitions can be targeted better. The crosswind level of raid routes is defined and if a low crosswind is found on the route, the crosswind inspection of the infrastructure is deemed to have been completed. In other cases, a detailed investigation is carried out by determining the limit value of the appropriate RCWCs. The crosswind inspection is considered completed if the calculated RCWC is equal to or less than the specified RCWC limit value. If the infrastructure or the vehicle does not meet the crosswind requirements, the safety goal can still be achieved with certain measures. The instruction uses the GAME-related principle of ensuring at least equivalent safety. The perceived collective crosswind risk is assumed to be the same for all passenger traffic, regardless of traffic speed. (UIC SAFIRST 2021)

2.4.3 Italy

There are no requirements in Italy for the use of a particular risk methodology or a target risk value for crosswind assessment (UIC SAFIRST 2021). However, there is a target risk value that is applied. This has been chosen based on evaluations using a method very similar to the ALARP, which is explained to the next chapter.

2.4.4 Spain

In determining the risk target, the already existing French model has been applied. Method attention only risks the train overturning. Warning zone with wind alarm systems is generally used as a mitigation measure. Depending on the number of alarms that occur, the risk level is adjusted for each zone (UIC SAFIRST 2021).

2.4.5 Sweden

Sweden has its own method to calculate the risk level, which has some similarity with the German method. The risk level is based on a proportion of the total risk of dying in railway traffic over a certain period (UIC SAFIRST 2021). This produces a figure, from which the acceptable risk value for a crosswind overturning is obtained. There are two acceptable risk levels depend on the length of track section:

1. Maximum of accidents per train-km over a 160 km long section, or over the whole line if the line is shorter.
2. Maximum of accidents per train-km over a 1 km short section.

2.4.6 United Kingdom

The UK uses the RIS-7704-INS Standard for evaluating crosswinds, which provides guidelines for evaluating acceptable risk. The risk is assessed for the train overturning. After this, mitigation methods are proposed when the baseline risk is exceeded. Figure 9 shows the methodology used in crosswind risk study for High Speed Two route (HS2) in the UK.

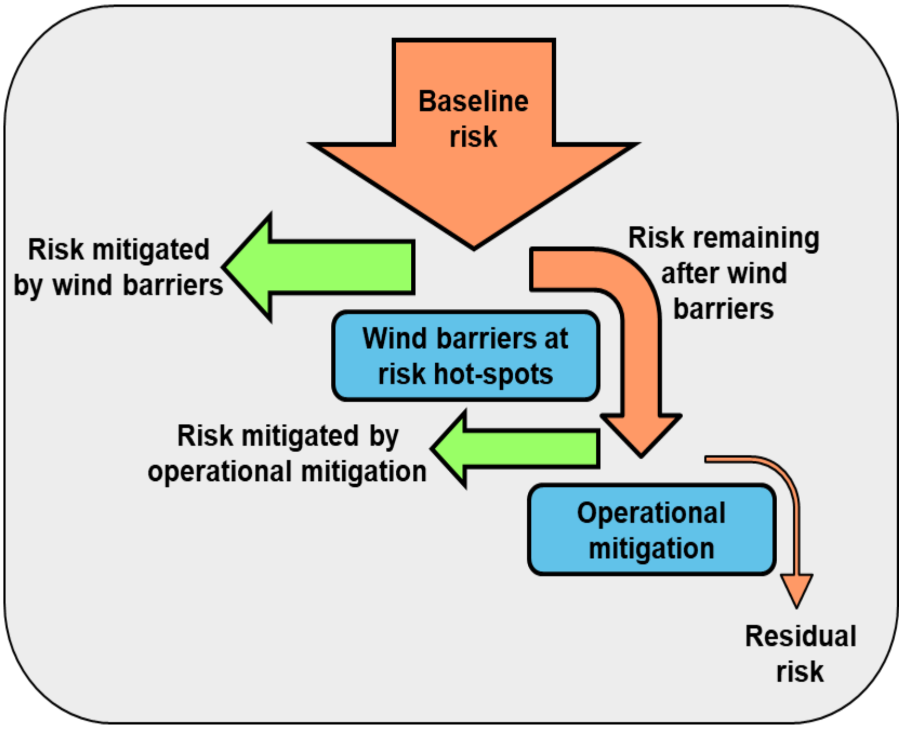

Figure 9. Crosswind risk methodology for HS2 line in UK (Glover & al. 2021).

2.4.7 Summary of MEM, GAME, and ALARP

In Europe, the MEM, GAME and ALARP methods are the most common methods, which are used or applied by different countries to determine acceptable risk level or value for crosswind overturning accident. The following is a table summarizing these methods (UIC SAFIRST 2021).

Table 1. Summary of MEM, GAME and ALARP methods.

	Country	**Idea**	**Pros**	**Cons**
MEM (The minimum endogenous mortality)	Germany	Calculate the acceptable risk based on the lowest human mortality rate in the general population	No need for a comparable system.	Not widely used
GAME (The globalement au moins équivalent)	France	Comparison of two systems, the new system must be as safe or safer than the old one	Keeps at least the current safety level and can develop this.	Needs a comparable system.
ALARP /SFAIRP (As low as is reasonably practicable / so far as is reasonably practicable)	UK	The railway entity should use any safety measurement that reduces the risk ALARP*	No reference system is needed. Allows consideration of cost efficiency in safety measurements	Approach: money for death/injury, is not acceptable practice in some countries.

*ALARP is a certain risk level, which requires that risks must be demonstrated to be tolerable and controlled.

2.4.8 The International Union of Railways

The International Union of Railways (UIC) has been operating since 1922 as an international organization for the rail transport sector. UIC's goal is to standardize railway practices. UIC develops International Railway Solutions (IRS) to help railway stakeholders achieve greater harmonization and cooperation. In 2022, UIC published IRS "Demonstrating crosswind safety of railway lines", which aims to close gaps in TSIs. This IRS provides common crosswind line assessment and safety evaluation methods. It is estimated to be exposed to wind along the railway between 140 km/h and 250 km/h and crosswind safety for passenger coaches. IRS demonstrates crosswind safety on railways where mitigation methods are required.

The IRS is not a legally binding guideline, but it has legitimacy in the railway sector and technical approval from the UIC. The safety evaluation methods are based on the EU standard EN 14067-6:2018 for high-speed trains. Thus, this method is suitable for European railways.

2.5 Current mitigation methods

This chapter examines currently used mitigation measures. As a general principle a crosswind mitigation measures should only be implemented in the areas of the railway line that needs it. Once these areas have been determined, the type of measure should be selected for the area. Mitigation measures can be divided into two types: passive and active. Passive and active mitigation measures are shown in Figure 10.

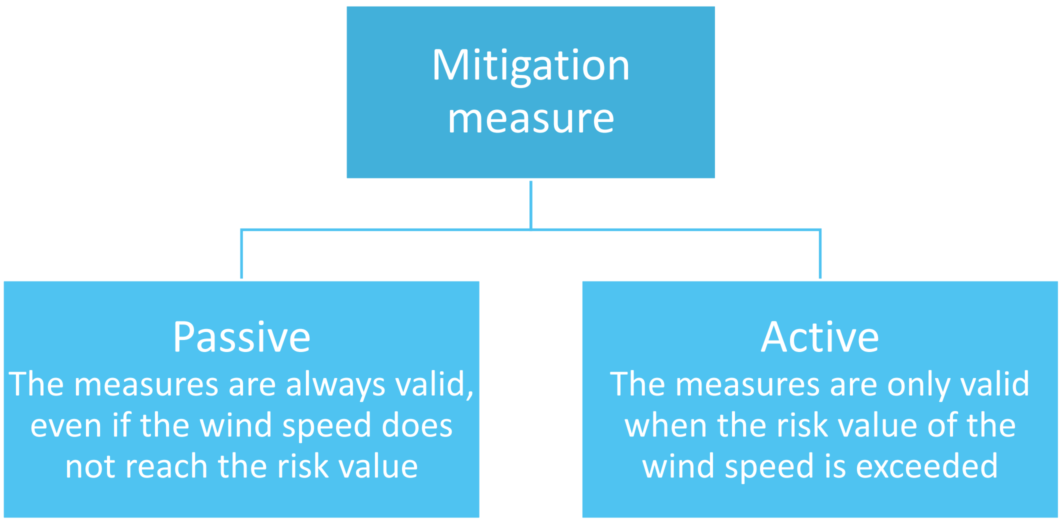

Figure 10. Passive and active mitigation measure.

2.5.1 Wind control & speed reduction

Wind control as a mitigation measure needs meteorological stations. In the case of meteorological stations belonging to external agents or organizations, the data needed as input is usually predicted rather than accurately measured data. The stations usually have a distance from the railway line. Thus, the stations don't consider the track's terrain or infrastructure. External weather station wind speed data can leave room for consideration, but the material is often less expensive than installing and using the infrastructure manager's stations.

Infrastructure manager is responsible for the installation and maintenance of their meteorological stations. These are located next to the railway line and produce more reliable data on wind speeds on the line. With better weather forecasts and situational speeds suitable for the weather infrastructure manager can guarantee better operational reliability of rail traffic (Nemry & Demirel 2012).

2.5.2 Wind barrier

Wind barrier are passive mitigation methods to reduce the effect of crosswind. They always work, even when the wind speed does not reach critical values. However, Wind barriers are structures that must be designed and built, which creates costs. It could be cost-effective to design Wind barriers in places where the critical wind speed value will reach and there is already small barrier structure, which could be modified to be suitable as a wind barrier.

The assessment of the protection efficiency of wind barriers is directly related to the safety of vehicles in crosswinds. Chein et al. (2015) study the *Effects of wind barrier on the safety of vehicles driven on bridges* show that wind barrier has significantly improved the driving stability of vehicles. The study indicates that the critical wind speed of vehicles can be increased from 15 m/s to 35 m/s by wind barrier. Figure 11 show wind barriers installed on the Xijiang Bridge in Nanning-Guangzhou high-speed railway in China.

Figure 11. Wind barriers installed on the Xijiang Bridge in China (Zou et al. 2019).

3 Methodology

This chapter reviews the study's methodologies. The goal of the thesis was to produce a method that could be used in track design in Finland to implement crosswind safety checks. The method was supposed to be tested in practice in a real railway project, in which case its functionality would be found out. This case study was realized with the help of four different methods, each of which produced information and results for the decision. In the Figure 12 methods are separated into three different groups and each different research method produced results for the case study.

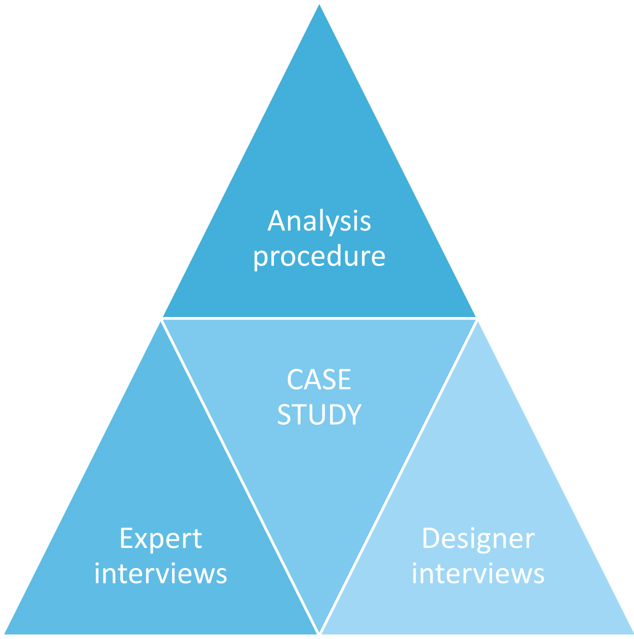

Figure 12. Research method.

3.1 Research framework

This thesis uses case study as the research method, which enables the use of different material for research. The definition of the case can take place before or after the collection of the material. The parallel use of different materials is typical for a case study (Eriksson & Koistinen 2014). The thesis meets the following conditions that are often prevalent in case studies:

- What, how and why questions are central.
- The researcher has little control over the factors, which affect the research.
- Little empirical research has been done on the topic.
- The object of research is a phenomenon in contemporary life.

Various materials are used in this thesis to find the result of the central questions. These questions begin with the words how and why, which fulfills one condition of the case study. The second fulfilled condition are factors that affect the thesis but are beyond its control. For example, the behavior of the wind and the design of rolling stock on the railway are factors related to the study, which the study cannot influence. Therefore, the study accepts and conforms to the specifications of these factors.

3.2 Expert interviews

The research was qualitative, i.e., qualitative interview research. The interview method was a semi-structured interview format, a theme interview. As a research method, the interview is suitable for situations where it is known that the subject of the research produces multi-faceted and multi-directional answers. The advantage of the interview format is also the possibility to clarify and deepen the answers received. Interviewees can, for example, be asked to give reasons for their answers. On the other hand, interview research has disadvantages. Conducting interviews can be demanding and requires skill and experience from the interviewer so that the interviewer knows how to gather information from the interviewees. Interpreting, analysing, and reporting the interview material is also often challenging. In addition, interviews always include numerous sources of error (Hirsijärvi & Hurme 2008 p. 35).

The interviewee always interprets the process from the point of view of the moment of the interview, when the situation or the time that has passed since the event may significantly affect what issues the interviewee brings up (Ruusuvuori et al. 2010 p. 381). Other influencing factors are, for example, the personal history of the interviewee and the tensions of the interview event. The interviewee's attitude towards the interviewer and the interviewer's actions in the interview situation also affect the answers. These can affect the flow of the interview and the information gathered from the interview.

In this study preparations were made for the interviews. Preliminary background about the interviewees and their preliminary studies related to the topic was explored. This helped target the questions to the expert, which led that the interviews went smoothly. The interviewers got advance some information about the research background and the interview questions (Appendix 1). The interviews lasted about half an hour to an hour. The interviews were divided into two groups, expert interviews, and designer interviews. All interviewees were interviewed separately. The goals and implementation of interviews will be explored in more detail in the following paragraphs.

The goal of the expert interviews was to survey the general situation in Finland regarding crosswind research and the necessity of research. The interviewers were selected based on their expertise. The starting points were to supplement the information obtained from the literature, especially for Finland, where crosswinds in rail traffic have been studied rather little. The expert interviews were divided into the following three perspectives:

1. Crosswinds on train traffic and infrastructure
2. Finland's climate, climate change and wind forecasting
3. Effect of crosswind on the rolling stock

The study carried out an interview from every point of view. The themes of the questions were the same for the interviewees, but they were targeted to suit the expertise. The themes of the expert interviews were:

- Need for research

- Expert's previous research
- Climate change impacts
- Procedures

The order of the questions varied, and additional questions were asked in the interviews. In a themed interview, there are no ready-made answer options, but the interviewees formulate their answers in their own words (Hirsijärjvi & Hurme 2008, p. 47). The thematic interview was chosen because it was well suited to achieve the objective and to achieve the research problem.

3.3 Designer interviews

After the expert interview was the designer interviews, which were carried out same interview method. Designers of railway projects from various backgrounds who are potential users of the method in the future were selected to be interviewed. Two track designers and one risk management expert were selected to be interviewed. The difference between the expert interviews and the designer interviews was the goal of the interview. The designer interviews were carried out after the expert interviews, and the crosswind analysis method and case studies used in the research were used as help. The interviews were therefore carried out towards the end of the study. The goal was to test the use of the crosswind analysis procedure with designers and to improve the procedure based on the interviews. This also included mitigation measures to reduce the effects of crosswinds.

At the beginning of the designer interviews, I explained the topic of the thesis to the designers a little more than the expert interviews. This is because the experts had already done research on the topic, so the research concepts and terms were already familiar. The opening of the interviews with a little briefing worked efficiently and produced a constructive discussion, which research received a lot of useful information from the interviewees outside of the questions.

3.4 Crosswinds analyse procedure

This section reviews how track infrastructure designers in Finland could guarantee crosswind safety. This method is only suitable for trains with speeds above 140 km/h and below 250 km/h. The method is based on five different steps:

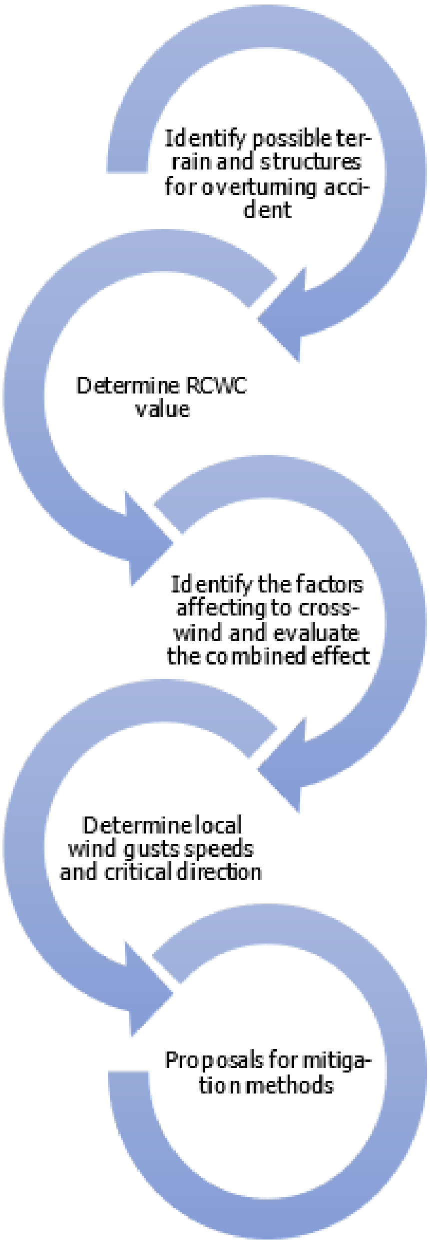

Figure 13. Five points to analyses and improve crosswind safety.

3.4.1 Identifies terrain and structures for oversensitive points to crosswind

Track location and structure data are required for output data. Track location influences local windiness, for example, near coastlines, wind gusts tend to be considerably louder than inland. Along the track, there can be different types of terrain such as forest, fields, and water bodies. Low growth and open areas are more sensitive to strong wind than forests because there are no trees that act as a mitigation effect. In addition to this track structures such as track bridges are affected by crosswind sensitivity. There are also structural factors that contribute to the track's sensitivity to wind. The following sections list different factors affecting crosswind sensitivity:

Bridges

Railway bridges are more wind sensitive areas and sensitivity is influenced by factors such as the length, height, structure, and location of the bridge. The higher the bridge and track is located, the more sensitive it is to the wind. Bridges usually have barriers, which also affect how strongly the wind affects the train. More about the effect of different heights of barriers in the lower sections. Figure 14 shows influence of viaduct on wind.

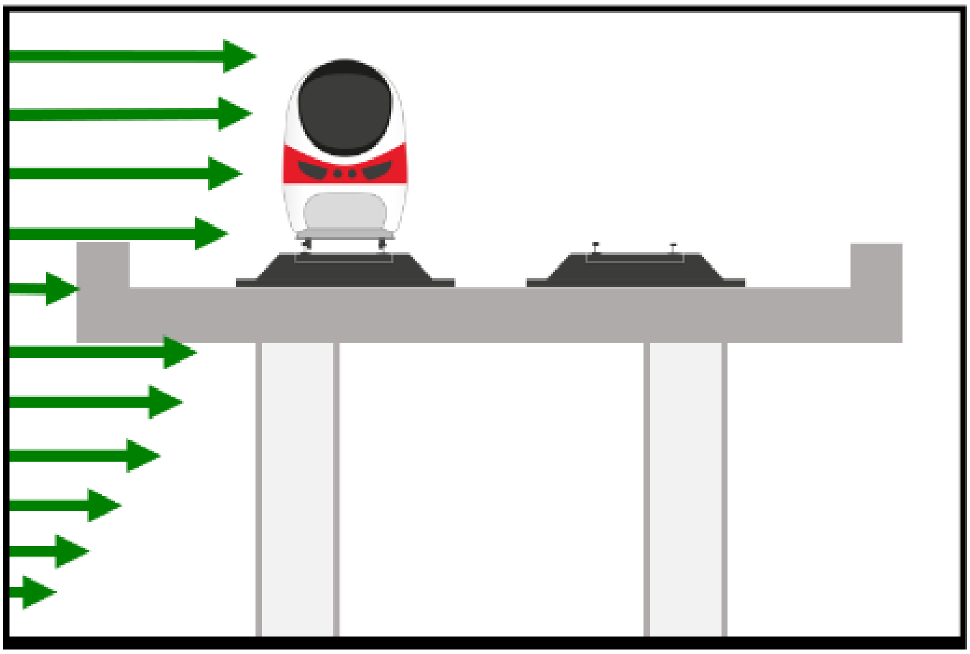

Figure 14. Influence of viaduct on wind (Glover & al. 2021).

Forest

The location of the railway in a forested area reduces the strength of the wind and thus acts as a contributing factor. Forest vegetation slows down the wind speed near the earth's surface. When assessing the contribution of the forest, measures directed at the forest in the near future should be considered also. In the construction of a new rail line, the trees are mainly completely removed from the protection area, this means about 30 m from the track (Väylävirasto 2022). Figure 15 shows example of the railway and the protection area. The forest can also be affected by external measures that cannot be influenced. One example can be that the forest owner can cut down the forest he owns, in which case the forest will not have a contributing effect on the railway.

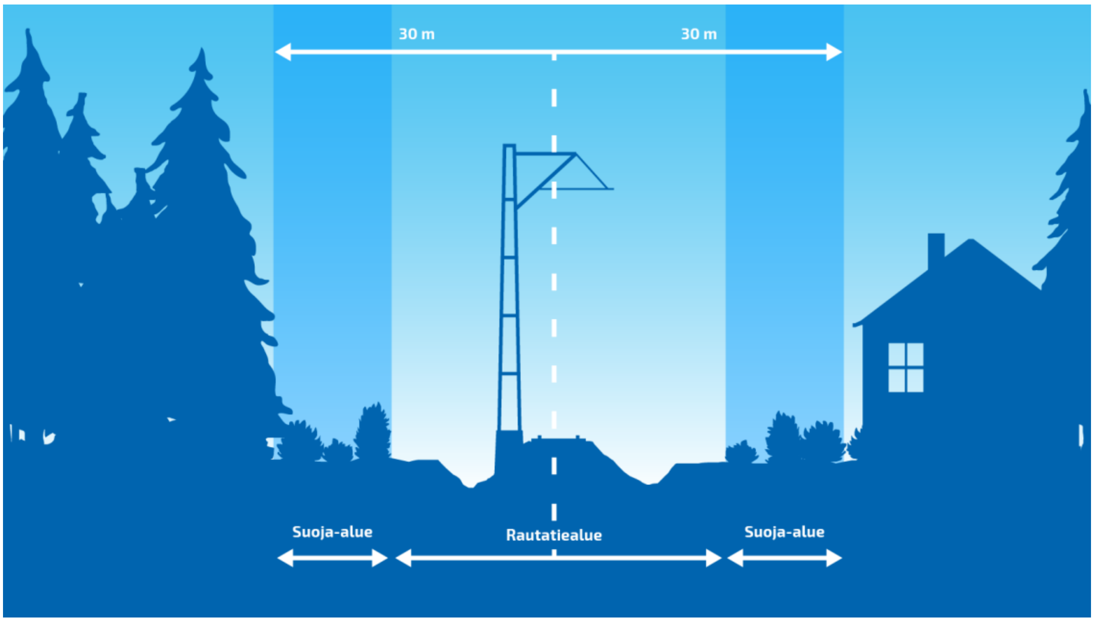

Figure 15. Railway area and protection area from the center line of the track (Väylävirasto 2022).

Field area

A field, i.e., a large area of cultivated land, is a factor that intensifies windiness. The fields are mainly cultivated with useful plants, which are low compared to the trees. Due to the large land area and low vegetation, the fields are more exposed to stronger winds. Low vegetation in arable areas is often permanent and it takes several years for the vegetation to turn into trees.

Water area

The water area is a factor that increases windiness. The wind can move along the waterways because the surface of the water areas is flat and there is no vegetation that reduces the wind. Water areas are mostly windy areas, but the strength of the wind often depends on the size of the water area. Generally, the larger the water area, the windier the area.

Embankment

The track embankment consists of the structural layers of the track and possible embankment filling. Typically, the effect of the train load on safety decreases the higher the embankment. A railway embankment that is too steep and high can lead to the collapse of the embankment slope. The higher the embankment is located, the stronger the wind is against the train. on a high embankment, the contribution caused by vegetation is also smaller. Figure 16 shows the influence of embankments on wind.

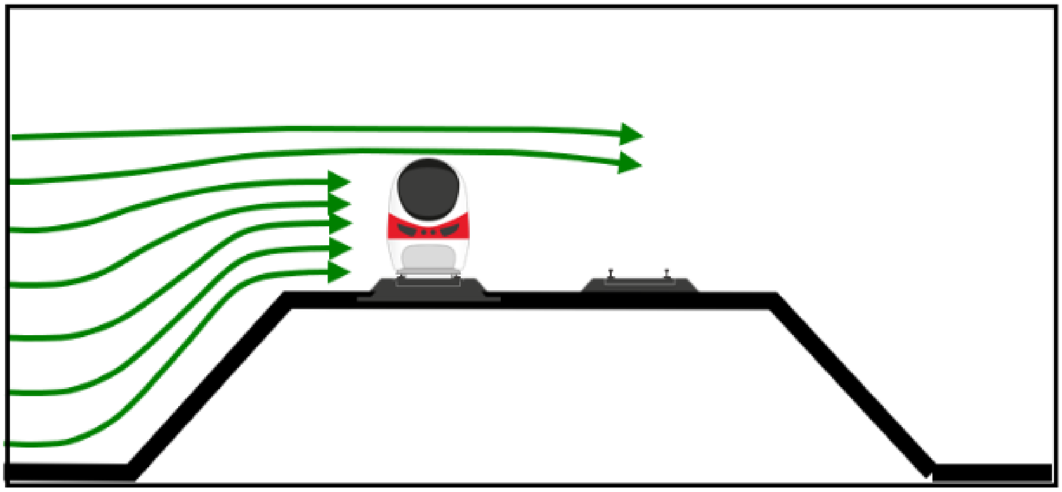

Figure 16. Influence of embankments on wind (Glover & al. 2021).

Cuttings

Track cutting refers to soil and rock cutting performed in connection with the construction of the track. The line in the cut is usually sheltered from the wind. Figure 17 shows how the wind strength affects the train. The depth of the cut affects its ability to protect from the wind.

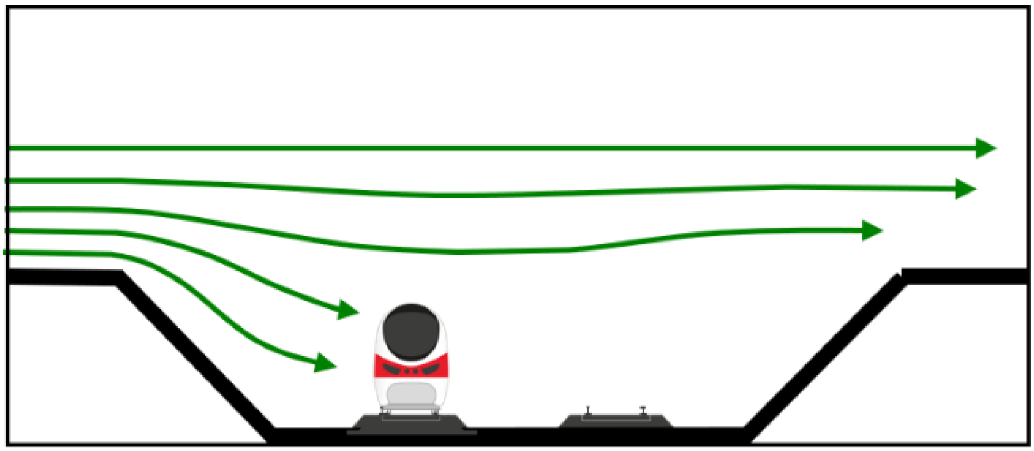

Figure 17. Influence of cuttings on local wind at the train (Glover & al. 2021).

Barrier

A railway can include various fence structures, such as noise barrier. Barrier prevents the wind from reaching the other side of it, but even so, the effect of fences on crosswind sensitivity is not always positive. The barrier's effect on crosswind sensitivity depends on the structure of the barrier, especially the length. According to a study conducted on an UK high-speed track, a 1–2-meter-high fence has negative effects on the crosswind sensitivity of the track. Again, a fence of more than 3 m has positive effects. (Glover & al. 2021).

Rail Safety and Standards Board (RSSB) standard with adaptations for consistency with current European practice the influence of acoustic and wind barriers on wind speed use a "Fence Factor" (KF) standard dependent on barrier height and porosity. Figure 18 shows that barriers 1–2 m high above top of rail have calculation by KF greater than 1, so it increases the overturning moment by redirecting wind onto the upper portion of the train. Therefore, present increased risk compared to no barrier. Barriers of 3 meters or higher provide a sheltering effect that reduces risk substantially. These height-dependent values of K are taken to apply to Viaduct parapets and other vertical obstructions on the Windward side of the train as well as to barriers.

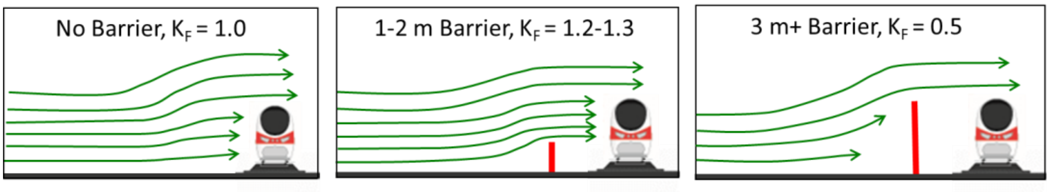

Figure 18. The influence of low and high barriers for fence factor (Glover & al. 2021).

In track projects, the final location and height of the noise barriers are only decided in the construction planning phase, thus the effects of the barriers will only be evaluated in the final stages of the design. Because of this, the effect of noise fences on crosswind cannot be analyzed very precisely until the location and height have been decided. Compared to the total price of the project, noise fences are expensive structures, and utilizing them against the wind would bring added value to the structure.

Open area

In open areas, there are no factors that weaken the wind, so the wind speed can reach higher values. The surface of the open area affects the strength of the wind. Generally, the larger the area, the stronger the wind can reach.

Coastal location

The coast has higher wind speeds than inland. Therefore, the location of the railway in the coastal area should be considered as an influencing factor. The area should always be evaluated separately because the surrounding terrain and the size of the water body affect the windiness.

3.4.2 Classification of the factors

These factors have been identified from the literature review of the previous section and through interviews. The geographical conditions of Finland have been considered in the selection of factors. New factors affecting the wind strength or new research result can arise over time, these should be considered in the cross-wind analysis.

Structure and location factors affecting overturning sensitive can be assessed by assigning values to different factors how negative or positive is the impact. Effects must be determined case-by-case and the examples given by Table 2 only serve as indicative. Evaluation and tabulation of impact values facilitates the evaluation of several factors in the same section.

Table 2. Example table of the impact of track structure and terrain.

Structures type / Terrain (examples)	Class	Measure
noise barrier	significant positive	no needs for measure
forest	positive	monitored
normal track structure	neutral	measures to be planned
open area	negative	measures to be implemented in the current phase
bridge	significant negative	immediate measures

3.4.3 Determine RCWC value

In this method, the characteristic wind curve values are determined instruction by the IRS research group in their study for the common European recommendation for the CWC value. This value is value is named recommended characteristic wind curve (RCWC). This method has four steps, which are shown in the Figure 19.

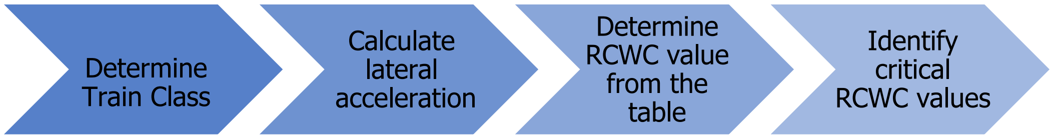

Figure 19. Four steps for determine RCWC value.

The first step determines which type of train you want to calculate the value. Infrastructure planning stage is usually not yet known by the equipment carried on the track. Secondly, the life cycle of the line tends to be longer than the fleet, so it is very difficult to consider future stock at this stage. More accurate CWC values are calculated for the fleet upon commissioning. The line also runs different equipment and, for example in Finland, most of the government Railway is mixed tracks, i.e., both freight trains and passenger trains run on the lines. However, this method is intended only for the calculation of RCWC values for passenger trains.

3.4.3.1 Determine train class

When choosing the type of train, one should choose the maximum of the train according to the speed. This can be determined by the maximum speed of the track geometry. This study has been conducted for speeds between 140 km/h and 250 km/h, so when exceeding this maximum speed, 250 km/h is used as the maximum speed. Table 3 shows the train classes that have been used in this thesis.

Table 3. Train classes determined by speed.

Train class	Max speed	Min Speed
A = Passenger train, maximum speed 250 km/h	250	200
B = Passenger train, maximum speed 230 km/h	230	200
C = Passenger train maximum speed 200 km/h	200	160
D = Passenger train maximum speed 160 km/h	160	120

For the section of line under consideration, only one type of train is used according to the maximum speed. Thus, the train type does not change to another even if there are points on a section of the track where the maximum speed of the train according to geometry would be maximum for the other class of trains.

In Finland, passenger train carriages are about a meter higher than in Europe. In this method, determining the train classes does not therefore consider whether it is a double-decker or a single-decker coach. Double-decker coach is more sensitive to crosswind due to its height, which means its CWC curves are slightly lower and the CWC values are lower than single-decker coach.

3.4.3.2 Calculate the lateral acceleration

Lateral acceleration is the horizontal acceleration caused by a key force, a force always directed towards or away from the centre of force. To calculate lateral acceleration, at least the cant of curves is needed. Later acceleration can be calculated using the formulas presented in the chapter 2.3.5. After this the RCWC value can be determined.

3.4.3.3 RCWC table and critical values

This analyses procedure use RCWC values from IRSs Demonstrating crosswind safety of railway lines by UIC. These RCWC values are determined for the average rolling stock in Europe. Because of this, the values are not the most suitable for rolling stock in Finland. Instead of these values, values more suitable for the situation obtained as initial data should be used. For example, previous wind studies in Finland have been done based on the CWC curves of Finnish double-decker coaches (Laapas & Latikka 2022). Followed tables show RCWC values used in this study for transverse acceleration values 0, 0.5 and 1.0.

Table 4. RCWC values for lateral acceleration 0.0.

$a_q = 0.0$										
Train class	**Speed (Km/h)**	**RCWC (m/s) angle**								
		90	**80***	**70**	**60**	**50**	**40**	**30**	**20**	**10**
A	250	26.15	25.89	26.43	27.86	30.43	34.68	41.78	45.00	45.00
	240	25.55	26.29	26.84	28.29	30.90	35.21	42.43	45.00	45.00
	220	27.36	27.09	27.65	29.15	31.83	36.28	43.72	45.00	45.00
	200	28.17	27.89	28.47	30.01	32.77	37.35	45.00	45.00	45.00
	180	28.98	28.69	29.29	30.87	33.71	38.42	45.00	45.00	45.00
	160	29.78	29.49	30.10	31.73	34.65	39.49	45.00	45.00	45.00
	140	30.59	30.29	30.92	32.59	35.59	40.56	45.00	45.00	45.00
	120	31.40	31.09	31.73	33.45	36.53	41.64	45.00	45.00	45.00
B	230	26.25	25.89	26.43	27.86	30.43	34.68	41.78	45.00	45.00
	220	26.55	26.29	26.84	28.29	30.90	35.21	42.43	45.00	45.00
	200	27.36	27.09	27.65	29.15	31.83	36.28	43.72	45.00	45.00
	180	28.17	27.89	28.47	30.01	32.77	37.35	45.00	45.00	45.00
	160	28.98	28.69	29.29	30.87	33.71	38.42	45.00	45.00	45.00
	140	29.78	29.49	30.10	31.73	34.65	39.49	45.00	45.00	45.00
	120	30.59	30.29	30.92	32.59	35.59	40.56	45.00	45.00	45.00
C	200	26.15	25.89	26.43	27.86	30.43	34.68	41.78	45.00	45.00
	180	26.96	26.69	27.25	28.72	31.37	35.75	43.07	45.00	45.00
	160	27.77	27.49	28.06	29.58	32.30	36.82	44.36	45.00	45.00
	140	28.57	28.29	28.88	30.44	33.24	37.89	45.00	45.00	45.00
	120	29.38	29.09	29.69	31.30	34.18	38.96	45.00	45.00	45.00
D	160	26.15	25.89	26.43	27.86	30.43	34.68	41.78	45.00	45.00
	140	26.96	26.69	27.25	28.72	31.37	35.75	43.07	45.00	45.00
	120	27.77	27.49	28.06	29.58	32.30	36.82	44.36	45.00	45.00

*The most critical angle for a crosswind

Table 5. RCWC values for lateral acceleration 0.5.

$a_q = 0.5$										
Train class	**Speed (Km/h)**	**RCWC (m/s) angle**								
		90	**80***	**70**	**60**	**50**	**40**	**30**	**20**	**10**
A	250	23.75	23.49	24.00	25.30	27.63	31.49	37.95	45.00	45.00
	240	24.15	23.89	24.41	25.73	28.10	32.03	38.59	45.00	45.00
	220	24.96	24.69	25.23	26.59	29.04	33.10	39.88	45.00	45.00
	200	25.77	25.49	26.04	27.45	29.98	34.17	41.17	45.00	45.00
	180	26.58	26.29	26.86	28.31	30.92	35.24	42.46	45.00	45.00
	160	27.38	27.09	27.68	29.17	31.86	36.31	43.75	45.00	45.00
	140	28.19	27.89	28.49	30.03	32.80	37.38	45.00	45.00	45.00
	120	29.00	28.69	29.31	30.89	33.74	38.45	45.00	45.00	45.00
B	230	23.75	23.49	24.00	25.30	27.63	31.49	37.95	45.00	45.00
	220	24.15	23.89	24.41	25.73	28.10	32.03	38.59	45.00	45.00
	200	24.96	24.69	25.23	26.59	29.04	33.10	39.88	45.00	45.00
	180	25.77	25.49	26.04	27.45	29.98	34.17	41.17	45.00	45.00
	160	26.58	26.29	26.86	28.31	30.92	35.24	42.46	45.00	45.00
	140	27.38	27.09	27.68	29.17	31.86	36.31	43.75	45.00	45.00
	120	28.19	27.89	28.49	30.03	32.80	37.38	45.00	45.00	45.00
C	200	23.75	23.49	24.00	25.30	27.63	31.49	37.95	45.00	45.00
	180	24.56	24.31	24.82	26.16	28.57	32.56	39.24	45.00	45.00
	160	25.37	25.11	25.64	27.02	29.51	33.63	40.53	45.00	45.00
	140	26.17	25.91	26.45	27.88	30.45	34.71	41.82	45.00	45.00
	120	26.98	26.71	27.27	28.74	31.39	35.78	43.11	45.00	45.00
D	160	23.75	23.49	24.00	25.30	27.63	31.49	37.95	45.00	45.00
	140	24.56	24.31	24.82	26.16	28.57	32.56	39.24	45.00	45.00
	120	25.37	25.11	25.64	27.02	29.51	33.63	40.53	45.00	45.00

*The most critical angle for a crosswind

Table 6. RCWC values for lateral acceleration 1.0.

		a_q = 1.0								
Train class	**Speed (Km/h)**	**RCWC (m/s) angle**								
		90	**80***	**70**	**60**	**50**	**40**	**30**	**20**	**10**
A	250	21.15	20.94	21.38	22.53	24.61	28.05	33.79	44.19	45.00
	240	21.55	21.34	21.78	22.96	25.08	28.58	34.44	45.00	45.00
	220	22.36	22.14	22.60	23.82	26.02	29.65	35.73	45.00	45.00
	200	23.17	22.94	23.42	24.68	26.96	30.72	37.02	45.00	45.00
	180	23.98	23.74	24.23	25.54	27.90	31.79	38.31	45.00	45.00
	160	24.78	24.54	25.05	26.40	28.84	32.86	39.60	45.00	45.00
	140	25.59	25.34	25.87	27.26	29.78	33.93	40.89	45.00	45.00
	120	26.40	26.14	26.68	28.12	30.72	35.01	42.18	45.00	45.00
B	230	21.15	20.94	21.38	22.53	24.61	28.05	33.79	44.19	45.00
	220	21.55	21.34	21.78	22.96	25.08	28.58	34.44	45.00	45.00
	200	22.36	22.14	22.60	23.82	26.02	29.65	35.73	45.00	45.00
	180	23.17	22.94	23.42	24.68	26.96	30.72	37.02	45.00	45.00
	160	23.98	23.74	24.23	25.54	27.90	31.79	38.31	45.00	45.00
	140	24.78	24.54	25.05	26.40	28.84	32.86	39.60	45.00	45.00
	120	25.59	25.34	25.87	27.26	29.78	33.93	40.89	45.00	45.00
C	200	21.15	20.94	21.38	22.53	24.61	28.05	33.79	44.19	45.00
	180	21.96	21.74	22.19	23.39	25-55	29.12	35.08	45.00	45.00
	160	22.77	22.54	23.01	24.25	26.49	30.19	36.37	45.00	45.00
	140	23.57	23.34	23.82	25.11	27.43	31.26	37.66	45.00	45.00
	120	24.38	24.14	24.64	25.97	28.37	32.33	38.95	45.00	45.00
D	160	21.15	20.94	21.38	22.53	24.61	28.05	33.79	44.19	45.00
	140	21.96	21.74	22.19	23.39	25.55	29.12	35.08	45.00	45.00
	120	22.77	22.54	23.01	24.25	26.49	30.19	36.37	45.00	45.00

*The most critical angle for a crosswind

3.4.4 Identifies multi-factor combined effect

After identifying all wind-related factors and calculating the RCWC value, the combined effect of the factors must be identified and the final risk of a train overturning in the area must be assessed.

3.4.5 Determination of wind gusts speeds and critical direction

The average wind speed (10-minute average) can be converted to wind gust speed (3-second average) using the gust coefficient method. The gust coefficient is the ratio of the wind gust to the average wind speed, describing the magnitude of the short-term variation of the wind. A gust factor of 1.5 is used in Finnish crosswind studies. The Figure 20 shows the average wind speed and wind gust speed measured in Liisa storm low pressure in Tulliniemi, Hanko on November 19, 2020.

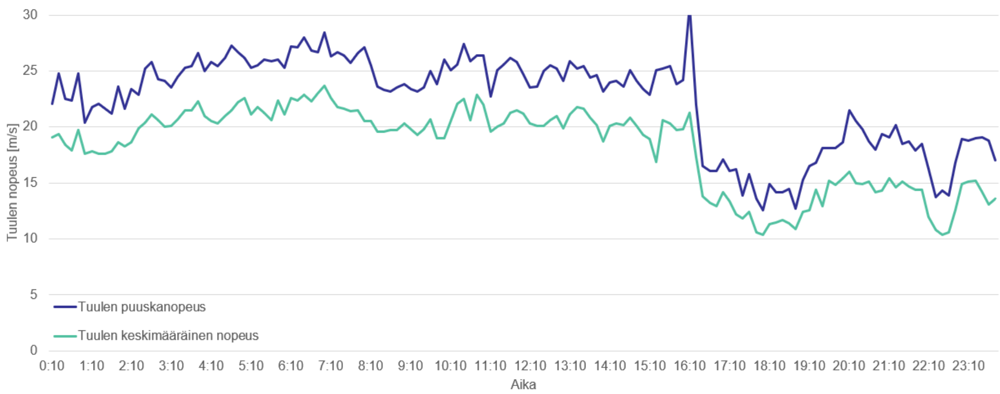

Figure 20. The difference between average wind speed and wind gust speed (Laapas & Latikka 2022).

Figure 21 shows a wind map from the geospatial data service of the FMI wind stations. The service shows wind strengths and directions on different days. With the help of the wind map it is possible to compare the strength of the wind on stormy days at the stations near the track section between to the coast. This can be helpful to get an idea of how wind warnings affect the winds on the track.

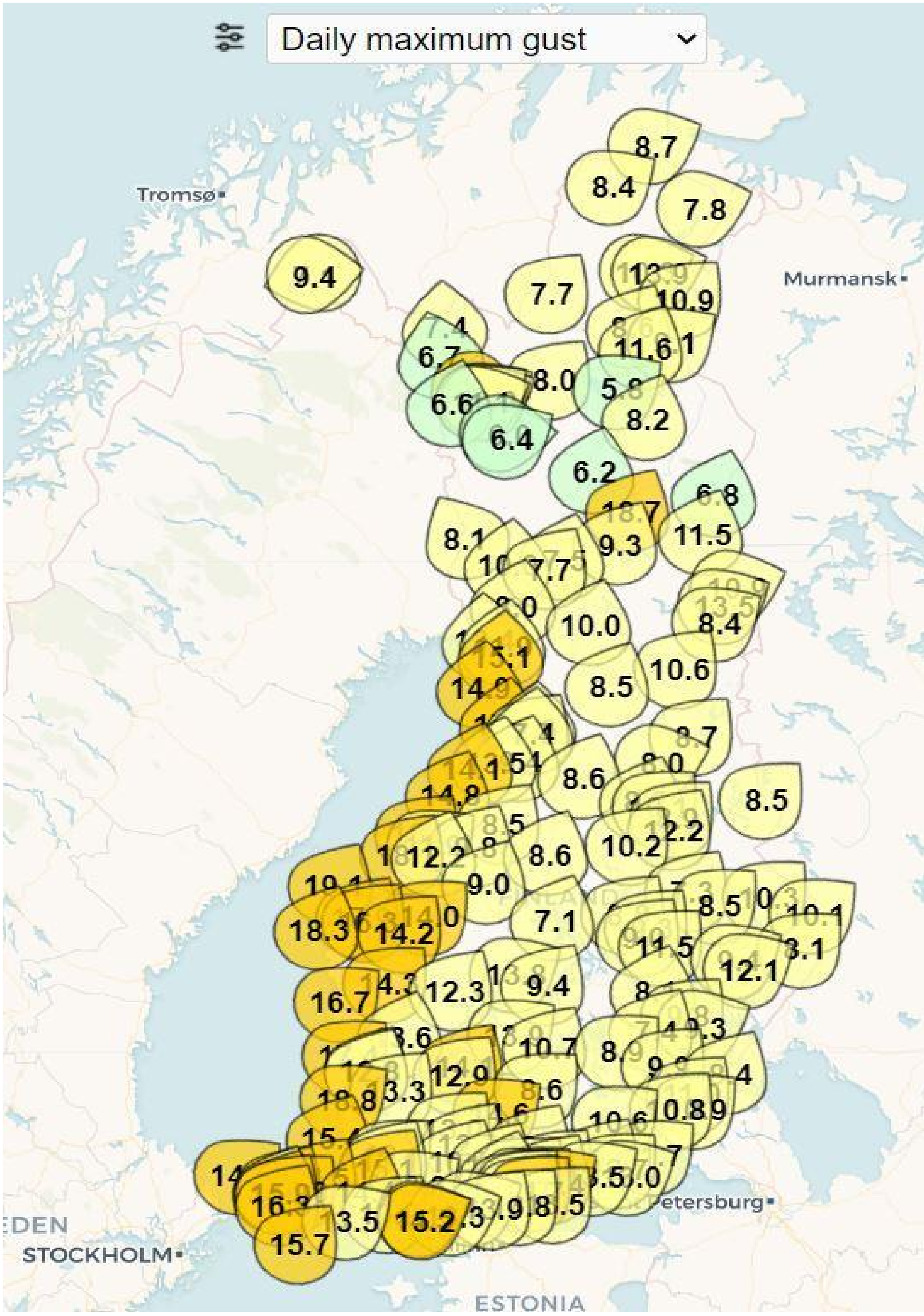

Figure 21. Wind map geospatial data service that shows the maximum daily wind gusts of the FMI wind stations (tuulikartta.info).

The resources and professional skills of the designers must be considered in the analyses related to wind speed. Reliable determination should be made by a specialist in this field In Finland, for example, the FMI has carried out wind analyses on sections of track in the past, and similar analyses could be used to determine wind speeds. Potentially, the FMI could make a data service that could be used by a rail designer to analyse the effect of crosswind.

3.4.6 Determination of critical wind direction

The RCWC value depends on the direction of the wind. The RCWC tables show that the RCWC values is lowest at an angle of 80 degrees, which means that at this wind angle the train is the most sensitive to overturn. Therefore, the RCWC value assigned to 80 degrees is the most critical. Critical RCWC values shall be identified from the area under consideration.

The track usually can move in two different directions, which means that each direction should be considered separately. The most common wind direction in Finland is the northwest wind. The points of the track where an angle of 80 degrees is reached during the northwest wind should be considered separately. Determining the critical wind direction of the track section can be helpful in proposals for mitigation methods. The terrain can also condense or intensify the winds from this direction. Figure 22 shows how the speed of the train affects the effect of the natural wind.

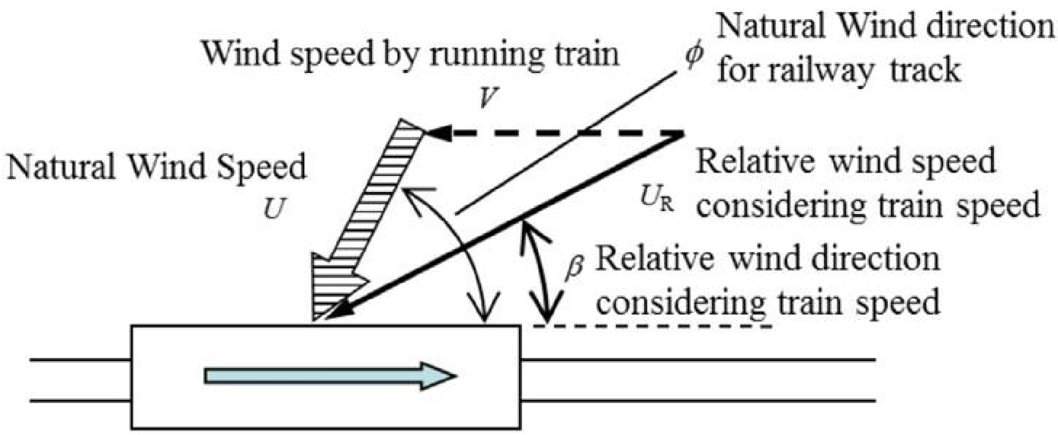

Figure 22. Wind direction considering train speed (Misu & Ishihara 2018).

3.4.7 Mitigation measure proposal

Proposal by designer in terms of infrastructure to guarantee crosswind safety. Proposals should consider costs, functionality, and maintenance. The client must determine which mitigation measures will be implemented or whether none will be implemented. Below an example table for making a proposal.

Table 7. Mitigation measure proposal.

Mitigation measure	Active / Passive	Cost *	Maintenance	Functionality	Cons	Pros
Wind barrier	Passive	$$$	if required	Works any wind speed	Expensive, can collect snow, construction carbon footprint	No need for active actions, works continuously, does not cause traffic inconvenience
External wind control + speed reduction	Active	$	$	Works when wind speed meet risk level.	External wind control leaves room for consideration, affects the operational capacity of rail traffic	Flexible, low cost
Infrastructure managers wind control + speed reduction	Active	$$	$$	Works when wind speed meet risk level	More detailed data on wind strengths near the line	Installing measuring stations and producing data creates costs

* The cost is indicative and should always be defined on a case-by-case basis

4 Results

4.1 Case Study

The crosswind analyse procedure of this thesis will be tested on the Hour Train track section. The hour Train project is suitable for experimenting with the crosswind analyse procedure because the speed of the rail link is between 140 km/h to 250 km/h. In addition, the track line is located quite close to the coast where strong winds occur. The study uses hourly train geometry data to determine the RCWC value. The geometry contains cant deficiency, radius, and speed, which are placed in the formula for transverse lateral acceleration mentioned in 2.3.5. Values and calculation formula were placed in an Excel table.

4.1.1 Project presentation

The One-hour Turku Rail Link is a new double-track rail link between Helsinki and Turku. The project consists of four different parts: the Espoo regional railway line, a new direct railway line from Espoo to Salo via Lohja, the Salo–Turku double track railway line and the Turku rail yard area. The goal of the one-hour train project is to shorten the travel time between Turku and Helsinki, as well as to compact the community structure (Turun Tunnin Juna 2022). There is already a current track connection between Turku Helsinki, which can be seen on the map in the Figure 23 with a lighter cross line in the south. The new rail line runs through arable land and the route will feature waterway crossings, which are generally windier areas for the track than the tracks passing through forest areas.

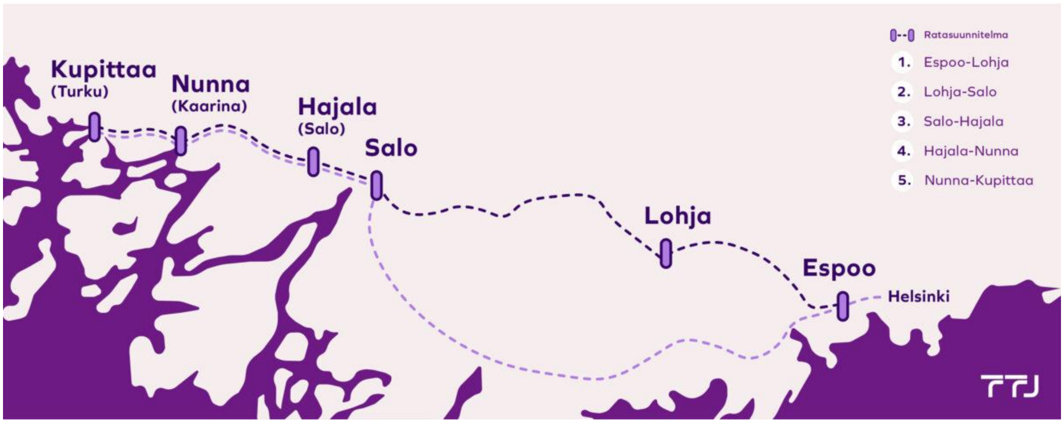

Figure 23. The One-hour Turku Rail Link route and stations (Turun Tunnin Juna 2022).

The project is now in the basic design phase and according to the target schedule, the design will be completed in technical terms at the end of 2023. The geometry of the new tracks is designed so that the speed of trains can increase by up to 300 km/h. The new tracks therefore allow for higher speeds and a more direct route to reduce travel time. In addition to this, the new tracks will provide additional capacity for operations.

4.1.2 The area of the case

The One-hour Turku Rail Link is divided into many separate sections. This Case Study deals with the second track section (Lohja–Salo) from Kekkosentie (track kilometer 88+000) to the beginning of Salonjoki (track kilometer 117+000).

4.1.3 Identification of wind-sensitive points

The method first identifies wind-sensitive factors such as bridge structures and location near a waterbody. One-hour Turku Rail Link map service shows the locations of the bridges on the map and tells the type of bridges. Bridges can be wind sensitive structures, which can be identified as risk points. The type, location, and structure of the bridge play a role in the bridge's wind sensitivity. Bridges allow the railway to cross a terrain obstacle or a body of water. These usually increase the slope of the track from the level of the terrain, and due to the increase in altitude, the wind speed also increases.

For the analysis of wind-sensitive points, this study used the LOUHI geospatial platform of the project. This gave the location of the bridges and the type of bridge. In addition, the orthoimage, was helping to determine the terrain-sensitive areas of the track section. From the orthographic image, water, and field areas can be identified. Vegetation and especially trees slower the wind speed of the area, the wind is stronger in water and field areas. This study identified Wind-sensitive points using section 3.3.1. Figure 24 shows these points (A–E) on the map.

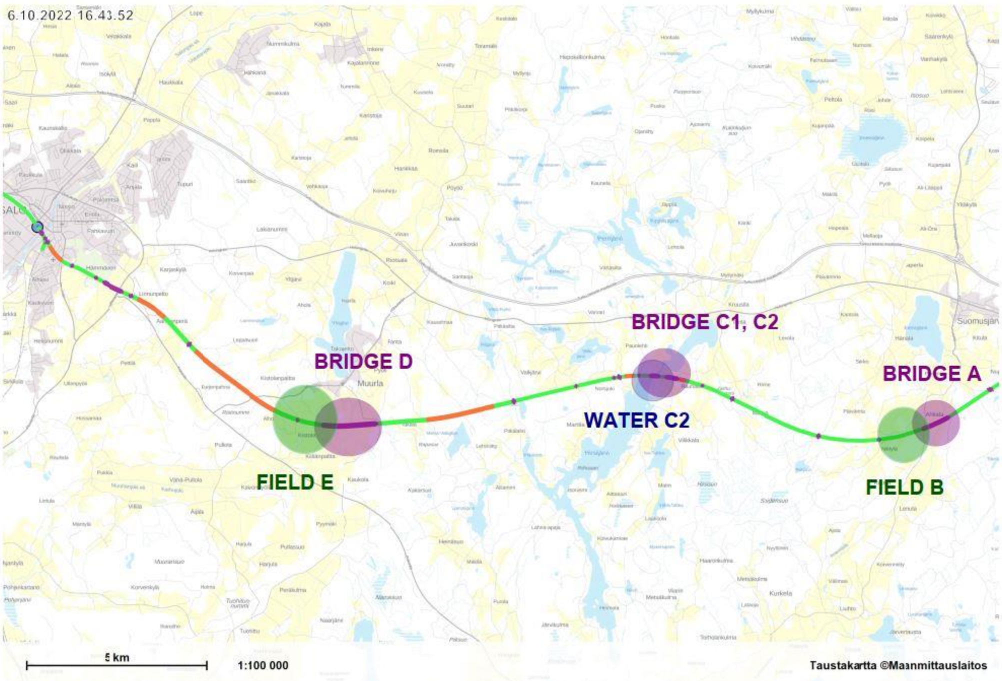

Figure 24. Wind-sensitive sites marked on the map.

After the general map analysis, the target is a slightly familiar. Thus, the study moves on to a more detailed model-based analysis. With the help of a data model, objects and their structures can be examined in more detail. In addition to that the combined effect of several factors can be easily noticed. Figure 25 is taken from the one-hour train data model at the Hirsijärvi railway bridge. From the model, can easily to see the factors affecting the wind, such as barriers. Also, the height of the barriers can also be easily visualized and measured from the model.

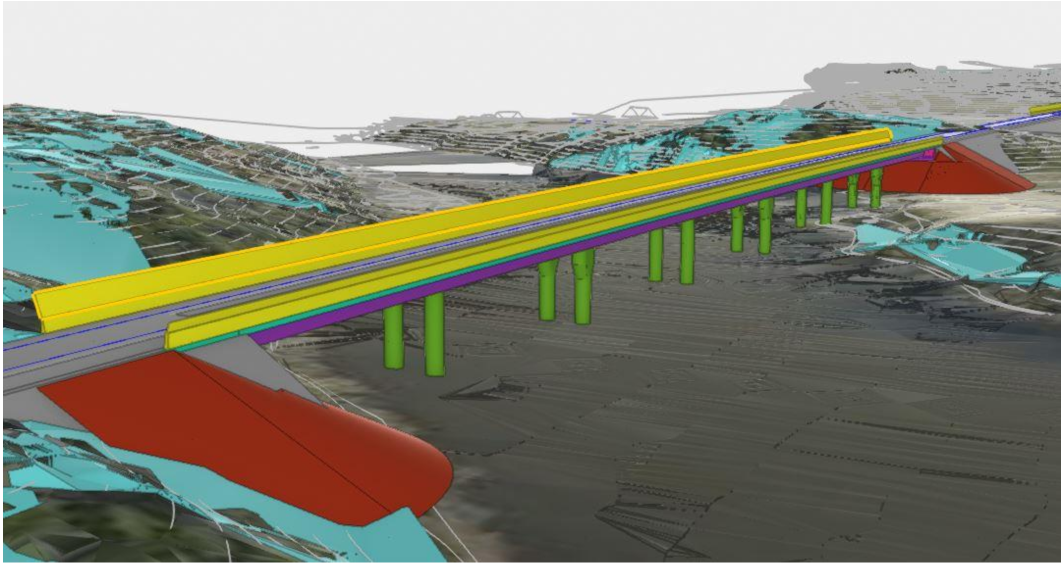

Figure 25. Image of data model at the Hirsijärvi bridge (Trimble Connect).

After identifying wind-sensitive points and their multiple factors, the effects of different factors must be listed. Multiply factors can influence the destination at the same time, for example a bridge crossing a water body. The study evaluated the impact using a five-level evaluation system:

1. Green = significant positive
2. Light Green = positive
3. Yellow = neutral
4. Orange = negative
5. Red = significant negative.

Table 8. Identification of wind-sensitive points.

Location	Location on the map	Structure	Environment	Measure
Ahtialan railway bridge	A	Bridge	Open field area	Immediate measures
Ahtiala (after bridge)	B	Normal track structure	Open field area	Measures to be implemented in the current phase
Sammalo underpass bridge	C1	Bridge	Open field area	Immediate measures
Hirsijärvi railway bridge	C2	Bridge, low barrier	Water crossing	Immediate measures
Muurla railway bridge	D	Railway bridge	Open field area	Immediate measures
Muurla (after bridge)	E	Normal track structure	Open field area	Measures to be implemented in the current phase

4.1.4 Calculating the RCWC value using track geometry

The terrain and track structures make the track more sensitive to wind gusts. The geometry of the track again influences the risks to the train caused by the wind. Track curves are part of the track's geometry, and the risk of crosswind related overturning in curves is greater than on a straight. This is because curves have lateral acceleration. The lateral acceleration is affected by the radius of the curve, the change in inclination, and the speed of the train. Lateral acceleration affects the CWC value.

In this Case Study, geometry values are used as input data, as well as the method from the previous paragraph to calculate RCWC. Inspections were carried out on two tracks, the southern and the northern track. The geometries of the tracks were entered into an Excel, which appear in Table 9 and Table 10, from which a value for the transverse acceleration was obtained. The RCWC value can be reeded from Table 4, Table 5, and Table 6 using the lateral acceleration and the speed of the train.

Table 9. RCWC calculate table for the northern track.

The geometry of the northern track (PR)

Curve start - end	Curve radius	Cant	Speed	Lateral acceleration*	Rounded lateral acceleration**	RCWC
Km	R	D	V	m/s2	m/s2	m/s
88 + 873 - 94 + 419	5000	100	250	0,351	0.5	23.49
95 + 893 - 99 + 684	5050	100	250	0,341	0.5	23.49
103 + 370 - 104 + 771	7000	80	250	0,198	0.5	23.49
106 + 495 - 109 + 608	3890	80	250	0,749	1.0	20.94
110 + 783 - 111 + 950	5000	80	250	0,474	0.5	23.49
112 + 429 - 114 + 019	3000	80	220	0,754	1.0	22.14
114 + 118 - 114 + 805	5000	50	220	0,440	0.5	24.69
115 + 401 - 115 + 774	2000	50	120	0,249	0.5	28.69
115 + 774 - 116 + 630	1100	60	120	0,642	1.0	26.14
116 + 630 - 116 + 798	1400	50	120	0,487	0.5	28.69

*If V< 120 km/h Aq max aq = 0.65 m/s2 and if V>= 120 km/h Aq max aq = 0.80 m/s2

**Lateral acceleration are always rounded up to a higher value

Table 10. RCWC calculate table for the southern track.

The geometry of the southern track (ER)

Curve start - end	Curve radius	Cant	Speed	Lateral acceleration*	Rounded lateral acceleration**	RCWC
Km	R	D	V	m/s2	m/s2	m/s
88 + 873 - 94 + 419	5005	100	250	0,350	0.5	23.49
95 + 893 - 99 + 684	5045	100	250	0,342	0.5	23.49
101+798 - 101+905	7000	50	250	0,382	0.5	23.49
102+205 - 102+313	7000	50	250	0,382	0.5	23.49
103+670 - 104+471	7000	80	250	0,198	0.5	23.49
106+495 - 109+608	3910	80	250	0,743	1.0	20.94
110+783 - 111+950	5020	80	250	0,470	0.5	23.49
112+429 - 113+839	2980	80	220	0,762	0.5	24.69
114+293 - 114+805	5004,7	50	220	0,439	1.0	22.14
115+388 - 115+769	1995,3	50	120	0,250	0.5	28.69
115+769 - 116+632	1104,7	60	120	0,638	1.0	26.14
116+632 - 116+803	2000	50	120	0,249	0.5	28.69

*If V< 120 km/h Aq max aq = 0.65 m/s2 and if V>= 120 km/h Aq max aq = 0.80 m/s2
**Lateral acceleration are always rounded up to a higher value

4.1.5 Speeds and directions of wind gusts in the study area

The storm readings measured at sea appear on the coasts and inland as a 10-minute average wind speed of at least 8–12 m/s but strong winds, i.e., around 14 m/s, rarely occur (Ilmatieteenlaitos 2022). However, wind gusts can reach readings significantly faster than the average wind. The Figure 26 show the highest wind gust readings of the day measured at wind stations on Thursday 6 October 2022. On the coast, storm readings of over 21 m/s 10-minute average wind speed were measured.

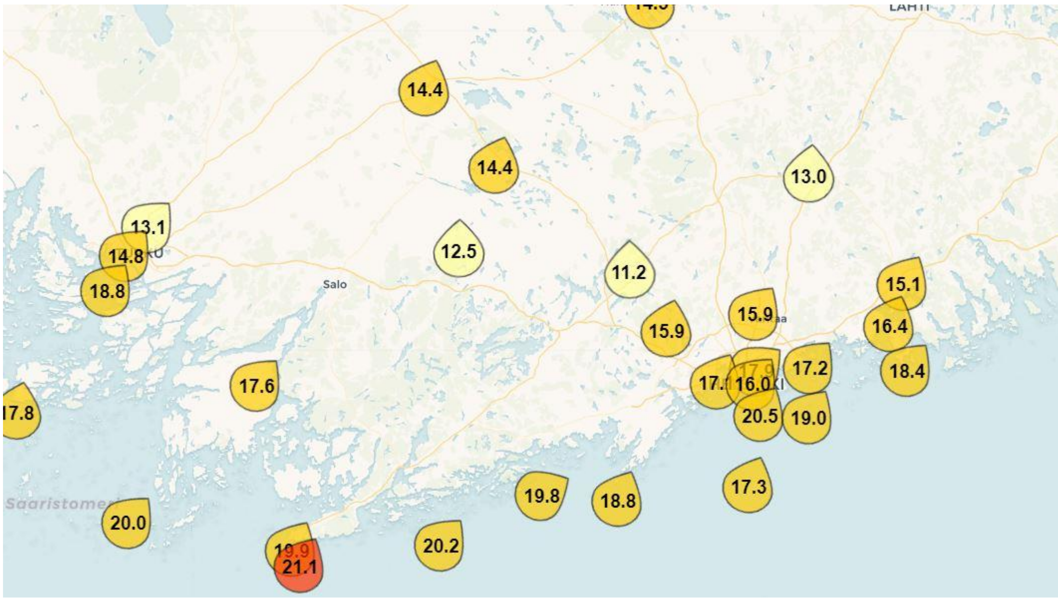

Figure 26. Image Thursday 6 October 2022. of the strongest wind gusts measured in southern Finland (Tuulikartta 2022).

The most common wind direction for the inspection area is the southwest wind blowing from the sea. The most critical wind directions towards the train are at an angle of 90–60 degrees, and the most critical direction is at an angle of about 80 degrees. On the analysed track section, the critical winds blow from a different direction on the trains running from Helsinki to Turku than on the trains running from Turku to Helsinki. The Figure 27 illustrates the most critical wind direction, i.e., the 80-degree direction towards the train, in point C1. The red arrow shows the critical wind direction for the Helsinki-Turku direction and the blue arrow for the Turku-Helsinki direction.

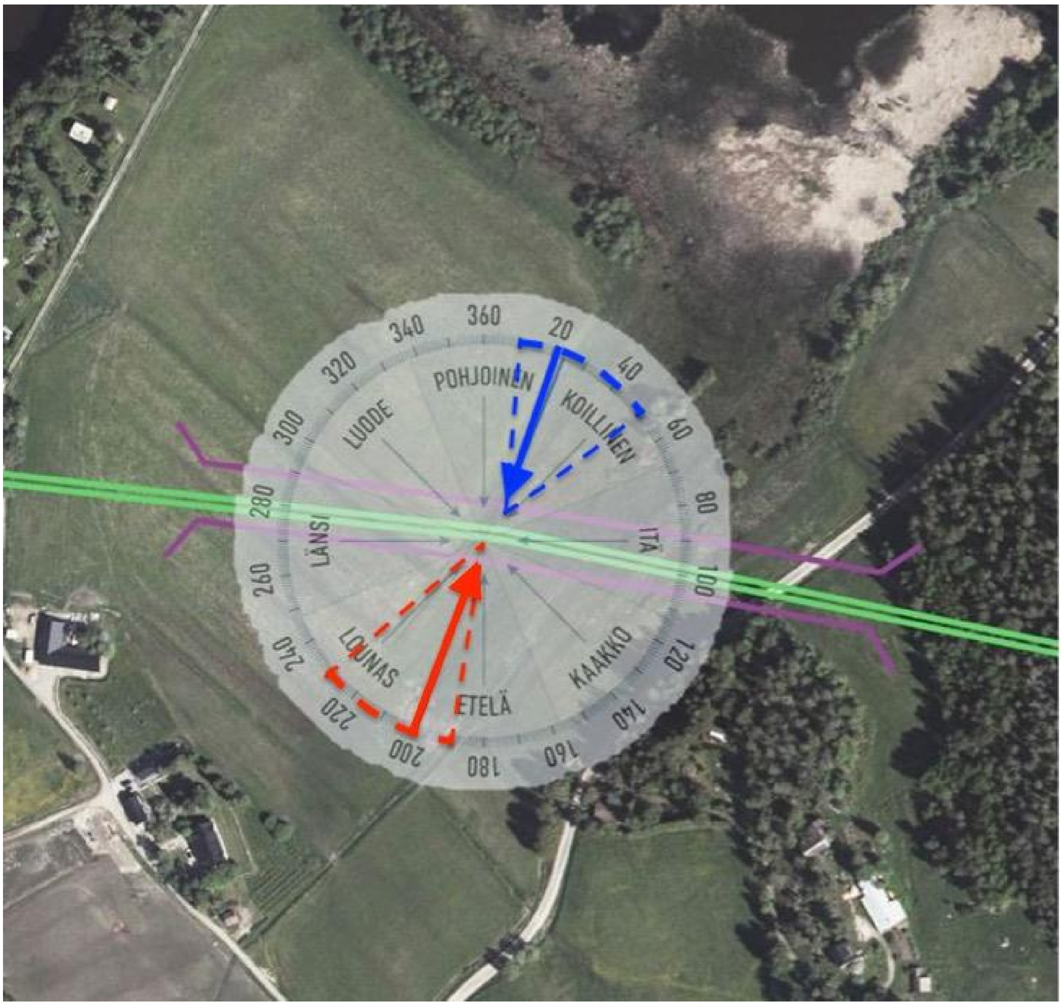

Figure 27. The most critical wind directions affecting the train in Sammalo underpass bridge.

4.1.6 Mitigation measures

After identifying the wind-sensitive points and their identification, appropriate mitigation measures for the points are determined. Table 11 shows an example for mitigation measure for the Hirsijärvi bridge (C2 in Figure 24).

Table 11. Example of the mitigation measure table for the Hirsijärvi railway bridge.

Mitigation measure	Active / Passive	Cost	Maintenance	Functionality	Cons	Pros
Building higher noise barriers, which also work wind barriers	Passive	$$	If required	Works any wind speed and does not affect operation.	Expensive to build, can collect snow in winter, construction cause bigger carbon footprint	No need for active actions, works continuously, does not cause traffic inconvenience
External wind control + speed reduction	Active	$	$	Works when wind speed meet risk level. Can affect operation.	External wind control leaves room for consideration, affects the operational capacity of rail traffic	Flexible, low cost

4.1.7 Summary table

At the end of the analysis, a summary table is compiled for the client. From this, the customer should clearly see the points, which are sensitive to crosswind. Table 12 shows an example a summary of example from the Sammalo underpass bridge (C1 in figure 14). The summary table 12 tells the location of the point, the measure level, the critical wind direction in relation to the train's direction, and the proposed measures identified for the target.

Table 12. Example of the summary table for the Sammalo underpass bridge.

Location	Location on the map	Measure	Critical wind direction	Proposed Measures
Sammalo underpass bridge	C1	Immediate measures	Hki-Tku: S & SW (about 200 degrees) Tku-Hki N & NE (about 20 degrees)	Higher bridge safety barrier. Speed limits.

4.1.8 Summary of the Case Study

In this case, the reliability of the analysis was affected by the available initial data. A more detailed analysis would need better measurement results of the speed of gusts at the identified wind-sensitive points. In terms of accuracy, the analysis would fit at the level of a general plan. The initial information obtained does not allow for crosswind analysis at the level of the detailed design. The track plan for the entire project is still in progress, so it was not possible to use all the information in the track plan for the case study. However, the track geometry of the track plan was obtained for the case study, and the general plan was used as initial data.

For the analyses of the more detailed planning stages, it would be important to check the project design and land use changes. Changes can increase or decrease the risk points or change the measure classes of points. As the plan becomes more detailed, the number of factors may increase, for example, the locations of the noise walls are often decided in the detailed design phase. The locations of the noise walls influence the track's wind sensitivity and can thus significantly affect the risky points.

5 Discussion

5.1 Discussion of crosswind methods

Finland as part of the European Union must comply with the directives set by the EU; therefore, the new method must be in accordance with these directives. When choosing a method, it is also essential to consider Finland's current system. The method is easier to implement if it is compatible with the old system. For example, the calculation methods used in Sweden and Germany would be rather challenging to bring to Finland's current model. In Germany and Sweden, the determination of safety limit values is based on a calculation where the probability of a person's death is determined in relation to track kilometres. Determining rail safety in Finland is not based on this type of probability calculation method. Therefore, Finland should first define this type of calculation method for safety limit values before introducing the crosswind method into the current system.

The calculation of France's critical risk number is based on the probability of the train overturning, not on the number of lives that may be lost because of the accident. This method considers the possibility of an overturning based on the characteristics of the track, the rolling stock, and the wind. Therefore, the method does not require defining a limit for the probability we allow for a person's death. The calculation method according to The French method would be significantly easier to implement in Finland than the Swedish or German calculation methods.

Calculations based on probabilities of death can be problematic in terms of transport policy. Some of those methods have a different value for different types of people, which can be perceived as discriminating. For example, the value of children may be higher than others, because they have more expected life years left than adults. This calculation methods can therefore lead to challenging questions that are not directly related to the probability of overturning due to crosswind.

In the study, it was decided to use RCWC values instead of CWC values. CWC is specific to the rolling stock, which makes it difficult to determine the value to be used during the railway planning phase. Railways are usually not designed for only one type of rolling stock, but the tracks can be operated with several different type of rolling stocks and speeds. Therefore, the determining rolling stock should determine according to which CWC values would be used in Finland.

In Finland, most of the tracks are mixed tracks, which means that both freight and passenger trains can run on them. However, this study deals only with passenger trains. The CWC curves of passenger trains are also different depending on their shapes and characteristics of the train. The CWC curves of the fleet are usually obtained from the rolling stock manufacturer. In addition, railways and rolling stock generally have very different lifespans. Railways are designed to last much longer than rolling stock. This leads to situations where the railways remain the same while the stock changes to a newer one.

5.2 Implementation of analysis

One of the results of the interview with the designer was that the crosswind analysis should start with the preliminary study and end with the detailed design. The analysis of the previous phase serves as the initial data for the next phase, this initial data should be updated and refined. The analysis becomes more detailed in each planning phase, at the same time internal and external changes affecting the plan must be considered again. As an example, terrain changes near the line can change the wind sensitivity of risk points A more detailed identification of risk points requires more detailed initial data. In the case of wind data, initial data is obtained from external meteorological services if necessary. Figure 28 summarize the crosswind analysis progress with the different design phases.

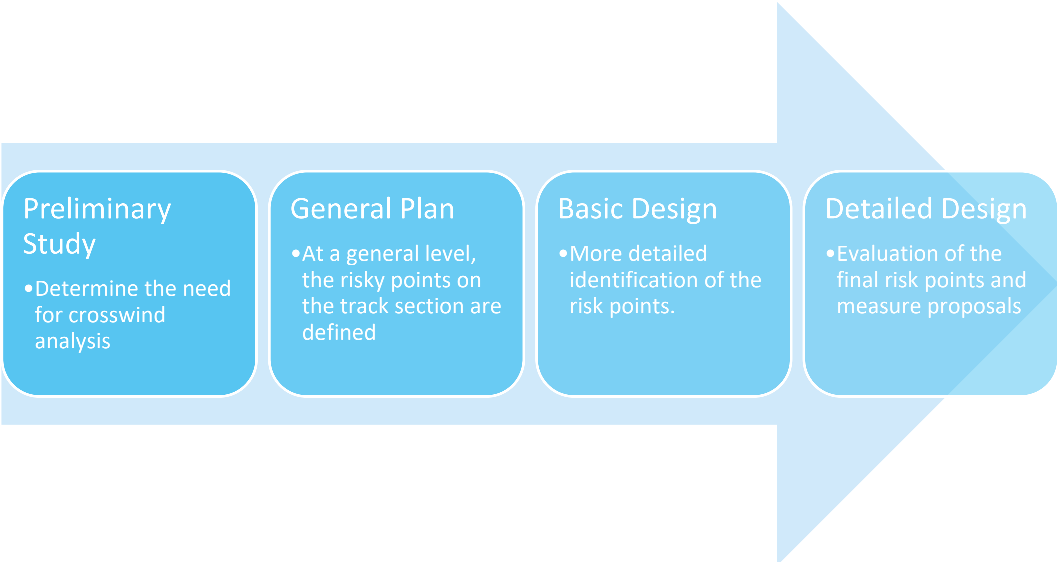

Figure 28. A revised crosswind analysis should be included in different design phases continuously.

Preliminary Study

The client and the designer must work together to find out the need for a crosswind analysis. This is mainly determined by the maximum speed planned for the line, but the geographical location of the line also affects the need for crosswind analysis (coastal areas). The final decision on the need for analysis is made by the project client.

General Plan

The designer makes crosswind analysis according to the customer's instructions. The client determines the accuracy level of the crosswind analysis to be suitable for the project. The designer must be given the necessary initial information. Client and designer agree on the programs used in the analysis.

Basic Design

The crosswind analysis carried out in the general plan must be handed over to the designer as initial information. The client determines the accuracy level for refining the crosswind analysis and gives the necessary information (may include, for example, additional metrological measurements of wind strengths in the line). The designer makes the analysis according to the customer's instructions.

Detailed Design

The crosswind analysis carried out in the basic design and possible additional measurements must be handed over to the designer as initial information. The client determines accuracy level of the final crosswind analysis, including final measure proposals. The designer makes the analysis according to the customer's instructions. The client is responsible for deciding on the final measure proposals for the risk target.

5.3 Limitations of the research

The reliability of the research is assessed through the limitations and possibilities of error related to the research. The reliability of the research can be examined by evaluating the validity and reliability of the research. Validity describes how well the research has been able to investigate its topic and phenomena and whether the chosen research method was successful. Reliability, on the other hand, refers to the repeatability of measurement results (Hirsijärvi et al. 2009).

In the interviews, a ready-made interview framework was used, based on which the interviews were conducted. An effort was made to preserve the reliability of the interviews by asking the questions clearly and by asking more detailed questions to find out the answers. The questions were sent to the interviewees a few days before, so that the interviewers are aware of the topic and can prepare for the interview. This way, the interviewer can prepare and check uncertain things before the interview. The interviewer of the study conducted the interviews independently, which makes the interpretation of the answers subjective. This may have an impact on the results obtained from the interviews.

The interviews were conducted as theme interviews, where the bias of the interviewer can affect the reliability of the interviews. During the interview, some of the prepared interview questions can be left out or additional questions can be asked if something that has been brought up needs to be clarified in more detail. In turn, the interviewer's beliefs, and background affect how the interviewer understands the answers received, which can cause the results to be biased. The results of the interviews may also have been affected by the limited number of interviewees. In Finland, there is a limited number of experts familiar with the subject, and on the other hand, the scope of the thesis also affects the number of interviewees. The results obtained in the interviews were compared with the results in the literature, which increases the equivalence of the results.

In this thesis, it was found out how the crosswind could be considered on the Finnish railway network. In addition, the study created a model that would allow the designer to identify sections of railway exposed to crosswinds and propose mitigation measures for them. Actual crosswind mitigation methods are not yet in use in Finland, so there is a need for further research. There are a lot of uncertain things related to the consideration of crosswinds and mitigation methods, which should be tested in projects. In the project profitability, relations between the parties, as well as the investment and maintenance costs of the mitigation measures could be studied. This thesis could serve as a basis for research on the project. The crosswind analysis procedure created in the study can also be used in further studies.

6 Conclusions

Rail-based transport is constantly being developed with faster connections, which raise the risk of train overturning caused by crosswinds. This thesis showed that train overturning caused by crosswinds has very serious consequences. Fortunately train overturning caused by crosswinds are so far unlikely in Europe. Crosswinds have been identified as a risk factor and measures to reduce the risk of overturning have been investigated. In Finland, the number of crosswind studies is limited, where the railway infrastructure perspective has been considered very slightly.

This thesis focused on how the effect of crosswind could be considered in railway design. The thesis found out which factors influence the crosswind. The most important factors were train speed, terrain, geographical location, track infrastructure structures such as track bridges, and track geometry. After this, the thesis found out which factors can be influenced in track design and which factors should be accepted. In terms of track design, the vertical and horizontal geometry of the track can be influenced. The crosswind is affected by the lateral acceleration, the higher the lateral acceleration is, the more sensitive the track is to the crosswind. In other words, railway sensitive points to crosswinds occur in curves. However, it does not necessarily make sense to make geometry changes due to crosswinds if the change has a negative effect on the overall geometry or other significant field. However, the track designer should be aware that, for example, designing a curve for a railway bridge is generally a bad option in terms of crosswinds. After all, when planning a railway, the entire project must be considered, and in terms of crosswind, a bad option can be the only option or the best option in terms of the whole project. In this situation, designer should think about what different measures can be taken to prevent the effect of the crosswind.

In Finland, the effect of crosswind on the rolling stock has been studied and crosswind reports have been made for selected sections of track, but no actual studies have been carried out on various mitigation measures. The thesis was limited to various mitigation measures to prevent the effects of crosswinds, which have been tested internationally. The measures focused on the measures during the planning phase of the railway infrastructure and did not consider much the measures related to the equipment or operation. The thesis determined the following measures: active wind control with speed reduction and passive wind barriers. The possibilities of the measures should always be analyzed on a case-by-case basis. There is no information on different mitigation measures in Finland, so it is very difficult to assess their functionality and costs. To clarify the different measures, more international experiments should be studied, and measures should be piloted in Finland.

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Appendix 1. Interview questions

21/06/2022

Master Thesis Interview

Sebastian Stichel, KTH Royal Institute of Technology

The need for research

- The effect of side winds on rail transport has been investigated since the 1970s by international research, especially by the railways in Germany, England, and Japan. How do you see research needs in the Nordic countries?

Previous knowledge of the expert on the subject

- You've done research on track maintenance. Do you see that level of maintenance also has an effect in wind-related accidents? Can the risk be prevented through good maintenance?

Climate change

- Climate change is increasing extreme weather conditions; do you see this as a threat to track safety? How should rail designers take this into account to guarantee train travel safety and common trust of train services?

Measures to ensure safety

- What options do you see as the most potential to reduce the risk of wind-related accidents? (Wind barriers, lower speed, geometry)

05/08/2022

Diplomityö, haastattelu

Ilmatieteenlaitoksen tutkija Mikko Laapas

Tutkimustarve Suomessa

- Näetkö sivutuulen tutkimisen tarpeellisena Suomen raideliikenteen turvallisuuden takaamisessa?
- Miten Suomi voisi hyödyntää aiempaa tutkimusta aiheesta?

Asiantuntijan aikaisempi tutkimus aiheesta

- Olette tehneet aikaisempaa tutkimusta tuulen vaikutuksesta Suomen pääradalla (Tampere-Oulu osuudella) ja rantaradalla (Karjaa-Turku osuudella). Miten määritけitte näissä tutkimuksissa tuulennopeudet kynnysarvot (kynnysarvot 21 m/s ja 23 m/s, kaarteissa 18 m/s)?
- Onko tutkimuksissa huomioitu Suomessa käytössä olevaa raidekalustoa?

Ilmastonmuutos

- Kuinka ilmastonmuutos vaikuttaa tuulten voimakkuuteen Suomessa?
- Kuinka ilmastonmuutos vaikuttaa maaston muuttumiseen Suomessa?

Toimenpiteet

- Tuulen nopeus ja suunta vaikuttaa junan kaatumisen riskiin. Miten hyvin Suomessa on mahdollista mitata tuulen suuntaa ja mallintaa mistä suunnasta tuuli kohdistuu junaan? Onko tuulen mittausantureita asennettuna radan lähettyville?
- Kuinka hyvin arvioit Ilmatieteenlaitoksen ja raidesuunnittelun tekevän yhteistyötä tuulimittauksien tiimoilta? Mitä haasteita näet yhteistyössä?
- Ilmatieteenlaitos tuottaa tuulipalveluita energiasektorille yhtenä esimerkkinä Tuuliatlas. Voisiko Ilmatieteenlaitos tuottaa palveluita junaliikenteen turvallisuuden takaamiseksi Suomessa?

07/09/2022

Diplomityö, haastattelu

Pasi Kaikkonen, Skoda Transtech Oy

Tutkimustarve Suomessa

- Näetkö sivutuulen tutkimisen tarpeellisena Suomen raideliikenteen turvallisuuden takaamisessa?
- Käytetäänkö junakaluston suunnittelussa ohjeistuksia sivutuulen huomioimisessa? Kuinka Suomi voisi hyödyntää aiempaa tutkimusta aiheesta?

Asiantuntijan aikaisempi tieto aiheesta

- Onko Suomessa käytössä olevassa junakalustossa huomioitu sivutuulen vaikutus? Onko radan ja kaluston yhteensovitus otettu huomioon? (esimerkiksi Suomen raideleveys tai geometria)
- Kuinka suuret ovat sivutuulen vaikutuksen erot 2 ja 1 kerroksisien vaunujen välillä? Voidaanko 2 kerroksisien vaunujen laskentakaavoja hyödyntää 1 kerroksisiin vaunuihin?

Ilmastonmuutos

- Ilmastonmuutoksen vaikutukset kaluston suunnitellussa?
- Varaudutaanko kaluston suunnittelussa sään ääri-ilmiöiden yleistymiseen?

Toimenpiteet junaturvallisuuden takaamiseksi

- Mitä eri sivutuulen lieventämismenetelmiä näet potentiaalisiksi kaluston ja raidesuunnittelun näkökulmasta? Entä operoinnin ja radan hallinnan näkökulmasta?
- Tulisiko kalustosuunnittelijoiden ja raidesuunnittelijoiden lisätä suunnitteluvaiheen yhteistyötä sivutuulen aiheuttamien uhkien vuoksi? Mitä hyötyjä ja haasteita näet yhteistyössä?

12/10/2022

Diplomityö, haastattelu

Karita Silander, riskienhallinnan suunnittelija

Suunnittelijan erikoisosaaminen: riskienhallinta

- Riskimatriisin käyttämisen hyvät ja huonot puolet? Ehdotukset kuinka matriisia voitaisiin käyttää paremmin ratasuunnittelussa?
- Vastuun jakaminen tilaajan ja suunnittelutoimeksiantajan kesken. Kuinka vastuu tulisi jakaa ja mitä lähtötietoja tilaajalta tarvitaan?
- Voisiko sivutuulen huomioimisen lisätä osaksi riskienhallintaa? Missä suunnitteluvaiheessa?

Ilmastonmuutos

- Ilmastonmuutoksen vaikutukset riskienhallintaan? Huomioidaanko sään ääri-ilmiöiden yleistymistä entistä enemmän?

Toimenpiteet ja ehdotukset turvallisuuden takaamiseksi

- Mitä eri sivutuulen lieventämismenetelmiä näet potentiaalisiksi riskienhallinnan näkökulmasta?

13/10/2022

Diplomityö, haastattelu

Anna Häkkänen, ratasuunnittelija

Suunnittelijan erikoisosaaminen: ratasuunnitelma

- Parannusehdotukset metodiin, kuinka ohjetta/toimintatapaa voisi helpottaa suunnittelijan näkökulmasta?
- Vastuun jakaminen tilaajan ja suunnittelutoimeksiantajan kesken. Kuinka vastuu tulisi jakaa ja mitä lähtötietoja tilaajalta tarvitaan?
- Kuinka sivutuuli tarkastelut voitaisiin käyttöönottaa osaksi ratasuunnittelua?

Ilmastonmuutos

- Ilmastonmuutoksen vaikutukset ratasuunnitteluun? Huomioidaanko sään ääri-ilmiöiden yleistymistä entistä enemmän?

Toimenpiteet ja ehdotukset turvallisuuden takaamiseksi

- Mitä eri sivutuulen lieventämismenetelmiä näet potentiaalisiksi ratasuunnittelijan näkökulmasta?

13/10/2022

Master Thesis Interview

Sergio Sánchez, Train Designer

Designer's specialty: Railways and high-speed railways

- Suggestions for improvements to the method, how could the instructions/method of operation be made easier from the designer's point of view?
- Division of responsibility between the client and the designer. How should responsibility be shared and what initial information is required from the client?
- How could crosswind safety checks be implemented as part of track design?

Climate change

- Effects of climate change on railway design? Is the increasing frequency of extreme weather phenomena being considered even more?

Measures and suggestions to ensure safety

- What different crosswind mitigation methods do you see as potential from a track designer's point of view?

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