ERA 2013 20 INTEROP OP
STUDY ON UNIVERSAL OVERHEAD CONTACT LINE DESIGN * PHASE 2 *

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Contents

Summary

The current study of ANA_3 & ANA_4 has the objective to develop a standard method for Inframanagers to assess the chance of dewirement and infringement on local infrastructures. To achieve the objectives, all factors that determine the position and movement of the related systems are examined. This involves the identification of their relevance and the study of their nature and significance.

It appears that current infrastructure designs are often based on worst-case scenarios and general load requirements. The study identifies reliable opportunities to exploit the reserve in existing design rules. The opportunities are based on a more nuanced and realistic view of the specific situation.

- Nuanced: Use the most accurate data available for the location, instead of general maximum values.
- Realistic: Adopt a risk-based approach, identifying the stochastic nature of significant parameters.

To effectively adopt a risk-based approach while totally eliminating the chance of disruption, the concept of dewirement is replaced by the idea of ‘contact wire launch’. The new approach for the design rules is laid out in guidelines with the aim to standardise the assessment method for existing local infrastructures. The method specifies a structured way to calculate margins to assess the chance of contact wire launch and the chance of infringement. The study also introduces the concept of ‘turning point’ in the wire deflection.

Some modifications in the calculation of wind load and wire deflection are proposed:

- The wind load perpendicular to the OCL span shall be calculated based on the distribution of the wind velocity for the angle of incidence according to the distribution of the wind direction and the orientation of the span.
- The wire deflection shall be calculated taking into account the sideways force from the pantograph according to the dynamic uplift force and the surface angle at the position of the contact point.
- The wire deflection shall also be calculated taking into account the coupling force between contact wire and catenary wire.

The design rules according to the guidelines are put to the test in trial simulations on a virtual railway line. This involves the following engineering:

- Analysis of the information provided by the previous study (ANA_1 & ANA_2);
- Analysis of the behaviour of stochastic parameters, typically wind pattern and vehicle sway;
- Programming of datasheets to perform simulations for contact wire launch and infringement;
- Building cases to find critical situations, investigating typical curve radius - span length ratio’s;
- Performing the simulations for contact wire launch;
- Analysis of the results of simulations to identify critical spans and propose cost-effective modifications to maintain performance levels.

The study showed that the proposed standard method allows Inframanagers to:

- Transparently asses the chance of contact wire launch and infringement;
- Tailor the local infrastructure and railway operation in a cost-effective way;

The first part of the study (ANA_3) recognises the need to validate the outcomes in real situations. The following activities are foreseen for the second part of the study (ANA_4):

- Repeat the simulations and analysis of the assessment with real data taken from a specific railway line.
- Analyse in detail the sensitivity of the pantograph shape and uplift force on the contact wire deflection.

1 Introduction

1.1 BACKGROUND

To achieve an acceptable standard for safe and reliable operation of electrified railway lines, close contact between the pantograph and overhead contact line should be maintained at all times. The design of trains and infrastructures to achieve this standard show many variations among the European countries, due to differences in operational requirements at the time in the design history.

The European Railway Agency (ERA) sets out the goal to obtain interoperability among countries of the European Union with the aim to achieve free access.

In order to do so, ERA has undertaken a study in which it investigates the possibility of taking two of the most common and widely used types of pantograph geometries and adopting these as a standard for the whole European Community. The two types of pantographs chosen differ in size and shape. Principally, the narrow pantograph has a length of 1600 mm, while the wide pantograph has a length of 1950 mm.

The obvious difficulties for countries to allow both standards on their existing networks were mapped in a pilot study. This study explored the consequences of narrow pantographs being introduced on networks designed for wide pantographs and vice-versa. The study was focussed on identifying opportunities to limit the chance of dewirement and infringement, based on a stochastic approach of dynamic parameters in the calculation of lateral movements in the Track/Train/OCL-interface.

Based on the positive outlook, ERA initiated a follow-up study to develop a method for Inframanagers to allow the Member States to assess local infrastructures in order to accommodate both types of pantograph, using a risk-based approach. The results of this study are treated in this report.

1.2 OBJECTIVES

The objectives are targeted on the safe and reliable operation of electrified infrastructures according to the lateral positions and movements of relevant systems. Therefore the scope of the initiated study is defined as the following:

- To allow narrow pantographs (1600 mm) on networks designed for wide pantographs, introducing the chance of dewirement;
- To allow wide pantographs (1950 mm) on networks designed for narrow pantographs, introducing the chance of infringement.

The precise shape and dimensions of the 1600 mm pantograph and the 1950 mm pantograph are defined in European Standard EN 50367:2012.

1.3 PREVIOUS STUDY ANA_1 & ANA_2

The following conclusions were drawn in the first part of the study (ANA_1 & ANA_2):

- It is possible to adapt OCL-designs, making them suitable for both pantographs with limited changes of the networks. However, intervention is necessary on some locations;
- No increased chance for dewirement in running trains with 1600 mm pantographs on straight tracks equipped with large spans designed for 1950 mm pantographs;
- No increased chance for infringement, except in presence of civil structures and station awnings. The scale of the problem is yet unknown;
- It is expected that a further relaxation of the limits for maximum allowable lateral deviation is possible, due to real dewirement probabilities (estimated in ANA_2).

The study recommended the following options:

- A modification in the stagger pattern, keeping chance of dewirement as low as it is now (on straight track and curves with R > 5000 m);
- For the current 1600 mm profile, enlargement of the position of contact point to 1435 mm does not result in dewirement (though with loss of connection);
- A comparison of the calculation methods in EU-standards with real wind blow-off measurements.

The study presented the following opportunity:
The calculated probability is the basis for the calculation that a dewirement would occur at a certain location. To calculate how often a dewirement will occur on a certain railway line or location on a line, the probabilities will have to be multiplied with the following probabilities:

- The probability that a pantograph of that type will be at that exact location or near it;
- The probability that the specified wind speed will occur at that location;
- The probability that the wind gust will be about perpendicular to the track.

1.4 CURRENT STUDY ANA_3 & ANA_4

The current study (ANA_3 & ANA_4) comprises the following scope of work:

- Analysis of outcomes from the first part of the study (ANA_1 and ANA_2) with the aim for changes in current OCL design rules;
- Development of procedures, calculations and steps needed to be performed to evaluate if specific current OCL designs can accommodate pantographs 1600 and 1950 based on the outcomes of the first phase of the study (ANA_1 and ANA_2);
- Proposals for necessary changes in OCL design rules or maintenance & operational rules in order to allow EP on 1950 network and 1950 on EP/1450 network;
- Proposals, methodology and execution plan of foreseen tests to be performed at ANA_4;
- Execution of proposed tests for evidence of location of contact point in real conditions and for confirmation of suggested changes according to ANA_3;
- Proposal of possible corrections to ANA_3 after execution of tests (if needed).

From a general perspective, the project goal is expressed as follows:

- To provide Inframanagers with general design rules and guidelines, to assess local infrastructures using a risk-based approach, transparently weighing interests in a shared responsibility.
- In short: A standard method for Inframanagers to determine the margins, make cost-effective modifications and identify optimization opportunities.

2 Approach

The approach in the current study (ANA_3 & ANA_4) follows the same simulation principles as the previous study (ANA_1 & ANA_2), adopting the Monte Carlo simulation as the standard method. However, the tools to recreate the models and perform the simulations are programmed based on the information provided in EU-Standards, TSI documents and other relevant sources. The study expands on the previous, incorporating focus points in special situations such as catenary overlap an OCL-switch.

2.1 REFLECTIONS ON ANA_1 & ANA_2

The previous study of ANA_1 & ANA_2 concludes that a probabilistic approach offers opportunities. This conclusion is supported by the current study of ANA_3.

The previous study of ANA_1 & ANA_2 calculates the chance of dewirement and infringement for specific types of rolling stock in spans defined by curve radius, speed, cant and OCL-type. Deterministic values for environmental parameters are used to calculate maximum wire deflection.

In the follow-up study of ANA_3 factors are taken from the previous study of ANA_1 & ANA_2 and checked on relevance and impact. It is recognized that the distributions of parameters in rolling stock characteristics are much narrower than the distributions of parameters in the wind pattern (wind speed and -angle). This leads to a focus on opportunities already identified in the previous study, suggesting the use of stochastic values for the wind pattern. Calculations show that dewirements can occur at medium wind speeds.

The previous study of ANA_1 & ANA_2 suggests to multiply the chance of dewirement originating from an infrastructure (track & OCL) and rolling stock point-of-view, by an environmental perspective based on the probability that:

1. A pantograph of that type will be at that exact location or near it;
2. The specified wind speed will occur at that location;
3. The wind gust will be about perpendicular to the track.

The follow-up study of ANA_3 uses Monte Carlo simulation to calculate the probability of dewirement and infringement, based on combined occurrences in stochastic parameters for the calculation of lateral movement of track, train and overhead contact lines. From an environmental perspective, the wind speed appears to behave according to a Weibull-distribution and the wind angle is generally divided into 12 separate wind directions. Individual occurrences of a pantograph passing are iterations in the simulation.

The previous study of ANA_1 & ANA_2 does not freely provide the simulation program or infrastructure model used in the simulations, so all calculations are programmed into a new tool. Formulas are taken directly from their source to check correct application and eliminate errors.

The previous study of ANA_1 & ANA_2 on the analysis of dewirement concludes that the idea on the functional range of the pantograph should be further explored. This is done in the follow-up study of ANA_3.

The previous study of ANA_1 & ANA_2 on the analysis of infringement concludes that the scale of the problem is yet unknown. This leaves no opportunity for meaningful exploration of the results in the follow-up study of ANA_3.

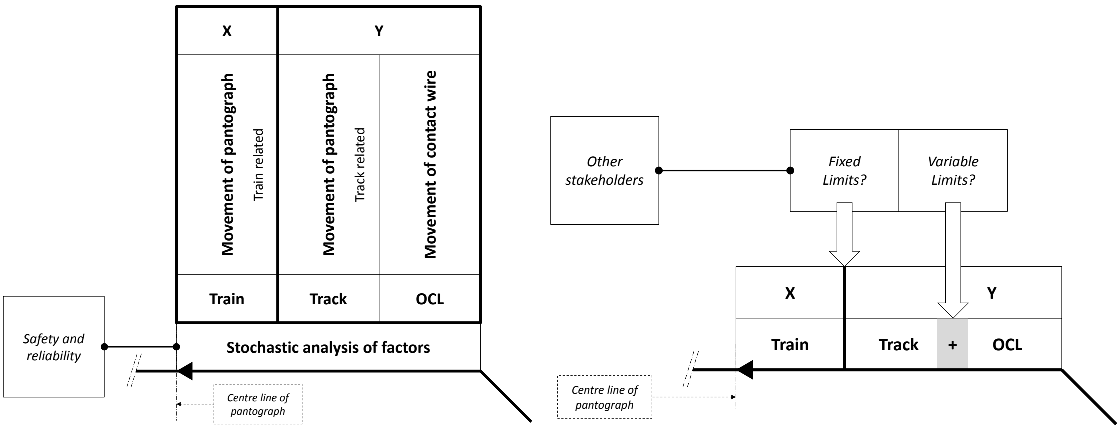
In general, the following elements from the previous study of ANA_1 & ANA_2 have led to further examination in the follow-up study of ANA_3:

- The previous study of ANA_1 & ANA_2 considers the wire deflection of different OCL-types as a function of curve radius and cant. The follow-up study of ANA_3 adopts a stochastic approach of the wind pattern (speed and direction) to calculate the wire deflection. This key-opportunity enables operational measures like speed reduction, currently accepted by some railway operators.
- The previous study of ANA_1 & ANA_2 uses tables for the curve radius – span length ratio. The follow-up study of ANA_3 takes this principle to the next level and introduces an assessment of a virtual track, providing a more realistic outcome.

These two elements are transformed into procedures to assess existing infrastructure.

2.2 INTEGRATED ANALYSIS

The approach in this study adopts an integrated analysis of the key systems combined: Train, track and overhead contact line (OCL). Their interdependency defines the design space available to each system. This is illustrated by the figures below, showing the combination on the half length of a pantograph.



Above: Combination of design space for movements (left) and the negotiation of limits (right).

2.3 BASIC ASSUMPTIONS

The current study of ANA_3 & ANA_4 is based on the following documents:

- ERA: Tender Specifications (Invitation to Tender No ERA 2013 20 INTEROP OP);
- ARCADIS: Contractor's Tender 0775188340 dated 5 February 2014;
- TUC Rail: ERA/2013/INTEROP/OP/01 - Final Report - 12th Decembre 2013;

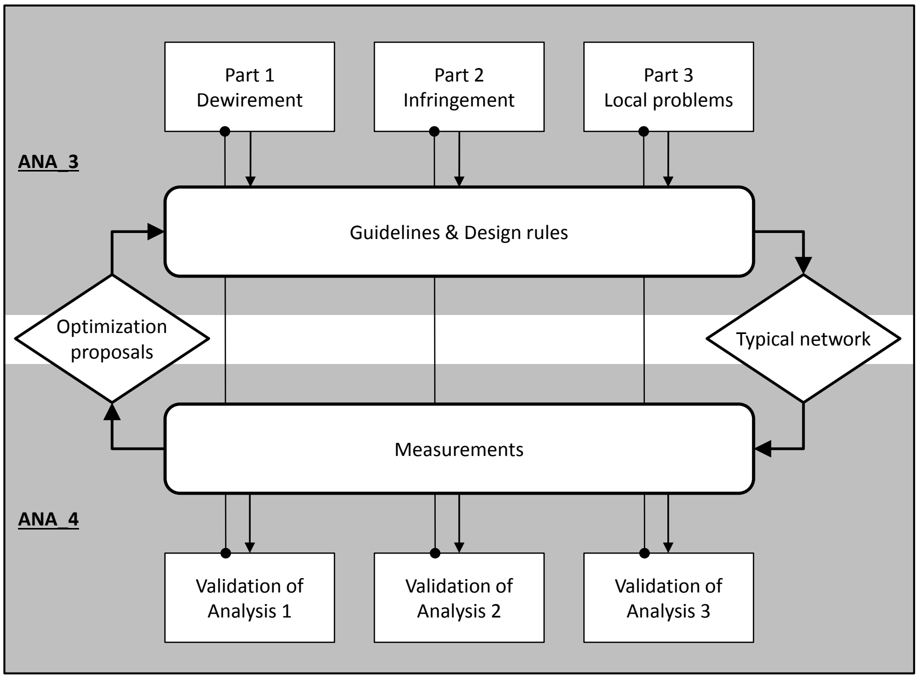
The following basic assumptions apply:

- All formulas are shown in the example calculations of Appendix 3.

2.4 MAIN ACTIVITIES

The current study revolves around the following three subjects:
- Chance of dewirement (narrow pantograph on wide pantograph network);
- Chance of infringement (wide pantograph on narrow pantograph network);
- Local Problems (catenary switch and overlap).

These subjects are treated in separate analyses, to be performed simultaneous, validating each part individually. The figure below shows the general outline of the work approach.



Above: Outline methodology of the study in ANA_3 & ANA_4.

The main activities within the work scope are summarised as follows:
- Propose a method and build a model to calculate the margins;
- Determine the relevance, nature and sensitivity of factors (deterministic / stochastic);
- Model a virtual railway line consisting of both critical and representative spots;
- Calculate the margins using Monte Carlo simulation;
- Review existing procedures and propose modifications to current standards;
- Document the method in a risk-based approach and draft general design rules and guidelines;
- Propose and execute measurements to validate the analyses.

2.5 GUIDELINES & DESIGN RULES

The current study of ANA_3 provides the guidelines for Inframanagers to assess the local infrastructure using a risk-based approach. The steps to prepare, execute and evaluate the assessment are visualised by 16 individual workflows, displayed on the page opposite to the page with the explanation of the subject. Every step is explained in a separate paragraph in chapter 3 of this report. Together, the workflows and the explanations form the guidelines. References are made to the design rules in the listed EU-standards and TSI's. They are not copied here. Relevant formulas and calculation examples are given in Appendix 3. Modification proposals as a Request for Standard are listed in the relevant paragraph, and bundled in Appendix 1.

Various questions are treated in this report, returning as solutions in the guidelines.

Common issues:
- Which factors have to be considered and where to find the relevant information?
- How to calculate the wind load and the wire deflection?
- What are the critical spots in catenary overlaps and switches?

New introductions:
- How to calculate the margins for dewirement and infringement?
- How to perform the Monte Carlo simulations and analyse the results?
- How to evaluate the outcomes?
- How to identify the critical spans?
- How to select cost-effective modifications?
- Which measurements to take?

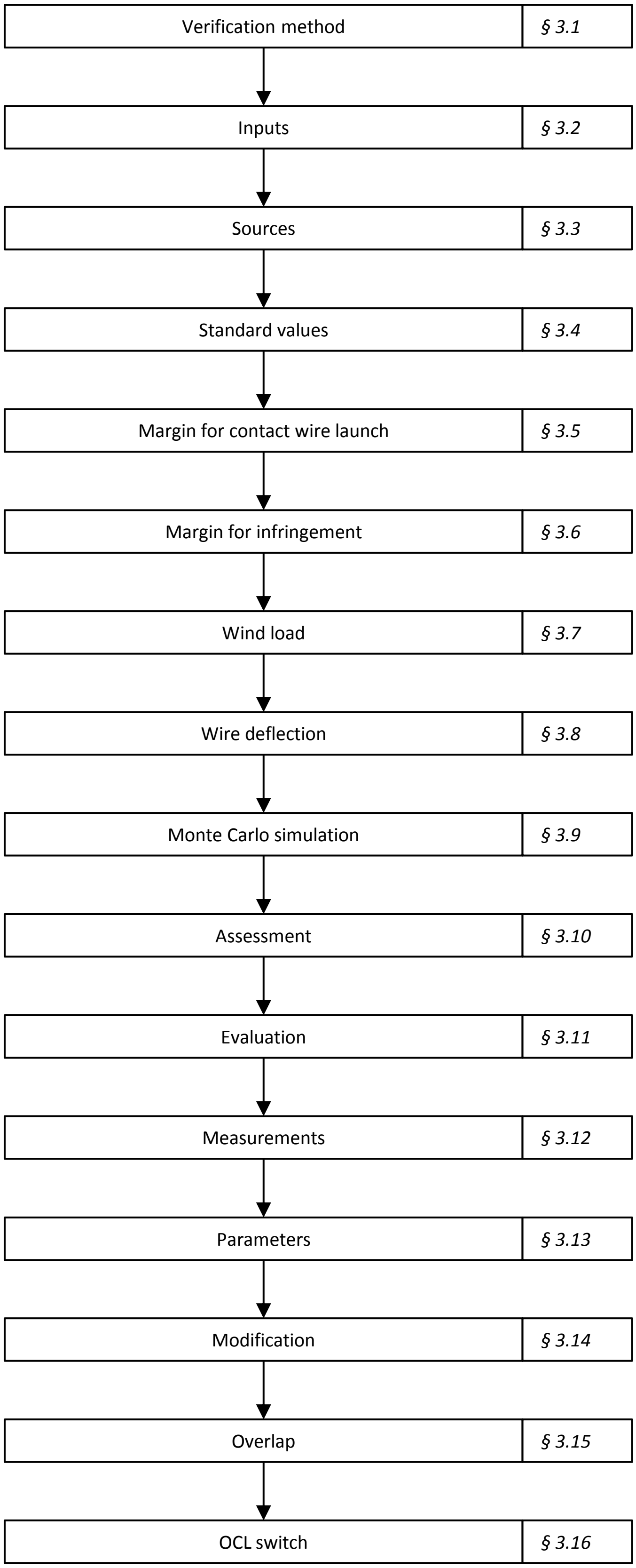
Detailed investigations:
- Is there such a thing as a 'point of no-return'?
- How to calculate a safety margin?

It is assumed that the chance of actual dewirement cannot be accepted by both Inframanagers and Service Providers. Instead, the assessment method presented in this report is meant to control the position of the contact point before it reaches the edge of the pantograph. This study regards the area on the pantograph head between the edge of the working zone and the edge of the pantograph as a dynamic safety margin. This area can be used in the rare occasion of combined occurrences and in extreme conditions. Exceeding the edge of the working zone introduces the chance of 'contact wire launch', an effect where the contact wire is forcefully withdrawn from the edge of the pantograph, instead of proceeding towards dewirement.

The study in this report replaces the concept of dewirement by the idea of contact wire launch. It is assumed that limited occurrences of contact wire launch are acceptable. The number of contact wire launches and the amount, by which the working zone is exceeded for each occurrence, is calculated in Monte Carlo simulations. The proposed guidelines provide opportunities to reduce the effect of contact wire launch by modification of the infrastructure, specifically targeting critical spans.

The guidelines to assess if the existing OCL can accommodate both 1600 and 1950 mm pantographs will be developed in the following chapter. The diagram on the next page defines the subsequent steps and indicates the subchapters describing them in detail.

Guidelines - *overview*



3 Analysis

3.1 VERIFICATION METHOD

The consequences of the introduction of foreign pantographs on existing national railway lines depend on the design background. The pantographs shall conform to the dimensions laid out in EN 50367:2012.

- Narrow pantographs on networks designed for wide pantographs will introduce a higher chance of contact wire launch;
- Wide pantographs on networks designed for narrow pantographs have the opposite effect: It introduces a higher chance of infringement.

The proposed steps in the verification method are shown on the opposite page, describing the check for contact wire launch (1) separately from the check for infringement (2).

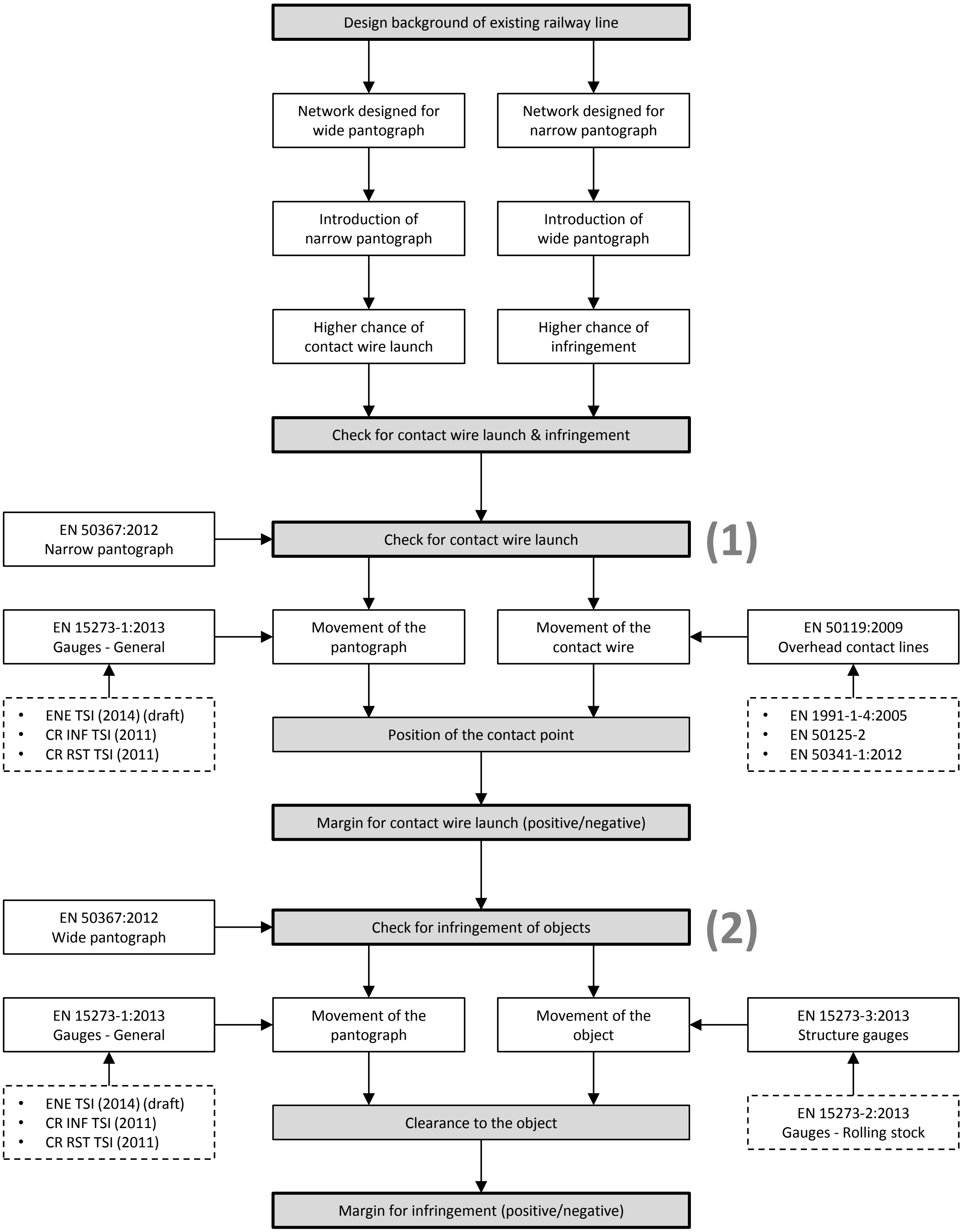
In the check for contact wire launch, the lateral movement of the pantograph is set against the lateral movement of the contact wire in opposite direction (worst-case scenario). The relative position of the moving contact wire on the moving pantograph is defined as the ‘contact point’. The remaining space on the pantograph head is measured horizontally and defined as the ’margin’. The margin for contact wire launch is explained in more detail in § 3.5 of this report.

- The movement of the pantograph is calculated according to the rules in EN 15273-1:2013 (Gauges - general), which are mirrored in the ENE TSI, CR INF TSI and CR RST TSI.
- The movement of the contact wire is calculated according to the rules in EN 50119:2009 (Overhead contact lines), in connection with the more detailed information background in EN 1991-1-4:2005, EN 50125-2 and EN 50341-1:2012.

In the check for infringement, the lateral movement of the pantograph is set against the lateral movement of an object in opposite direction (worst-case scenario). The distance between the moving pantograph and the moving object is measured horizontally and defined as the clearance. The margin for infringement is explained in more detail in § 3.6 of this report.

- As is the case for contact wire launch, the movement of the pantograph is also calculated according to the rules in EN 15273-1:2013, mirrored in TSI’s.
- The required clearance is calculated according to the rules set out in EN 15273-3:2013 (Structure gauges), supplemented by EN 15273-2:2013 (Gauges - Rolling stock). The calculation of the movement of the object depends on the specific characteristics of the object and the loads on that that object.

Verification method



3.2 INPUTS

The input parameters to consider in the calculations of the lateral movements of pantograph, contact wire and objects are listed on the opposite pages. The parameters are distinguished according to significance (significant impact or minor influence) and allocated according to the following subject categories:

- System design;
- Allocation design;
- Structures;
- Construction & maintenance;
- Environment;
- Train construction & Railway operation;
- Pantograph dimensions & tolerances.

The input parameters are listed in this way to show their sensitivity, illustrating the effect of modifications.

On the next page, the parameters are listed again, allocated according to subject category, but now they are distinguished according to the nature of their values:

- 'Stochastic' (or dynamic) parameters are parameters whose values are unknown at the time. Values may vary randomly according to a distribution within a probable range and average. In calculations, values for these parameters must be selected in a probabilistic approach.
- 'Deterministic' (or static) parameters are parameters whose values are chosen in the design or calculated based on fixed input. They may only vary according to a pre-determined situation.

The input parameters are listed in this way to show their stability, illustrating the probability of success.

Inputs - *significance*

Significant impact | Minor influence

System design

Significant impact
- Main wire dimensions & tension
- Second contact wire orientation
- Dropper length & distribution

Minor influence
- Track gauge
- Contact wire weight & pre-sag
- Stitch & anchor wire dimensions

Allocation design

Significant impact
- Angle of the span
- Curve radius
- Cant & cant deficiency
- Span length & stagger
- Contact wire & system height
- Clearances - mechanical

Minor influence
- Projected area of insulators & other components

Structures

Significant impact
- Structure orientation & dimensions
- Structure shape & material

Construction & maintenance

Significant impact
- Cant tolerance
- Track unevenness

Minor influence
- Track alignment tolerance
- OCL positioning tolerance

Environment

Significant impact
- Wind velocity
- Angle of origin of wind direction
- Air density

Minor influence
- Track height
- Terrain roughness
- Temperature

Train construction & Railway operation

Significant impact
- Assessment interval (years)
- Running speed
- Load distribution
- Verification height

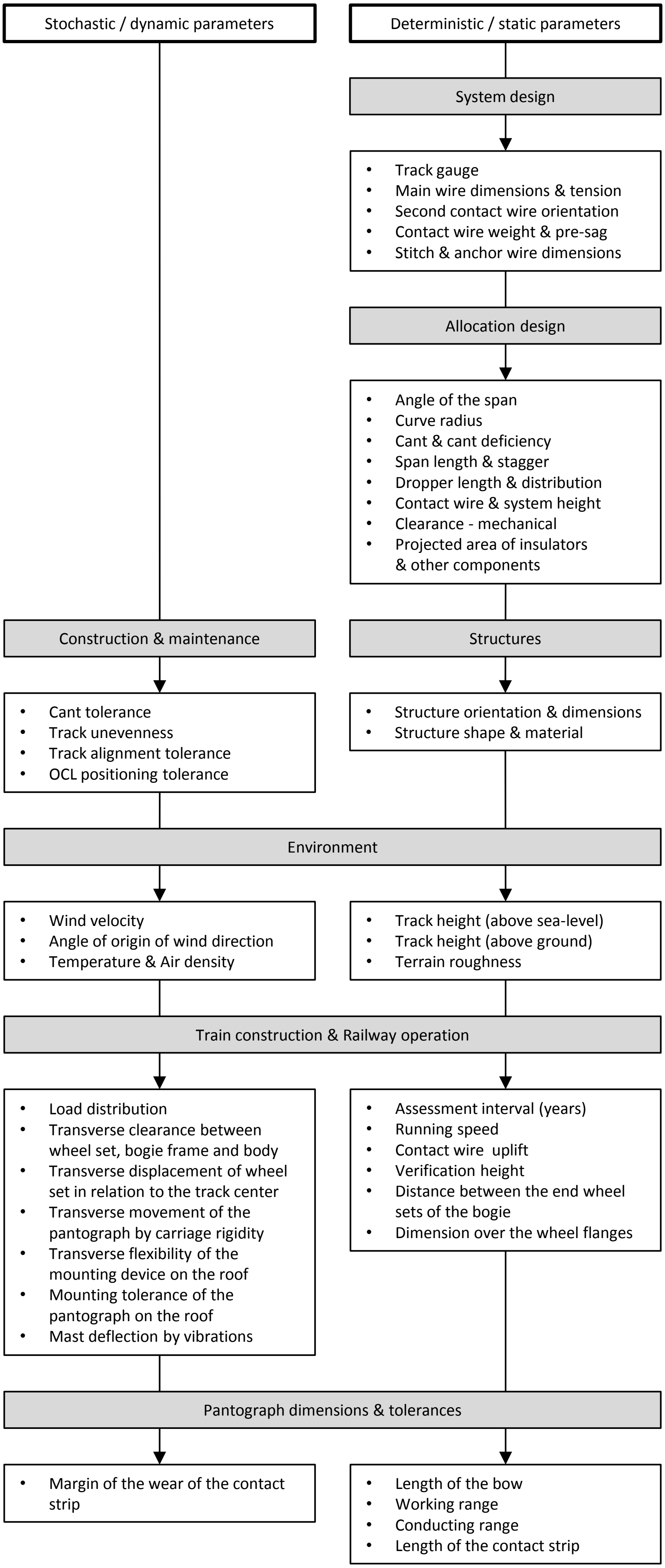
Minor influence
- Transverse clearance between wheel set, bogie frame and body
- Transverse displacement of wheel set in relation to the track center
- Transverse movement of the pantograph by carriage rigidity
- Transverse flexibility of the mounting device on the roof
- Mounting tolerance of the pantograph on the roof
- Mast deflection by vibrations
- Contact wire uplift

Pantograph dimensions & tolerances

Significant impact
- Length of the bow
- Working range
- Conducting range

Minor influence
- Length of the contact strip
- Margin of the wear of the contact strip

Inputs - *nature*



3.3 SOURCES

The source references according to topic are listed on the opposite pages. The paragraphs link to the required background information on the subject matter.

EU Standards provide calculations used in the assessment. Topics are allocated according to research area:
- Movement of the pantograph;
- Movement of the contact wire;
- Environmental effects;
- Wire dimensions;
- Pantograph dimensions.

Technical Specifications for Interoperability (TSI's) according to Directive 2008/57/EG provide requirements for the assessment. Topics are allocated according to TSI-document:
- CR EN TSI (26 April 2011) - Energy subsystem for conventional rail;
- ENE TSI (2014) - Energy subsystem - draft;
- CR INF TSI (26 April 2011) - Infrastructure subsystem for conventional rail;
- CR RST TSI (26 April 2011) - Rolling Stock subsystem for conventional rail - 'Locomotives and passenger rolling stock'.

Other sources provide information about the design, location and operational management of the railway line, as well as design & engineering examples. Topics are allocated according to source:
- Design documentation;
- Build installation;
- Operation;
- Literature.

Sources - *EU Standards*

Source reference	Topic
Movement of the pantograph	
EN 15273-1:2013 • § 3.12 and § 5.1 • § 5.1.1 • § 5.1.2 • § 3.13 and § 5.2 • § 3.14 and § 5.3 • § 3.15 and § 5.4 • § 3.16 • § 3.19 and § 5.6 • § 3.21 • Annex J.3.1 - T_1 • Annex J.3.1 - T_2 • Annex J.3.1 - T_3 • Annex J.3.1 - T_4 • Annex J.3.1 - T_5	**Railway applications - Gauges - General - Common rules for infrastructure and rolling stock** • Geometric overthrow • Geometric overthrow between the vehicle body • Additional geometric overthrow due to the bogies • Flexibility coefficient • Dissymmetry • Clearance between the wheelsets and the track • Transverse clearance between wheelset and body • Roll centre • Quasi-static roll • The transverse displacement of the track between two maintenance periods • Cant defects (geometric effect and dynamic effect) • Oscillations (other than those generated by a crosslevel error) • The construction or adjustment dissymmetries of the vehicles • Loading dissymmetries
EN 15273-2:2013	**Railway applications - Gauges - Rolling stock gauge**
EN 15273-3:2013	**Railway applications - Gauges - Structure gauges**
Movement of the contact wire	
EN 50119:2009 • § 6.2.4.2 • § 6.2.4.3 • § 6.2.4.4 • § 6.2.4.7	**Electric traction overhead contact lines** • Dynamic wind pressure • Wind forces on conductors • Wind forces on insulators and other line fittings • Wind forces on structures
Environmental effects	
EN 1991-1-4:2005	**Actions on structures - General actions - Wind actions**
EN 50125-2 • § 4.4.1	**Environmental conditions for fixed electrical installations** • Wind
EN 50341-1:2012 • § 4.3 • § 4.4	**Overhead electrical lines exceeding AC 1 kV - General requirements - Common specifications** • Wind loads • Wind forces on overhead line components
Wire dimensions	
EN 50149:2012 • § 4.5.4 and Annex A (figure A.2/A.4)	**Copper and copper alloy grooved contact wires** • Configurations (of wires)
EN 50182:2001 • § 5 • Annex F	**Round wire concentric lay stranded conductors** • Requirements for stranded conductor • Conductors in frequent use in some member countries
Pantograph dimensions	
EN 50367:2012 • § 5.2.5 and Annex A.2.1 (figure A.6) • § 5.2.5 and Annex A.2.2 (figure A.7)	**Current collection systems - Technical criteria for the interaction between pantograph and overhead line** • Pantograph head with length of 1600 mm • Pantograph head with length of 1950 mm

Sources - *TSI's*

Source reference	Topic

DIRECTIVE 2008/57/EG - TECHNICAL SPECIFICATION FOR INTEROPERABILITY (TSI)

CR ENE TSI (26 April 2011)
- § 4.2.13
- § 4.2.14
- § 4.2.18

'Energy' subsystem for conventional rail
- Geometry of the overhead contact line
- Pantograph gauge
- Contact wire material

ENE TSI (2014) (draft)
- § 4.2.9
- § 4.2.9.1
- § 4.2.9.2
- § 4.2.10
- § 4.2.14
- Appendix D.1.2
- Appendix D.1.2.1
- Appendix D.1.2.1.1
- Appendix D.1.2.1.2
- Appendix D.1.2.1.3
- Appendix D.1.2.1.4
- Appendix D.1.2.1.6
- Appendix D.1.2.1.7
- Appendix D.1.2.1.8
- Appendix D.1.2.2
- Appendix D.1.3
- Appendix D.1.4

'Energy' subsystem
- Geometry of the overhead contact line
- Contact wire height
- Maximum lateral deviation
- Pantograph gauge
- Contact wire material
- Specification of the mechanical kinematic pantograph gauge
- Specification of the width of the mechanical gauge
- Scope
- Calculation methodology
- Half-length bw of the pantograph bow
- Pantograph sway ep
- Additional overthrows
- Quasi-static effect
- Allowances
- Specification of the height of the mechanical gauge
- Reference parameters
- Calculation of maximum lateral deviation of contact wire

CR INF TSI (26 April 2011)
- § 4.2.4.4
- § 4.2.5.1
- § 4.2.5.2
- § 4.2.5.4

'Infrastructure' subsystem for conventional rail
- Minimum radius of horizontal curve
- Nominal track gauge
- Cant
- Cant deficiency

CR RST TSI (26 April 2011)
- § 4.2.2.10
- § 4.2.3
- § 4.2.3.1
- § 4.2.3.4
- § 4.2.3.4.2
- § 4.2.3.5
- § 4.2.3.6
- § 4.2.8.2.9
- § 4.2.8.2.9.1
- § 4.2.8.2.9.2

'Rolling Stock' subsystem for conventional rail - 'Locomotives and passenger rolling stock'
- Load conditions and weighted mass
- Track interaction and gauging
- Gauging
- Rolling stock dynamic behaviour
- Running dynamic behaviour
- Running gear
- Minimum curve radius
- Requirements linked to pantograph
- Working range in height of pantograph
- Pantograph head geometry (IC level)

Sources - *Other*

Design documentation

Source reference	Topic
• System & subsystem design specifications • Allocation design principles, calculation rules & comfort criteria • Construction guidelines	• Track & OCL system & subsystem configuration and component dimensions • Speed / curve radius / cant & cant deficiency ratio, curve radius / span length / stagger ratio, encumbrance / wire inclination / pre-sag / uplift ratio, structure shape, /material / orientation ratio • Tolerances and adjustments

Build installation

Source reference	Topic
• Geographical location • Environmental conditions • As-built drawings	• Track height, span orientation, terrain roughness • Wind pattern (distribution of velocity & direction) • System & subsystem design specifications

Operation

Source reference	Topic
• Railway operational plan • Railway safety plan • Railway maintenance plan • Maintenance history	• Train characteristics, # of trains, running speed • Safety regulations, clearances • Safety margin • Measurement data

Literature

Source reference	Topic
Kießling, 3rd edition - 2014	
• § 2.4.2	• Wind velocity and wind load
• § 4.9	• Wire deflection by wind load
• § 4.9.1	• Wind load on conductors
• § 4.9.2	• Wire deflection on straight track
• § 4.9.3	• Static wire position and wind deflection in curves
• § 4.9.4	• Static wire position in transition arcs
• § 4.9.5	• Wind deflection of the span / coupling force
• § 12.11.2	• Electrification of switches
• § 12.11.5	• Switch electrification with cross-wire
• § 12.11.6	• Switch electrification with parallel wire

3.4 STANDARD VALUES

Standard values to be used in calculation formulas are listed on the opposite page, according to their relevant parameter. They originate from the EU Standards and TSI-documents mentioned as a source. Parameters are allocated according to the following subject categories:

- Track system design;
- OCL system design;
- Structures;
- Environment;
- Train construction;
- Pantograph construction.

Standard Values

Parameter	Value
Track system design	
Reference cant	66 mm
Reference cant deficiency	66 mm
Standard gauge	1435 mm
Distance between rail centres	1500 mm
OCL system design	
Structural response factor for conductors	0,75
Structural resonance factor for insulators	1,05
Aerodynamic drag factor for grooved contact wires	1,20
Aerodynamic drag factor for round conductors	1,00
Aerodynamic drag factor for insulators	1,20
Clearances - electrical (static, dynamic)	According to the voltage level for AC & DC currents
Structures	
Structural response factor for structures	1,00
Aerodynamic drag factor for structures	1,40 (varies with mast-profile)
Environment	
Terrain factor	1,00
Gust response factor	2,05
Train construction	
Flexibility coefficient	0,225
Reference roll centre height	500 mm
Distance between the end wheel sets of the bogie	2600 mm (varies)
Dimension over the wheel flanges	1435 mm
Pantograph construction	
Margin of the bow trespassing the contact wire height	60 mm

3.5 MARGIN FOR CONTACT WIRE LAUNCH

The margin for contact wire launch is defined as the surplus or short in the remaining space on the pantograph head as a result of the combined movement of the pantograph and the contact wire in opposite directions, for which the chance of contact wire launch has to be checked

The proposed steps to calculate the margin for contact wire launch are shown on the opposite page. Displayed is the 1600 mm pantograph, which has the most critical length for the chance of contact wire launch.

The margin for contact wire launch uses the design track centre as a reference. The margin is calculated as the difference between the available space on the pantograph head and the taken space by the contact wire.

- The available space is defined as the half-length of the pantograph working zone (currently equal to the conducting range), minus the lateral movement of the pantograph in the unfavourable direction relative to the design track centre line.
- The taken space is defined as the position of the contact wire in a lateral deflected state towards the unfavourable direction (opposite to the pantograph movement) relative to the design track centre line.

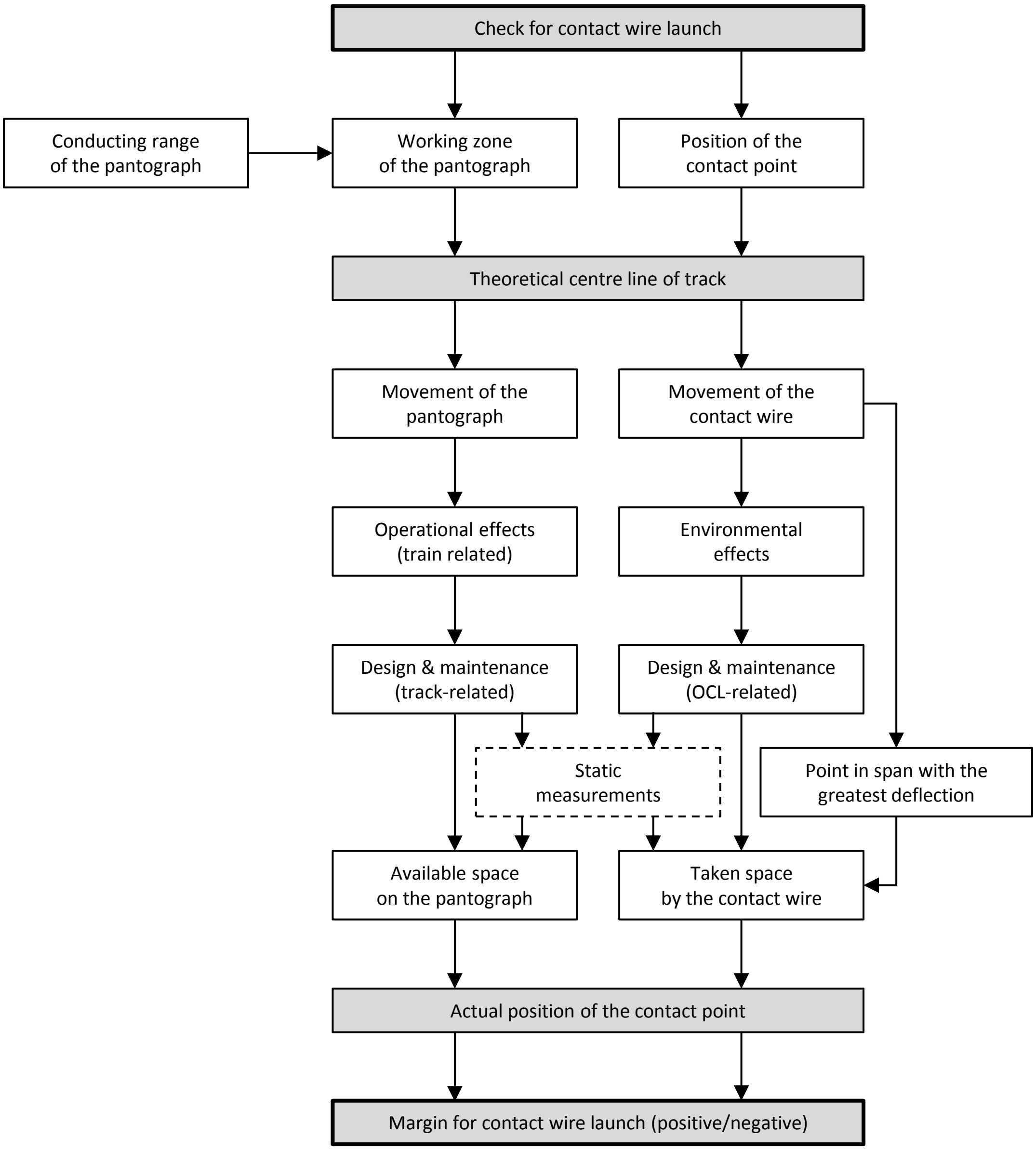
Note: The working zone of the pantograph is limited by the maximum allowed position of the contact point on the pantograph head. Because this maximum is not yet unambiguously set, the calculation method in this study proposes the edge of the conducting range as the limit value.

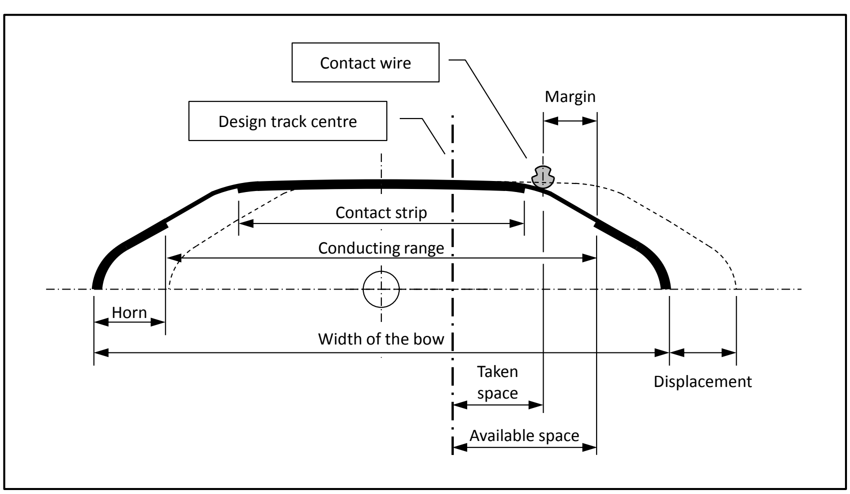
The position of the deflected contact wire on the displaced pantograph is the actual position of the contact point. When the contact point exceeds the maximum, the chance of contact wire launch is increased.

The movement of the pantograph and the contact wire is calculated according to the example calculations in Appendix 3.

- The movement of the pantograph is mainly determined by operational effects (train related) and design & maintenance tolerances (track related).
- The movement of the contact wire is mainly determined by environmental effects and design & maintenance tolerances (OCL related).

Margin - *contact wire launch*





Head of the 1600 mm pantograph

3.6 MARGIN FOR INFRINGEMENT

The margin for infringement is defined as the surplus or short in the clearance to insulated or live objects as a result of the combined movement of the pantograph and the object in opposite directions, for which the chance of infringement has to be checked.

The proposed steps to calculate the margin for infringement are shown on the opposite page. Displayed is the 1950 mm pantograph, which has the most critical length for the chance of infringement.

The margin for infringement uses the design track centre as a reference. The margin is calculated as the difference between the required distance and the given distance to objects that are live (conducting) of neutral (insulated).

- The required distance is defined as the half-length of the pantograph bow (including horns), plus the lateral movement of the pantograph in the unfavourable direction (towards the object) relative to the design track centre line, plus the appropriate mechanical or electrical clearance (static or dynamic).
- The given distance is defined as the position of the near edge of the design object boundary relative to the design track centre line, minus the to be foreseen movement or deflection of the object in the unfavourable direction (opposite to the pantograph movement).

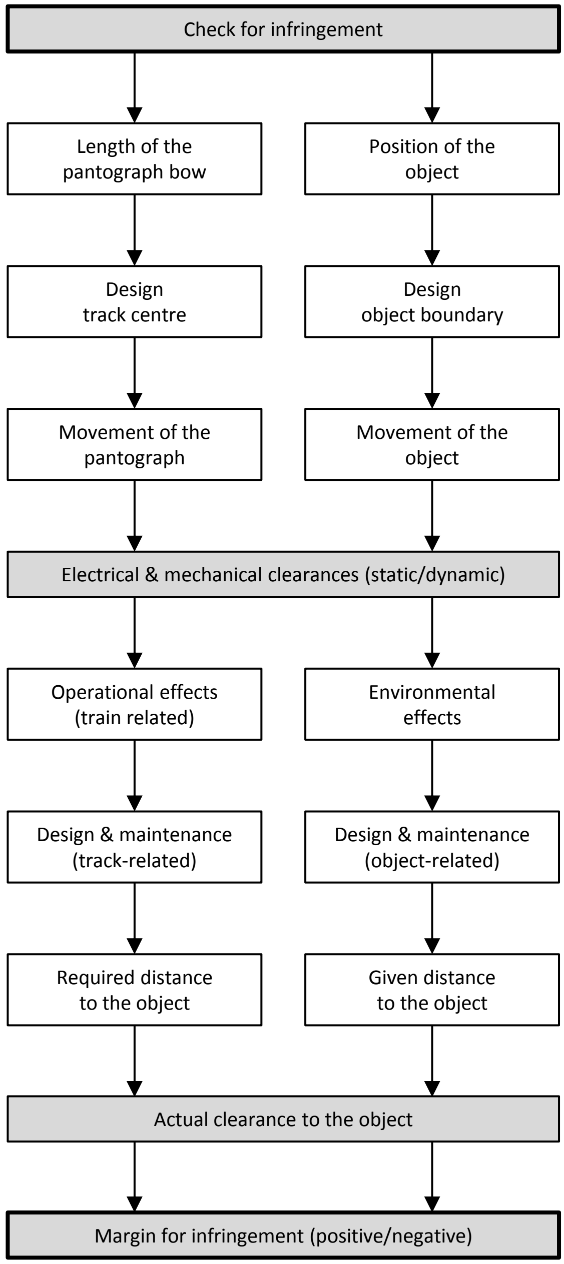
Note: The minimum distance to the object is limited by the electrical potential of the object, which could be live or neutral. Because it is not required to insulate the horns of the 1950 mm pantograph, the calculation method in this study assumes the horns to be non-insulating. The electrical clearance must conform to EN 50119:2009 - § 5.1.3 - Table 2. The mechanical clearance must be set by the Inframanager.

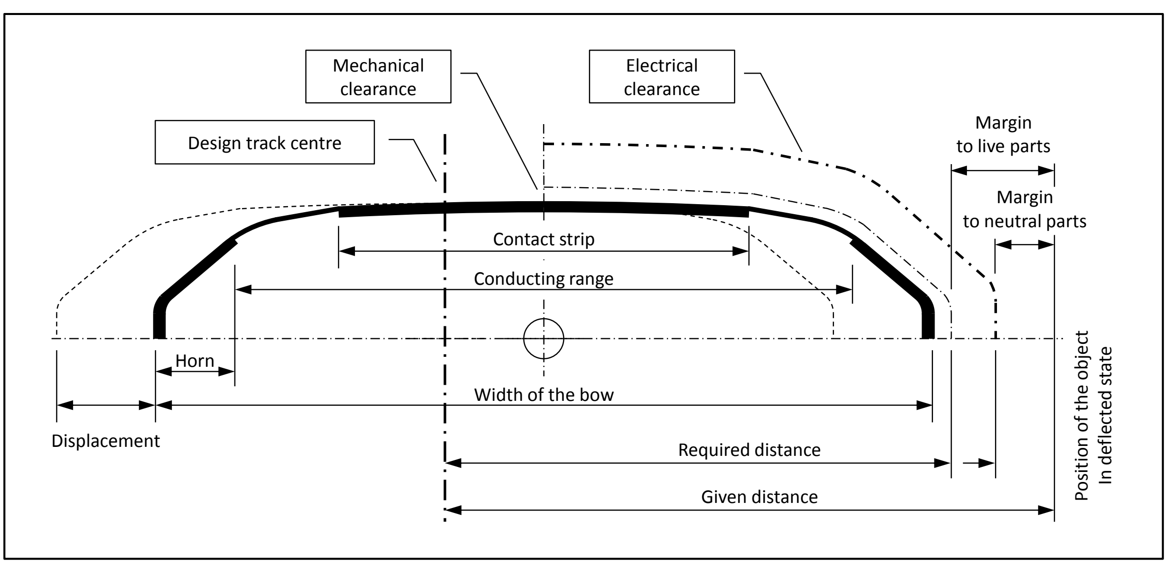
The distance of the displaced pantograph to the displaced object, is the actual clearance to the object. When the clearance exceeds the minimum, the chance of infringement is increased.

The movement of the pantograph is calculated according to the example calculations in Appendix 3. The movement of the object shall be calculated according to national rules applicable to the type and location of the object.

- The movement of the pantograph is mainly determined by operational effects (train related) and design & maintenance tolerances (track related).
- The movement of the object is mainly determined by environmental effects and design & maintenance tolerances (object related).

Margin - *infringement*





Head of the 1950 mm pantograph

3.7 WIND LOAD

The wind load is subject to the wind pattern (wind direction and wind velocity), which not only displays the widest variation in values, it also has the most significant impact of all factors on the position of the contact point and the margin for contact wire launch.

The proposed steps to calculate the wind load are shown on the opposite pages. The wind load is calculated according to the example calculations in Appendix 3. Several environmental parameters are taken into account:

- The base value of the dynamic wind pressure is calculated with the air density, based on altitude above sea-level and air temperature.
- The nominal value of the dynamic wind pressure is calculated based on altitude above ground and terrain characteristics.

Subsequently, the wind load on primary and secondary OCL components and structures is calculated based on the shape and dimensions of main- and other wires, additional components (e.g. insulators) and structures, incorporating factors for aerodynamic drag and structural resonance.

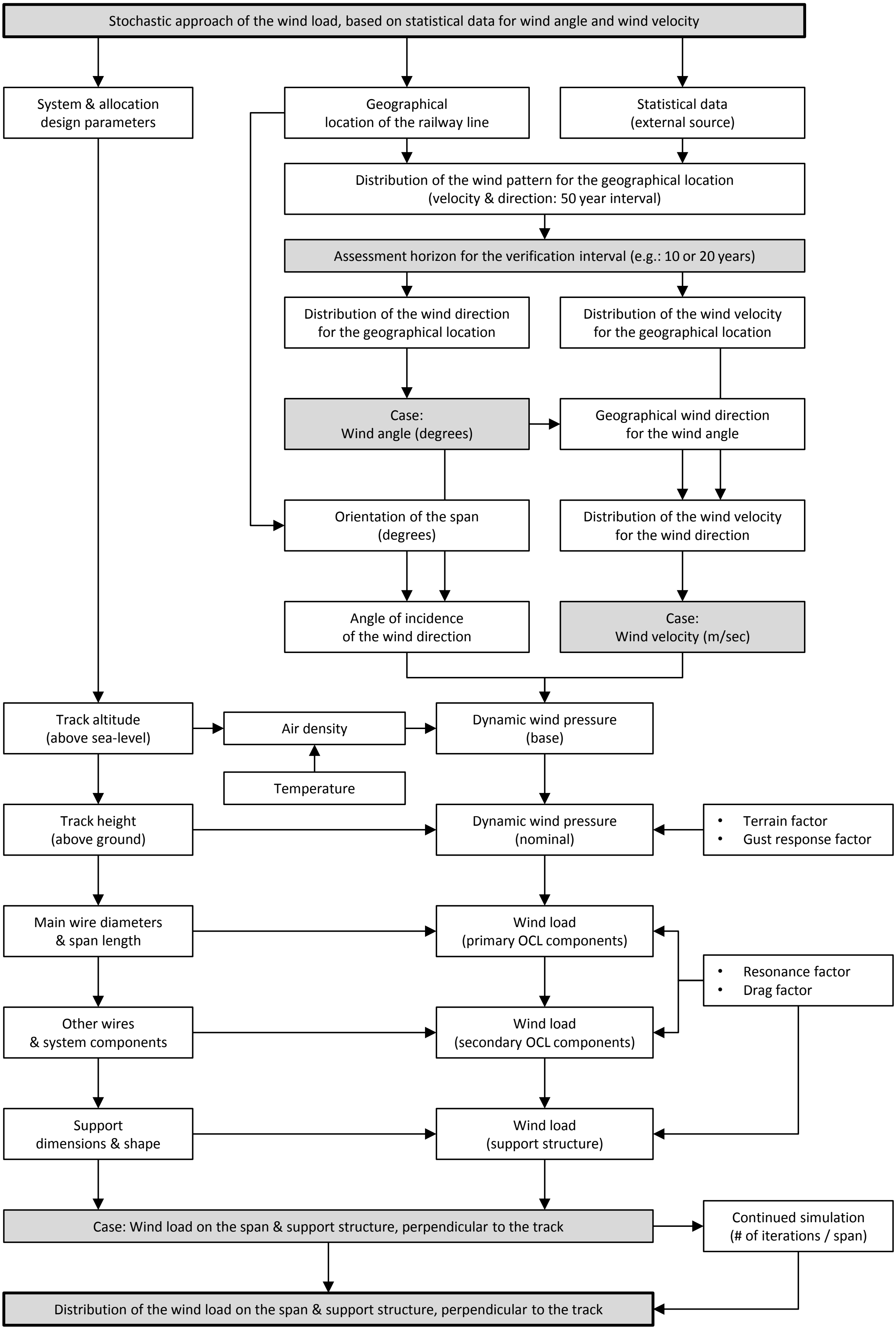
EN 50119:2009 states that the dynamic wind pressure shall be calculated from the reference wind velocity (§ 6.2.4.2). Also, the wind force on conductors shall be calculated from the angle of incidence of the critical wind direction in respect to the perpendicular to the conductor. In general this angle (Φ) is assumed to be zero (§ 6.2.4.3).

In the previous study of ANA_1 & ANA_2 the following opportunity was identified: To calculate how often a contact wire launch will occur on a certain railway line or location on a line, the probabilities have to be multiplied with the probability that:

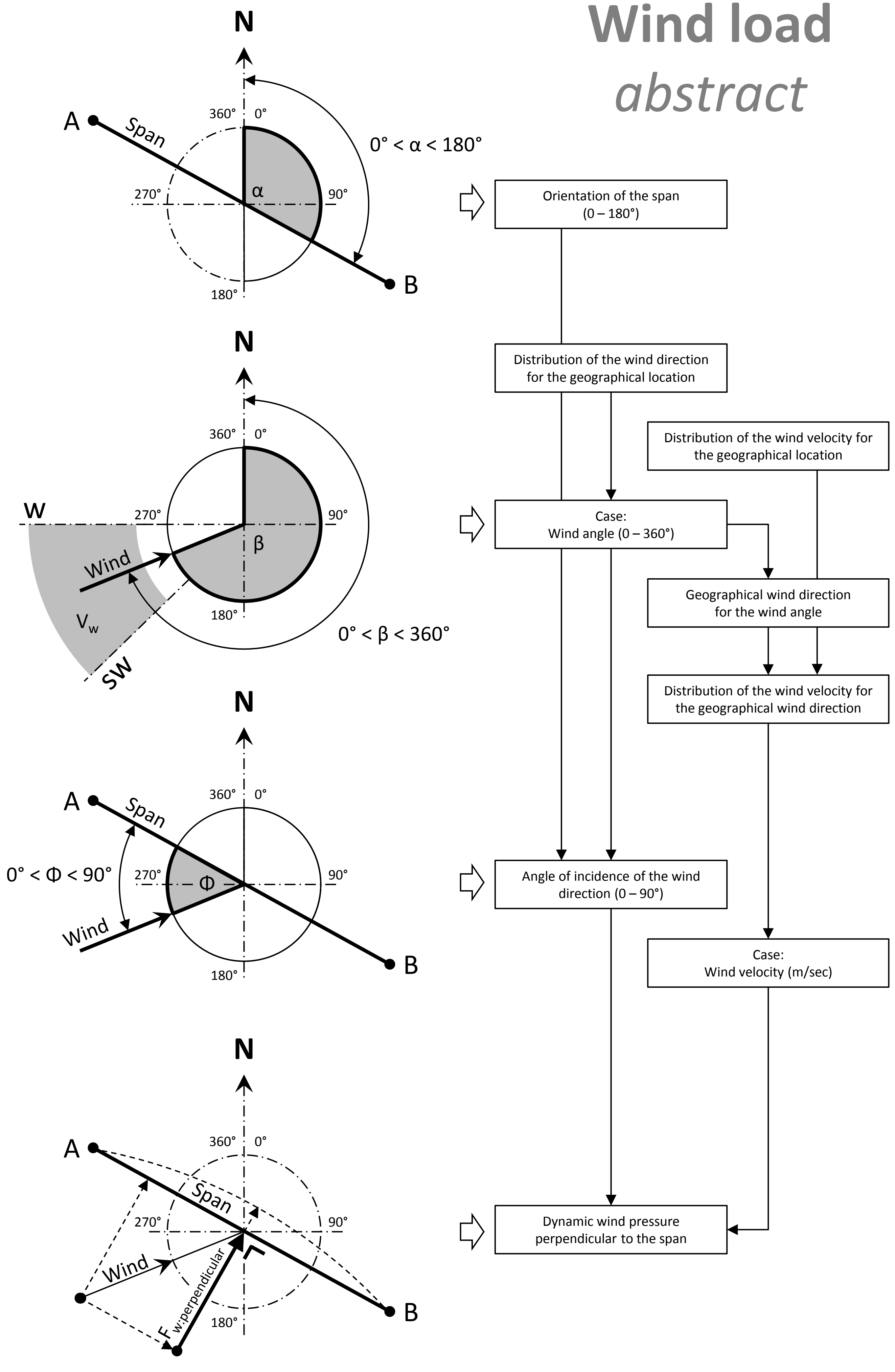
- A pantograph of that type will be at that exact location or near it;
- The specified wind velocity will occur at that location;
- The wind gust will be about perpendicular to the span.

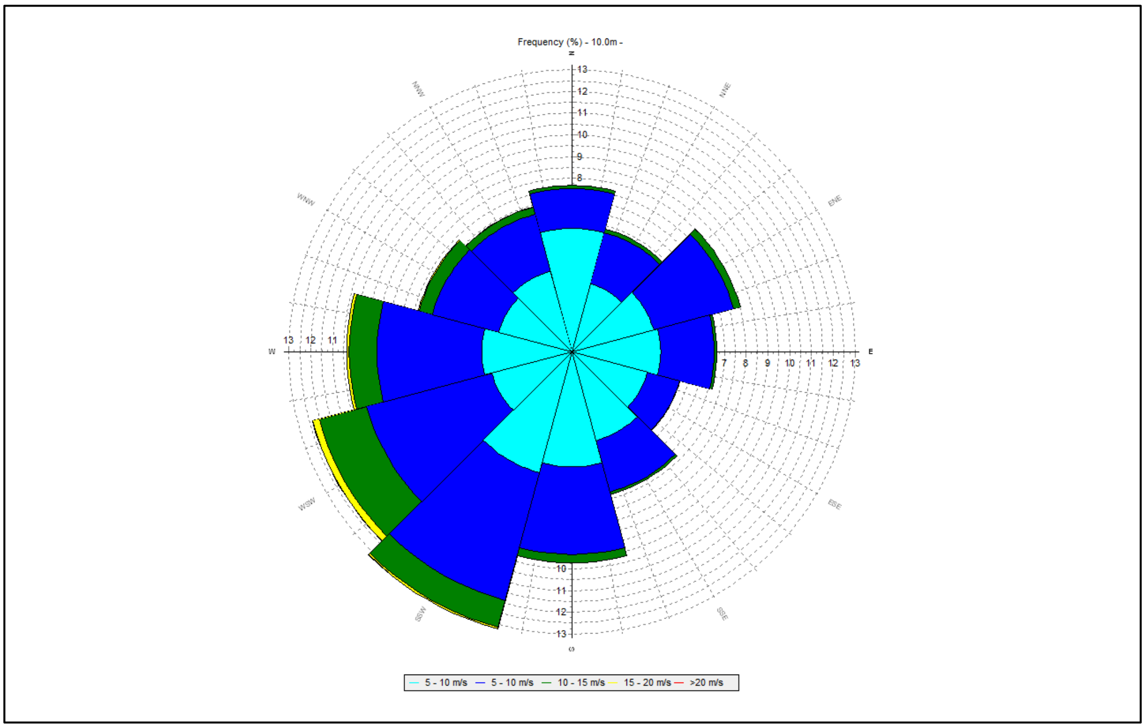
The figures illustrate the large difference between a calculation of the wire deflection based on extreme wind loads for all locations (worst-case), and a calculation of the wire deflection based on the wind velocity and wind angle for specific geographical locations and orientations of spans.

Wind load

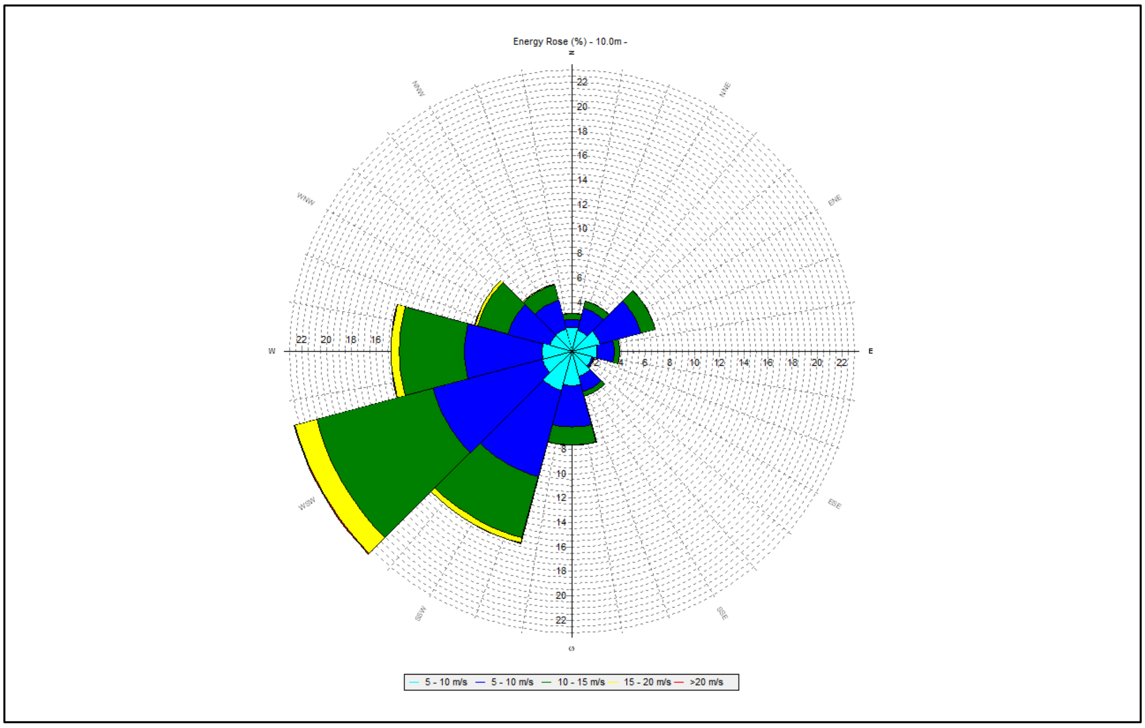

Stochastic approach of the wind load, based on statistical data for wind angle and wind velocity
System & allocation design parameters
Geographical location of the railway line
Statistical data (external source)
Distribution of the wind pattern for the geographical location (velocity & direction: 50 year interval)
Assessment horizon for the verification interval (e.g.: 10 or 20 years)
Distribution of the wind direction for the geographical location
Distribution of the wind velocity for the geographical location
Case: Wind angle (degrees)
Geographical wind direction for the wind angle
Orientation of the span (degrees)
Distribution of the wind velocity for the wind direction
Angle of incidence of the wind direction
Case: Wind velocity (m/sec)
Track altitude (above sea-level)
Air density
Dynamic wind pressure (base)
Temperature
Track height (above ground)
Dynamic wind pressure (nominal)
Terrain factor
Gust response factor
Main wire diameters & span length
Wind load (primary OCL components)
Resonance factor
Drag factor
Other wires & system components
Wind load (secondary OCL components)
Support dimensions & shape
Wind load (support structure)
Case: Wind load on the span & support structure, perpendicular to the track
Continued simulation (# of iterations / span)
Distribution of the wind load on the span & support structure, perpendicular to the track

Wind load *abstract*





Above: Graphical representation of the wind pattern (frequency and velocity).



Above: Graphical representation of the wind pattern (energy and velocity).

OCL designed to operate at maximum wind velocity at all times no matter the direction, contain a large amount of ‘locked value’. It is therefore that this study proposes to use statistical data (generally obtained from an external source) to find the distribution of the wind pattern for the geographical location of the railway line.

Statistical data is typically represented for a 50 year interval, but can be recalculated to represent intervals best matching the assessment horizon (e.g. 10 or 20 years). The wind pattern shows the distribution of the wind direction and the wind velocity.

- Analysis of the data shows the distribution of the wind velocity for any of the wind directions (typically 12 areas of 30°) according to the distribution of the wind direction for the location.
- The dynamic wind pressure (base value) can now be calculated for any of the wind velocities according to the distribution of the wind velocity for the wind direction.
- The angle of incidence of the wind direction is calculated with the angle of origin of the wind direction and the orientation of the span.

The stochastic nature of the variables in the wind pattern is used in Monte Carlo simulations to calculate the distribution of the margin:

- For contact wire launch (significant impact on the position of the contact point);
- For infringement (minor influence on the position of the object).

Note: A request for standard EN 50119:2009 is proposed to specify the use of local statistical data for the wind pattern and to take into account the stochastic nature of wind direction and wind velocity, replacing the currently suggested entry of worst-case values. The following rules in the standard are targeted:

- The reference wind velocity (V_R) in the calculation of the dynamic wind pressure (§ 6.2.4.2). This rule should be modified to represent the probability that "the specified wind velocity will occur at that location".
- The angle of incidence of the critical wind direction (Φ) in the calculation of the wind force on conductors (§ 6.2.4.3), other components and structures ((§ 6.2.4.4. - § 6.2.4.7). This rule should be modified to represent the probability that "the wind gust will be about perpendicular to the span".

The probability that "a pantograph of that type will be at that exact location or near it", is represented by the number of iterations in a simulation (# of iterations = # of pantographs passing).

3.8 WIRE DEFLECTION

Deflection of the OCL wires is primarily caused by a combination of the following mechanisms:
- Static deflection of the OCL span, depending on span length, stagger and curve radius;
- Dynamic deflection of the OCL span, depending on wind load and wire tension;
- Dynamic deflection of the structure, depending on wind load on wires suspended from the structure according to the handle height, wind load on the structure itself and other components, and properties of the structure (material elasticity and moment of inertia of the structure profile);
- Dynamic deflection of the contact wire by the sideways push from the pantograph's uplift force.

The effect of the sideways push from the pantograph's uplift force is increased at higher speeds. This push depends on the following variables:
- Shape of the pantograph head;
- Pantograph dynamic contact force, uplift and tilt;
- Contact wire(s) tension;
- Train running speed.

Notes:
- Dynamic friction between pantograph and contact wire can be discarded because of its low value and minor influence in the calculation of horizontal and vertical contact forces.
- The pantograph moves up and down, but pushes up and left. The contact wire moves left and right, but pushes down and right.

The contact wire moves to the edge (more deflection) and the pantograph will move up, when:
- The vertical uplift force of the pantograph is increased (dynamic behaviour), resulting in more horizontal push from the hinge;
- The horizontal component of the contact wire tensions is decreased (passing the support and entering the span), providing less resistance;
- The wind load on the span increases.

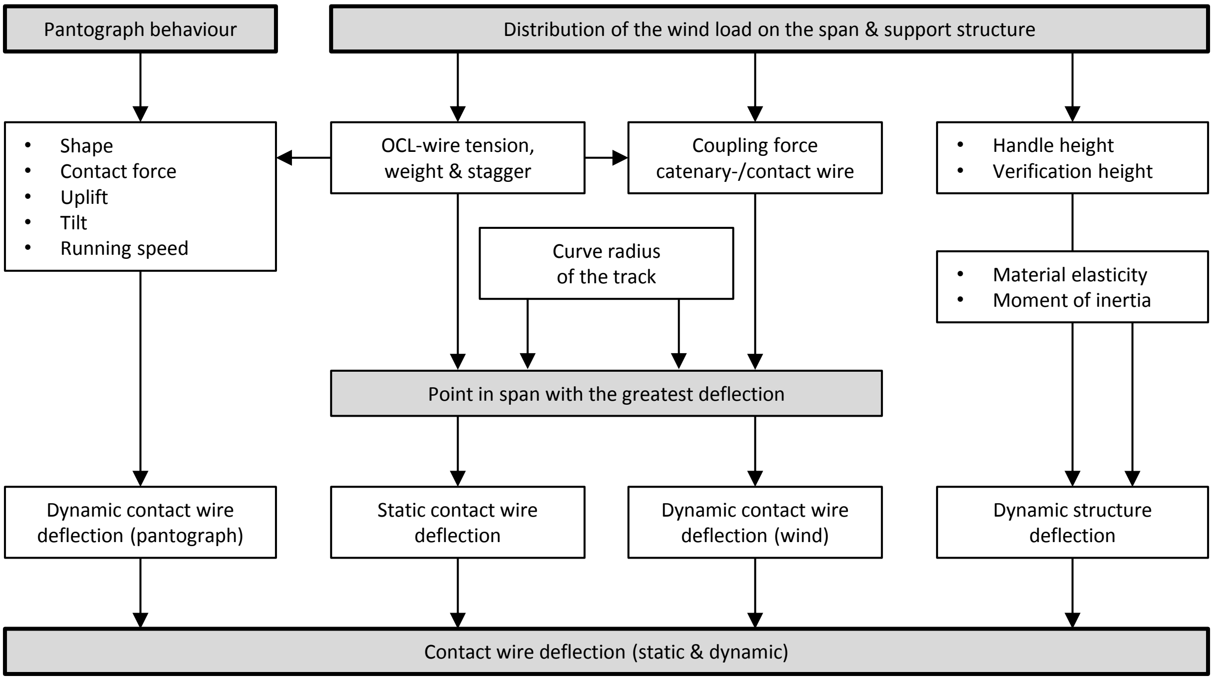
The contact wire moves to the centre (less deflection) and the pantograph will move down, when:
- The vertical uplift force of the pantograph is decreased (dynamic behaviour), resulting in less horizontal push from the hinge;
- The horizontal component of the contact wire tensions is increased (leaving the span and approaching the next support), providing more resistance;
- The wind load on the span decreases.

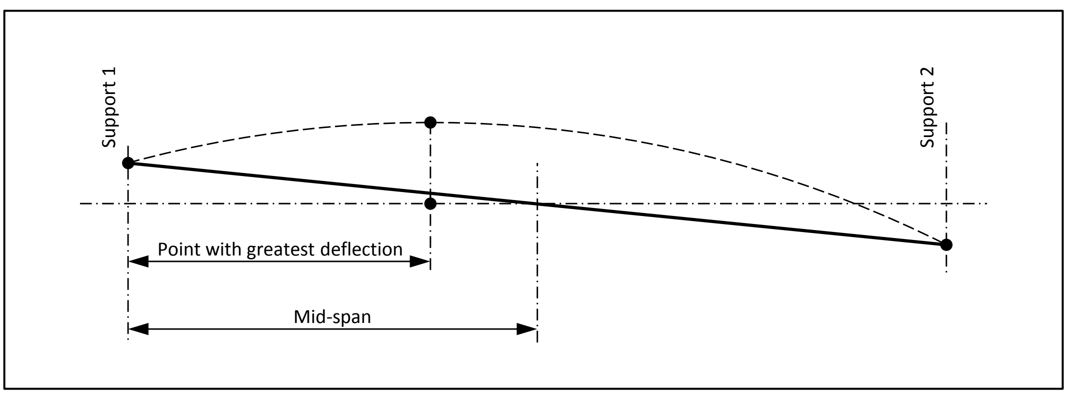
It is assumed that static deflection of the structure is compensated by adjustments in the design or during construction. The wire deflection is calculated relative to the design track centre, at the point in span with the greatest deflection.

The proposed steps to calculate the wire deflection are shown on the opposite page. The wire deflection shall be calculated according to existing standards.

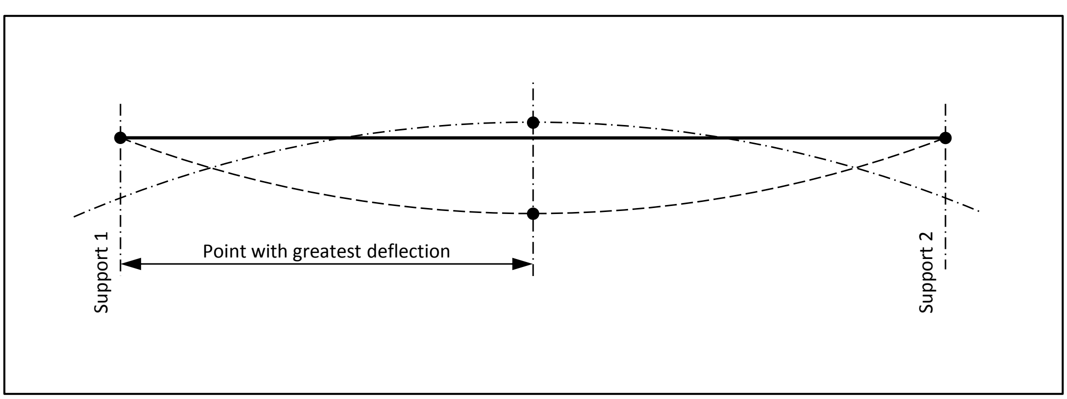
Note: Requests for standard EN 50119:2009 are proposed to:
- Incorporate the coupling force into the calculation of the wire deflection, based on the different deflection values of catenary and contact wires.
- Describe the effects of the dimensions, shape and dynamic behaviour of the pantograph on the wire deflection, according to the position, speed and travel direction of the pantograph in the span.

Wire deflection





Straight track



Curved track

3.9 MONTE CARLO SIMULATION

Many parameters in the calculation of the margin have a stochastic nature. The value of these parameters is not fixed, but subject to random nature and combined occurrences within a probability constraint. As a result, the margin must be expressed as a distribution, according to the distributions of input parameters.

The distribution of the margin can be approximated by performing repetitive calculations of the margin, using random values within the distribution of stochastic parameters taking part in the calculation. The entirety of calculations is called a simulation. Single calculations are iterations. More iterations provide better accuracy of the distribution. More simulations provide better reliability. Taking random values means no interdependency between individual parameters. This method is the ‘Monte Carlo’ simulation.

In the assessment of the chance of contact wire launch or infringement on a specific location, realism of the margin distribution is significantly improved by using the most accurate statistical data available for that location.

Statistical data should be available for:
- Operational effects;
- Environmental effects;
- Construction & maintenance tolerances.

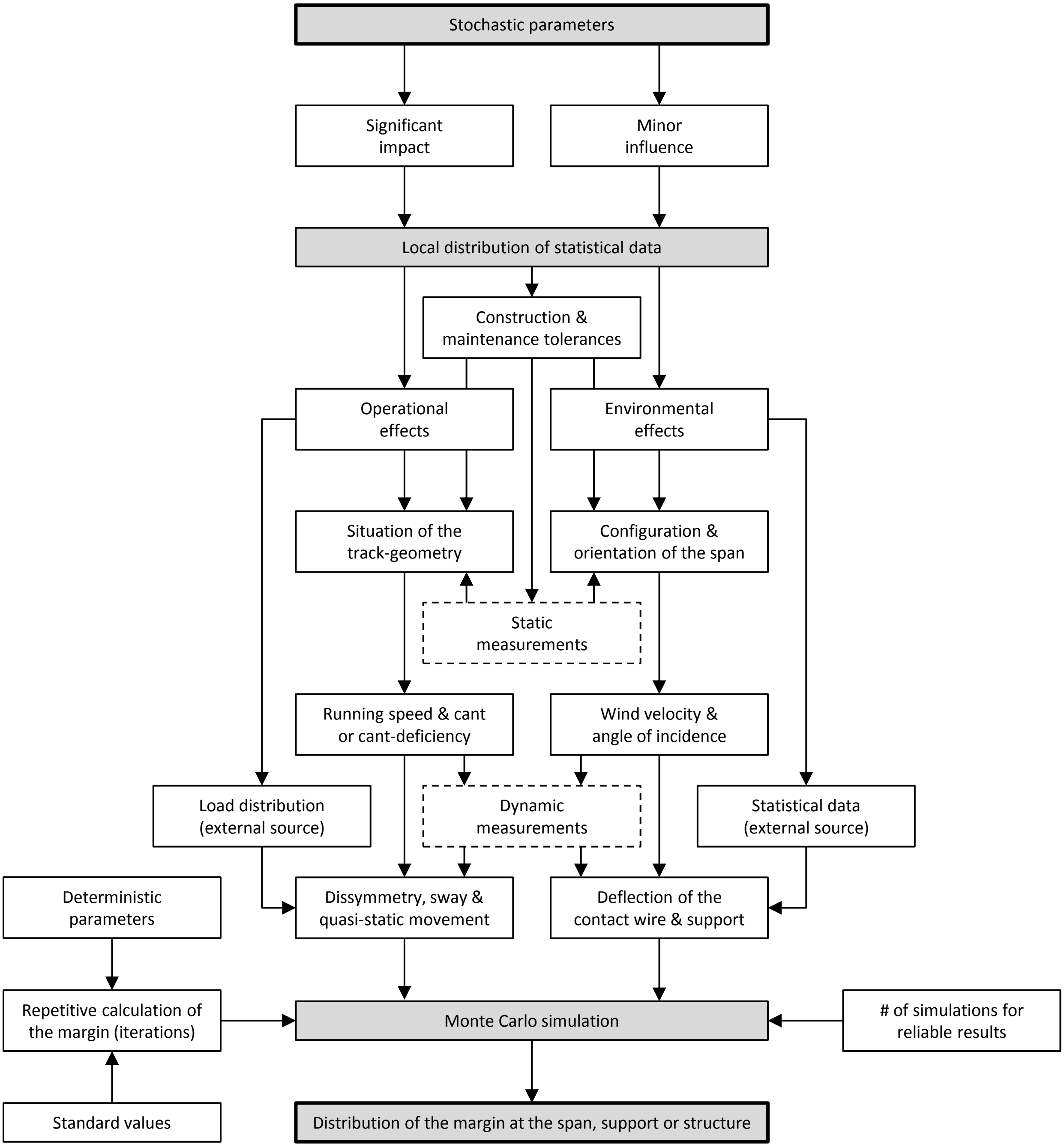
With the combination of operational effects (e.g. running speed) and the situation of the track geometry (e.g. cant or cant deficiency), the vehicle sway and the quasi static movement is calculated. The load distribution for the calculation of dissymmetry is obtained from the railway operator (external source).

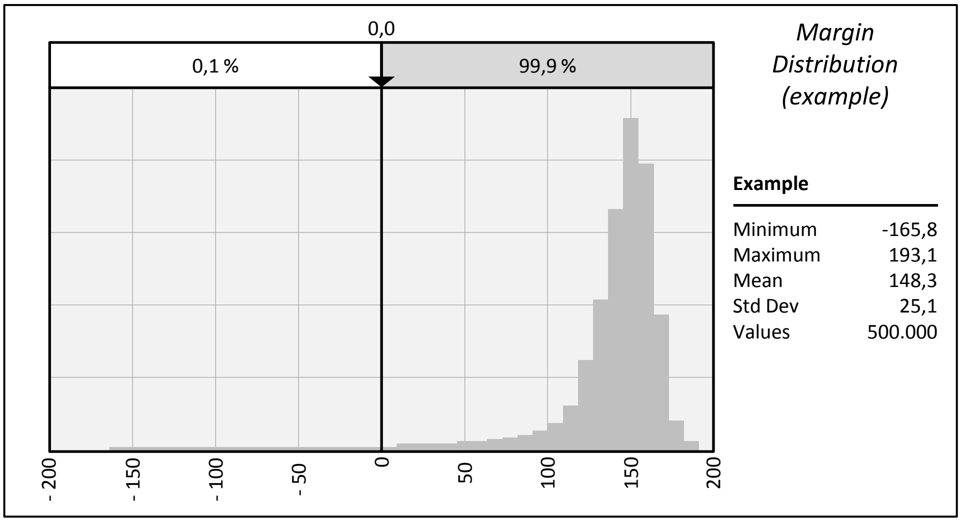
With the combination of environmental effects (e.g. wind velocity) and orientation of the span (e.g. angle of incidence), the deflection of the contact wire and support structure is calculated. Statistical data can be obtained from meteorological institutes (external source).

Accuracy of the distribution of stochastic parameters is enhanced by long-term measurements. Individual measurements provide deterministic values for a specific moment in time.
- Static measurements are sufficient to determine the situation of the track & OCL geometry;
- The consequences of operational and environmental effects require dynamic measurements.

The proposed steps to perform the Monte Carlo simulations are shown on the opposite page.

Monte Carlo simulation





3.10 ASSESSMENT

Monte Carlo simulations are performed with data from the system & allocation design, the railway operational plan and environmental conditions within the assessment scope (area).

The distribution of the margin shall be representative for the ratio between:

- The number of simulations (according to the type of pantograph and reliability of outcomes) and the number of iterations (according to the required accuracy of the results and simulation runtime).
- The number of pantographs passing according to the exploitation model in the railway operational plan.

The exploitation model within the assessment horizon (time) shall provide information on:

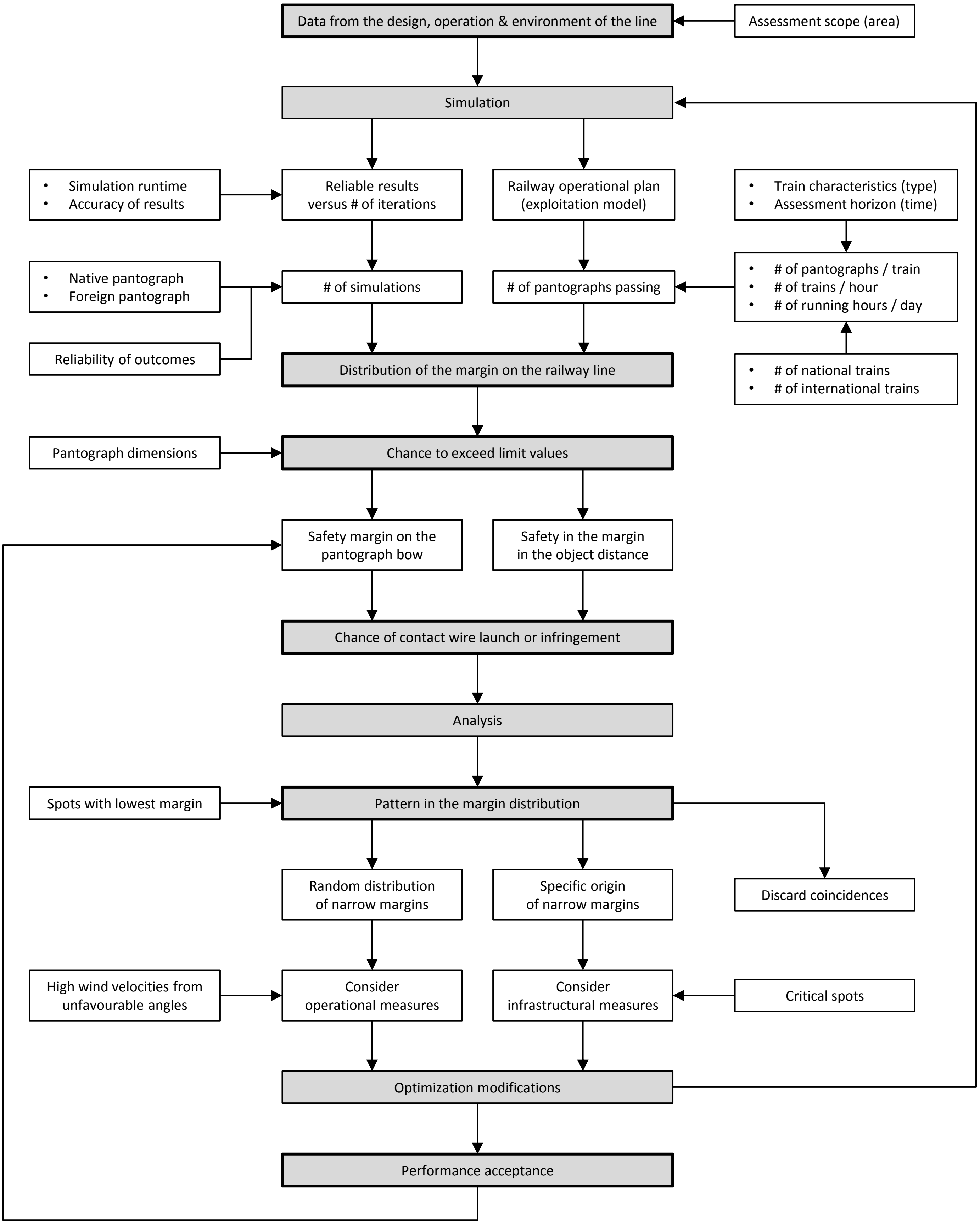
- The origin of trains (national or international);
- The number of pantographs per train and train characteristics;
- The number of trains per hour and the amount of running hours per day.

The proposed steps to perform the assessment are shown on the opposite page. The assessment is based on analysis of the pattern in the margin distribution, focussing on the locations with the lowest margin (most critical for the chance of contact wire launch or infringement).

- Random distribution of narrow margins on locations with comparable situations, provide few cost-effective options for modification of the infrastructure. Operational measures should be considered when high wind velocities from unfavourable angles are expected.
- When specific origins of narrow margins are identified, modification of the infrastructure at critical spots can solve the problem locally and enhance performance of the entire line.
- Situations where the margin is far beyond the acceptable limit of even the most favourable pantograph dimensions, must be seen as coincidences and are best discarded.

The analysis is targeted at finding the most effective solutions with the lowest cost. Simulations shall be repeated to optimize effectiveness and validate results. Performance acceptance is based on acceptance of the safety margin.

Assessment - *analysis*



3.11 EVALUATION

In this study an effort has been made to investigate a position for the contact point on the pantograph head from where the contact wire should not be able to return to the other side, no matter how great the forces at work. This so-called 'point of no-return' could not be identified. Instead, it was proven that for every position on the pantograph head, a lateral force could be imagined to pull the contact wire back towards the centre. This force is calculated as a function of:

- The dynamic uplift force of the pantograph according to the weight of the contact wire and the vertical component of the contact wire tension. The complexities in running conditions are calculated in dynamic simulations;
- The angle of the pantograph head according to the position of the contact point;
- The horizontal displacement of the contact wire.

In this equation, typical high-speed OCL systems will perform well. These systems generally have high contact wire tension and low weight.

As an alternative to the point of no-return, the turning point for the contact wire is proposed. The turning point is calculated as the position of the contact point where the pantograph and contact wire are balanced. This situation occurs when the horizontal component of the contact wire's tension, plus a force to compensate for wind load, together are strong enough to induce a force lateral to the pantograph's surface (up the slope), that equals a force lateral to the pantograph's surface in opposite direction (down the slope), resulting from the weight of the contact wire plus the vertical component of the contact wire's tension, in response to the pantograph's dynamic uplift force.

Trial situations for the turning point are shown on the opposite page.

- Image (1) shows the contact point on the 30° slope of the 1600 mm pantograph, on the insulated horn, past the edge of the working zone. The margin is negative. The contact point will move in the direction of the greatest force lateral to the pantograph's surface. In the example, the contact point is balanced.
- Image (2) shows the contact point in a 60° angle to the horizontal, on the insulated horn of the 1600 mm pantograph. In the example, the contact point is moving away from the centre, towards the edge of the pantograph bow. The downward surface-lateral force is greater than the upward surface-lateral force. Dewirement is imminent, unless a sudden shift in forces occur, triggering a contact wire launch. These actions take place within the area of the safety margin.

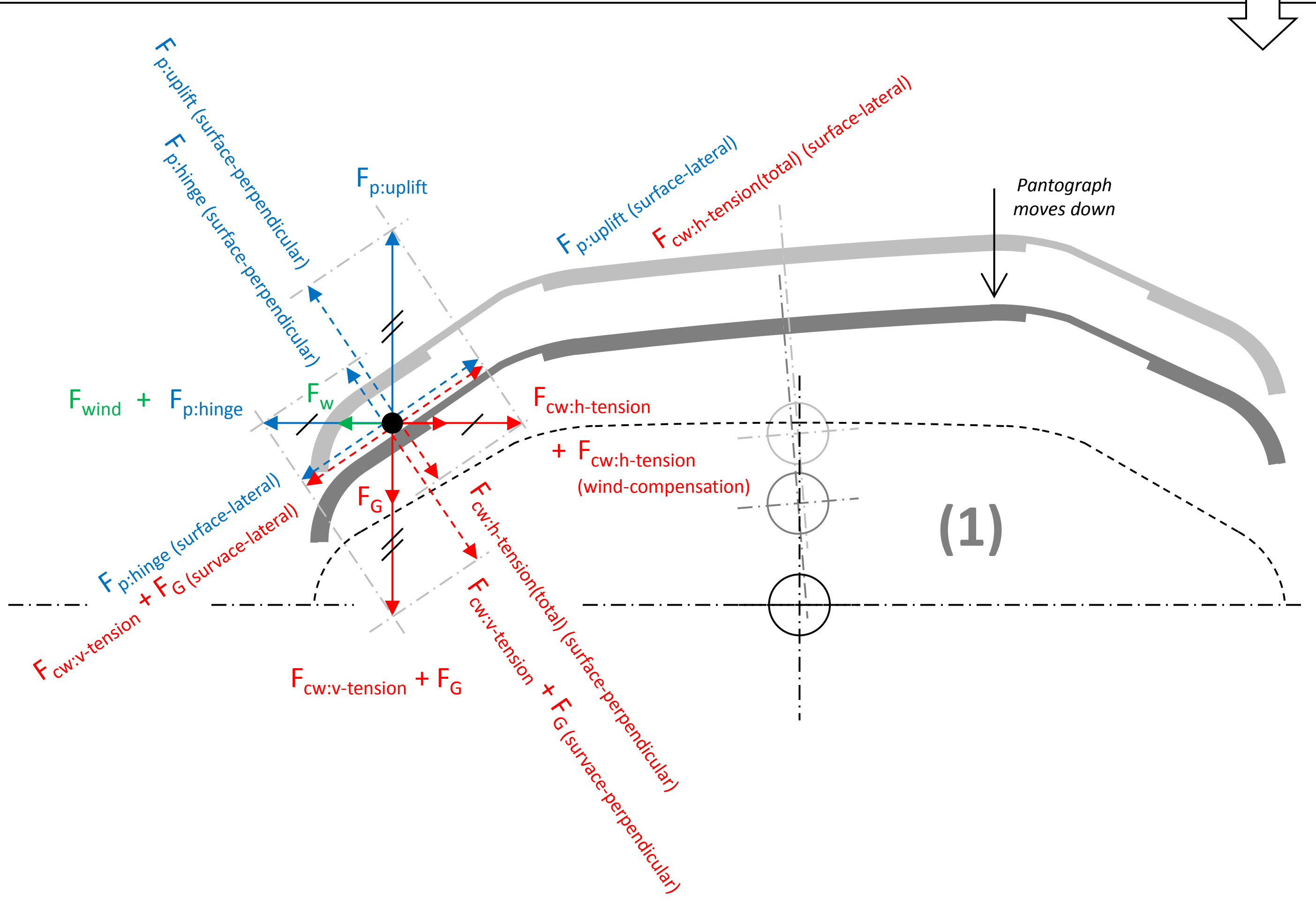
Note: When the contact point has become this far near the edge of the pantograph bow, the pantograph will have considerable uplift as a result of the contact wire deflection, not counting the pantograph tilt as a result of the uneven load.

Note: The allowed position of the contact point near the edge of the pantograph bow has to be checked for infringement of dropper clamps and for the relation between the lateral push from the contact wire and pantograph rigidity.

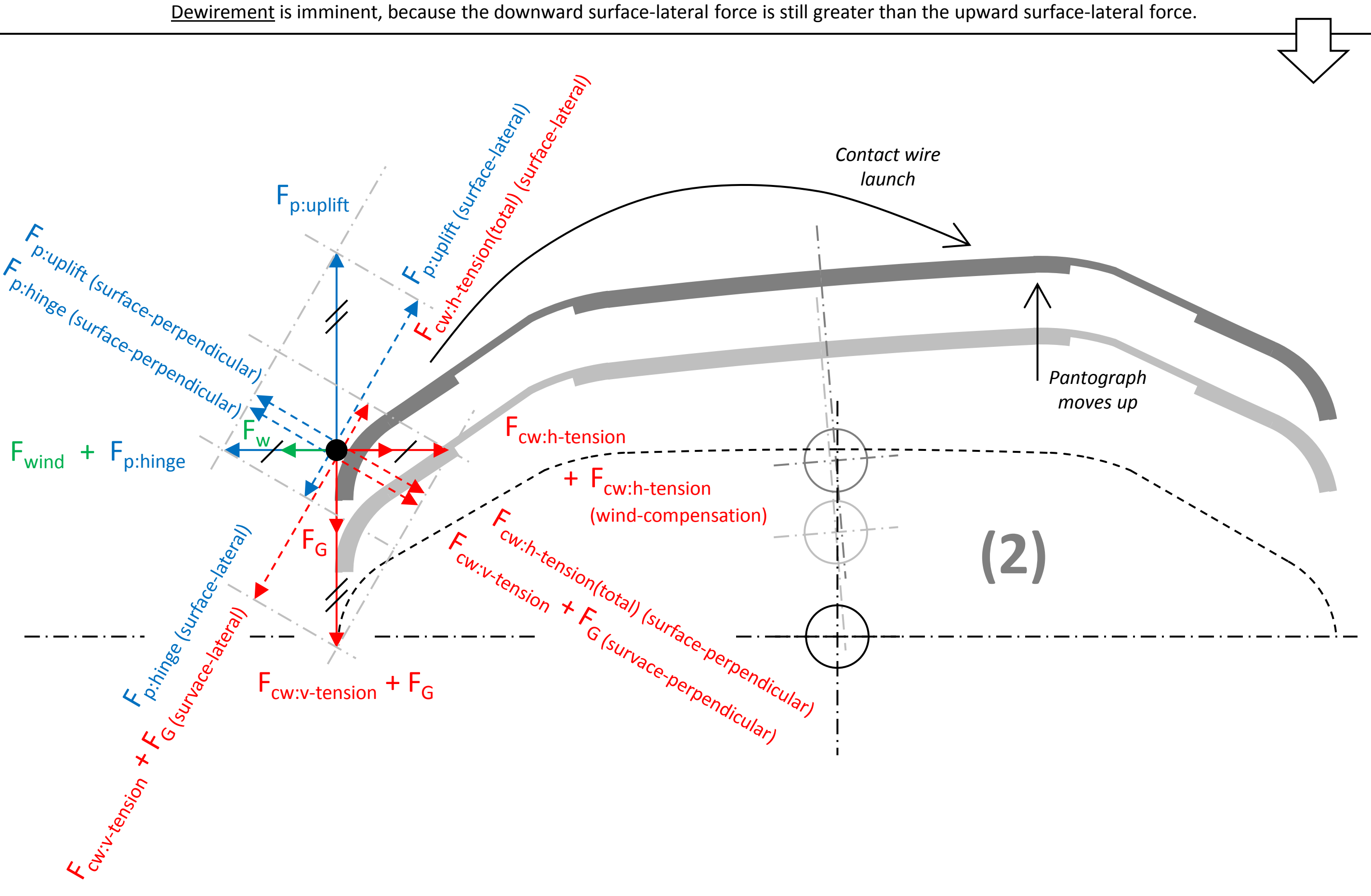
Because of the uncertainties in the approach of the edge of the pantograph bow, the assessment will focus on the contact point exceeding the working zone (negative margin), introducing the chance of contact wire launch. The remaining distance to the edge of the pantograph bow is reserved as a safety margin.

The safety margin can be regarded as a static value according to the limits set by the dimensions and pre-defined functional ranges of the pantograph head. However, because of the stochastic nature of many parameters, it is useful in the assessment to consider a dynamic range for the safety margin.

The contact point is on the 30° slope of the 1600 mm pantograph, on the insulated horn, past the edge of the working zone. The margin is negative.
Relative displacement: The contact point will move in the direction of the greatest force lateral to the pantograph's surface.
Absolute displacements: The contact wire will move left or right to the horizontal. The pantograph will move up or down to the vertical.



The contact point is in a 60° angle to the horizontal, on the insulated horn of the 1600 mm pantograph.
Contact wire launch can occur if the upward surface-lateral force suddenly becomes greater than the downward surface-lateral force.
Dewirement is imminent, because the downward surface-lateral force is still greater than the upward surface-lateral force.



The conventional definitions of the safety margins are straightforward:

- The safety margin for infringement is an area around the circumference of the pantograph head, similar to the definition of mechanical and electrical clearances (see § 3.6 of this report).
- The safety margin for contact wire launch is the area on the pantograph head between the edge of the working zone and the edge of the pantograph bow.

The dynamic range of the safety margin is defined as the difference between the smallest margin and the edge of the pantograph bow (for contact wire launch) or the edge of the structure (for infringement).

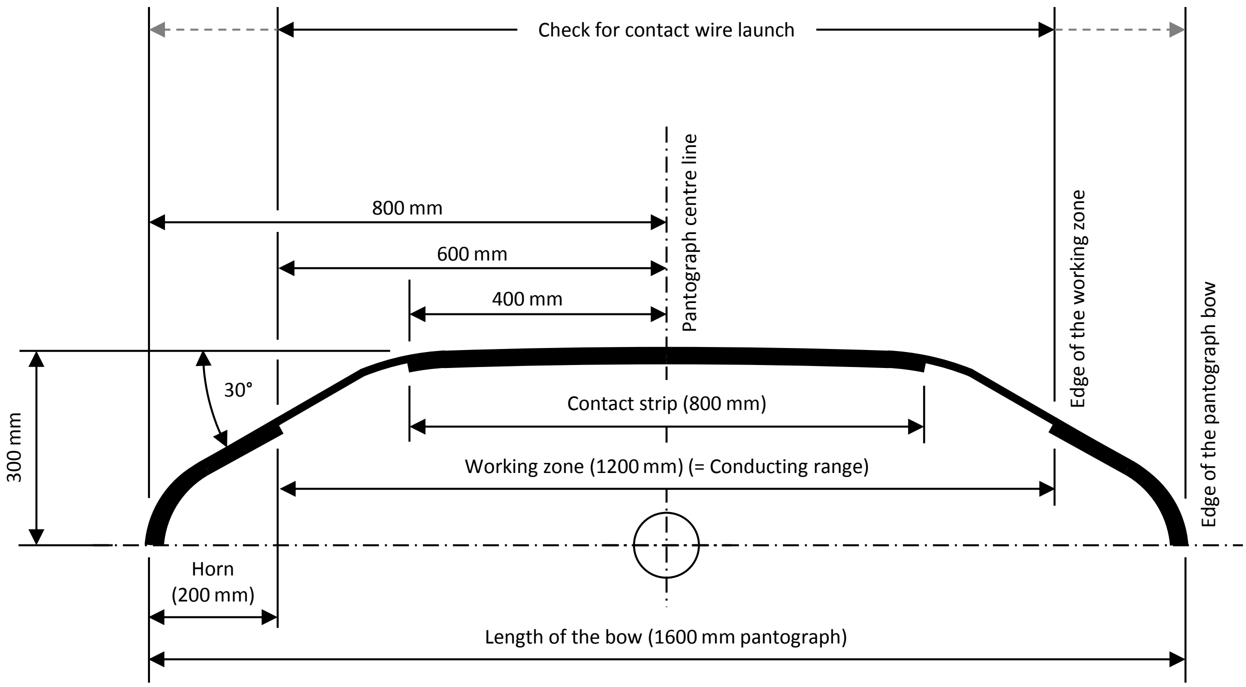
The dynamic range of the safety margin for contact wire launch is shown on the opposite page.

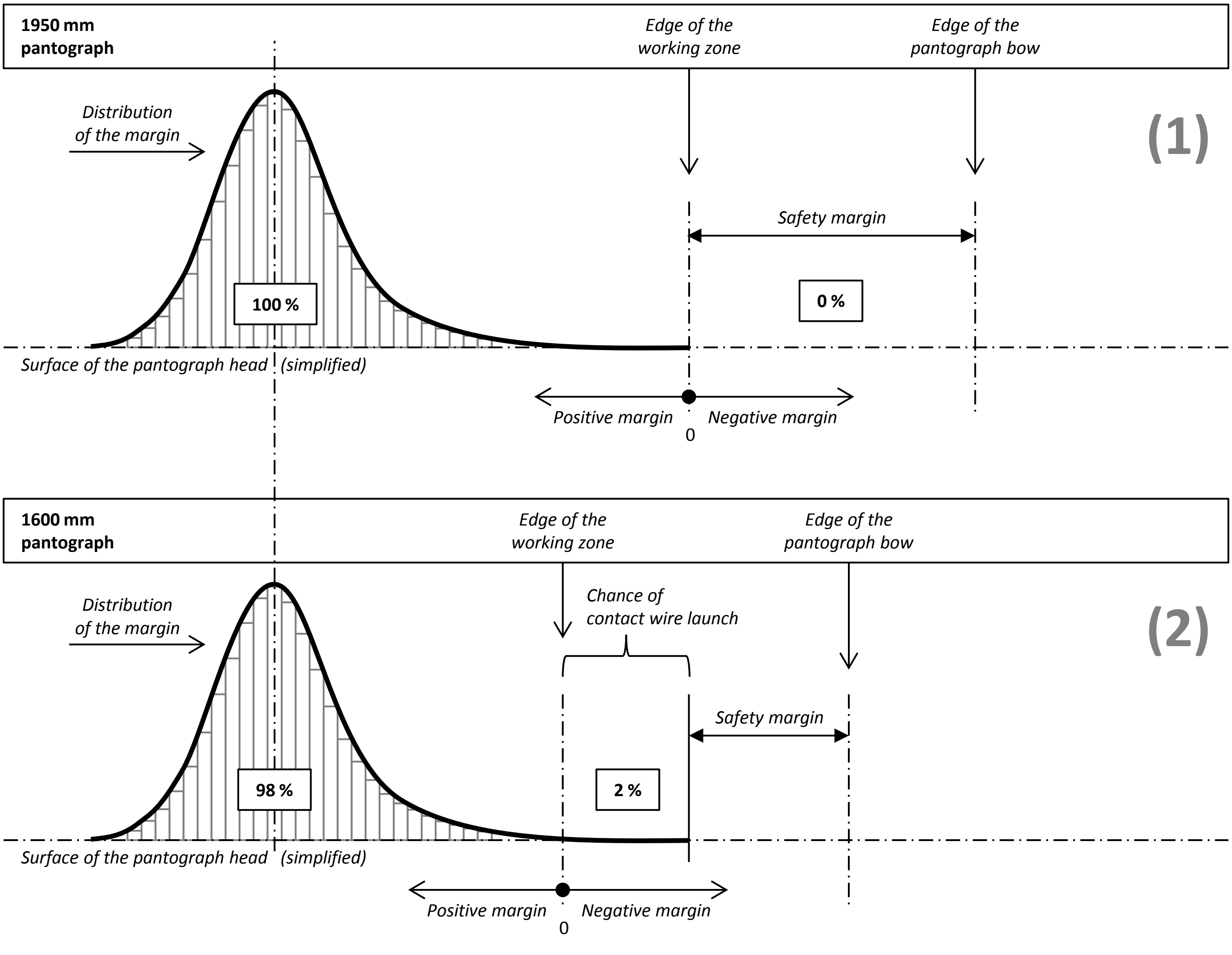
- Image (1) shows a situation for a 1950 mm pantograph. The contact point does not exceed the edge of the working zone (no negative margin). The chance of contact wire launch is zero percent (0 %).
  The safety margin is the difference between the edge of the working zone and the edge of the pantograph bow.
- Image (2) shows the situation with the 1600 mm pantograph. The contact point does incidentally exceed the edge of the working zone. The chance of contact wire launch is two percent (2 %).
  The safety margin is the difference between the smallest margin and the edge of the pantograph bow.

Note: An assessment of the chance of contact wire launch is tested in trial simulations of a virtual railway line, described in chapter 4 of this report. Chances are calculated in Monte Carlo simulations. These simulations must be repeated with real data to validate the results.

To reach an acceptable chance of contact wire launch, the distribution of the margin (according to the distributions of available and taken space) can be influenced by modification of the infrastructure or operation, increasing performance.

Evaluation – *Safety margin*





3.12 MEASUREMENTS

There are two types of measurements, each one with distinctive objectives:
- Static measurements, with the aim to establish the current value of stochastic parameters;
- Dynamic measurements, with the aim to narrow the distribution of stochastic parameters.

Additional result from static measurements is the ability to assess the urgency and required frequency of maintenance actions. The proposed objects suitable for measurements are listed on the opposite page.

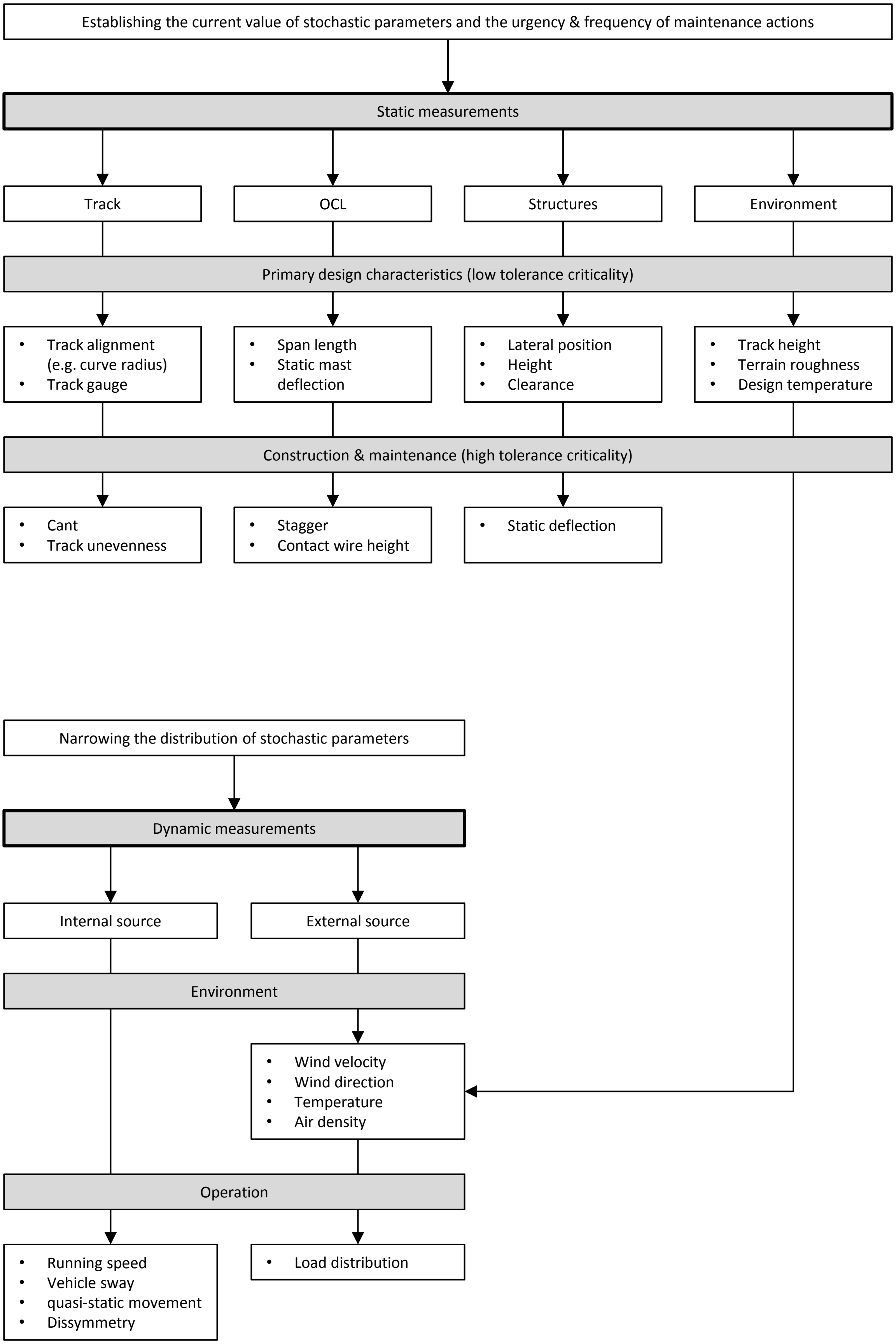
Parameters for track, OCL, structures and environment are distinguished according to tolerance criticality in static measurements:
- Primary design characteristics (low criticality);
- Construction & maintenance (high criticality).

Parameters from internal and external sources are distinguished according to relevance:
- Environment;
- Operation.

Statistical data of wind patterns is widely available at low cost and in a resolution of at least 50 square km. Data commonly contains the distribution of the wind velocity for the wind angle, temperature and air density. Reliability of forecasts is higher for a longer measurement history.

In general, measurements will provide Inframanagers with the most accurate information available for the location, giving a more realistic representation of local situations by which the assessments can be performed more accurately.

Measurements



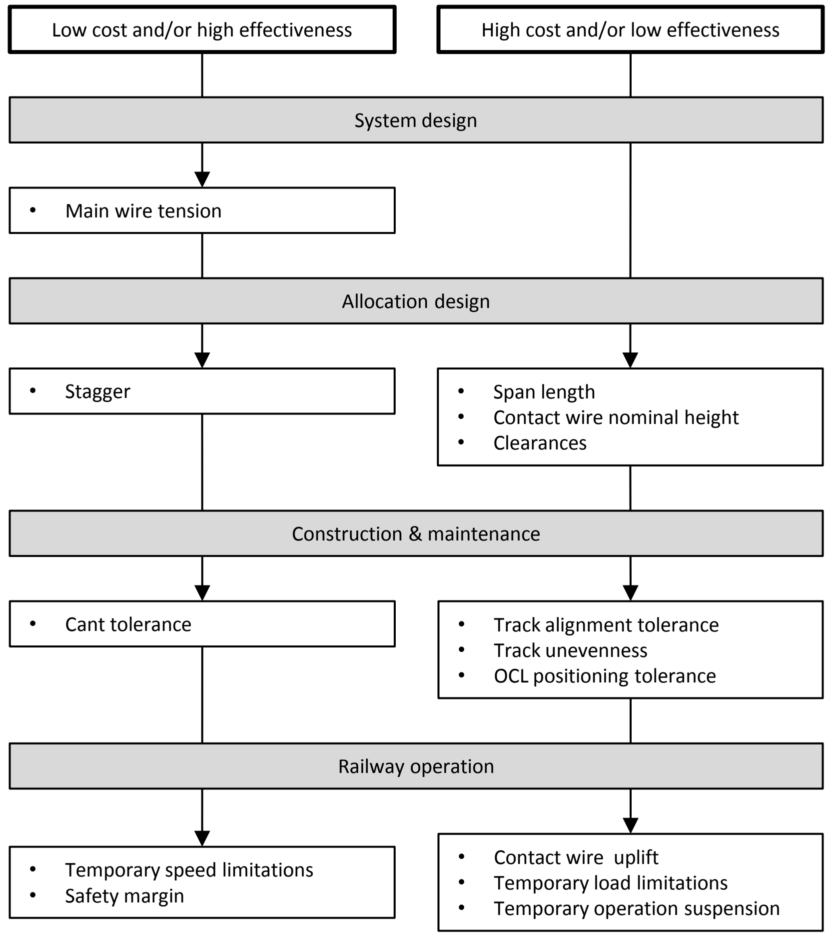
3.13 PARAMETERS

The parameters that can be altered in the calculation of the margin for contact wire launch and infringement are distinguished according to the ratio between the cost and effectiveness of modifications. The cost-effectiveness is indicated on the opposite page, along with examples of typical usage of the length of the pantograph bow. Parameters are grouped according to relevance:

- System design;
- Allocation design;
- Construction & maintenance;
- Railway operation.

The typical contribution in the use of the length of the working zone on the 1600 mm pantograph is indicated in the table for each parameter in the calculation of contact wire launch on straight track and curve with a radius of 1500 m. The table is an example, showing the different factors and indicating focus areas for modification proposals. Cases are tailored to represent optimal use. Values are listed absolute (mm) and relative (%).

Parameters – *cost effectiveness*



Typical usage of the length of the bow (1600 mm pantograph / contact wire launch / optimal use of working zone)

	Straight track		Curve R=1500 m	
1600 mm pantograph				
• Half of the length of the conducting range	600 mm	100 %	600 mm	100 %
Movement of the pantograph - Track related				
• Transverse displacement of the track between two maintenance actions	20 mm	3,3 %	20 mm	3,3 %
• Cant decrease between two maintenance actions	8 mm	1,3 %	38 mm	6,3 %
• Oscillations generated by track unevenness	2 mm	0,3 %	8 mm	1,3 %
• Transverse displacement of the wheel set in relation to the track center	15 mm	2,5 %	15 mm	2,5 %
Movement of the pantograph - Train related				
• Additional geometric overthrow due to the bogies	0 mm	0,0 %	-1 mm	-0,2 %
• Transverse clearance between wheelset, bogie frame and body	6 mm	1,0 %	6 mm	1,0 %
• Transverse movement of pantograph by carriage rigidity	0 mm	0,0 %	0 mm	0,0 %
• Transverse flexibility of the mounting device on the roof	30 mm	5,0 %	30 mm	5,0 %
• Mounting tolerance of the pantograph on the roof	10 mm	1,7 %	10 mm	1,7 %
• Pantograph sway due to the vehicle characteristics	15 mm	2,5 %	48 mm	8,0 %
• Additional overthrow on the inside/outside of the curve	0 mm	0,0 %	17 mm	2,8 %
• Quasi-static movement	0 mm	0,0 %	0 mm	0,0 %
• Loading dissymmetry	90 mm	15,0 %	92 mm	15,3 %
Movement of the contact wire				
• Contact wire position (static displacement)	59 mm	9,8 %	43 mm	7,2 %
• Contact wire positioning tolerance	10 mm	1,7 %	10 mm	1,7 %
• Contact wire deflection - dynamic load (wind)	315 mm	52,5 %	241 mm	40,2 %
• Mast deflection - dynamic load (wind)	13 mm	2,2 %	12 mm	2,0 %
• Mast deflection - dynamic load (vibrations)	10 mm	1,7 %	10 mm	1,7 %
Margin for contact wire launch	-3 mm	-0,5 %	1 mm	0,2 %

3.14 MODIFICATION

The proposed modification options are listed on the opposite page. Options are sequenced according to cost-effectiveness and grouped according to relevance:

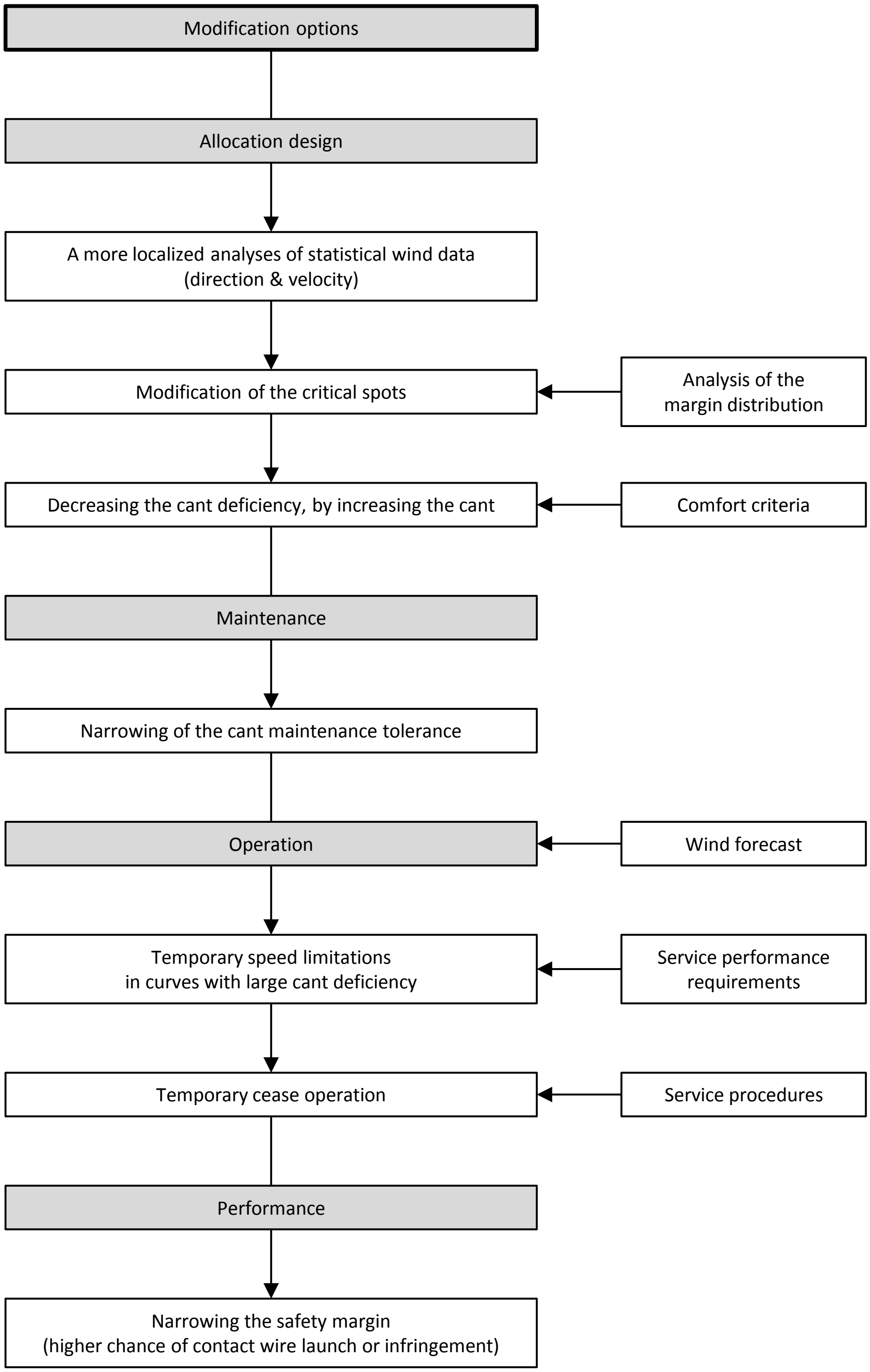
- Allocation design;
- Maintenance;
- Railway operation;
- Performance.

Railway operational measures at times with high wind loads require acting based on the wind forecast.

- Temporary speed limitations are most effective in curves with high cant or cant deficiency, so this measure is best used locally. The effect on the performance of the line can be calculated in simulations;
- Temporary cease operation is most effective when margin-overruns randomly occur in many spans with similar characteristics, mostly expected on straight track. Few alternative options are available. The maximum wind velocity for safe operation can be calculated in simulations.

When margin-overruns selectively occur in some spans with specific characteristics, mostly expected in curves, infrastructure modification can be tailored to the local situation. The effect on the performance of the entire line can be calculated in simulations, making modifications until the chance of contact wire launch or infringement becomes insignificant.

Modification - *options*

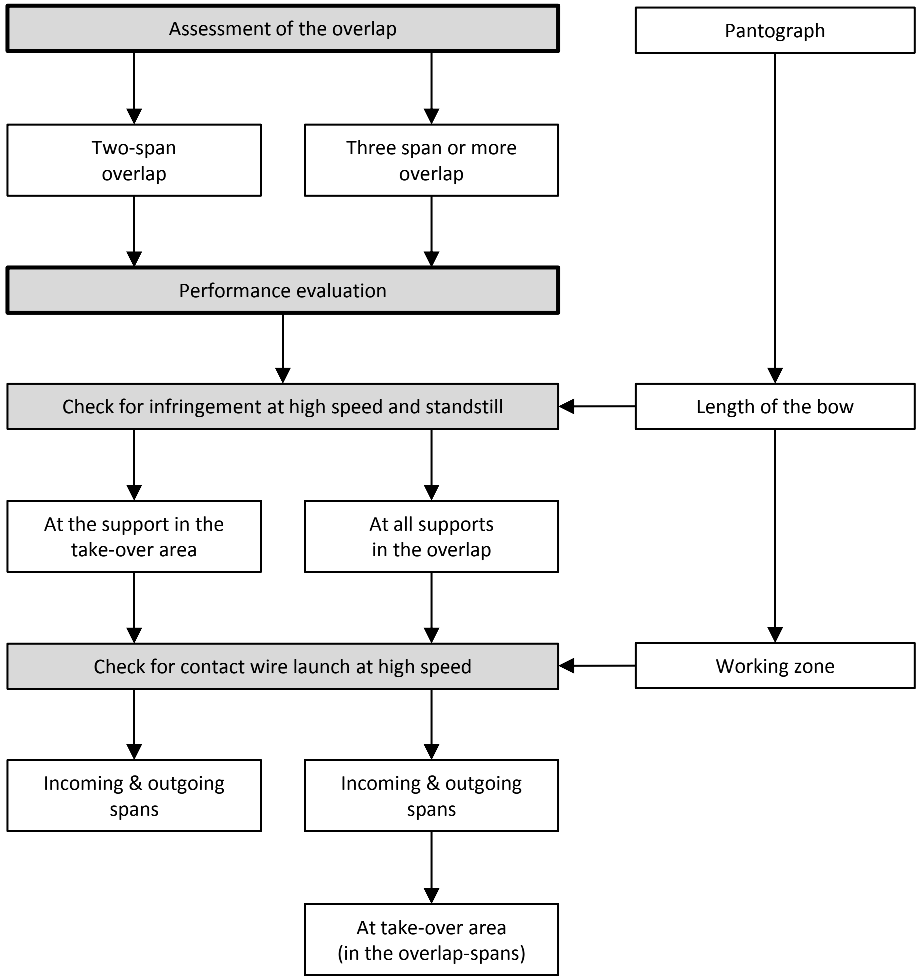


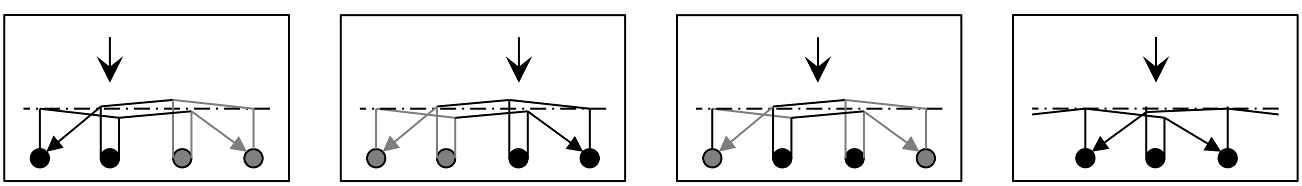
3.15 OVERLAP

The proposed steps to assess catenary overlaps are shown on the opposite page. The assessment basically involves a check for contact wire launch and infringement according to the proposed steps in § 3.5 and 3.6 of this report.

- The chance of infringement is checked at the positions of the support structures at high speed and stand-still, using the length of the pantograph bow.
- The chance of contact wire launch is checked in the incoming & outgoing spans and at the take-over area in the overlap spans, using the working zone on the pantograph.

Overlap





First overlap support | *Second overlap support* | *At takeover area (type 1)* | *At takeover area (type 2)*

Travel direction →

3.16 OCL SWITCH

The general steps to assess catenary switches are proposed on the opposite page. Both cross-wire and parallel wire electrification shall be considered.

- Switches electrified with the parallel wire principle conform to the basic principles of overlaps.
- Switches electrified with the cross-wire principle are considered to conform to the design principles shown in the example on the second page. The illustration represents a turnout-ratio of 1:15, scaled to a horizontal/vertical ratio of 1:10.

The combination of spans from main and switch track shall be checked for the chance of infringement of fittings, for both narrow and wide pantographs, according to figure (1).

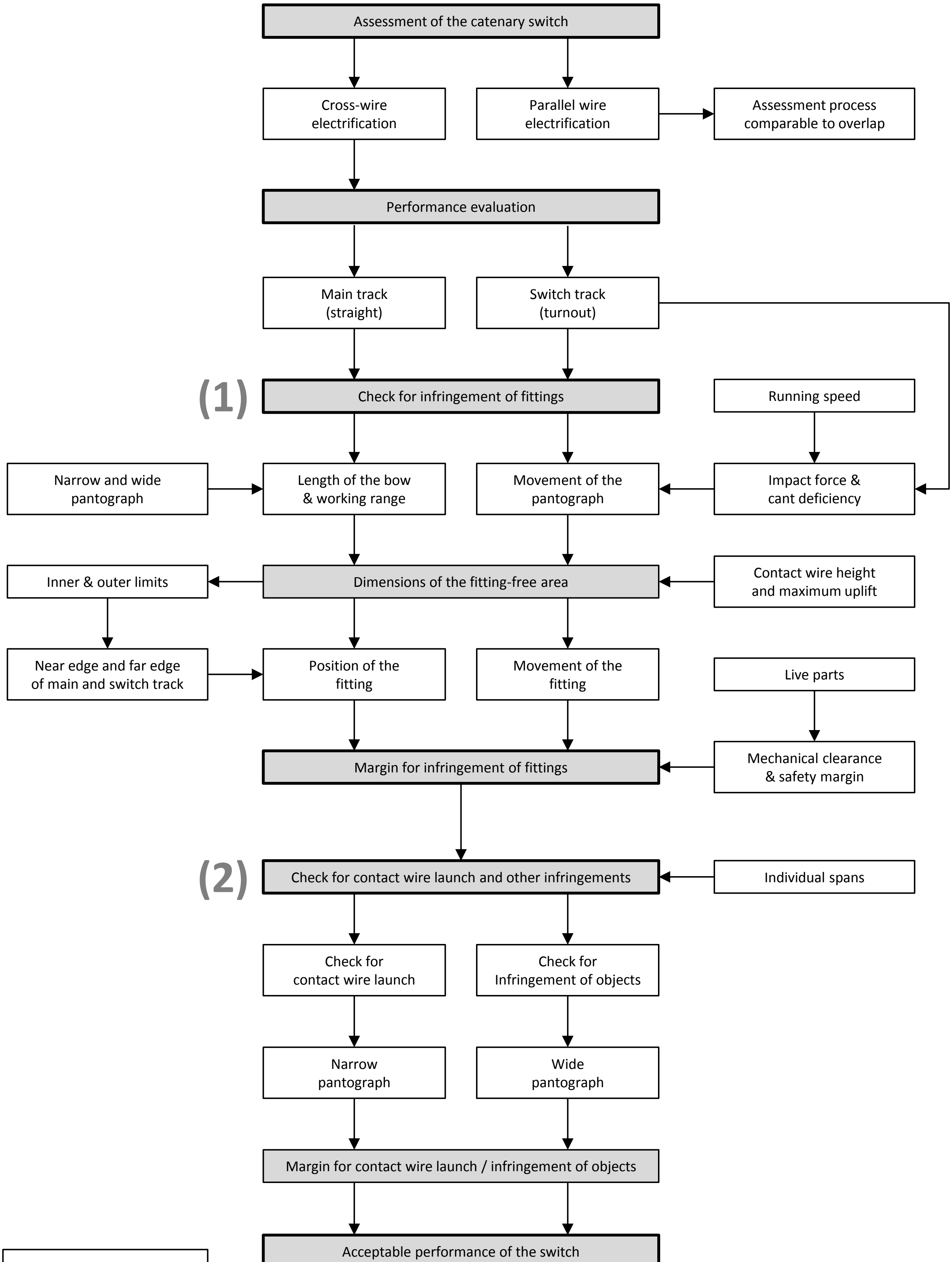
- The vehicle sway from the impact force and cant deficiency according to the running speed in the switch track shall be taken into account in the calculation of the pantograph movement.
- The dimensions of the fitting-free area for each track shall represent horizontal inner- and outer limits, and vertically consider both nominal contact wire height and maximum uplift.
- The position and movement of the fitting shall be checked at the near- and far edge of the main- and switch track. The margin for infringement shall consider the mechanical clearance and a safety margin.

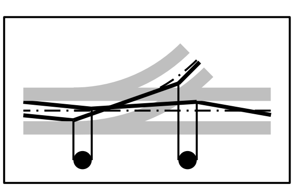
Individual spans on main and switch track shall be checked for the chance of contact wire launch for narrow pantographs and other infringements for wide pantographs, according to figure (2).

The proposed steps in the example on the third page illustrate the assessment of a narrow pantograph on a wide-pantograph network. In the example, no modification of the OCL-switch is required.

The proposed steps in the example on the fourth page illustrate the assessment of a wide pantograph on a narrow-pantograph network. In this example, a conflict is detected: Fittings are within the fitting free area. The problem is solved by a modification of the stagger at the supports. The support structures do not have to be moved.

OCL switch - *general*





OCL switch - *design principles*

Deterministic / static parameters | **Stochastic / dynamic parameters**

Track geometry

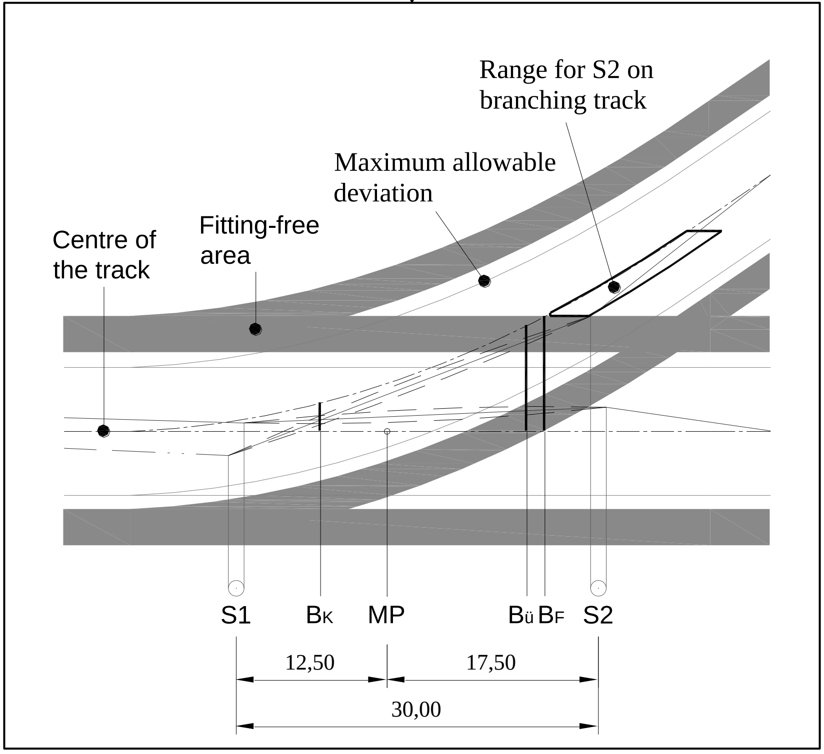
- MP
  - Centre line of main track
  - Centre line of switch track
  - Mathematical point of the switch

OCL geometry

- S1
- S2
  - Position of first support
  - Position of second support

- Maximum allowable deflection
- Fitting-free areas
- Wires intersection (optimal) — B_K
- Start of overtake area (to front-end of switch) — $B_ü$
- Start of infringement-free area (to rear-end of switch) — B_F
- Range for S2 on switch track
- Contact wires position (static)
- Contact wires deflection (dynamic position)

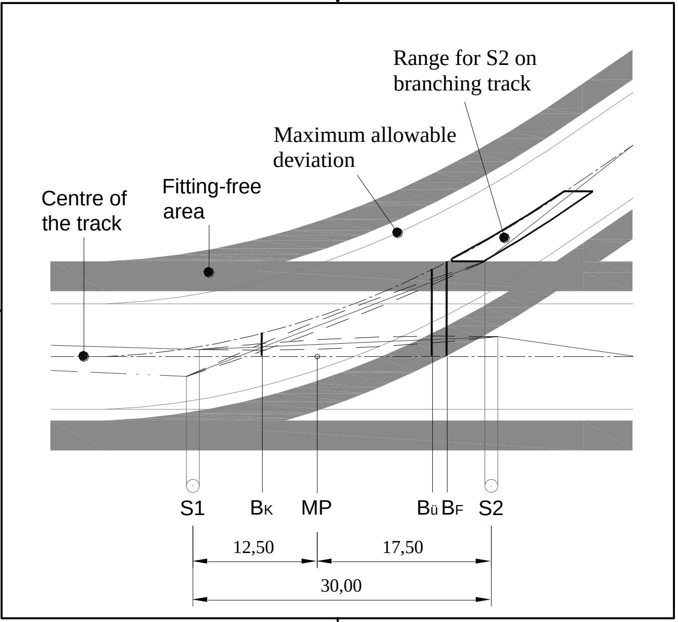
OCL-switch design for 1950 mm pantograph (1:15 turnout-ratio)



OCL switch - *from 1950 to 1600*

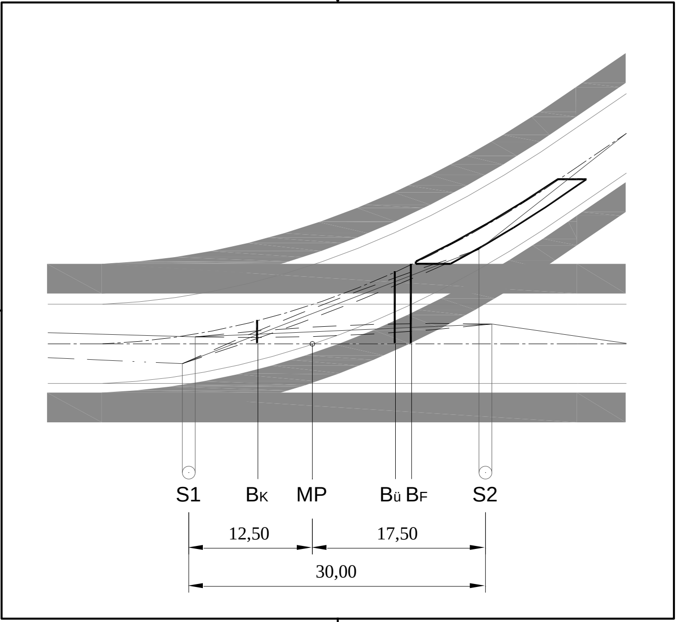
Example → **Design background of OCL-switch for 1950 mm pantograph (1:15)**

Drawing scale 1:10 →



Introduction of the narrow pantograph (1600 mm)

Example → **OCL-switch design for 1600 mm pantograph (1:15 turnout-ratio)**



Compare the width of the fitting-free area

Other checks

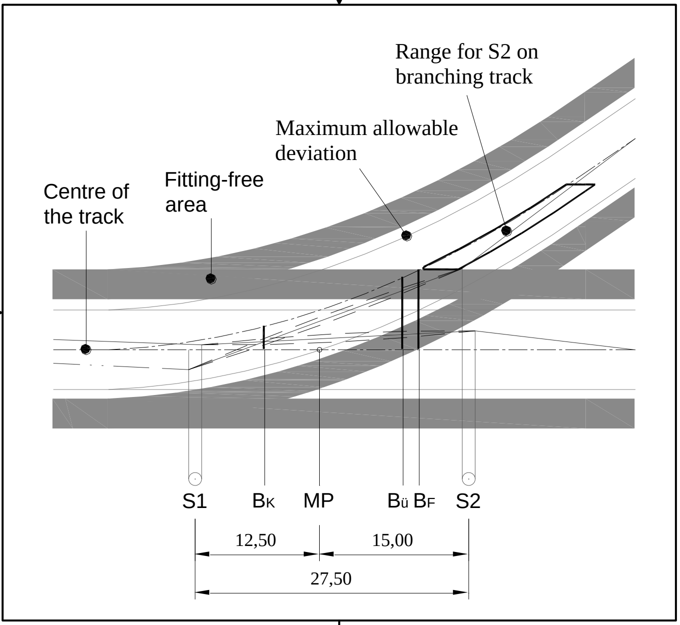
- Favourable position of the intersection between the wires
- Position of the contact wires relative to the track centre
- Infringement of fittings in the fitting-free area

Larger range for S2 on switch track, no modifications required

OCL switch - *from 1600 to 1950*

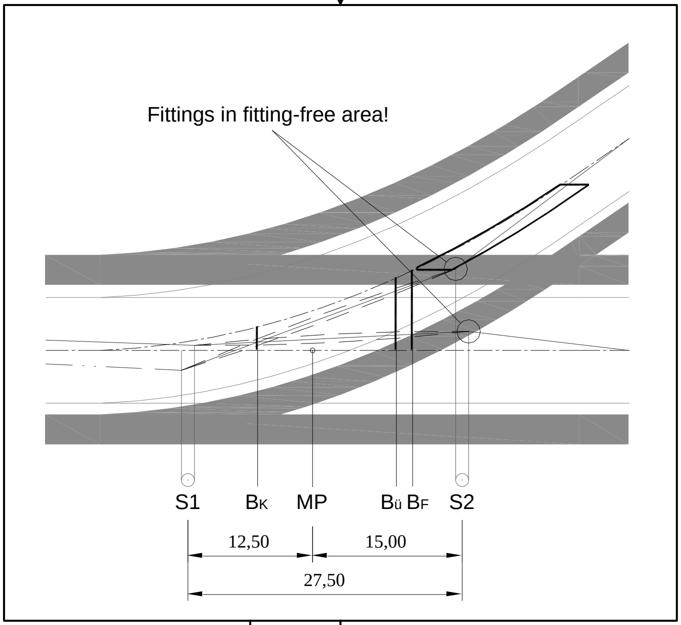
Example → Design background of OCL-switch for 1600 mm pantograph (1:15)

Drawing scale 1:10



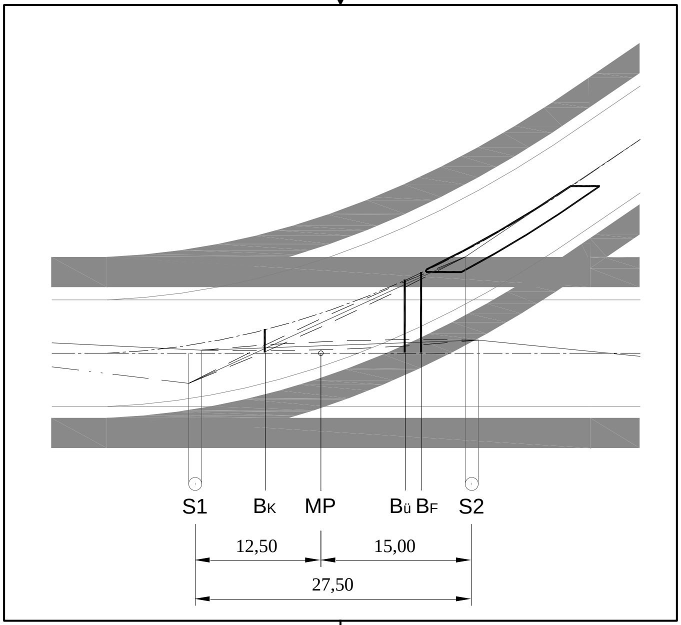
Introduction of the wide pantograph (1950 mm)

Conflicts for wide pantograph, in switch designed for narrow pantograph



Infringement of fittings in the fitting-free area

Modifications for wide pantograph, in switch designed for narrow pantograph



Modification of the stagger at supports S1 and S2

Other checks

- Favourable position of the intersection between the wires
- Position of the contact wires relative to the track centre

4 Trial simulations

In trial simulations of a virtual route, the chance of contact wire launch is assessed. The virtual route is modelled based on a section from the real route with double track between Schiphol and Leiden stations in the Netherlands. The route consists of 204 spans (numbered individually) of various length in straight track and curves, amounting for a total track length of about 10 km. The OCL features a full compensating system, designed for the 1950 mm pantograph:

- Catenary wire: 2x150 mm² CuAg with 2x11 kN;
- Contact wire: 2x100 mm² CuAg with 2x10 kN;
- System height: 1,75 m with stitch wire;
- Maximum span length: 65 m;
- Maximum stagger: +/- 0,35 m;
- Maximum wire deflection: +/-0,55 m.

The track features curves with a radius of 2000 m and 105 mm cant, resulting in a maximum cant deficiency of 46 mm for line speeds up to 160 km/h.

The following stochastic parameters are used:

- Cant maintenance tolerance;
- Wind velocity;
- Environmental temperature;
- Origin of the wind direction;
- Dissymmetry;
- Transverse clearance between wheel set, bogie frame and body;
- Transverse displacement of the track between two maintenance actions;
- Transverse movement of the pantograph caused by carriage rigidity;
- Transverse flexibility of the mounting device on the roof;
- Mounting tolerance of the pantograph on the roof;
- Contact wire positioning tolerance;
- Mast deflection caused by vibrations.

The following deterministic parameters are used:

- Curve radius;
- Distance between the rail running edges;
- Track height above ground;
- Span length;
- Angle of the span;
- Stagger (first and second support);
- Contact wire height;
- Catenary wire height / System height;

- Stitch wire length and diameter;
- Anchor wire length and diameter;
- Projected area of insulators;
- Contact wire diameter and tension;
- Catenary wire diameter and tension;
- Dropper diameter;
- Contact wire weight;
- Mast profile length and width;
- Moment of inertia of the mast profile;
- Margin to take into account of the raising of the contact wire.

The following reference parameters are used:
- Reference cant;
- Reference cant deficiency;
- Distance between rail centres of a track;
- Standard gauge;
- Structural resonance factor for insulator sets;
- Aerodynamic drag factor for insulators;
- Aerodynamic drag factor of grooved contact wires;
- Aerodynamic drag factor of round conductors (catenary wire, dropper, stitch wire and anchor wire);
- Structural resonance factor for structures;
- Aerodynamic drag factor for structures;
- Mast material elasticity;
- Yearly interval factor for wind velocity;
- Height above sea level;
- Terrain factor;
- Gust response factor;
- Margin of the bow trespassing the contact wire;
- Margin of the wear of the pantograph contact strip;
- Flexibility coefficient of the vehicle;
- Reference roll centre height;
- Distance between the end wheel sets of the bogie;
- Dimension over the wheel flanges;
- Working range of the pantograph.

The simulation model has set no limits for the wind velocity for safe and reliable operation.

In the Monte-Carlo simulation, the spans are passed, one after another. In each individual span, random values are drawn from the distributions of stochastic parameters. With these values, and the values for deterministic and reference parameters, the position of the contact point and the margin is calculated.

The margin in each span is temporarily stored in memory, but after one single run through all the spans of the virtual route (an 'iteration'), only the smallest margin of the entire run is saved into a file. This process is repeated many times (a 'simulation'), representing the number of train runs on the virtual route corresponding to the railway operational plan (frequency) and assessment horizon (time period).

The chance of contact wire launch is in fact calculated in a simulation with 500.000 iterations (number of pantographs passing), to capture unlikely events. This amounts for 10 years of operation according to the exploitation model below. The calculated number of 52.560 pantographs per year is rounded to 50.000.

- 2 pantographs per train;
- 4 trains per hour;
- 18 operational hours per day;
- 365 operational days per year.

The simulation is performed without modifications to the virtual route design. The margin for contact wire launch is calculated for both the 1600 mm and 1950 mm pantographs according to the steps in § 3.5 of this report. The chances of contact wire launch are compared. The simulation runtime is approximately 12 hours. The results of the trial simulation are displayed numerically and graphically in Appendix 2.

Counting the number of negative margins (where the contact point is outside the working zone), the results are the following, as indicated in figure 1 on the first page of Appendix 2:

- 1950 mm pantograph: 1 (one) contact wire launch;
- 1600 mm pantograph: 266 contact wire launches.

In the first (most left) column of the figure, the value for the margin is listed in mm. The smallest margin has a value of -185 mm (top row). This means that the contact point is 185 mm beyond the edge of the working zone. This value appears only one time in the entire simulation, as can be seen in the second column from the left of figure 1: “Number of iterations (Total: 500.000) (distribution)”. Following this column downwards, the number of incidents is increased, also visualised by horizontal blue bars representing the sum of all incidents for the specific range of margin values. The initial increase and subsequent decrease of the lengths of the blue bars represents the frequency of occurrences of margin values in the range between the listed value in the corresponding row and the value in the next row of the column directly to the left. Looking from top-to-bottom, the distribution of the margin can be seen.

In the range of margin values between -185 and 0 mm (edge of the working zone for the 1600 mm pantograph), a total of 266 incidents is counted, all accounting for contact wire launch if the virtual route is assessed with the 1600 mm pantograph. This number is the sum of all the incidents listed in the third column to the left of figure 1: “Launches with the 1600 mm pantograph (total: 266)”. If the 1950 mm pantograph is used for the assessment, only 1 (one) incident is counted (top row).

The distribution of the margin for the 1600 mm pantograph is displayed in the graph of figure 4 on the third page of Appendix 2. This graph with the red vertical bars is a 90° rotated and scaled-up view of the blue horizontal bars in the second column of figure 1 on the first page of Appendix 2.

A closer look at the value of the margins shows that of the 266 contact wire launches for the 1600 mm pantograph:

- All margins remain within the pantograph range (the turning point is reached before the edge of the pantograph bow). These margins have values between 0 mm (zero) and -200 mm (negative);
- In one occurrence the margin is very close near the edge of the pantograph bow, with a negative value of -185 mm. This occurrence amounts for the single contact wire launch on the 1950 mm pantograph.

Analysis of the origins of the negative margins reveals the following, as indicated in figures 2 and 3 on the second page of Appendix 2:

- A total number of 127 negative margins with the chance of contact wire launch can be traced back to just 7 specific spans, counting only groups of 10 or more occurrences on the same location. These spans are rated "very critical" (see below) and are highlighted by thick black rectangular boxes. In figure 2 the critical spans (small black boxes) are scattered, because the spans are listed by span number, resembling their position in the virtual route. In figure 3 the critical spans are grouped into one large black box (top 7 rows, marked red), because now the spans are listed according to their criticality.
- The most critical individual span amounts for 35 negative margins (top-row of figure 3).

A qualification of the criticality of the spans shows the following rating (top-to-bottom in figure 3):

- 3% of the spans is "very critical" (127 negative margins with 10 to 35 incidents per span);
- 6% of the spans is rated "critical" (61 negative margins with 4 to 9 incidents per span);
- 8% of the spans is rated "rather critical" (39 negative margins with 2 or 3 incidents per span);
- 19% of the spans is rated "unlucky" (39 negative margins with only 1 (one) incident per span);
- 64% of the spans is rated "OK" (no negative margins).

The 3% very critical spans in the rating accounts for approximately 50% of all chances of contact wire launch with the 1600 mm pantograph. With intervention at the most critical locations it is possible to reduce the chance of contact wire launch significantly. The spans which are very critical are displayed in the graph of figure 5 on the third page of Appendix 2. The individual amounts of contact wire launches are indicated.

Not taking action means that 266 probable contact wire launches with the 1600 mm pantograph are accepted, resulting in one chance of launch in approximately 1900 pantographs passing. This accounts for a 0,05% chance of launch, possibly requiring more regular inspection of the integrity of the carbon strip.

To put the numbers in perspective: 266 launches in 10 years means one chance of launch every two weeks. Obviously, this chance is not evenly distributed over the year. In statistical data can be seen that high wind velocities primarily occur during the changing of the seasons, in spring and fall. If operational measures were taken at times when high wind velocities from an unfavourable angle are expected, the chance of contact wire launch will be reduced dramatically. It is expected that the results can reach a level that will be acceptable to Inframanagers.

Imaginatively speaking: "The best way to play the OCL is like a violin. Playing like a guitar should be avoided. But once in 2000 notes a single key out-of-tune is perhaps not an entirely bad performance."

5 Conclusions

The standard method developed in this study allows Inframanagers to assess the chance of contact wire launch and the chance of infringement when a foreign pantograph is introduced on existing infrastructure. This is realised by following the step-by-step the guidelines in this report, adopting a risk-based approach to indicate critical spots in existing designs.

5.1 NARROW PANTOGRAPH ON WIDE PANTOGRAPH NETWORKS

This study showed that it is possible to allow the 1600 mm pantograph on networks designed for the 1950 mm pantograph and still maintain acceptable performance.

Trial simulations for the check of contact wire launch on a virtual route bring the following conclusions:

- The 1600 mm pantograph on the 1950 mm network triggered no dewirements;
- Contact wire launches are relatively scarce. This is explained by the significantly lower values for stochastic parameters applied in local situations, compared to general maximum values;
- Accepting the chance of contact wire launch, caused by the rare occasion of combined occurrences, avoids the need of major modifications, while keeping performance at the current level;
- The method in the guidelines proves very effective in localising critical spans, making it possible to tailor the infrastructure and/or railway operational plan to local circumstances in a cost-effective way.

The wind pattern is available in many nuances with commonly accepted reliability, providing cost-effective opportunities to differentiate areas and assess specific situations.

- Analysis of the wind-pattern shows the variations in wind velocity according to the wind direction.
- Forecasts are reliable if they are based on a long history of measurements.
- Statistical data is widely available at low cost.

5.2 WIDE PANTOGRAPH ON NARROW PANTOGRAPH NETWORKS

This study developed a standard method to assess the chance of infringement. While the method contains all the nuances available in the stochastic nature of parameters, the positions of objects designed according to the structure gauge are mainly fixed by deterministic parameters.

Comparing the cost-effectiveness of modifications to reduce the chance of contact wire launch and to reduce the chance of infringement, it is expected that wide pantographs on narrow pantograph networks will prove to be more difficult than the other way around. In the previous study of ANA_1 & ANA_2, it was pointed out that the scale of the problem with structures is yet unknown. At this time in the study of ANA_3 & ANA_4, expectations remain low. Figuratively speaking: “Wind can be better controlled than structures.”

5.3 OUTLOOK ON ANA_4

The findings of the current study described in this report indicate the need to compare results from trial-simulation based on theoretical data with simulations based on measurements of track and OCL geometry. The following activities are foreseen in the validation phase of ANA_4:

The simulation and analysis of the assessment are repeated with real data taken from a specific railway line, with the aim to confirm outcomes from ANA_3. The following parameters will be taken from the specific situation:
- Geographical location of the line;
- Geographical orientation of the spans;
- Applied OCL system design;
- Track & OCL allocation design;
- Track & OCL maintenance tolerances;
- Railway operational plan.

The chance of contact wire launch is calculated as the risk-profile of the railway line, according to the guidelines in this report. Critical parameters are changed in the simulation model, representing modifications of the actual infrastructure or railway operation to enhance performance.

The problem of infringement is assessed for individual spans, using the relevant measurements of that span. A simulation to assess the chance of infringement on a specific railway line is not foreseen at this moment, because the principle stochastic parameters to be investigated for this purpose are basically the same as the ones for contact wire launch. The structure gauge is considered to be principally defined by deterministic parameters, not requiring the need of measurements for the purpose of validating the proposed assessment method according to the proposed guidelines.

A second important research subject is a detailed analysis of the sensitivity of the pantograph shape and uplift force on the contact wire deflection, with the aim to provide a more accurate calculation of the position of the turning point for the wire deflection. This value is used in the calculation of the margin, which is the basis for the chance of contact wire launch and the safety margin.

6 Recommendations

6.1 CURRENT CONSIDERATIONS

Adopt a stochastic approach of the margin, leading to a more realistic chance of contact wire launch and infringement.

- Unfavourable conditions at the same time is a rare event;
- Unlock the value in current designs, often based on worst-case scenarios.

Use the most accurate data available for the location, to approximate reality.

- Statistical data of wind patterns is widely available in a resolution of 50 square km. Data commonly contains the distribution of the wind velocity for the wind angle, with a long measurement history;
- Take the geographical location of the line and the orientation of the span into account to calculate the wind load for the angle of incidence;
- Measurements of track- and OCL-geometry provide insight in the current status of maintenance and the urgency of corrective measures.

Reduce the running speed at times with high wind loads.

- Most effective in curves with high cant or cant deficiency;
- Use the simulation to calculate the effect on the performance of the line.

Cease operation at times with high wind loads.

- When margin-overruns randomly occur in many spans with similar characteristics, mostly expected on straight track, few modification options are available;
- Use the simulation to approximate the maximum wind velocity for safe operation.

Consider modification of the infrastructure, to allow high wind loads.

- When margin-overruns selectively occur in some spans with specific characteristics, mostly expected in curves, infrastructure modifications can be tailored to the local situation;
- Use the simulation to calculate the effect on the performance of the entire line, making modifications until the chance of contact wire launch or infringement becomes insignificant.

Take seemingly minor forces into account:

- The coupling force based on the difference in deflection between catenary & contact wire;
- The lateral 'push' from the pantographs' uplift force.

Keep the working zone as it is now, the same length as the conducting range.

- Focus on the chance of contact wire 'launch', when the contact point exceeds the working zone;

6.2 FUTURE STUDIES

Some elements of the pantograph geometry are not specified in the EU-Standard or the TSI. In the course of this study it appeared that missing requirements have significant impact on the chance of contact wire launch, since they determine the shape of the pantograph head and are expected to be of influence on the contact wire deflection and the turning point.

In a situation where performance standards cannot be met by cost-effective modifications of the infrastructure and where operational measures are not acceptable, the possibility of modifications of the pantograph shape and/or construction details could be investigated.

When difficulties between the 1950 mm pantograph and civil structures and tunnels cannot be resolved, the option to adopt the 1600 mm pantograph as the single European standard could be considered.

Appendix 1 Requests for standards

Requests for standard EN 50119:2009 are proposed to:

- Specify the use of local statistical data for the wind pattern and take into account the stochastic nature of wind direction and wind velocity, replacing the currently suggested entry of worst-case values. The following rules in the standard are targeted:
  - The reference wind velocity (V_R) in the calculation of the dynamic wind pressure (§ 6.2.4.2). This rule should be modified to represent the probability that "the specified wind velocity will occur at that location".
  - The angle of incidence of the critical wind direction (Φ) in the calculation of the wind force on conductors (§ 6.2.4.3), other components and structures ((§ 6.2.4.4. - § 6.2.4.7). This rule should be modified to represent the probability that "the wind gust will be about perpendicular to the span".
- Incorporate the coupling force into the calculation of the wire deflection, based on the different deflection values of catenary and contact wires.
- Describe the effects of the dimensions, shape and dynamic behaviour of the pantograph on the wire deflection, according to the position, speed and travel direction of the pantograph in the span.

Appendix 2 Trial simulation results

All results

Margin (mm)	Number of iterations (Total: 500.000) (distribution)	"Launches" with the 1600 mm pantograph (Total: 266)	"Launches" with the 1950 mm pantograph (Total: 1)
-185	1	1	1
-179	0	0	0
-174	0	0	
-168	0	0	
-162	0	0	
-156	0	0	
-151	0	0	
-145	2	2	
-139	1	1	
-134	1	1	
-128	0	0	
-122	0	0	
-117	2	2	
-111	1	1	
-105	0	0	
-99	1	1	
-94	1	1	
-88	1	1	
-82	0	0	
-77	5	5	
-71	6	6	
-65	2	2	
-60	4	4	
-54	7	7	
-48	18	18	
-43	12	12	
-37	15	15	
-31	11	11	
-25	22	22	
-20	34	34	
-14	41	41	
-8	43	43	
-3	95	35	
3	134		
9	244		
14	412		
20	803		
26	1358		
31	2377		
37	3912		
43	6679		
49	10900		
54	17040		
60	25987		
66	37584		
71	51856		
77	64473		
83	73188		
88	72463		
94	60582		
100	39900		
105	20456		
111	7243		
117	1793		
123	265		
128	25		
134	0		

Margin = -175 mm
(Edge of the working zone for 1950 mm pantograph)

Total: 266 contact wire launches with the 1600 mm pantograph; 1 contact wire launch with the 1950 mm pantograph.

Margin = 0 mm
(Edge of the working zone for 1600 mm pantograph)

Figure 1 (above): Margin distribution for the 1600 mm pantograph (numeric results).

Wich spans are launched?

Span Nr. (sequential)	Number of iterations (Total: 266) (incidents)	"Launches" with the 1600 mm pantograph (Total: 266)
2	14	14
4	1	1
6	1	1
7	1	1
8	1	1
9	2	2
13	1	1
14	1	1
15	1	1
17	3	3
19	11	11
21	1	1
22	1	1
23	1	1
24	1	1
25	1	1
26	2	2
27	2	2
28	1	1
29	1	1
30	3	3
34	28	28
36	1	1
37	15	15
39	1	1
40	1	1
45	1	1
47	2	2
48	2	2
49	1	1
52	3	3
53	1	1
54	1	1
56	10	10
58	1	1
59	1	1
61	1	1
62	1	1
63	5	5
66	1	1
67	1	1
69	1	1
85	7	7
87	1	1
90	4	4
93	4	4
94	1	1
96	1	1
97	3	3
99	1	1
100	14	14
102	3	3
103	9	9
105	1	1
110	1	1
115	4	4
116	1	1
118	1	1
121	35	35
146	6	6
167	8	8
171	2	2
172	2	2
173	1	1
175	2	2
176	1	1
177	2	2
178	2	2
181	2	2
182	4	4
184	1	1
185	5	5
187	2	2
202	5	5

Qualification of critical spans

Span Nr.	Number of iterations (Total: 266) (incidents) (sequential)	"Launches" with the 1600 mm pantograph (Total: 266)	Qualification (criticality)		
121	35	35	Very critical	3%	of the spans is very critical
34	28	28			
37	15	15			
2	14	14			
100	14	14			
19	11	11			
56	10	10			
103	9	9	Critical	5%	of the spans is critical
167	8	8			
85	7	7			
146	6	6			
63	5	5			
185	5	5			
202	5	5			
90	4	4			
93	4	4			
115	4	4			
182	4	4			
17	3	3	Rather critical	8%	of the spans is rather critical
30	3	3			
52	3	3			
97	3	3			
102	3	3			
9	2	2			
26	2	2			
27	2	2			
47	2	2			
48	2	2			
171	2	2			
172	2	2			
175	2	2			
177	2	2			
178	2	2			
181	2	2			
187	2	2			
4	1	1	Unlucky...	19%	of the spans is unlucky
6	1	1			
7	1	1			
8	1	1			
13	1	1			
14	1	1			
15	1	1			
21	1	1			
22	1	1			
23	1	1			
24	1	1			
25	1	1			
28	1	1			
29	1	1			
36	1	1			
39	1	1			
40	1	1			
45	1	1			
49	1	1			
53	1	1			
54	1	1			
58	1	1			
59	1	1			
61	1	1			
62	1	1			
66	1	1			
67	1	1			
69	1	1			
87	1	1			
94	1	1			
96	1	1			
99	1	1			
105	1	1			
110	1	1			
116	1	1			
118	1	1			
173	1	1			
176	1	1			
184	1	1			
			O.K.	64%	of the spans is O.K.

Total: 127 contact wire launches with the 1600 mm pantograph.

Figure 2 and 3 (above): Number of launches for each span (left) and rating the criticality of spans (right).

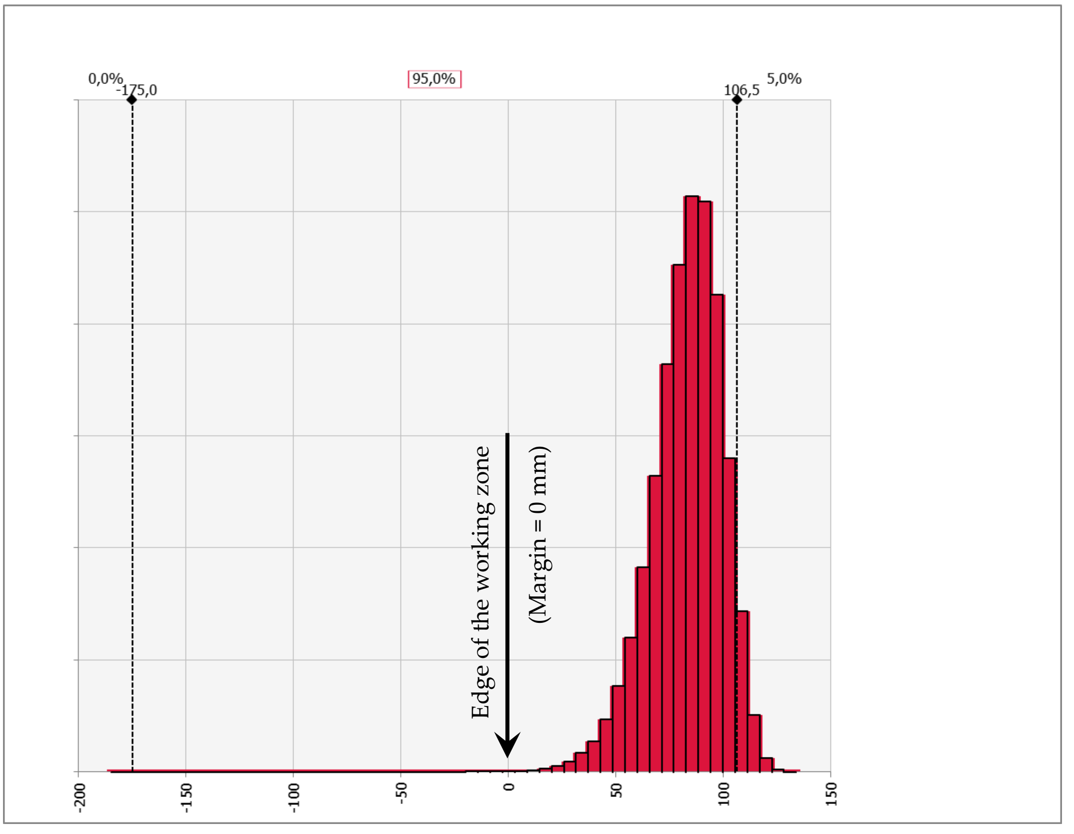


Figure 4 (above): Margin distribution for 1600 mm pantograph in trial simulation according to chapter 4.

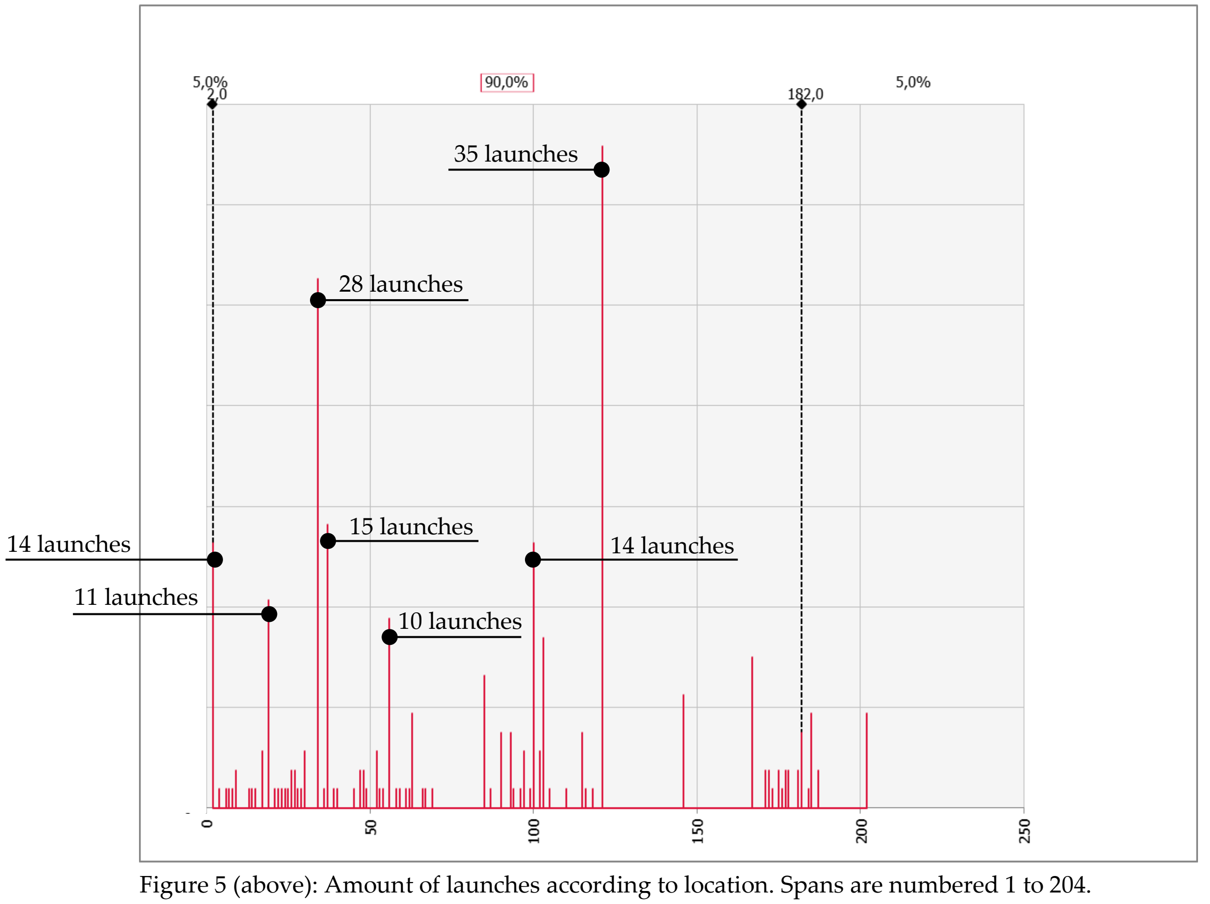


Figure 5 (above): Amount of launches according to location. Spans are numbered 1 to 204.

Appendix 3 Example calculations

The following sheets provide the formulas and calculations used in the assessment of the virtual route described in chapter 4. The sequence of calculations shows the result from one iteration in the simulation, representing the value for the margin in a single span based on fixed values for both deterministic and stochastic parameters.

The calculation sheet adopts a top-down approach: First the margin is calculated. See § 3.5 for explanation. Reading down the sheet, the calculations become more detailed.

All calculations are numbered sequentially in the extreme right column (1 through 50) and logically in the extreme left column (basically: 1 / 1.1 / 1.1.1 / etc.). The values for the margin are calculated for both the 1950 mm (“230”, indicated in blue) and the 1600 mm pantograph “55” (indicated in blue). Typically, the difference is 175 mm, which is half the difference in pantograph length (1950 mm – 1600 mm = 350 mm).

For every formula in a top segment (dark-grey area) of individual calculations, all parameters used in the calculation are listed in the lower segment (light-grey area). Most parameters originate from a more detailed calculation further in the sheets. The red arrows illustrate this principle of redirections. All parameters are individually numbered. Example: Values for (1) “Available space” and (2) “Taken space” are calculated elsewhere and then transported. The origins can be found by following the red arrows backwards (in the example) or looking for corresponding numbers (in general).

The coloured columns on the right provide the value and nature of parameters in the calculation example:

- Blue marks a positive value for the margin;
- Red marks a negative value for the margin (not shown in the example);
- Green marks a calculation being performed;
- Light grey marks a reference value (taken from source documentation) being introduced;
- Dark grey marks a reference value that is copied within the sheets;
- Yellow marks a value to be entered for a parameter (stochastic or deterministic);
- Orange marks a value for a stochastic or deterministic parameter that is copied within the sheets;
- White marks a parameter that was expected in the situation, but appeared not applicable.

	Calculation of the margin for dewirement (high speed in span)	Symbol	Unit	Value	Nature	Nr.
0a	**Margin (1950 mm pantograph)**					
	$M_p=L_a-L_t$	M_p	mm	230	Calculation	1
1a	Available space (1950 mm pantograph)	L_a	mm	537	Copy	
2	Taken space	L_t	mm	307	Copy	
0	**Margin (1600 mm pantograph)**					
	$M_p=L_a-L_t$	M_p	mm	55	Calculation	2
1	Available space (1600 mm pantograph)	L_a	mm	362	Copy	
2	Taken space	L_t	mm	307	Copy	
1a	**Available space (1950 mm pantograph)**					
	$L_a=L_{P:wz}-(M_{p:track}+M_{p:train})$	L_a	mm	537	Calculation	3
1a.1	Working zone of 1950 mm pantograph (single half)	$L_{P:wz}$	mm	775	Reference	
1.2	Total movement of the pantograph (track related) (left or outside curve = -)	$M_{p:track}$	mm	-81	Copy	
1.3	Total movement of the pantograph (train related) (left or outside curve = -)	$M_{p:train}$	mm	-157	Copy	
1	**Available space (1600 mm pantograph)**					
	$L_a=L_{P:wz}-(M_{p:track}+M_{p:train})$	L_a	mm	362	Calculation	4
1.1	Working zone of the pantograph (single half)	$L_{P:wz}$	mm	600	Reference	
1.2	Total movement of the pantograph (track related) (left or outside curve = -)	$M_{p:track}$	mm	-81	Copy	
1.3	Total movement of the pantograph (train related) (left or outside curve = -)	$M_{p:train}$	mm	-157	Copy	
2	**Taken space**					
	$L_t=M_{cw}$	L_t	mm	307	Calculation	5
2.1	Total movement of the contact wire	M_{cw}	mm	307	Copy	
1.2	**Total movement of the pantograph (track related) (left or outside curve = -)**					
	$M_{p:track}=(T_1+T_2+T_3+T_{hunt})$	$M_{p:track}$	mm	-81	Calculation	6
1.2.1	Transverse displacement of the track between maintenance actions	$T_1=T_{voie}$	mm	-20	Stochastic	
1.2.2	Cant decrease between two maintenance actions (less cant = -)	$T_2=T_D$	mm	-38	Copy	
1.2.3	Oscillations generated by track unevenness (roll increase) (less cant = -)	$T_3=T_{osc}$	mm	-8	Copy	
1.2.4	Transverse displacement of the wheel set in relation to the track centre (hunting)	T_{hunt}	mm	-15	Copy	
1.3	**Total movement of the pantograph (train related) (left or outside curve = -)**					
	$M_{p:train}=(Dg_i+(q+w)+T_{cr}+T_{4a}+T_{4b}+E_p+S'_{i/a}+qs'_{i/a}+T_5)$	$M_{p:train}$	mm	-157	Calculation	7
1.3.1	Additional geometric overthrow (due to the bogies) (inside curve = +)	dg_i	mm	1	Copy	
1.3.2	Transverse clearance between wheel set, bogie frame and body	$q + w$	mm	-6	Copy	
1.3.3	Transverse movement of pantograph caused by carriage rigidity	T_{cr}	mm	0	Stochastic	
1.3.4	Transverse flexibility of the mounting device on the roof (inside curve = +)	$T_{4a}=T_{susp}$	mm	-3	Stochastic	
1.3.5	Mounting tolerance of the pantograph on the roof (inside curve = +)	$T_{4b}=T_{susp}$	mm	-2	Stochastic	
1.3.6	Pantograph sway due to the vehicle characteristics	E_p	mm	-39	Copy	
1.3.7	Additional overthrow on the inside/outside of the curve	$S'_{i/a}$	mm	-17	Copy	
1.3.8	Quasi-static movement (roll)	$qs'_{i/a}$	mm	0	Copy	
1.3.9	Loading dissymmetry (uneven load distribution)	$T_5=T_{charge}$	mm	-91	Copy	
2.1	**Total movement of the contact wire (right or inside curve = +)**					
	$M_{cw}=(e_{s:x}(x)+M_{dst:h}+M_{dst:v}+U_{cw}+Ct_{cw}+Mt_{ss}+e_{d:x}(x)+f_w+f_v)$	M_{cw}	mm	307	Calculation	8
2.1.1	Contact wire position (static)	$e_{s:x}(x)$	mm	8	Copy	
2.1.2	Mast deflection static load (horizontal) (compensated in assembly)	$M_{dst:h}$	mm	0	N.A.	
2.1.3	Mast deflection static load (vertical) (compensated in assembly)	$M_{dst:v}$	mm	0	N.A.	
2.1.4	Contact wire rotation by pantograph uplift	U_{cw}	mm	0	N.A.	
2.1.5	Contact wire positioning tolerance (contact wire clamp) (outside curve = -)	Ct_{cw}	mm	0	Stochastic	
2.1.6	Support structure maintenance tolerance (in contact wire positioning)	Mt_{ss}	mm	0	N.A.	
2.1.7	OCL deflection dynamic load (wind)	$e_{d:x}(x)$	mm	271	Copy	
2.1.8	Mast deflection dynamic load (wind)	f_w	mm	18	Copy	
2.1.9	Mast deflection dynamic load (vibration) (outside curve = -)	f_v	mm	10	Stochastic	
1.2.2	**Cant decrease between two maintenance actions (less cant = -)**					
	$T_2=(h_{ver}/L_{track}).D_{tol}$	$T_2=T_D$	mm	-38	Calculation	9
1.2.2.1	Verification height (above track)	h_{ver}	mm	5.733	Copy	
1.2.2.2	Distance between rail centres of a track	L_{track}	mm	1.500	Reference	
1.2.2.3	Cant maintenance tolerance (more cant = +) (less cant = -)	D_{tol}	mm	-10	Stochastic	
1.2.3	**Oscillations generated by track unevenness (roll increase) (less cant = -)**					
	$T_3=(s'_o/L_{track}).D_{tol}.(h_{ver}-h'_{co})$	$T_3=T_{osc}$	mm	-8	Calculation	10
1.2.3.1	Flexibility coefficient (agreement between vehicle and infrastructure)	s'_o	abs	0,225	Reference	
1.2.2.2	Distance between rail centres of a track	L_{track}	mm	1.500	Copy	
1.2.2.3	Cant maintenance tolerance (more cant = +) (less cant = -)	D_{tol}	mm	-10	Copy	
1.2.2.1	Verification height (above track)	h_{ver}	mm	5.733	Copy	
1.2.3.5	Reference roll centre height	h'_{co}	mm	500	Reference	

1.2.4	**Transverse displacement of the wheel set in relation to the track centre (hunting)**					
	$T_{hunt}=-(l_{max}-d)/2$	T_{hunt}	mm	-15	**Calculation**	**11**
1.2.4.1	Track gauge, distance between the rail running edges	l_{max}	mm	1.465	Deterministic	
1.2.4.2	Dimension over wheel flanges	d	mm	1.435	Reference	
1.3.1	**Additional geometric overthrow (due to the bogies) (inside curve = +)**					
	$dg_i=(p^2/(8.R)).1000$	dg_i	mm	1	**Calculation**	**12**
1.3.1.1	Distance between the end wheel sets of the bogie	p	m	2,60	Reference	
1.3.1.2	Curve radius (> 150 m)	R	m	1.500	Deterministic	
1.3.2	**Transverse clearance between wheel set, bogie frame and body**					
	"q + w"=q+w	q + w	mm	-6	**Calculation**	**13**
1.3.2.1	Transverse clearance between wheel set and bogie frame (left and outside curve = -)	q	mm	-3	Stochastic	
1.3.2.2	Transverse clearance between body and bogie (left and outside curve = -)	w	mm	-3	Stochastic	
1.3.6	**Pantograph sway due to the vehicle characteristics**					
	$E_p=(s'_o/L_{track}).I.(h_{ver}-h'_{co})$ (valid for $I \geq I'_o$)	E_p	mm	-39	**Calculation**	**14**
1.3.6.1	Cant deficiency (≤ 130 mm) (≤ 150 mm) (deficiency = -)	I	mm	-49	Copy	
1.3.6.2	Reference cant deficiency (deficiency = -)	I'_0	mm	-66	Reference	
1.2.3.1	Flexibility coefficient (agreement between vehicle and infrastructure)	s'_o	abs	0,225	Copy	
1.2.2.2	Distance between rail centres of a track	L_{track}	mm	1.500	Copy	
1.2.2.1	Verification height (above track)	h_{ver}	mm	5.733	Copy	
1.2.3.5	Reference roll centre height	h'_{co}	mm	500	Copy	
1.3.7	**Additional overthrow on the inside/outside of the curve**					
	$S'_{i/a}=((2,5/R).1000+(l_{max}-SG)/2)$	$S'_{i/a}$	mm	-17	**Calculation**	**15**
1.3.1.2	Curve radius (> 150 m)	R	m	1.500	Copy	
1.2.4.1	Track gauge, distance between the rail running edges	l_{max}	mm	1.465	Copy	
1.3.7.3	Standard gauge	SG	mm	1.435	Reference	
1.3.8	**Quasi-static movement (roll)**					
	$E_p=(s'_o/L_{track}).(I-I'_o).(h_{ver}-h'_{co})$ (valid for $I < I'_o$)	$qs'_{i/a}$	mm	0	**Calculation**	**16**
1.3.6.1	Cant deficiency (≤ 130 mm) (≤ 150 mm) (deficiency = -)	I	mm	-49	Copy	
1.3.6.2	Reference cant deficiency (deficiency = -)	I'_0	mm	-66	Copy	
1.2.3.1	Flexibility coefficient (agreement between vehicle and infrastructure)	s'_o	abs	0,225	Copy	
1.2.2.2	Distance between rail centres of a track	L_{track}	mm	1.500	Copy	
1.2.2.1	Verification height (above track)	h_{ver}	mm	5.733	Copy	
1.2.3.5	Reference roll centre height	h'_{co}	mm	500	Copy	
1.3.9	**Loading dissymmetry (uneven load distribution)**					
	$T_5=tng(\eta_0.(\pi/180)).(h_{ver}-h'_{co})$	$T_5=T_{charge}$	mm	-91	**Calculation**	**17**
1.3.9.1	Angle by vehicle centre line to the vertical (outside curve = -)	η_0	degrees	-1,00	Copy	
1.2.2.1	Verification height (above track)	h_{ver}	mm	5.733	Copy	
1.2.3.5	Reference roll centre height	h'_{co}	mm	500	Copy	
2.1.1	**Contact wire position (static)**					
	$e_{s:x}(x)=((b_{i+1}-b_i).L_{ver}/L_{1:ver}+b_i+L_{ver}.(L_{1:ver}-L_{ver})/(2.R)).1000$	$e_{s:x}(x)$	mm	8	**Calculation**	**18**
2.1.1.1	Stagger (right) (left side and outside curve = -)	b_{i+1}	m	-0,20	Deterministic	
2.1.1.2	Stagger (left) (left side and outside curve = -)	b_i	m	-0,20	Deterministic	
2.1.1.3	Verification point in span (with greatest deflection)	L_{ver}	m	25,00	Copy	
2.1.1.4.1	Span length (left) - Verification span	$L_{1:ver}$	m	50,00	Copy	
1.3.1.2	Curve radius (> 150 m)	R	m	1.500	Copy	
2.1.7	**OCL deflection dynamic load (wind)**					
	$e_{d:x}(x)=(F_{w:con1+2}-F_{w:con-cat}).L_{ver}.(L_{1:ver}-L_{ver})/(2.H_{con1+2:act})).1000$	$e_{d:x}(x)$	mm	271	**Calculation**	**19**
2.1.7.1	Wind load on contact wire(s) per unit length	$F_{w:con1+2}$	N/m	17,11	Copy	
2.1.7.2	Coupling force per unit length	$F_{w:con-cat}$	N/m	-0,214	Copy	
2.1.1.3	Verification point in span (with greatest deflection)	L_{ver}	m	25,00	Copy	
2.1.1.4.1	Span length (left) - Verification span	$L_{1:ver}$	m	50,00	Copy	
2.1.7.5	Contact wire tension (actual)	$H_{con1+2:act}$	N	20.000	Copy	
2.1.8	**Mast deflection dynamic load (wind)**					
	$f_w=((1/6).((Q_{w:con1+2}+Q_{w:cat}+Q_{w:dr}+Q_{w:st}+Q_{w:aw}+Q_{w:ins})/(E.I_x)).((h_{ocl}-h_{ver})^3-3.h_{ocl}^2.(h_{ocl}-h_{ver})+2.h_{ocl}^3))+$ $((1/6).(Q_{w:str}/(E.I_x)).(((L/2)-h_{ver})^3-3.(L/2)^2.((L/2)-h_{ver})+2.(L/2)^3))$	f_w	mm	18	**Calculation**	**20**
2.1.8.1	Wind force on contact wire (s)	$Q_{w:con1+2}$	N	855	Copy	
2.1.8.2	Wind force on catenary wire	$Q_{w:cat}$	N	521	Copy	
2.1.8.3	Wind force on droppers	$Q_{w:dr}$	N	60	Copy	
2.1.8.4	Wind force on stitch wire(s)	$Q_{w:st}$	N	67	Copy	
2.1.8.5	Wind force on anchor wire(s)	$Q_{w:aw}$	N	0	Copy	
2.1.8.6	Wind force on insulators and other line fittings	$Q_{w:ins}$	N	0	Copy	
2.1.8.7	Mast material elasticity	E	N/mm²	210.000	Reference	
2.1.8.8	Moment of inertia	I_x	mm^4	5,41E+07	Deterministic	
2.1.8.9	Handle height for OCL loads (above track)	h_{ocl}	mm	7.588	Copy	
1.2.2.1	Verification height (above track)	h_{ver}	mm	5.733	Copy	
2.1.8.11	Wind force on structures (mast)	$Q_{w:str}$	N	1.748	Copy	
2.1.8.12	Mast profile length (HE-005)	L	mm	8.600	Deterministic	

1.2.2.1	**Verification height (above track)**					
	$h_{ver}=h_{con:act}+f_s+f_{ws}+f_{wa}$	h_{ver}	mm	5.733	Calculation	21
1.2.2.1.1	Contact wire height - actual (above track)	$h_{con:act}$	mm	5.553	Copy	
1.2.2.1.2	Margin to take account of the raising of the contact wire (uplift = +)	f_s	mm	120	Deterministic	
1.2.2.1.3	Margin of the bow trespassing the contact wire (vertical) (trespassing = +)	f_{ws}	mm	50	Reference	
1.2.2.1.4	Margin of the wear of the pantograph contact strip (wear = +)	f_{wa}	mm	10	Reference	

1.3.6.1	**Cant deficiency (≤ 130 mm) (≤ 150 mm) (deficiency = -)**					
	$I=D-D_{th}$	I	mm	-49	Calculation	22
1.3.6.1.1	Cant (actual) (40 < Vmax ≤ 200) (≤ 160 mm) (≤ 180 mm) (cant = +)	D	mm	105	Copy	
1.3.6.1.2	Cant (theoretical) (cant = +)	D_{th}	mm	154	Copy	

1.3.9.1	**Angle by vehicle centre line to the vertical (outside curve = -)**					
	$\eta_0=(1+S'_o).\lambda$	η_0	degrees	-1,00	Calculation	23
1.2.3.1	Flexibility coefficient (agreement between vehicle and infrastructure)	s'_o	abs	0,225	Copy	
1.3.9.1.2	Angle by line between point of gravity and reference roll centre to the vertical (outside curve = -)	λ	degrees	-0,82	Stochastic	

2.1.1.3	**Verification point in span (with greatest deflection)**					
	$L_{ver}=((L_{1:ver}/2+(b_{i+1}-b_i)/(L_{1:ver}.(1/R+(F_{w:con1+2}-F_{w:con-cat})/H_{con1+2:act})))$ (valid for $0 \le L_{ver} \le L_{1:ver}$)	L_{ver}	m	25,00	Calculation	24
2.1.1.4.1	Span length (left) - Verification span	$L_{1:ver}$	m	50,00	Copy	
2.1.1.1	Stagger (right) (left side and outside curve = -)	b_{i+1}	m	-0,20	Copy	
2.1.1.2	Stagger (left) (left side and outside curve = -)	b_i	m	-0,20	Copy	
1.3.1.2	Curve radius (> 150 m)	R	m	1.500	Copy	
2.1.7.1	Wind load on contact wire(s) per unit length	$F_{w:con1+2}$	N/m	17,11	Copy	
2.1.7.2	Coupling force per unit length	$F_{w:con-cat}$	N/m	-0,214	Copy	
2.1.7.5	Contact wire tension (actual)	$H_{con1+2:act}$	N	20.000	Copy	

2.1.1.4	**Span length (average)**					
	$L_{sp}=(L_{1:ver}+L_2)/2$	L_{sp}	m	50,00	Calculation	25
2.1.1.4.1	Span length (left) - Verification span	$L_{1:ver}$	m	50,00	Deterministic	
2.1.1.4.2	Span length (right)	L_2	m	50,00	Deterministic	

2.1.7.1	**Wind load on contact wire(s) per unit length**					
	$F_{w:con1+2}=q_{h:p}.G_c.((d_{con1}/1000).C_{con1}+(d_{con2}/1000).C_{con2}).\sin(\Phi.(\pi/180))^2$	$F_{w:con1+2}$	N/m	17,11	Calculation	26
2.1.7.1.1	Dynamic wind pressure (nominal)	$q_{h:p}$	N/m²	660	Copy	
2.1.8.3.2	Structural response factor for conductors (resonance factor) (0,75)	G_c	abs	1,00	Reference	
2.1.7.1.3	Contact wire diameter (first wire) (AC 100) (AC 120)	d_{con1}	mm	12,0	Deterministic	
2.1.7.1.6.2	Aerodynamic drag factor of contact wire (first wire) (1,2)	C_{con1}	abs	1,2	Reference	
2.1.7.1.5	Contact wire diameter (second wire) (AC 100)	d_{con2}	mm	12,0	Deterministic	
2.1.7.1.6	Aerodynamic drag factor of contact wire (second wire) (80% reduction)	C_{con2}	abs	0,96	Copy	
2.1.7.1.7	Angle of incidence of the critical wind direction (in respect to the perpendicular to the conductor)	Φ	degrees	90	Copy	

2.1.7.2	**Coupling force per unit length**					
	$F_{wcon-cat}=(F_{wcon:1+2}.H_{cat:act}-F_{w:cat}.H_{con1+2:act})/(H_{con1+2:act}+H_{cat:act}+(16.H_{con1+2:act}.H_{cat:act}.((h_{cat}-h_{con:act})/1000))/(3.L_{1:ver}^2.G'_{con}))$	$F_{w:con-cat}$	N/m	-0,214	Calculation	27
2.1.7.1	Wind load on contact wire(s) per unit length	$F_{w:con1+2}$	N/m	17,11	Copy	
2.1.7.2.2	Catenary wire tension actual	$H_{cat:act}$	N	10.800	Copy	
2.1.7.2.3	Wind load on catenary wire per unit length	$F_{w:cat}$	N/m	10,43	Copy	
2.1.7.5	Contact wire tension (actual)	$H_{con1+2:act}$	N	20.000	Copy	
2.1.7.2.5	Catenary wire height - actual (above track)	h_{cat}	mm	8.605	Copy	
1.2.2.1.1	Contact wire height - actual (above track)	$h_{con:act}$	mm	5.553	Copy	
2.1.1.4.1	Span length (left) - Verification span	$L_{1:ver}$	m	50,00	Copy	
2.1.7.2.8	Contact wire(s) weight (average) (CuAg0,1)	G'_{con}	N/m	17,44	Copy	

2.1.7.5	**Contact wire tension (actual)**					
	$H_{con1+2:act}=H_{con1+2:nom}-(H_{con1+2:red}.H_{con1+2:nom})$	$H_{con1+2:act}$	N	20.000	Calculation	28
2.1.7.5.1	Contact wire tension nominal	$H_{con1+2:nom}$	N	20.000	Deterministic	
2.1.7.5.2	Contact wire tension reduction (0% - 8%)	$H_{con1+2:red}$	%	0%	Deterministic	

2.1.8.1	**Wind force on contact wire (s)**					
	$Q_{w:con1+2}=F_{w:con1+2}.L_{1:ver}$	$Q_{w:con1+2}$	N	855	Calculation	29
2.1.7.1	Wind load on contact wire(s) per unit length	$F_{w:con1+2}$	N/m	17,11	Copy	
2.1.1.4.1	Span length (left) - Verification span	$L_{1:ver}$	m	50,00	Copy	

2.1.8.2	**Wind force on catenary wire**					
	$Q_{w:cat}=F_{w:cat}.L_{1:ver}$	$Q_{w:cat}$	N	521	Calculation	30
2.1.7.2.3	Wind load on catenary wire per unit length	$F_{w:cat}$	N/m	10,43	Copy	
2.1.1.4.1	Span length (left) - Verification span	$L_{1:ver}$	m	50,00	Copy	

2.1.8.3	**Wind force on droppers**					
	$Q_{w:dr}=q_{h:p}.G_c.((d_{dr}/1000).C_{dr}).L_{dr}.\sin(\Phi.(\pi/180))^2$	$Q_{w:dr}$	N	60	Calculation	31
2.1.7.1.1	Dynamic wind pressure (nominal)	$q_{h:p}$	N/m²	660	Copy	
2.1.8.3.2	Structural response factor for conductors (resonance factor) (0,75)	G_c	abs	1,00	Copy	
2.1.8.3.3	Dropper diameter	d_{dr}	mm	4,5	Deterministic	
2.1.8.3.4	Aerodynamic drag factor of dropper wire (1,00)	C_{dr}	abs	1,0	Reference	
2.1.8.3.5	Dropper length in span (approximate)	L_{dr}	m	20	Copy	
2.1.7.1.7	Angle of incidence of the critical wind direction (in respect to the perpendicular to the conductor)	Φ	degrees	90	Copy	

2.1.8.4	**Wind force on stitch wire(s)**					
	$Q_{w:st}=q_{h:p}.G_c.((d_{st}/1000).C_{st}).L_{st}.\sin(\Phi.(\pi/180))^2$	$Q_{w:st}$	N	67	Calculation	32
2.1.7.1.1	Dynamic wind pressure (nominal)	$q_{h:p}$	N/m²	660	Copy	
2.1.8.3.2	Structural response factor for conductors (resonance factor) (0,75)	G_c	abs	1,00	Copy	
2.1.8.4.3	Stitch wire diameter	d_{st}	mm	6,3	Deterministic	
2.1.8.4.4	Aerodynamic drag factor of stitch wire (1,00)	C_{st}	abs	1,0	Reference	
2.1.8.4.5	Stitch wire length	L_{st}	m	16	Deterministic	
2.1.7.1.7	Angle of incidence of the critical wind direction (in respect to the perpendicular to the conductor)	Φ	degrees	90	Copy	

2.1.8.5	**Wind force on anchor wire(s)**					
	$Q_{w:aw}=q_{h:p}.G_c.((d_{aw}/1000).C_{aw}).L_{aw}.\sin(\Phi.(\pi/180))^2$	$Q_{w:aw}$	N	0	Calculation	33
2.1.7.1.1	Dynamic wind pressure (nominal)	$q_{h:p}$	N/m²	660	Copy	
2.1.8.3.2	Structural response factor for conductors (resonance factor) (0,75)	G_c	abs	1,00	Copy	
2.1.8.5.3	Anchor wire diameter	d_{aw}	mm	6,3	Deterministic	
2.1.8.5.4	Aerodynamic drag factor of anchor wire (1,00)	C_{aw}	abs	1,0	Reference	
2.1.8.5.5	anchor wire length	L_{aw}	m	0	Deterministic	
2.1.7.1.7	Angle of incidence of the critical wind direction (in respect to the perpendicular to the conductor)	Φ	degrees	90	Copy	

2.1.8.6	**Wind force on insulators and other line fittings**					
	$Q_{w:ins}=q_{h:p}.G_{ins}.(A_{ins}.C_{ins}).\sin(\Phi.(\pi/180))^2$	$Q_{w:ins}$	N	0	Calculation	34
2.1.7.1.1	Dynamic wind pressure (nominal)	$q_{h:p}$	N/m²	660	Copy	
2.1.8.6.2	Structural resonance factor for insulator sets (1,05)	G_{ins}	abs	1,05	Reference	
2.1.8.6.3	Projected area of insulator(s)	A_{ins}	m²	0,00	Deterministic	
2.1.8.6.4	Aerodynamic drag factor for insulators (1,2)	C_{ins}	abs	1,2	Reference	
2.1.7.1.7	Angle of incidence of the critical wind direction (in respect to the perpendicular to the conductor)	Φ	degrees	90	Copy	

2.1.8.9	**Handle height for OCL loads (above track)**					
	$h_{ocl}=h_{con:act}+(2/3).(h_{cat}-h_{con:act})$	h_{ocl}	mm	7.588	Calculation	35
1.2.2.1.1	Contact wire height - actual (above track)	$h_{con:act}$	mm	5.553	Copy	
2.1.7.2.5	Catenary wire height - actual (above track)	h_{cat}	mm	8.605	Copy	

2.1.8.11	**Wind force on structures (mast)**					
	$Q_{w:str}=q_{h:p}.G_{str}.(A.C_{str}).\sin(\Phi.(\pi/180))^2$	$Q_{w:str}$	N	1.748	Calculation	36
2.1.7.1.1	Dynamic wind pressure (nominal)	$q_{h:p}$	N/m²	660	Copy	
2.1.8.11.2	Structural resonance factor for structures (1,00)	G_{str}	abs	1,00	Reference	
2.1.8.11.3	Projected area (mast)	A	m²	1,89	Copy	
2.1.8.11.4	Aerodynamic drag factor for structures (1,4)	C_{str}	abs	1,4	Reference	
2.1.7.1.7	Angle of incidence of the critical wind direction (in respect to the perpendicular to the conductor)	Φ	degrees	90	Copy	

1.2.2.1.1	**Contact wire height - actual (above track)**					
	$h_{con:act}=h_{con:nom}+(D/2)$	$h_{con:act}$	mm	5.553	Calculation	37
1.2.2.1.1.1	Contact wire height - nominal (above track)	$h_{con:nom}$	mm	5.500	Deterministic	
1.3.6.1.1	Cant (actual) (40 < Vmax ≤ 200) (≤ 160 mm) (≤ 180 mm) (cant = +)	D	mm	105	Copy	

1.3.6.1.1	**Cant (actual) (40 < Vmax ≤ 200) (≤ 160 mm) (≤ 180 mm) (cant = +)**					
	$D=((½.D_{th})+(D_{th}-20))/2$ (valid for $20 \le D_{th} \le 180$)	D	mm	105	Calculation	38
1.3.6.1.2	Cant (theoretical) (cant = +)	D_{th}	mm	154	Copy	

1.3.6.1.2	**Cant (theoretical) (cant = +)**					
	$D_{th}=(11{,}8.V_{max}^2)/R$	D_{th}	mm	154	Calculation	39
1.3.6.1.2.1	Maximum running speed at verification point of line	V_{max}	km/h	140	Deterministic	
1.3.1.2	Curve radius (> 150 m)	R	m	1.500	Copy	

2.1.7.1.1	**Dynamic wind pressure (nominal)**					
	$q_{h:p}=(½.G_q).G_t.\varrho.v_{b:0,10}^2$	$q_{h:p}$	N/m²	660	Calculation	40
2.1.7.1.1.1	Gust response factor (±10m above ground)	G_q	abs	2,05	Reference	
2.1.7.1.1.2	Terrain factor	G_t	abs	1,0	Reference	
2.1.7.1.1.3	Air density	ϱ	kg/m³	1,246	Copy	
2.1.7.1.1.4	Wind velocity (base) 10 year interval (ground averaged 10 min)	$v_{b:0,10}$	m/sec	22,7	Copy	

2.1.7.1.6	**Aerodynamic drag factor of contact wire (second wire) (80% reduction)**					
	$C_{con2}=C_{con1}-(C_{con2:red}.C_{con1})$	C_{con2}	abs	0,96	Calculation	41
2.1.7.1.6.1	Drag reduction of contact wire (second wire)	$C_{con2:red}$	abs	20%	Reference	
2.1.7.1.6.2	Aerodynamic drag factor of contact wire (first wire) (1,2)	C_{con1}	abs	1,20	Copy	

2.1.7.1.7	**Angle of incidence of the critical wind direction (in respect to the perpendicular to the conductor)**					
	Φ=360-(β-α) (valid for β-α>270°) | Φ=180-(β-α) (valid for β-α>90°) | Φ=β-α (valid for β-α<90°) | (All angles ≥ 0)	Φ	degrees	90	Calculation	42
2.1.7.1.7.1	Angle of origin of the wind direction (in respect to the North, clockwise) (0 - 360°)	β	degrees	310	Stochastic	
2.1.7.1.7.2	Angle of the span (in respect to the North, clockwise) (0 - 180°)	α	degrees	40	Deterministic	

2.1.7.2.2	**Catenary wire tension actual**					
	$H_{cat:act}=H_{cat:nom}-(H_{cat:red}.H_{cat:nom})$	$H_{cat:act}$	N	10.800	Calculation	43
2.1.7.2.2.1	Catenary wire tension nominal	$H_{cat:nom}$	N	10.800	Deterministic	
2.1.7.2.2.2	Catenary wire tension reduction (0% - 8%)	$H_{cat:red}$	%	0%	Deterministic	

2.1.7.2.3	**Wind load on catenary wire per unit length**					
	$F_{w:cat}=q_{h:p}.G_c.((d_{cat}/1000).C_{cat}).sin(\Phi.(\pi/180))^2$	$F_{w:cat}$	N/m	10,43	**Calculation**	**44**
2.1.7.1.1	Dynamic wind pressure (nominal)	$q_{h:p}$	N/m²	660	Copy	
2.1.8.3.2	Structural response factor for conductors (resonance factor) (0,75)	G_c	abs	1,00	Copy	
2.1.7.2.3.3	Catenary wire diameter	d_{cat}	mm	15,8	Deterministic	
2.1.7.2.3.4	Aerodynamic drag factor of catenary wire (1,00)	C_{cat}	abs	1,0	Reference	
2.1.7.1.7	Angle of incidence of the critical wind direction (in respect to the perpendicular to the conductor)	Φ	degrees	90	Copy	

2.1.7.2.5	**Catenary wire height - actual (above track)**					
	$h_{cat}=h_{con:nom}+sh_{nom}+D$	h_{cat}	mm	8.605	**Calculation**	**45**
1.2.2.1.1.1	Contact wire height - nominal (above track)	$h_{con:nom}$	mm	5.500	Copy	
2.1.7.2.5.2	System height nominal (encumbrance)	sh_{nom}	mm	3.000	Deterministic	
1.3.6.1.1	Cant (actual) (40 < Vmax ≤ 200) (≤ 160 mm) (≤ 180 mm) (cant = +)	D	mm	105	Copy	

2.1.7.2.8	**Contact wire(s) weight (average) (CuAg0,1)**					
	$G'_{con}=Nr_{con}.(((F_{G:con:min}+F_{G:con:max})/2).9,81)/1000$	G'_{con}	N/m	17,44	**Calculation**	**46**
2.1.7.2.8.1	Number of wires	Nr_{con}	abs	2	Deterministic	
2.1.7.2.8.2	Minimum weight of single wire per unit length	$F_{G:con:min}$	g/m	862	Deterministic	
2.1.7.2.8.3	Maximum weight of single wire per unit length	$F_{g:con:max}$	g/m	916	Deterministic	

2.1.8.3.5	**Dropper length in span (approximate)**					
	$L_{dr}=(L_{1:ver}.0,4).((h_{cat}-h_{con:act})/sh_{nom})$	L_{dr}	m	20	**Calculation**	**47**
2.1.1.4.1	Span length (left) - Verification span	$L_{1:ver}$	m	50,00	Copy	
2.1.7.2.5	Catenary wire height - actual (above track)	h_{cat}	mm	8.605	Copy	
1.2.2.1.1	Contact wire height - actual (above track)	$h_{con:act}$	mm	5.553	Copy	

2.1.8.11.3	**Projected area (mast)**					
	$A=(L.b).10^{-6}$	A	m²	1,89	**Calculation**	**48**
2.1.8.12	Mast profile length (HE-005)	L	mm	8.600	Copy	
2.1.8.11.3.2	Mast profile width (HE-005)	b	mm	220	Deterministic	

2.1.7.1.1.3	**Air density**					
	$\varrho=1,225.(288/(273,15+T)).EXP(-0,00012.H)$	ϱ	kg/m³	1,246	**Calculation**	**49**
2.1.7.1.1.3.1	Temperature (environment)	T	°C	10	Stochastic	
2.1.7.1.1.3.2	Height above sea level	H	m	0	Reference	

2.1.7.1.1.4	**Wind velocity (base) 10 year interval (ground averaged 10 min)**					
	$v_{b:0,10}=v_{b:0,2}.YIF$	$v_{b:0,10}$	m/sec	22,7	**Calculation**	**50**
2.1.7.1.1.4.1	Wind velocity (base) 50 year interval (2% chance per year)	$v_{b:0,02}$	m/sec	25,2	Stochastic	
2.1.7.1.1.4.2	Yearly Interval Factor (Table)	YIF	abs	0,902	Reference	

Colophon

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STUDY ON UNIVERSAL OVERHEAD CONTACT LINE DESIGN * PHASE 2 *

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