Ciclo Sampa

A generalised bicycle network design method applied to São Paulo

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CIE4061 Multidisciplinary project
Faculty of Civil Engineering and Geosciences
June 11, 2019

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by

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as part of CIE4061 Multidisciplinary project
at the Delft University of Technology,
in cooperation with Universidade de São Paulo.

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Project duration:	February 11, 2019 – April 5, 2019	
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TU Delft

Preface

As part of the Master Civil Engineering, the TU Delft offers the possibility to do a Multidisciplinary Project abroad. This project will be performed in a group of four to six students with different specialisations to solve a problem by doing research and write a research report.

From February to April 2019 our group developed a bicycle pilot plan for a part of the city of São Paulo, Brazil, to reduce traffic jams. The plan has the potential for extending to other parts of the city as well in future bicycle lane expansion projects.

At this place we want to thank the Universidade de São Paulo for their support. In particular our special thanks goes to José Tadeu Balbo, our main supervisor there. It is hard to imagine how many time and effort you invest us by preparing our stay and our project!

Besides, of course we want to thank our supervisors, that helped to bring our project to a higher level. We want to thank Martijn Leijten and Karin Regina de Castro for their help concerning the stakeholder analysis and development of the list of requirements. Their feedback and creative input helped us to create a solid basis for the rest of the design.

Then we want to thank Lambert Houben, Kalil Jose Skaf, Rui Oyamada, Ruy Marcelo Pauletti for their help with the structural design and parametric modelling of the bicycle and pedestrian bridges in Grasshopper. And we also thank José Tadeu Balbo, Cassiano Isler, Haneen Farah and Victor Knoop for their help with the traffic data and the suggestion on the establishment of the model.

The group really appreciates your hospitality and hope that the results of this research can be used to improve the bicycle infrastructure of São Paulo.

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Delft, April 2019

Abstract

Nowadays the city of São Paulo has to deal with a lot of traffic jams. Extending the road network is no option and the public transport network cannot keep up with the capacity either. A solution must be found in another type of transport: cycling. The current bicycle infrastructure is not sufficient in terms of connectivity. In this research, a standardised bicycle network is developed for a part of the city, which can be used during future bicycle expansion projects in São Paulo.

The development of the bicycle infrastructure concerns the whole city of São Paulo, resulting in a lot of interests being affected. The people behind these interests, the stakeholders, can have an influence over the project decisions, but do usually have conflicting interests. Therefore, these stakeholders are identified and analysed, through literature review and semi-structured interviews. In this case however, most stakeholders did not seem to experience any conflicts. The biggest problem in the development of the bicycle network, is that the stakeholders all work towards the same goal, but do now cooperate towards that goal. Cooperation between multiple stakeholders would result in more power, meaning they could make more of an impact together. Most of the stakeholder's expectations could be met in this case, resulting in a satisfying design for most people.

As a result of literature review and the performed interviews, a list of requirements is developed as a basis for the rest of the design of the bicycle network. The conclusion was made that not only a sufficient network needed to be designed, but that incentives for use were also needed. Therefore, the list of requirements is divided into three categories: infrastructure network, incentives for use and long-term guidelines and recommendations. The rest of the standardised design is based on the list of requirements.

According to the requirement list, the new cycling network has been designed by greedy algorithm. The new plan can achieve 99.51% inhabitants with 320 metres of the walking distance. And it requires a new bridge for only cyclists and pedestrians' use to cross Pinheiros River.

Due to the demand of a bridge, a structural design is required. A literature review was performed, investigating the existing situation regarding the infrastructure. In the literature study, the different bridge types with their pro's and con's are described. Based on the existing situation and the literature study, a sound bicycle and pedestrian bridge design is designed.

In this situation, for the standardised bridge, an arch bridge is the best choice. The standardised design allows for an efficient and fast design and execution process. This design process is obtained by using a parametric design in Rhinoceros and Grasshopper, so the design of the bridge can be used for multiple spans.

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List of Acronyms

ABNT Brazilian National Standards Organisation (Brasileira de Normas Technics)

CET Traffic Engineering Company

FOSS free and open source software

FRP fibre reinforced polymer

GIS geographic information system

ITDP Institute for Transportation & Development Policy

MCLP maximum covering location model

MST minimum spanning tree

PI power versus interest

PT Partido dos Trabalhadores

QGIS Quantum GIS (https://www.qgis.org)

SLS Serviceability limit state

UCB Union of Cyclists of Brazil

ULS Ultimate limit state

USP Universidade de São Paulo

VoT value of time

List of Symbols

A_a	cross sectional area of main beam
a	height of origin of collision force
α	linear expansion coefficient
A_p	area of steel decking
A_s	reinforcement to resist hogging moments
b	deck width
b_{eff}	effective width of the main beam
β	in-plane buckling length factor
F_{dx}	horizontal collision force in x-direction
F_{dy}	horizontal collision force in y-direction
κ	curvature of the geometry arch, $\kappa = \frac{d^2z}{dx^2}$
d	distance of a structural element to centre of road
d_0	reference distance of a structural element to centre of road
D_{tot}	assumed deck height for wind calculations
ΔL_{force}	elongation due to an axial force
ΔL_{temp}	elongation due to a temperature difference
ΔL_{tot}	total elongation
ΔT	difference in temperature
E	young's modulus of steel
EA	axial stiffness
E_{cm}	secant modulus of concrete
E_{crack}	young's modulus of the cracked concrete
EI	bending stiffness
f	crest height
f_{ck}	characteristic cylindrical compression strength
h_1	free profile between the road and the bottom of the bridge deck
f_y	characteristic yield strength of steel
f_{yp}	characteristic yield strength of steel decking
f_{ys}	characteristic yield strength of reinforcement
$G_{k,j}$	permanent load
γ_c	partial factor for concrete
H	horizontal load in the arch
h_1	cross section height of the arch
h_2	cross section height of the deck main beam
h_c	thickness of concrete slab
$H_{axial,max}$	maximum axial force
$H_{axial,min}$	minimum axial force
h_p	thickness of steel decking
h_w	web height
I_{zz}	second moment of intertia
λ_1	geometry ratio of the arch
λ_2	slenderness of the deck and arch combined
M_{Ed}	maximum bending moment due to design load
$M_{Rd;no,slab}$	bending resistance of the girder without the concrete slab
$M_{Rd;slab;hog}$	hogging bending resistance of the girder with the concrete slab
$M_{Rd;slab;sag}$	sagging bending resistance of the girder with the concrete slab
$M_{Rd,x,N,max}$	moment resistance with respect to weak axis (around x), based on maximum normal force

$M_{Rd,x,N,min}$	moment resistance with respect to weak axis (around x), based on minimum normal force
$M_{Rd,y,N,max}$	moment resistance with respect to strong axis (around y), based on maximum normal force
$M_{Rd,y,N,min}$	moment resistance with respect to strong axis (around y), based on minimum normal force
N_{cr}	critical in-plane buckling force
n_r	number of studs in a rib
n_{req}	required number of studs in a rib
$\psi_{1,1}$	momentary factor
$Q_{k,i}$	variable load
q	distributed load
$q_{f;k}$	uniformly distributed load
q_{hor}	horizontal distributed load
Q_{serv}	load of the service vehicle
$q_{approach}$	load from approaching bridge
R	approximate radius of the arch
s	length of the half of the arch
L	span of the bridge
t_1	thickness of upper flange
t_2	thickness of bottom flange
t_3	thickness of left web
t_4	thickness of right web
t_5	thickness of left stiffener
t_6	thickness of left stiffener
V_{Ed}	maximum shear force due to design load
$V_{Pl,Rd}$	plastic shear force resistance
w	deformation of the arch
$W_{z,pl}$	plastic section modulus
z	function of the height of the arch

1 Introduction

São Paulo suffers from a lot of traffic congestion, resulting in additional travel time for cars. Moreover, there is a high dependency on cars and the public transport infrastructure is saturated. Cycling has only been promoted as a leisure activity instead of a transportation alternative, which resulted in the current bicycle network, not sufficient in terms of connectivity for commuters. Moreover, casualties with cyclists are high.

In 2014 the Strategic Masterplan was accepted by the Municipality of São Paulo, under Haddad's term as mayor. This plan acknowledged the bicycle as an important form of transport, meaning the improvement and extension of the cycling infrastructure was adopted in the plan. However, this plan was not without resistance due to the fact that São Paulo is a car-based city, not used to cyclists at all. This on top of the fact that the mayor after Haddad, João Doria, was anti-cycling, slowed down the progress tremendously. The views of the new mayor Bruno Covas, who took over after Doria resigned in 2018, are not clear yet. Even in the worst case, it is important to act now and to develop a bicycle network with a minimal impact on infrastructure, to satisfy politicians as well as inhabitants in the city.

Therefore, the goal of this research project is to *develop a standardised way of designing a bicycle network for São Paulo*. Standardised means that the network can be applied to all areas of São Paulo for future bicycle network expansions. The project goal fulfils a part of the Masterplan of São Paulo, which defined guidelines for the city's growth for the next sixteen years. One of the goals is developing a more balanced city by integrating and articulating different means of transportation, including infrastructure for non-motorised modes including bicycles and pedestrians. Due to the immense size of São Paulo this will be done by designing a pilot-plan for the network, which can be extended through the rest of the city.

The main goal of the project is reached by answering a set of research questions, including one main research question and several sub-questions. The main research question is:

Which standardised design for a bicycle network, would solve São Paulo 's traffic congestion, with minimal impact on the current motorised vehicle infrastructure while acknowledging stakeholders' wishes?

To be able to answer the main question, the following sub-questions will be discussed:

- Which stakeholders are involved during the development of a bicycle network for São Paulo?
- Which requirements should be fulfilled in the bicycle network design to fulfil stakeholder's wishes and demands?
- What attributes should be considered into the new cycling network design?
- What algorithm is applicable for generating the new network?
- What is the current bicycle infrastructure regarding bicycle paths and bicycle and pedestrian bridges?

- How could one design bicycle bridges in a standardised and parametric way to create an efficient design process?

The research questions will be focused on a pilot-area, existing of the neighbourhoods of Butant, Pinheiros, Alto de Pinheiros and Jaguar, which can be seen in figure 1.1. These areas involve the Universidade de São Paulo (USP) campus and its surroundings, due to the fact that our research project is located at USP.

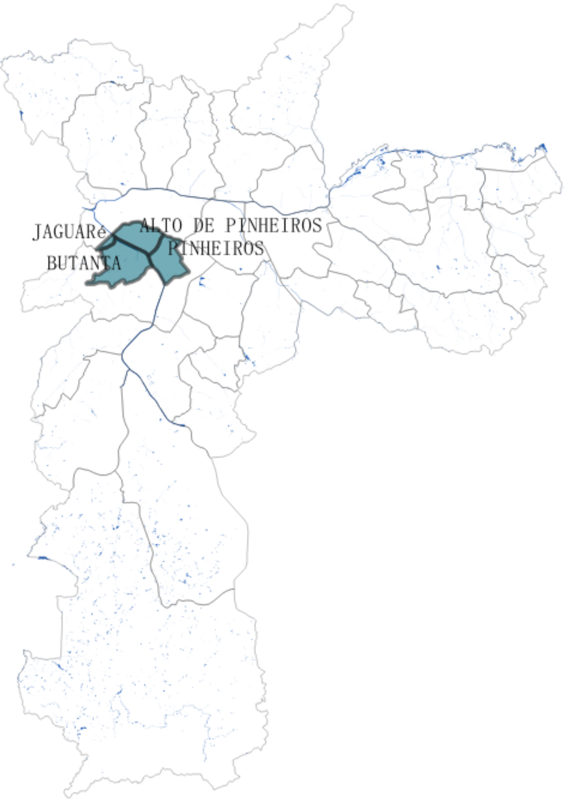


Figure 1.1: Pilot area of interest

The report will start with researching background information in chapter 2. This is followed by the identification of all stakeholders that might be interested in the project through research, brainstorming and consulting experts and afterwards analysed in terms of interests, goals, perceptions and potential interdependencies in chapter 3. Semi-structured interviews are held with stakeholders to map their wishes and needs. This input is used to create a solid list of requirements to base the design of the bicycle network on.

The list of requirements is used to start with the design with the transportation network in chapter 4. First, the current road structure is identified by using geographic information system (GIS) retrieved from Prefeitura de Sao Paulo (2019). This model covers the maximum number of inhabitants within a specified covering distance. The covering distance depends on local preferences and is extracted from interviews with locals. The number and location of nodes should cover almost all inhabitants. Secondly, one needs to classify the bicycle network. Candidate links are selected by classifying the current road network in classes and selecting suitable links for cycling. The nodal points need to be connected by the selected candidate links. This will be done by using minimum spanning tree (MST). The MST allows obtaining the minimum level of connections of the road network. Existing bicycle infrastructure and candidate links are used to obtain the MST bicycle network.

Two main rivers cross São Paulo, meaning the chances are high that rivers need to be crossed. The result of the network design gives the location of the nodes, which need to be connected by bicycle paths. By taking into account stakeholders and risks and the available construction area, the optimal location of the bridges is be determined, which can be read in chapter 5. To create a design that can be implemented in different locations, a parametric design process executed, which can be implemented in different parts of the city. Due to the limited available amount of time, the structural design is limited to the main span. A literature study is performed to get insight in the current situation, different bridge types, possible execution methods and information about parametric programming by using Rhinoceros and the Grasshopper plugin and the possibility to do structural analysis by using Karamba3D (FEM-package). The approaching bridges and the design of the foundations are excluded because they cannot be standardised. Next, a conceptual design for bicycle and pedestrian bridges will be made. Finally, each part is designed in more details, by using the force distribution as calculated by hand, checked by Karamba3D.

The report finishes with a standardised design proposal for the development of the bicycle infrastructure for São Paulo, followed by recommendations for further research and implementation.

2
Background

As a solid start for this research, it is needed to be aware of some basic information about São Paulo. The investigation mainly focuses on the population, geography, transportation networks and the traffic impacts on the socio-economics and can be read in this chapter.

2.1. City description

São Paulo, founded by two Jesuit Missionaries in 1554, became an official city in 1711 (Minster, 2019). In the colonial period, it grew rapidly, mainly due to the coffee industry and today it is one of the largest economic centres in Brazil with the population of over 12 million people.

With a great number of immigrates, the annual population growth has been 1.13% since 2015 (World Population Review, 2018). The population distribution of the city, seen in figure 2.1, is not uniform. The population density is approximately 7,200 people per square kilometre, with the densest areas located at the city centre. These high densities make traffic congestion a serious problem in São Paulo (Rolnik & Klintowitz, 2011).

The geographic profile in figure 2.1 of the City of São Paulo can be divided into three zones: the mountain range, named Serra da Cantareira, to the north of the city, the relatively flat river base in the medium zone with the low altitude and the interior plateau of the southern part because of an abrupt mountain chain, called Serra do Mar. Affected by the mountains and rivers, the elevation of the city differs much from various districts with a range of 760 to 2100 meters. (Wikipedia, 2019)

The main hydroelectric potential and irrigation comes from two rivers, namely the Pinheiros river and the Tietê river (Rabello, 2014). In the urban region, multiple bridges, seen in figure 2.1, provide the ways of transport between the shores.

2.2. Urban transportation

The mobility in São Paulo has multi-modes. Vehicles and public transport as the main ways take 28% and 31% respectively, and cycling is a rather minority mode only with a share of 1%. (Deloitte, 2018).

2.2.1. Cycling

The development of cycling in São Paulo is contributed by the heated discussion in the media and the simulation of the governmental policies that advocate the transport mode is good for leisure and tourism. There have been plans constructed for a bicycle structure, but these were lacking clear and proactive policies (Medeiros & Duarte, 2013). The first bicycle lane originates in 1975, the first plan 'Planning cycle infrastructure: A politics for the bicycles' in 1976, which also started an ongoing debate (Barifouse, 2015). From 2009, São Paulo, as well as other Brazilian cities, have invested and promoted cycling increasingly. A major trigger were the

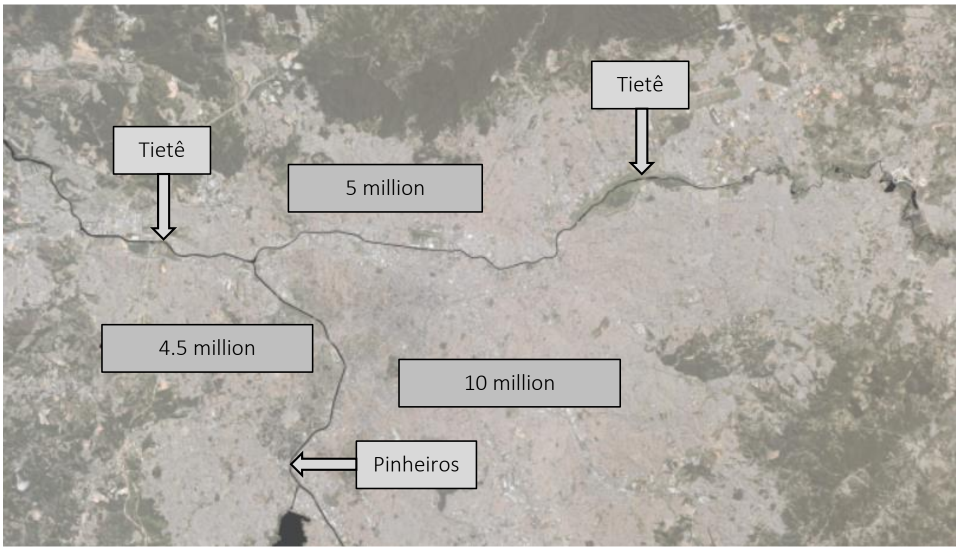


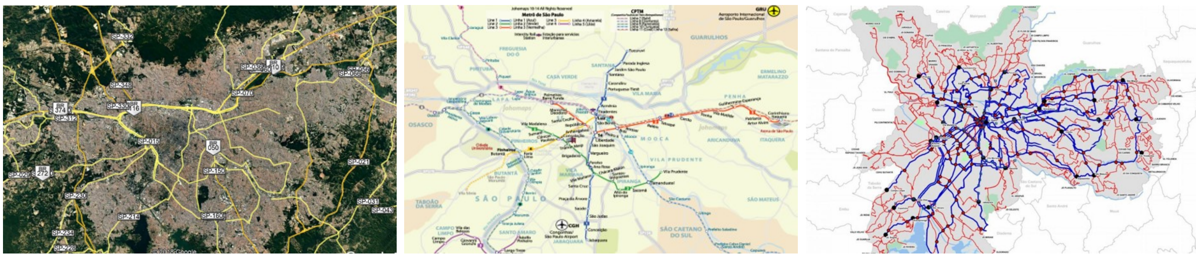
Figure 2.1: Overview of the existing rivers Tietê and Pinheiros in São Paulo including the approximate population distribution of the metropolis with respect to these rivers.

Olympic games of 2016 in Rio de Janeiro. To prepare for the competition, São Paulo launched bicycle project in 2009 and 2013 (Correa, 2013). Bicycle sharing programs were launched and bicycle lanes where added. In addition, operational bicycle lanes that closed motorised traffic, especially for the cyclists and pedestrians, were introduced. The programs were focused on rich neighbourhoods and were funded by private banks, which led to protests around the city (Correa, 2013). The bicycle network has been expanded to around 400 km (ITDP, n.d.) during the term of Mayor Haddad (Lemos, 2014). Although the municipality tried several projects to promote cycling, the main purpose is still for leisure and tourist activities São Paulo (Medeiros & Duarte, 2013).

2.2.2. Road network

São Paulo has a road structure with an irregular pattern, contrary to other Brazilian cities like Belo Horizonte and Brasília. This irregular pattern results in a large number of intersections and traffic lights, leading to an additional travel time of around 28 minutes per day (TomTom, 2018).

The basis of the current road network originated from the start of the 20th century and included major boulevards that opened up the city centre. However, due to the rapid growth of the city, the road infrastructure could not handle the growing amount of traffic, and the heavy traffic jams are the consequence (Rolnik & Klintowitz, 2011). In the 1950s, the first motorways were built around the city centre in order to increase the capacities, which is the SP-150 connecting São Paulo to Santos. The new ring roads (like the *SP-015*) were constructed in the later years. Another additional ring road is currently under construction *SP-021*. This road has locations with more than 12 lanes. The current motorway network (figure 2.2a) consists of ten radial motorways which mostly starts at the ring road *SP-116* and *SP-015* (TomTom, 2018).



(a) Motorway network (b) Metro map (c) Bus network

Figure 2.2: General overview of urban transportation networks.

2.2.3. Public transit network

Metro

The construction of the first metro line started in 1968. From then on, the network gradually increased and today it consists of six metro lines with a total length of 96 km. It transports more than 4 million passengers every day and the *CPTM* is used by more than 2.8 million people (CPTM, 2019). A map of the metro network is depicted in figure 2.2a (dos Transportes Metropolitanos, 2015).

Train

Moreover, there is a 260 km suburban rail network which is operated by Companhia Paulista de Trens Metropolitanos (CPTM) (CPTM, 2019). The train network is included in figure 2.2a. The current metropolitan railways do not cover all areas of São Paulo. Nowadays the network is still expanding, especially in the north part, line 6, and south part of the city, line 17. However, large parts in the north, east, and west of the São Paulo are still uncovered (Urbanrail, 2019).

Bus

The bus system in figure 2.2c is the other public transit mode in São Paulo. There are exclusive bus lanes in the city road plan, but they are only at use for 29.5% of all the bus-tracks. Most of them are sharing the infrastructure with cars and motorcycles. Thus, during the rush hours, the busses can only travel at an average speed of 12 km/h on average (Rolnik & Klintowitz, 2011).

2.3. The interaction between traffic and socio-economics

Car ownership rates give an indication of the reliance on motorised vehicles. Data shows for Brazil that in 2010 car ownership was 249 per 1,000 inhabitants and it is predicted to increase as 377 cars per 1,000 inhabitants in 2030 with the growth rate of 5.1% (Roque & Masoumi, 2016). Moreover, car ownership in São Paulo differs between the socio-economic classes. In 2012, around 91.8% of families in the highest income quintile owned a motorised vehicle, where only 28.9% of families in the lowest quintile own a motorized vehicle. Compared to 2007 the difference increased; 95.6% and 23.5% for respectively the highest and lowest quintile. A reason for this growth originates in the regulation introduced by the municipality in 2010 that made car ownership more affordable (Presidência da República, 2010).

Another observation is that people living in the northern region of Brazil and in rural areas use active mobility more than average. The mode is most frequently used among low-income individuals and people living in less economically developed areas (Sá, Pereira, Duran, & Monteiro, 2016). Comparing the lowest with the highest quintile of income, the rates are between two to five times higher for people with low income (Sá et al., 2016).

According to Jones and de Azevedo (2013), low-income families of a population live in the peripheral neighbourhoods of São Paulo and have to commute further to work. This spatial segregation, in combination with inefficient public transport, contributes to people covering longer distances by feet or bicycles (Florindo et al., 2009; Rydin et al., 2012). All these impacts of socio-economic set up the foundation of the stakeholder analysis in chapter 3.

3 Stakeholder analysis

Before diving into the identification and analysis of stakeholders, it is important to know how the history of cycling in São Paulo developed. This in combination with the role of the media might have an impact on the perspective of certain stakeholders on this topic.

Nowadays, São Paulo is the largest city in Latin America with a population of more than 12 million inhabitants (IBGE, 2018). With over 8 million vehicles in the city, according to statistics of December 2017, daily traffic congestion is only one of the problems this city encounters (Bazani, 2018; TomTom, 2018). A recent increase in the construction of bicycle lanes and the use thereof, resulted in support as well as resistance.

3.1. History of cycling in São Paulo

As mentioned in the introduction and in the above paragraph, cars are not only a form of transportation, but also a status symbol in Brazil. The first bicycle pioneer measures found their way during the tenure of Olavo Setúbal from 1975 until 1979. During this time, the oil crisis led to a reduction in oil supply, which started a search for other forms of transportation. Nevertheless, only few measures were implemented during the next two decades (Kerches da Silva Leite, Feijó Cruz, & Bravo Rosin, 2018).

From 2005 and onward, the bicycle made its way to the governmental agenda. In combination with the cycling-activist movement, it mobilised international experience and the policy of cycling was eventually transferred to the Municipal Bureau of Transportation. However, the bureau‘s actions fell short, due to the fact that they ignored various knowledgeable and experienced actors. In 2009 the Municipal Bureau of International signed a cooperation agreement with the Institute for Transportation & Development Policy (ITDP) to acquire knowledge on the implementation of bicycles. In the period from 2009 to 2012, leisure cycling lanes were successfully implemented in the central streets of São Paulo (Kerches da Silva Leite et al., 2018).

In the period from 2005 to 2012, Eduardo Jorge was head of the Municipal Environment Bureau and a political entrepreneur. His role was to promote and advertise a public image in favour of daily use of bicycles as a mean of transportation in São Paulo. He played an important role, because it helped to create a positive image towards the use of bicycles (Kerches da Silva Leite et al., 2018).

3.2. The role of the media

The media has had a huge impact on the inhabitants‘ view on bicycles. It is an important source to influence a huge group of stakeholders and make them support or resist the plan. Therefore, the role of the media will be discussed in the beginning of this chapter. During the tenure of Fernando Haddad, stories published by the media acted as real instruments of resistance to change the transport paradigm towards cycling. They influenced the public sentiment against government initiatives. Kerches da Silva Leite et al. (2018) analysed 1681 newspapers in the period from 2013 to 2016, while Haddad was mayor. In these papers a distinction between different themes and aspects is made: what the media was actually telling, what type of words they used to define cycle paths and personal attacks they made on Haddad.

The two largest paid newspapers in the circulation of the city of São Paulo during the tenure of Fernando Haddad, werer used in their case study: Folha de S. Paulo (FSP) and O Estado de S. Paulo (Oesp). The audience of these newspapers were people who were on the top of the socioeconomic ladder, therefore completely missing their goal of being a watchdog of governmental action and focusing on the aspects which are especially important for their audience. In doing so, they bypassed the fact that there is also a positive side to the changes in the urban mobility policy in São Paulo, aligning with the state-of-the-art mobility in the world. Newspapers, however, exaggerated the negative aspects of the cycle paths, in order to rule out the new policy.

3.3. The need for stakeholder management

During all stages of a large project, an extensive number of interests will be affected, either positively or negatively. The people behind these interests, who can have an influence over the project decisions, are called the project‘s stakeholders (Olander, 2007; Olander & Landin, 2005). Their often conflicting interests will be expressed in terms of needs and expectations of the project, resulting in an unlikeliness that all stakeholder‘s expectations will be met (McManus, 2002). In order to decide which ones are to be met, the needs and expectations have to be thoroughly evaluated in relation to the main project goal. If this is not executed concisely, the project might not be noted as successful, even though the original parameters of time, budget and scope were met. Managing the process during the whole timeline of the project maximises a positive stakeholder input in terms of knowledge, insights and support, and minimises potential negative impact. In order to better understand the potential impact of stakeholders on the project, it is important to identify legitimate and valid stakeholders and to map their power and influence (Bourne & Walker, 2005). Usually a stakeholder engagement plan is created during initiation, however, it is sensitive to changes during the process, as the power of stakeholders rise and diminish over time (Crichton, 2013). Therefore a forecast on the shift of power and interest should be created to minimise the chances of dramatic changes during the process. The analysis done for this project can be seen as a pre-analysis, since it is not possible to gather all stakeholders within the time limit of eight weeks.

3.4. Stakeholder identification

As described above, it is crucial to first identify legitimate and valid stakeholders who might be engaged in the project in any way possible. The projects‘ stakeholders can be either groups or individuals, that have a stake in or an expectation of the project‘s performance. They interact with each other on two primary areas: the cultural arena, based on ideology or values to shape or constrain changes, and the political arena, where powerful stakeholders exercise power to achieve their personal objectives (Newcombe, 2003). Stakeholders are identified through literature research, consulting experts as well as stakeholders and searching the media. This resulted in a list of 24 stakeholders, as can be seen in table 3.1.

After identification, the next step is to investigate each stakeholder to gain understanding of who they are and why they are engaged in this project. This extensive research can be found in appendix B. Resulting from this research, in combination with interviews, the main stake of each stakeholder is defined. The main stake is described as the expectation that each stakeholder has of the project. This is also related to the even bigger process of bicycles within São Paulo, not only to this pilot project. The satisfaction of each stakeholder considering the current situation is also identified. This is assigned by either a green, yellow, red or blue dot, meaning positive, medium, negative or neutral satisfaction consecutively. The requirements analysis in the end is focused on both the long and the short term and will use the input from the stakeholder table. It helps to determine what actions can be taken on the short term to satisfy stakeholders but also which actions are needed on the long term (Bryson, 2004).

To gain more information on all relevant stakeholders, semi-structured interviews are executed. These interviews are executed parallel to the rest of the stakeholder analysis, which will be constantly updated during the execution of the interviews. The interviews will be discussed in paragraph 3.10.

Stakeholders	Main stakes	Satisfaction
Prefeitura de São Paulo	To provide their inhabitants with a connected and safe bicycle network.	yellow
CET	To maintain good and safe roads.	yellow
Prefeitura do Campus USP	To provide their students with a connected bicycle network to reach all faculties.	red
ITDP	To implement solutions for cycling infrastructure.	green
Emergency Services	To reach their destination within the given time limit for the emergency.	blue
Inhabitants of São Paulo		
- High income	To improve their health.	green
- Low income	Freedom of mobility and to decrease travel time.	red
Road users		
- Leisure	To bike safely through the city.	yellow
- Work	To reach their work as soon as possible.	red
- A to B	To reach their destination as soon as possible.	red
Bicycle Sharing Companies		
- Yellow	To maintain the current high quality service and to extend their availability through São Paulo.	yellow
- Mobike	To enlarge their area of usage in São Paulo and to increase the amount of Mobikes.	blue
- Tembici (BikeSampa)	To extend their amount of bicycles in São Paulo.	yellow
- CicloSampa	To extend their amont of bicycles in São Paulo.	green
Public Transport Companies		
- Bus: EMTU, SPTrans	To not have the bicycle paths interfere with their buslines.	blue
- Train: CPTM	To offer a better transportation service by having connecting possibilities: so people are able to reach their destination to the end.	yellow
- Subway: Metrô	To offer a better transportation service by having connecting possibilities: so people are able to reach their destination to the end.	yellow

Figure 3.1: Stakeholders including their main interest and their current level of satisfaction towards the bicycle network. Green means a positive satisfaction, yellow a medium satisfaction, red a negative satisfaction and blue a neutral satisfaction with the current infrastructure (part 1).

Stakeholders	Main Stakes	Satisfaction
Bicycle Promoting Programs		
- Aliança Bike	To stimulate the use of bicycles as an effective means of transportation.	🟡
- Instituto CicloBR	To create extra incentives for people to use bicycles as means of transportation, leisure, tourism and sports.	🟡
- Bike Anjo	To increase the rate of bicycle users in São Paulo.	🟡
- Bycs	To increase the rate of bicycle users in São Paulo.	🟡
Private Companies		
- Itaú	To improve their imago by promoting sustainable mobility.	🟢
- Bradesco	To improve their imago by promoting sustainable mobility.	🟢
UCB	To promote the use of bicycles as a means of transport, leisure and sports in urban and rural areas.	🟡

Figure 3.2: Stakeholders including their main interest and their current level of satisfaction towards the bicycle network. Green means a positive satisfaction, yellow a medium satisfaction, red a negative satisfaction and blue a neutral satisfaction with the current infrastructure (part 2).

3.5. Defining interest and power

A power versus interest (PI)-grid helps to determine which stakeholders‘ interests and power should be taken into account when addressing the problem. The grid allocates stakeholders on a two-by-two matrix with the interest in the issue at hand on one axis, and their power to affect the issue‘s future on the other, showing the stakeholders‘ position relative to each other. They can also emphasise which coalitions should be encouraged and which behaviour should be supported.

The grid shows four categories of stakeholders: Key Players, Subjects, Context Setters and Crowd. Key Players have both a significant power and interest, so are important to keep close in the process. Subjects have an interest but only a little power, so should be informed on all changes. Context Setters have more power but little interest, so should mainly be kept satisfied. The Crowd has both low interest and power, so can be involved minimally. The information from the grid can help to increase the interest of the powerless and to convince stakeholders to change their views (Bryson, 2004). The PI-grid that has been established for this project can be seen in figure 3.3.

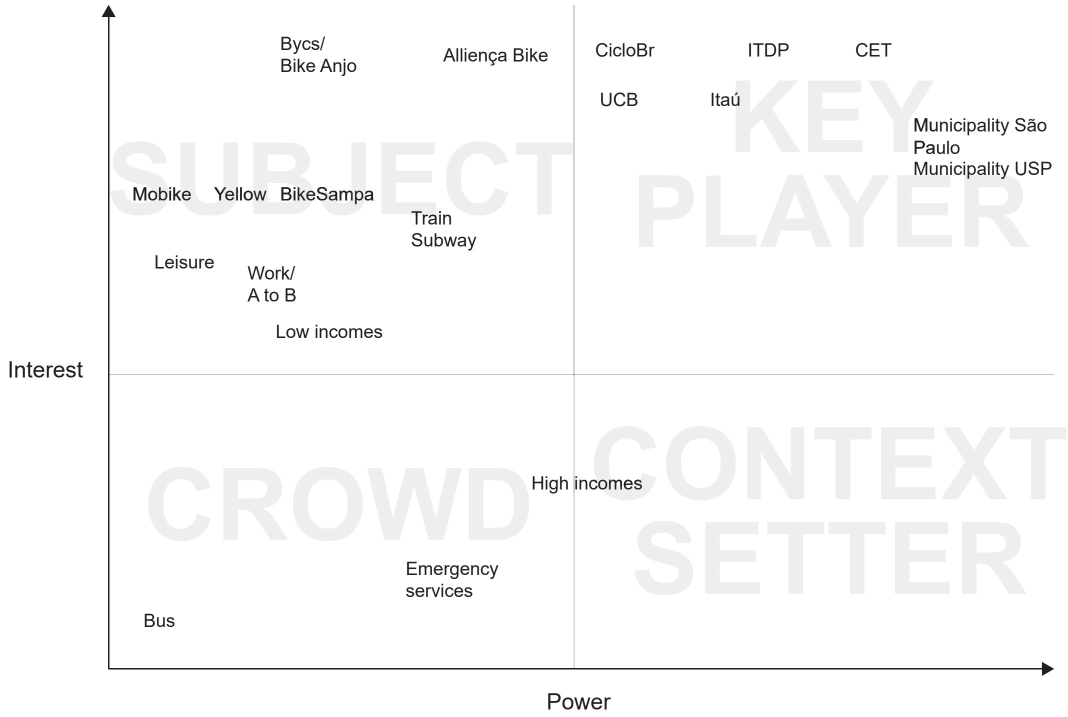


Figure 3.3: The PI-Grid, showing the relative power and interest of each stakeholder.

The PI-grid shows that there are seven stakeholders that can be defined as Key Players: CicloBR, Union of Cyclists of Brazil (UCB), Itaú, ITDP, Traffic Engineering Company (CET), the Prefeitura de São Paulo, and the Prefeitura do Campus USP. The CET, the Prefeitura de São Paulo and the Prefeitura do Campus USP are the most important ones considering this type of classification. SPTrans and emergency services are both Crowd and therefore the least important. High-income inhabitants are in between Crowd and Context Setters, because they are not very important but should be kept satisfied due to their power.

As can be seen, most of the stakeholders are classified as Subjects. They should mainly be informed during the whole project because they have relatively high interest, but do not have significant power to have an influence on the project outcomes. This, however, could change in the case where the Subjects would decide to work together and thereby significantly increase their power.

3.6. Stakeholder influence diagram

Next, to know the relative power and interest of all stakeholders, it is crucial to know in which way all stakeholders influence each other. This may be needed to forecast the dynamics of the stakeholder network. These interdependencies are visualised in a stakeholder influence diagram. The direction of the arrows show which stakeholder influences whom. The primary direction of influence is shown in the diagram, which sometimes can be both ways (Bryson, 2004). If the potential influence is only small, a dotted line is drawn. The stakeholder influence diagram can be seen in figure 3.4.

As can be seen from the figure, Bycs is not linked to any of the stakeholders. Resulting from the analysis, it seems that Bycs is only a way of promotion from the government, but is not known by other stakeholders. Therefore it is too small to have any influence or be influenced by the other stakeholders and does not have to be further taken into account. Mobike is also not linked to any other of the stakeholders, because they are a new player and not yet functioning. They will not be taken into account further. The link from all stakeholders to UCB is only meant for the part of this group that uses a bicycle. The UCB is the union for bicycle users and is therefore influenced by all of them.

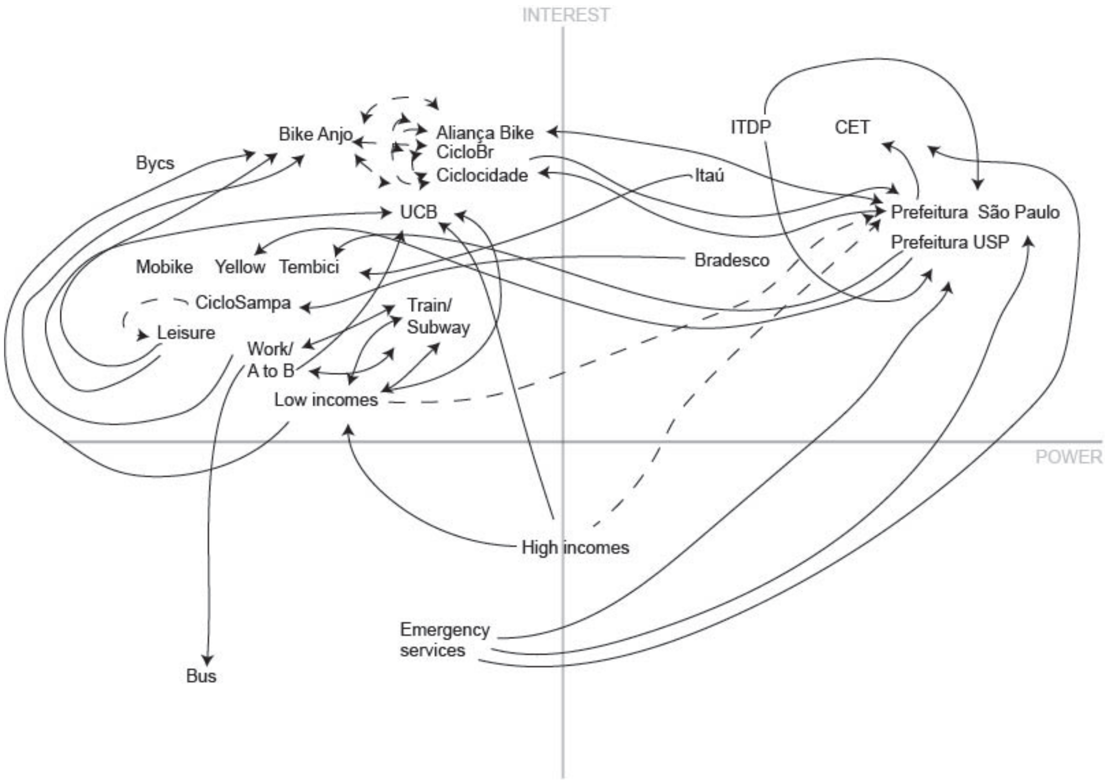


Figure 3.4: The stakeholder influence diagram.

3.7. Critical Actors

In the stakeholder identification, the involved parties and their stakes are established. The next step is to assess the resources of the stated parties. Resources of a party are 'the things over which they have control and in which they have some interest' (Coleman, 1990, p.28). These resources make actors able to influence the network and the project they are involved in. By assessing these resources, their importance for the realisation of the bicycle network is visualised. Resources are therefore closely related to power and influence (Enserink et al., 2010). When these resources are vital to the project, the resource's owner is a critical actor. This means that their cooperation is needed to a certain extent, to guarantee the implementation of the project. Another way for an actor to be critical is to have a potential blocking power. Another type of power that can be identified is diffusive power, where it the position of the actor is unclear and whether or not he wants to use his resources and relations. Lastly, there are actors with productive power, which could use their resources for example to make funds available (De Bruijn & Ten Heuvelhof, 2018). To further determine if an actor is critical or not, the dependency-relations between actors need to be mapped. In this way, an overview of the network and the relationship between actors is given. The dependency is determined by three aspects, namely: the importance of the resources, replace-ability of the resources and the degree of interest. An actor can have formal and informal resources at its disposal. Formal resources are, for example, authority and instruments, while an informal resource could be information. The resource dependencies depend on the replaceability of that resource and can best be explained with table 3.1 (Enserink et al., 2010):

Table 3.1: Dependency and replaceability explanation

	Limited importance	**Great Importance**
Limited options to replace	Moderate dependency	High dependency
Easily replaced	Low dependency	Moderate dependency

This table is best explained by an example, for instance with the municipality of São Paulo. The municipality has the resources regarding permits and regulations for the execution of new bicycle lanes. In São Paulo it depends on which party has tenure for that period, because the Brazilian National Standards Organisation (Brasileira de Normas Technics) (ABNT) is more resistant against bicycles than the Partido dos Trabalhadores (PT), known as the Worker‘s Party. They can use their power over the media to influence the inhabitants, both negatively as positively, to support or resist the uprising of bicycles. The municipality cannot be replaced (unless there are elections) and therefore their replaceability is low and they have a high dependency. Dependency is defined as the extent to which the progress of the project depends on that specific resource. The criticality table, including the stakeholders‘ resources, replaceability and dependency, can be seen in table 3.2.

Table 3.2: Criticality table

Actor	Important resources	Replaceability	Dependency	Critical actor
Prefeitura de São Paulo	Permits and regulations Influence on media Financial resources Authority Strategic master plan (land use plan) Infrastructure owner Pluriannual plan (PPA)	Hard Hard Moderate Hard Low Hard Moderate	High High High High Moderate High Moderate	Yes
Prefeitura do Campus USP	Permits and regulations Authority Financial resources Land use plan	Hard Hard Moderate Moderate	High High High Moderate	Yes
Companhia de Engenharia de Trafego (CET)	Reports on road system performance (volumes and speed) and accidents Authority to write fines Paking lots owner Road policies	Moderate Hard Easy Hard	Moderate High Low High	Yes
Institute for Transportation and Development Policy (ITDP)	Knowledge and experience on implementation of bicycle paths	Hard	High	Yes
Emergency services	Fire/police/medical emergency services Knowledge on emergency response	Hard Hard	Moderate Moderate	No
Inhabitants high income	Financial resources Reputation on certain things (car = status symbol) Protesting/Support Voting power	Easy Moderate Moderate Easy	Low Moderate Moderate Moderate	Yes
Inhabitants low income	Protesting/Support Voting power	Moderate Easy	Moderate Moderate	Yes
Road users leisure	Protesting/Support Voting power Public opinion of current problems	Easy Easy Easy	Low Moderate Moderate	Yes
Road users A to B	Protesting/Support Voting power Public opinion about problem areas	Moderate Easy Easy	Moderate Moderate Moderate	Yes
Road users work	Protesting/Support Voting power Public opinion about problem areas	Moderate Easy Easy	Moderate Moderate Moderate	Yes
Bycs	Bicycle mayor	Easy	Low	No
Bike Anjo	Public opinion Knowledge on bicycle users Bicycle teaching programme Community of cyclists	Moderate Hard Moderate Hard	Moderate Moderate Moderate High	Yes
Yellow	Bicycles Knowledge on bicycle users‘ profiles Knowledge on demand of bicycles per location Information about bicycle users‘ profiles	Easy Easy Moderate Moderate	Moderate Moderate High Moderate	Yes
Mobike	Bicycles	Easy	Low	No
Tembici	Bicycles Bicycle stations Knowledge on demand of bicycles per location Information about bicycle users‘ profiles	Easy Easy Moderate Moderate	Moderate Low High Moderate	Yes
EMTU/SPTrans	Bus lines Bus stations	Hard Hard	Moderate Moderate	No
Metrô	Metro stations Metro cars	Hard Hard	High Moderate	Yes
Aliança Bike	Knowledge on involved parties and cooperations Research on the bicycle economy Policy making	Moderate Hard Hard	High High High	Yes
Instituto CicloBR	Knowledge about current cyclists Knowledge about incentives for cycling	Moderate Moderate	Moderate High	Yes
CicloCidade	Research Cycling garage	Hard Easy	High Low	Yes
Itaú	Financial resources	Hard	High	Yes
União de Ciclistas do Brasil (UCB)	Support and financial resources	Moderate	Low	No
CicloSampa	Bicycles	Easy	Low	No

3.8. Advanced stakeholder typology

It is known how all stakeholders are placed relative to each other on their power and interest. However, there is another very important factor to be included: attitude to the project, measured by the extent to which a stakeholder will support or resist the project. Creating a three-dimensional grid instead of a two dimensional one helps to gain even more insight in stakeholders. It helps to stimulate thought and to inform the project in a more meaningful way, since by only considering two factors might give only a partial picture (Murray-Webster & Simon, 2006).

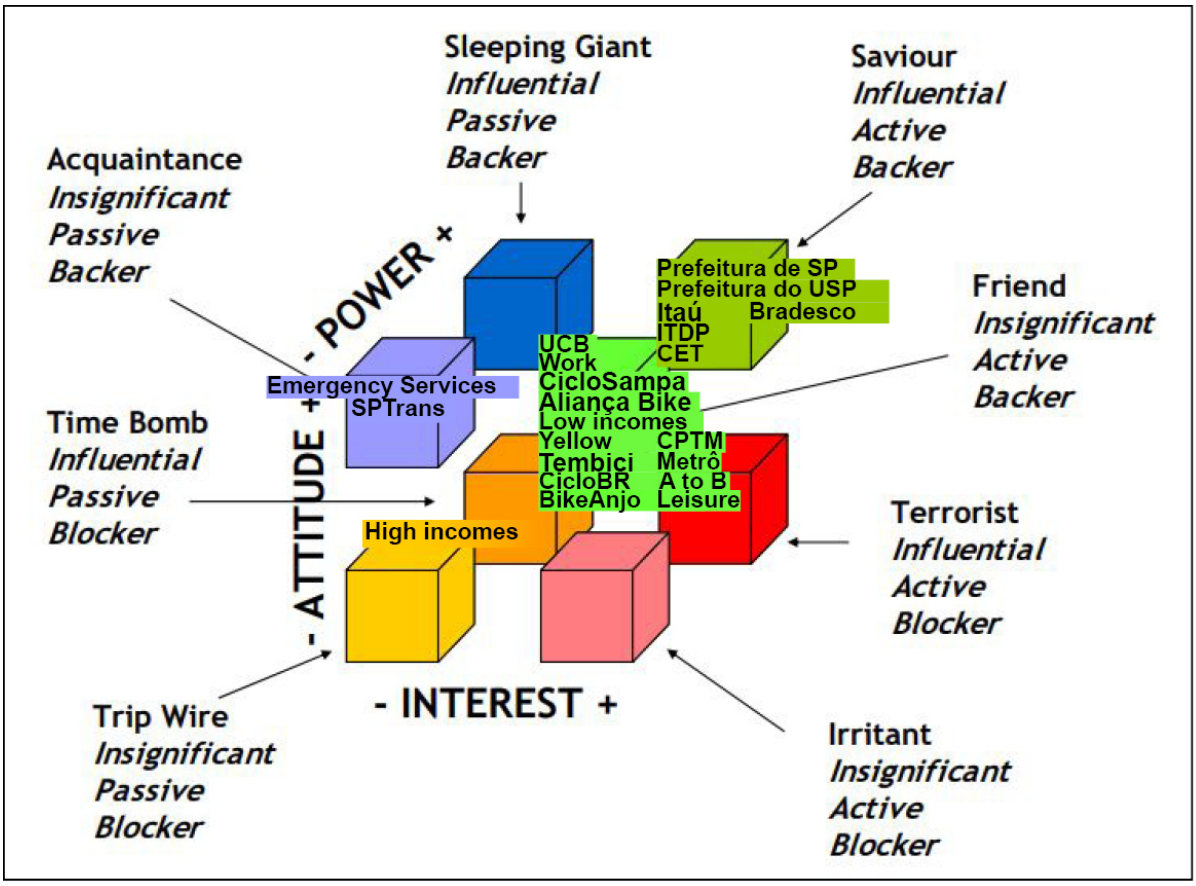


Figure 3.5: Advanced stakeholder typology.

Figure 3.5 shows the division of the stakeholders over the advanced stakeholder typology map, structured into the labels Saviour, Friend, Saboteur, Irritant, Sleeping Giant, Acquaintance, Time Bomb and Trip Wire. More explanation on these labels can be found in Appendix C. The Sleeping Giant and the Terrorist should be taken into account most. The terrorist can influence the project crucially with its blocking power and can, therefore, be a danger to the success of the project. The Sleeping Giant should be kept satisfied because he can have a great influence.

As seen in figure 3.5, there are no Trip Wires or Terrorists in the development of the bicycle project for São Paulo. This means there are no real enemies to the project. Prefeitura de São Paulo, Prefeitura do Campus USP, Itaú, ITDP, and the CET are the most powerful, but they are all mostly positive towards the project. The only ones with a negative interest and attitude are the high-income inhabitants of São Paulo. They should be paid attention to, even though they are not very powerful. Most of the stakeholders are labelled as Friends, meaning they have a positive attitude, a high interest, but no or few power. As mentioned before, they have the ability to become very powerful if they group together, but this would only have a positive influence.

3.9. Important stakeholders

From this analysis, it becomes clear who the most important stakeholders are in the bicycle network. The municipality of both São Paulo and USP are the policymakers and have the authority over their juridical area. The CET is also an important actor to be taken into account, because only they have the power to uphold road policies and write fines if necessary. IDTP is an important stakeholder due to the fact that they have a lot of knowledge on road usage and bicycle policies and eventually how to evaluate them. They had an important role in the making of the Strategic Masterplan of São Paulo. Itaú is defined as an important stakeholder, because the bank funds a bicycle sharing company and bicycle infrastructure. Bradesco is important for the same reason, however less than Itaú.

Furthermore, there are a couple of smaller bicycle associations that are important to consider: Bike Anjo, Aliança Bike and CicloBR. On their own, they have a tough time voicing their arguments and stakes within the municipality and pushing them towards action. However, if they would combine their strengths they could have a lot more influence and be a force to reckon with. This is also seen in the PI-grid, where these associations are all placed relatively close to each other, on the lower side of power. If they would bundle their power, together they might be more of an influence and make a shift to the right. In that case they could more easily speak to the municipality on equal grounds. Along with these associations, the bicycle sharing companies Yellow and Tembici should be named as important stakeholders. Although they are relatively small, they both grow rapidly, creating demand in the process.

Of course, the road users are included as important stakeholders. Either way, if they go by bike, car or another form of transport, they will profit from an improved system and reduction of cars on the road. However, with wrong or even false information, they can easily be turned against the plans and form a blockage. Last, but not least, are the mass transportation companies, especially the train and subway. They transport enormous numbers of people every day, most of them who do not have a high income. To decrease their travel time and optimise their journey, the operational companies behind these forms of transport need to be taken into account.

Important to note is that there are no stakeholders that have high power and interest, but a negative attitude towards the project. All powerful stakeholders have a positive attitude towards the development of a bicycle network, the thing that lacks most in the perseverance of it, is the motivation. The only stakeholder that has a somewhat negative attitude, is the high-income inhabitants group. They should be paid attention to, however they are not very powerful and their interest is low. SPTrans, EMTU and the emergency services have a positive attitude but have low interest and power. Therefore they should be taken into account the least of all stakeholders.

3.10. Interviews

Stakeholders are interviewed to gain more understanding of their stake in the bicycle network and to gather more relevant information for the requirement analysis. In a larger time span, all stakeholders would have been interviewed. However, this was no option during the short period of this project and therefore a selection was made based on importance and availability. The interviewees were also asked personal questions to gain more knowledge on the inhabitant‘s view, since there was no time to do these interviews separately. This chapter will first explain the interview set-up, then the analysis of the interview results and the requirements that each stakeholder forms for the bicycle network design.

3.10.1. Interview set-up

The interview will be semi-structured, meaning that the structure is prepared beforehand with a set of general questions for the stakeholder, however, if needed it is permitted to ask extra questions on the spot. Semi-structured interviews usually have lower validity than structured interviews, but the decision for this type of interviews is made because of the time-limit and because the main goal is to gain more information, not to execute statistical analysis on the results. With this type of interviews, more flexibility is accepted, meaning more useful information could be collected in a short time. All interviews will be recorded, after approval of the interviewers, and will be held at the interviewer‘s office. The recordings will be transcripted afterwards and then analysed. The prepared questions that were asked are listed in the following:

About (company name)

1. Could you give us a brief introduction of yourself?
2. Could you give us an overview of your work at (*company name*)?
3. What is the main goal of (*company name*) and how do they plan to achieve this?
4. Has (*company name*) been growing São Paulo during the last years?
5. What are the future plans for (*company name*)? Are there plans to expand?
6. Does (*company name*) cooperate with other bicycle sharing companies, or are the others considered competitors? In the case of the first, in what way do they cooperate and with whom? And in the case of the latter, who is the main competitor?
7. We have created a list of stakeholders to create an overview of all stakeholders involved in the bicycle network development in SSão Paulo, do you think there are relevant stakeholders missing?

Personal questions
At last, we would like to ask you some personal questions, about your opinion on cycling.

1. What is your view on the current situation of the bicycle network in the city?
2. What is your view on cycling as a way of transportation within São Paulo? Do you use the bike yourself?
3. Could you rank the following parameters for us from what is most important to least important to you, when using your bicycle on the streets of São Paulo (*1 is most important, 3 is least important*):
   - Comfort (pavement conditions, slope, shade)
   - Risk (by interacting with motorised traffic)
   - Commuting time (compared to other traffic modes)
4. Could you describe your itinerary from home to work in terms of distance and way of transportation? From which area in São Paulo do you need to come?
5. Consider, you are living in a street where no dedicated bicycle infrastructure is present. What would be an acceptable distance to ride your bicycle without the dedicated bicycle infrastructure such as the bike path or bike lane (a bike path is separated from the road, a bike lane is on the same road as cars)? In other words: how many blocks are you willing to travel to reach dedicated bike infrastructure?

A total of 24 stakeholders were identified, which unfortunately could not all be interviewed. Within the possibilities of the availability of the stakeholders, it was possible to interview 7 stakeholders that were determined to be critical stakeholders: Yellow, Tembici, CicloCidade, Aliança Bike, Bike Anjo/Bycs, Prefeitura do campus USP and Metrô. Tembici and Yellow are two different bicycle sharing companies which have bikes scattered around the city, but work totally separated from each other. Metrô is the executing metro company in São Paulo and could give us insight in their view on combining metro and the bike. CicloCidade and Bike Anjo/Bycs were estimated to be useful to gain more insight from the cyclists‘ point of view. Aliança Bike tackles the situation from a different angle than the other bicycle promoting programmes. Last but not least the Prefeitura do Campus USP was needed to understand the interaction between both municipalities in São Paulo. The transcripted interviews can be found in Appendix A.

3.10.2. Analysis of the interviews (company-based)

After talking with various stakeholders of the project, it can be concluded that the problem of creating a network is a complex one. A city of 12 million people, a metropolitan area of 21.4 million people and 80 years of car policies, makes changing towards a new method of mobility quite a challenging one (Guth, 2019). Fortunately, it is not a problem that needs to be tackled by one person or one company and it does not require one solution. It takes the collaboration of different companies using different strategies in order to guide São Paulo towards a new era of transportation.

During this project, interviews have been held with several stakeholders. In these interviews, each stakeholder‘s view the problem and their way of tackling it became clear. The stakeholders that were spoken with are: Yellow, Aliança Bike, Tembici, Metrô, Bike Anjo and Bycs, Prefeitura do Campus USP and CicloCidade.

Yellow has, what they call, an aggressive strategy to change cities and with that the way people transport themselves. There is room to improve São Paulo, which means more space for pedestrians and cyclists. However, they do not only aim at an increase in active mobility but an increase in micro-mobility as a whole. This means bicycles, scooters, but also electric cars. By focusing on the whole picture of micro-mobility, they try to create demand, which should lead to a change in the way of thinking of the government. The government, especially since Jãoa Doria became mayor in 2016, is for the wealthiest inhabitants of São Paulo and directed towards cars.

During the interview with Daniel Guth, executive director of Aliança Bike since 2017, the problem of São Paulo ‘s mobility system becomes more clear. Daniel‘s story and involvement in cycling started in 2006 when he bought his first folding bike. From 2007 he was the guy that everybody came to for any case that involved cycling, including the city hall and the secretary of sports, leisure, and entertainment. The main goal of Aliança Bike is to promote the bicycle economy in Brazil. This concerns the whole bicycle industry, not only producing but also selling and using bikes, cycle tourism, events, sports, etc. This is all focused at helping the bicycle economy grow and make bicycles more affordable. Lower taxes, making better infrastructure, more bicycle lanes, are all examples that are tackled with this statement.

Renata Rabello and Mariana Gontow are part of the design team at Tembici and gave us an insight into Tembici‘s strategy. They study the whole city and then decide on the best area to place bicycle stations. The main goal is to be the best quality bicycle sharing company and have more daily trips. To decide whether or not a bicycle station should be placed, they study infrastructure, transport systems and service areas. Both Rabello and Gontow (2019) agree that the connections in the city are terrible. Rabello used to cycle a lot to work, but now she moved further away she does not do this anymore. When cycling on dedicated infrastructure it is fine, but when she needs to interact with traffic on the streets she prefers to not cycle at all. Gontow cycles a lot more, almost every day, and admits that safety is no longer her biggest concern, but travel time to work is.

An interview with JP Amaral, co-founder of Bike Anjo and the current Bicycle Mayor of São Paulo, concluded more or less the same. The bicycle network improved a lot compared to ten years ago, however, a lot of progress still has to be made. Bike Anjo is a non-governmental organisation (NGO) and its goal is to mobilise people and change cities. They focus less on creating bicycle spaces, but more on changing cities through cycling. Moreover, they focus on the environmental part to create a better environment for cyclists. This all is attempted through creating a community of cyclists with whom they organise campaigns such as “Bike to work” and several activities in collaboration with taxi and bus drivers. They also focus on advocacy campaigns and on how to implement public policies in the city.

The Prefeitura de São Paulo has no jurisdiction whatsoever within the USP campus, meaning they should both be taken into account as distinct parties. The university campus has its own municipality, Prefeitura do Campus USP. To gain more understanding about this distinct municipality, Douglas C. Costa, the project manager of Prefeitura do Campus USP, was interviewed. He explained that because of the administrative autonomy of the university, the CET, the traffic engineering company from the municipality of São Paulo, has no authority over the campus. This means that they are not allowed to fine people nor execute any kind of monitoring on the traffic within the campus, resulting in a lot of accidents over the last years. Some measures were taken during the last years, for example by creating a speed limit of 40 km/h on all roads. However, these limits are not always obeyed to, because there is no controlling power. The solution to do so, Douglas thinks, is reducing the space for cars. This claim is also supported by the research performed by the CET. Right now, the roads on campus are very spacious. In a new plan for the campus‘ infrastructure, that hopefully will be realised by 2020, cars have less space, forcing them to slow down. This will also create more space for bicycle infrastructure, which is already being worked on. Figure 3.6 shows an analysis of the current bicycle infrastructure on the campus, which makes clear that the infrastructure is very basic. Figure 3.7 shows the bicycle lanes that the USP campus has proposed and wants to have realised by 2020. The proposed network improves the connectivity of roads on the campus, increasing the benefits of using a bicycle.

Figure 3.6: USP bicycle network nowadays

Even though she left Metrô a month ago, Haydee Svab was willing to explain to us about the projects Metrô did over the years and how they contribute to the bicycle network in São Paulo. Metrô operates the subway system in São Paulo, which also includes their latest project: the first mass-transit monorail line. When executing interventions within urban planning, certain compensation is required. They re-developed the urban space around the monorail with a focus on pedestrians and bike users. They constructed a bicycle lane, redesigned all intersections and tried to create a sustainable environment for the surrounding inhabitants. Besides this project, Metrô has very little to do with cycling or the bicycle network. They do promote that bikes are welcome in the subway, however, this only applies for weekdays after 8 PM and during the weekends. Furthermore, the Metrô cars are overcrowded during rush hour, meaning that taking your bicycle in there is impossible anyway. Extending these bicycle-friendly hours would not solve any problem, in the opinion of Svab. She thinks however that creating a connection between bike and metro, or bike and train, would be a very good solution. This would especially help people from peripheries to reach their destination more easily. In order to make this possible, Metrô and SPTrans should install bicycle racks at their stations.

Furthermore, an interview with Flavio Soares from CicloCidade was executed, to gain knowledge about the perspective of active cyclists in São Paulo. CicloCidade is the voice of people that cycle or want to cycle in the city. The association also works on analysing the existing infrastructure and monitors ongoing projects from the city hall. To achieve their mission of a more sustainable city, they operate from three fronts: bicycle culture, change policy-making and in a partnership with the government. The association who started nine years ago within the critical mass on Paulista Avenue are now in close cooperation with the city hall.

To summarise, these are the goals of the interviewed companies:

- **Yellow**: more room for pedestrians and bicycles and micro-mobility overall. Combination of micro

Figure 3.7: The proposed bicycle lanes

mobility and public transportation is the key, because only cycling is not the solution for the problem.

- **Aliança Bike**: their focus is on the bicycle economy, so in order for this to grow, the whole network needs to improve. However, not only the infrastructure and routes, but everything within the industry.
- **Tembici**: want to have the best system and to have a billion trips in five years. They want to achieve this by placing bicycle stations next to (existing) infrastructure. By doing so, new cyclists are encouraged to use them.
- **Bike Anjo**: its main goal is to mobilise people and change cities. Their focus is broader than just creating more space for bicycles, they want to change cities through cycling and also focusing on improving the environment.
- **CicloCidade**: the association wants a more sustainable city, where cycling is used as a form for transformation and they operate from 3 fronts to achieve this goal.
- **Municipality of USP**: the focus of the campus is to create a safe infrastructure and lowering the number of traffic accidents. To achieve this, they created a plan which reduces the road width, and thus the space for cars and their speed, and implementing more bicycle infrastructure.
- **Metrô**: Metrô's main focus is to offer better transportation services, however including bicycles are not a point of discussion right now.

What becomes clear from these interviews is that everybody recognises the problem and has their own perspective on it and work towards a solution from that angle. All the interviewed stakeholders agreed that collaboration is needed and most organisations do not see competitors but only opportunities, but still everyone is lobbying on their own with the municipality. The fact that there are no contradictory goals between the stakeholders, however, opens a new perspective in the process. As mentioned in section 3.5, the bicycle promoting companies would have more power if they would cooperate, however they would still have to be persuaded to do so.

It became clear that the problem of implementing a bicycle network is bigger than anticipated. Bureaucracy is a huge problem in São Paulo and one of the biggest problems that need to be taken into account is the change of administration every four years. This seems contradictory, because plans have been created for the next sixteen years, as seen in previous research. Several stakeholders claimed that this does not work in reality, because once the government changes, so do most of the plans (Costa, 2019; Guth, 2019)

Bicycles have made their way through history, as have many cyclist movements. CicloCidade, CicloBR, Bike Anjo and Aliança Bike are a few of the associations that were formalised around 2009 from the Critical Mass. A Critical Mass is an event that does not exist in the Netherlands, however, this is an important tool and therefore of relevance to explain. Critical Mass is a massive group of cyclists that hit the road all together in order to get a message in the world. This message is creating awareness of cyclists and the importance of this awareness. Obviously, people are aware of large groups of cyclists, but in the case of just two cyclists, they are commonly overlooked or ignored on the streets. The mindset of people needs to be changed and that is what the Critical Mass is trying to achieve (CriticalMass, n.d.). The Critical Mass gained influence in New York and San Francisco and also found its way to Brazil. In the beginning it was only attended by three to four people, but nowadays it gained enough support that it led to the creation of several associations (Wisnik et al., 2017).

As the literature study explained, bicycles and cyclists have not had the easiest time to become recognised by the municipality and motorised vehicles. The three bicycle associations CicloCidade, CicloBR and Bike Anjo all have more or less the same goal, but tackle it separately and from different angles. They all want to change cities through cycling, mobilise people and promote the use of the bicycle. Aliança Bike is sometimes mentioned in the same list of cycling associations. However, they focus not only on promoting cycling and creating better infrastructure, but they want to promote the bicycle economy in Brazil. All the organisations know each other and occasionally work together. They each feel that knowing what the other association does is enough, to eventually create a change in the system (Amaral, 2019; Guth, 2019; Soares, 2019)

As became clear in the interview with Guth (2019), bicycle development and change in policy in São Paulo is for the long-term. The terminology “bike clashes” is commonly used and indicates to the periods where drivers of motorised vehicles become more resistant against cyclists and these periods are also reflected in the politics and which party held the administrative power at that time. The vice-mayor Bruno Covas took over from João Doria, who left the office in 2018 and is more positively oriented toward bicycles than its predecessor (Guth, 2019; Soares, 2019). Policies only address one aspect of the multi-model-way of transportation but fail to mention the multiple opportunities that it offers. It is not only cars versus bicycles, but there are also multiple ways of transportation, which are still growing. For example, there are trains, busses, bicycles, electric bicycles, electric scooters, walking, subways, etc. It appears that 50 percent of all trips made by cars in the city are within a distance of 5 km. If you can even reduce half of the trips made by cars, you take 5 to 6 million cars away from the street (Guth, 2019). Another research that was conducted showed that over 50% of the transportation of goods can easily be done by tricycles (Guth, 2019). It can be concluded that there is a major car addiction in São Paulo and it is going to take a lot more than individually talking by the different associations to promote and implement bicycles.

3.11. Analysis interviews (personal questions)

All stakeholders, representing a company, are also inhabitants of São Paulo with a personal view on the matter. Therefore they were also asked personal questions, to gain more information from different perspectives. It must be noted that their answers might be one-sided, since most of them are involved in the bicycle path policies in São Paulo. However, due to time limits but mostly due to the language barriers, it is decided to handle these interviewees as locals of São Paulo as well. The personal questions were already shown in the interview set up. They are focused on the current bicycle network and cycling as a way of transportation in São Paulo. To analyse the seven interviews, all remarkable statements were highlighted and then compared to the other ones. It then becomes clear which statements are the most important ones mentioned.

The statement that is mentioned by almost all stakeholders, is that the network has improved a lot during the last years, but that it also still needs a lot of work. More people start to use bicycles, but this will only increase with better infrastructure. The second most important statements involve the bad connectivity of the bicycle network in São Paulo. This is something that was already concluded from literature, and shows that this is actually experienced by locals as well. Another statement mentioned five times is the car-based culture that dominates the city. Cars are still seen as the status symbol and as the most important way of transportation. As a result, most conductors are still against the idea of cyclists and are therefore very aggressive to cyclists on the road. This can be improved by having the dedicated infrastructure, so that cyclists do not have to share the road with cars anymore. Another option mentioned is that by having more cyclists on the streets, awareness will be created effortlessly.

A surprising note was that more than half of the stakeholders think that bicycle paths and lanes are constructed only for people that are new to cycling. Experienced cyclists will cycle anywhere, since they are used to not having dedicated bicycle infrastructure. For them the new lanes or paths would not have a lot of benefits, however, they do see the need for them, in order for the car-based-culture to be changed. Next to the fact that dedicated infrastructure is needed, it is also needed to create other incentives for people to start using bikes and show them the benefits. Most people that have never experienced biking do not know them and therefore stick to their cars. The benefits that have been stated by multiple stakeholders are the environment, health and the avoidance of traffic jams.

Another statement is based on the combination of mass transportation and the bicycle. There is the idea that cycling would be most beneficial at this stage for short trips through the city. This short trips could be combined with the use of metro or train, meaning people could reach further distances. Right now metro and train stations are not linked to the bicycle infrastructure yet and also lack bicycle parking spaces.

Regarding safety, it is mentioned that people feel that bicycle paths are safer than bicycle lanes, so cyclists are fully segregated from cars and motorbikes. This also aligns with the statement that cyclists do not feel comfortable by sharing the road with cars or pedestrians, which happens a lot nowadays. People do not feel safe to cycle on big and busy avenues either, which would also be solved by using bicycle paths instead of lanes.

Another important note is that people do not feel comfortable driving on steep roads. This needs to be taken into account when developing the bicycle network, by finding the most optimal route with the least slopes. Another problem linked to this, is the fact that people do not seem to be comfortable by cycling over a bridge. This does not only involve the steepness of the bridge, but also the fact that there is no dedicated infrastructure for bicycles, and the path has to be shared with pedestrians most of the time.

The last important note is the politics that seem to hold the development of the bicycle network back. Each administration only has four years, which does not seem to be enough time to make a real difference. Long-term plans are usually not continued, withholding the development during each change of administration.

3.12. Analysis of interviews in literature

Besides the analysis of the companies and the individuals, literature proves also to give an interesting perspective. In 2017 a research project was organised between the University of Applied Sciences in Amsterdam, Universidade de São Paulo (USP) and Het Nieuwe Instituut (de Waal, Martijn, 2017). Mapping and stimulating the bicycle culture in São Paulo where the aim of this research. One of the results were the three challenges to overcome in the near future, to stimulate the bicycle community. Awareness and respect, bad maintenance and no continuous flow of infrastructure are determined as the main items to be tackled. This, however, is from the perspective of people who are already using a bike. This dilemma is faced several times, while researching the attitude towards bicycles in the literature, it all seemed very positive. However, when talking to the stakeholders, they talk about the resistance quite a lot. Bike clashes, anger towards cyclists and negative news articles are a few examples of this resistance. In the research of Wisnik et al. (2017) it became clear that people have the common idea that cycling as a cause is "just for cyclists". It is critical for the acceptation of bicycles, in what way the network is presented to the car adoring mass. As became clear during the tenure of mayor Haddad, who encountered a wall of resistance against his plans. According to the research done by the CET, 60% of the drivers drives alone. Therefore the average person/ vehicle is 1.4 (Wisnik et al., 2017). Another vivid idea that is prevalent amongst drivers is that they think bicycles hinder traffic. Moreover, they think that cyclists are responsible for making traffic jams worse (Wisnik et al., 2017). What is previously seen and heard in the interviews, the lack of willingness to share road space is once again emphasised in the literature.

Providing the inhabitants of São Paulo with information on the bicycle network is an important task, to get everybody on board. In the past years, the information was one-sided and created a lot of struggle with a lot of people. In a conventional way only certain advantages were mentioned, such as health, reducing pollution, saving resources, etc. However, most people in São Paulo do not consider the incentives to take a bicycle and therefore find the plans unnecessary. The emphasis for drivers of motorised vehicles should be more on the advantages for them, what would they gain if more people traded their car for a bicycle (Wisnik et al., 2017).

3.13. Four Domain Solutions

The stakeholder analysis revealed which stakeholders are the ones to keep close and which ones might be less important to take into account. All of this information is needed for the requirements analysis that will be executed through a systems engineering approach. All individual stakeholder requirements and needs will be developed into detailed, agreed requirements on which the project has to be based.

The approach to tackle this task, is called the Four Domain Solutions method. System design is composed of Four Domain Solutions, sequenced in a logical workflow, from Requirements, Operations, Behavioural to Physical Domain Solution. This workflow is based on decision dependencies to minimise redesign and rework (Wasson, 2015).

This method grants the opportunity to take apart an abstract mission and distinguish level details, to select the optimal end solution. Five steps need to be undertaken, that explain the domain solutions:

- **Step 1**: understand the User's Operational Needs, Problem, or Issue Space.
  Outcome: problem definition.
- **Step 2**: bound and Specify the User's Problem and Solution Spaces.
  Outcome: Requirements domain solution with a list of requirements.
- **Step 3**: understand How the User Intends to deploy; operate, maintain and sustain, and retire/dispose the System.
  Outcome: Operations Domain Solution.
- **Step 4**: Model System Engagements and logical/Behavioural Interactions with Its Operating Environment.
  Outcome: behavioural domain solution.
- **Step 5**: determine a Cost-Effective, Acceptable Risk, Physical Implementation.
  Outcome: physical domain solution. (Wasson, 2015, p.248)

In this report only the first two steps will be covered. Since this method is meant for the whole project and not just for a pilot plan, step 3 until 5 fall outside the scope of this project. After step 2, a list of requirements is made. This list takes into account all the requirements, both gathered from literature and interviews.

The list of requirements will form the base for the design of the bicycle network for São Paulo. The proposed infrastructure serves only as a pilot, meaning it will not take into account requirements that might only relate to the bigger picture.

3.13.1. Workflow elaborated

The first step in the workflow is to define the problem statement. This is done in chapter 1. The problem statement is defined as the following: São Paulo suffers from a lot of traffic congestion, resulting in additional travel time for cars. Moreover, there is a high dependency on cars and the public transport infrastructure is saturated. Cycling has only been promoted as a leisure activity instead of a transportation alternative, which resulted in the current bicycle network that is not sufficient in terms of connectivity for commuters.

The second step is to use this problem statement as the base to formulate, bound and specify a Requirements Domain Solution. As (Wasson, 2015) explains, technology, development cost and schedule, and risks are in balance. The requirements are written down as results that need to be achieved in the operation of the system.

3.13.2. List of requirements

The list of requirements is a recap of all the research that has been shown before. The requirements are subtracted from literature reviews, from the stakeholder analyses and from the interviews. They are all combined together in a list of requirements, that the bicycle network should fulfil in order to be successful. The requirements are divided into three categories: infrastructure network, incentives for bicycle use and long-term guidelines.

Infrastructure network

- The bicycle network need to be connected to reach the most important nodes.
- The bicycle network is reached within a maximum of 350m from the starting point of the trip.
- The cycle path or lane is only for cyclists to use, and not shared with pedestrians.
- The bicycle network needs to be linked to the Metrô stations.
- The bicycle network needs to be linked to the CPTM stations.
- Metrô stations need to have bicycle parking opportunities.
- CPTM stations need to have bicycle parking opportunities.
- The bicycle paths or lanes cannot be placed on roads that have a hill of more than 5%.
- Bicycle paths or lanes may not be placed on big avenues.
- Bus lanes should not interfere with bicycle paths or lanes.
- If the bike path or lane crosses a road, a traffic light is needed. An incentive should be added that cyclists have the right of way, when pushing the button of the traffic light.
- The Prefeitura of USP Campus wants a connection between the USP campus and Villa Lobos Park, across the Pinheiros river.
- Bicycle lanes should not hinder other motorised traffic.
- Bicycle lanes have to be maintained.
- There should be locations where bicycle sharing bicycles and stations can be placed, next to the bicycle infrastructure.
- The bicycle network should be inline with CET and USP campus regulations.
- Parking spots and racks should be available around the campus (faculties, restaurants, sports facilities, etc.) to park your bicycle.
- Bicycle lanes should be free of trees, lampposts, other big obstacles, etc.

Incentives for use

- Compensating of some sort for parking places, that are removed to make space for bicycle lanes.
- More entrances to the USP campus, only intended for bicycles.
- The campus should allow cars, but not promote them. This means, paid to park and far more easy access for other forms of transport, like bus, bicycle, etc.

Long-term guidelines and recommendations

- Investment in the “poorer” areas, the ones where the people live, but not work and have to travel huge distances each day to reach their work. They need to be able to safely reach the train/subway station, so that they can continue their journey.
- A research should be executed on ‘feeling safe’ and what this is. Especially since a lot of women are not cycling right now due to safety issues.
- Driving lessons should include the awareness of cyclists.
- Bus drivers should be obligated to take an additional course to know how to deal with cyclists.
- CET, or an independent company, should receive authority to monitor the speed limit on the campus and should be authorised to hand out fines if necessary.

4

Cycling network design

In this chapter the design of a bicycle network is performed. It contains five parts: modelling framework, software selection, data selection and preparation, the set-up of the model, and the application of the model to the selected areas of interest. The objective of the proposed model is to maximise service coverage. The model considers road volume, road type and potential demand. A minimum spanning tree algorithm has been used to find a solution for the stated objective.

4.1. Modelling framework

The model framework can be divided into three phases: preparation, pre-modelling, and modelling. The preparation contains the software selection and data processing. During pre-modelling input, data will be selected and prepared for the modelling phase. During the modelling phase, the prepared data will be used to find a solution for the model objective. The following sections elaborate on these topics.

Coverage and risk are important factors for optimising a network (Ana, Pinto, Ribeiro, & Delgado, 2014; Lin & Yu, 2012; Shrestha, Benta, Lopes, & Lopes, 2013). A multi-objective model is often used for such kind of optimisation problems. However, the goal of this project is to find a generalised solution, and hence a less complex single objective optimisation is preferred, since this is easier implemented in new situations. The goal of the pre-modelling phase is to narrow down the selection of links[1] in the network based on link attributes: road type, traffic volume, coverage and the presence of bicycle infrastructure. This is elaborated in section 4.4. The modelling objective uses a function that maximises the number of people that are can make use (coverage) of the network design. This part elaborates on the selection of nodes in the network that will be connected by the new bicycle network and can be found in section 4.5.

4.2. Software selection

To be able to solve and present the data GIS software will be used. GIS is widely used as a tool for spatial analysis. It has the capability of gathering, managing and analysing data. It can organise and visualise using 2D and 3D scenes, which makes it a powerful tool for spatial analysis and network design.

Quantum GIS (https://www.qgis.org) (QGIS) is a free and open source software (FOSS) package that can be expanded by adding Python-based plugins and it has a large community, which is used in the project. Besides, TransCAD that is designed specifically for use by transportation professionals to store, display, manage, and analyze transportation data, due to QGIS limitations (bug) in relevant plugins for minimum spanning tree MST and maximum covering location model (MCLP).

[1] Links are connections between nodes (locations)

4.3. Data input

GIS data files are retrieved from (Prefeitura de Sao Paulo, 2019). Traffic flow data is obtained from de Engenharia de Tráfego (2018). Table 4.1 shows the used data sets and their source, (if applicable) scale and date of origin.

Table 4.1: Overview of data sources

Name	Source	Scale	Date
Declividade	Prefeitura de Sao Paulo (2019)	1:100.000	2000
Densidade demográfica	Prefeitura de Sao Paulo (2019)	1:10.000	2010
Distrito	Prefeitura de Sao Paulo (2019)	1:1.000	2011
Logradouro	Prefeitura de Sao Paulo (2019)	1:1.000	2014
Mapa base	Prefeitura de Sao Paulo (2019)	1:1.000	2014
Metrô estacão	Prefeitura de Sao Paulo (2019)	1:1.000	2016
Rede ciclovaria	Prefeitura de Sao Paulo (2019)	1:5.000	2016
Terminal de ônibus	Prefeitura de Sao Paulo (2019)	1:1.000	2016
Trem estacão	Prefeitura de Sao Paulo (2019)	1:1.000	2016
Volume e Velocidade	de Engenharia de Tráfego (2018)	Road based	2017

4.4. Pre-modelling

The goal of the pre-modelling phase is to select candidate links as input for the modelling phase. To be clear about terminology first some important terms will be explained. Features are entities in QGIS, and depending on the data set these can, for example be links, demand zones or subway stations. Links are building blocks of a road. I.e. a road can consist of two links, one in each direction. In practice, roads are divided into several parts, for example between every intersection. Nodes are points on a map that and are for example used as departure and arrival points, representative (centroids) points for zones where where people live.

The area of interest as described in chapter 1 contains 7002 features. The number of features is higher than the actual number of roads as the roads are divided into smaller sections.

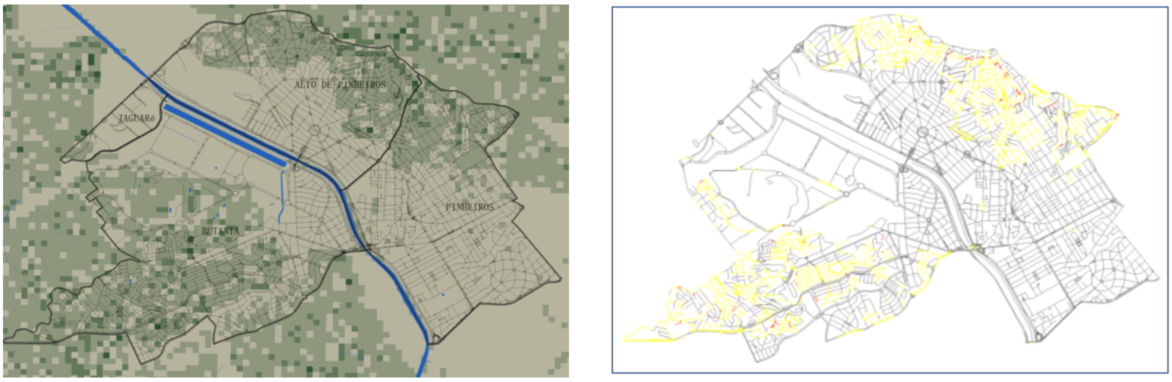
Candidate links are supposed to be suitable to be part of the bicycle network. Three attributes are taken into account for this selection: road elevation, presence of bicycle infrastructure, a bicycle and pedestrian bridge, and road hierarchy. This will be discussed in the following sections. Links that have existing bicycle infrastructure will also be included.

4.4.1. Road elevation

São Paulo is a city with height differences which is shown in figure 4.1a. The deeper a cube is coloured, the steeper the region is. Steep roads makes riding a bicycle difficult. Roads with a slope of more than 5% are considered as not comfortable for riding a bike (Lin & Yu, 2012). Moreover, the available data (see table 4.1) classifies the slope in four categories, namely: less than 5%, between 5% and 25%, between 25% and 60% and more than 60%. To select suitable candidate links, only links with a slope of less than 5% are included in the road network and the steeper roadways as coloured in figure 4.1 is filtered out.

The used data contains slope slopes per area of 100 square metres, without linking the slope to the roads in that area. It is clear that theoretically the actual road slope depends on the direction of the road along the elevated surface. I.e. a road that goes (like an ISO line) around a sloped terrain has no slope at all. And a road going up the sloped terrain, or down do have different slopes.

Because of the limited amount of time for this project two assumptions have been made. 1) The slope in an area is used as the slope of the road, regardless the direction of the road. 2) There will be no distinction in road direction; up- or downhill. It is assumed that driving down a steep road is as uncomfortable as driving uphill.



(a) Geographical elevation

(b) Road elevation classification

Figure 4.1: Elevation maps

Figure 4.2: The cycling network development for the years 2000, 2015 and 2018.

4.4.2. Presence of bicycle infrastructure

In section 2.2.1, the current bicycle infrastructure is shown. The current infrastructure is unconnected and scattered throughout the city. It is assumed that available bicycle infrastructure always will be incorporated in the network design.

The cycling infrastructure has developed in the study area among years. The historical process is shown in figure 4.2.

4.4.3. Bridge variants

The current infrastructure does not provide a safe way to across River Pinheiros as mentioned in chapter 1. Thus, a bicycle and pedestrian bridge is considered as the solution. The stakeholder analysis in chapter 3 concludes that USP plays the role as the secondary actor among all the participants so that when designing the network, the campus should be well connected by the cycling paths. Therefore, three options for the cycling bridge are defined where USP entrances or the residential populated location are considered as the origin of the bridge:

1. From Villa Lobos-Jaguare to USP P2 entrance (left)
2. From Avenue Arruda Botelho to the main student accommodation building (Conjunto Residencial da USP) (middle)
3. From Cidade Universitaria to USP P1 entrance (right)

The geographic locations and the candidate links representing each in GIS map are shown in fig 4.3.

4.4.4. Road hierarchy

The Netherlands is the world leader in bicycle use and safety, with a reduction of 80% in the numbers of cyclist killed per billion bicycle kilometres over the past 30 years (Schepers, Twisk, Fishman, Fyhri, & Jensen, 2017). The data file Logradouro retrieved from Prefeitura de Sao Paulo (2019) defines 49 road types, based on the

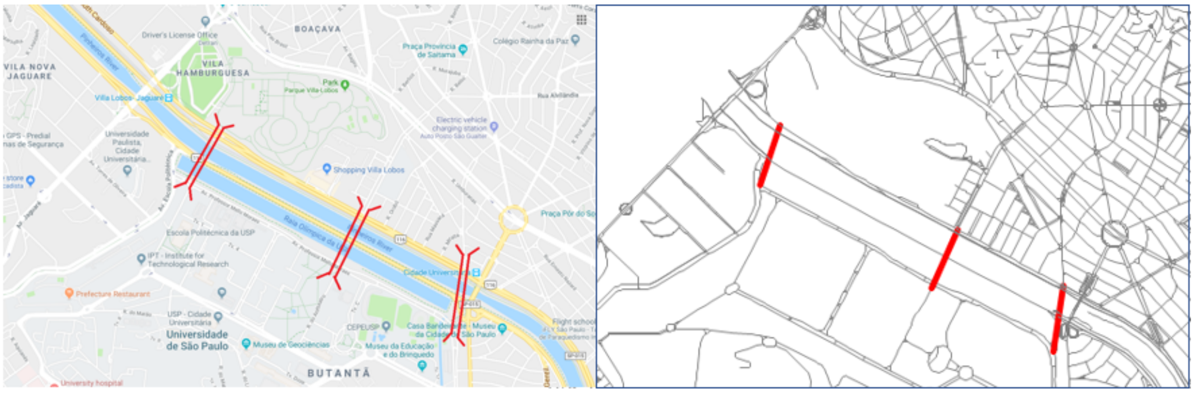


Figure 4.3: Three location options for the bicycle and pedestrian bridge.

typology and function of the road. Flow and speed information of 2017 is obtained from (de Engenharia de Tráfego, 2018). To design a general approach this categorisation will be simplified based on a slightly altered version of the road hierarchy system as presented in (Schepers et al., 2017).

The three-level hierarchy by Schepers et al. (2017) contains access roads, distributor roads and through roads. Through roads are considered highways with speeds higher than 100km/h. On distributor roads, the speed ranges between 50km/h and 70km/h and are sometimes called collectors (Eppell, McClurg, & Bunker, 2001). Access roads are local roads with speeds of approximately 30km/h.

Due to the road structure and speed regulations, this classification cannot be one on one applied to the study area. Speed regulations in Brazil and in São Paulo specifically are different from the Netherlands. Access roads vary in speed from 30km/h to 60km/h, distributor roads between 60km/h and 100km/h and highways have a speed up to 110km/h (OpenStreetMap contributors, 2017).

Avenues are considered major arterial roads, however, in São Paulo the avenues have multiple lanes and flow. To have a better distinction between distributor roads and high volume distributor roads a bifurcation is carried out, which leads to arterial roads with low volume, minor arterial, and major arterial roads with higher volume. The result is a three-level hierarchy: access roads, minor arterial roads, and major arterial roads.

Table 4.2 contains an overview of the hierarchy. To be categorised as a major arterial road, the road must have multiple lanes and a peak volume of more than 2000 veh/h. Flow data is gathered from (de Engenharia de Tráfego, 2018), which contains the recent flow and speed data of most roads in São Paulo. These are considered as dangerous and are hard to cross (Schepers et al., 2017). Therefore a bike path is mandatory for a major arterial road. A detailed list of the categorisation based on the proposed four-level hierarchy can be found in Appendix D.

The resulting classification, as input for the model, contains three categories, namely: Roads suitable for mixed traffic, roads that need a separate bicycle lane and roads that are not suitable for cycling at all. Table 4.2 gives an overview of the classification and figure 4.4 shows the result after applying the classification to the current road network.

Table 4.2: Four level hierarchic road classification

Level	Speed limit	Conditions	Cyclist location
Access roads	<60 km/h		Mixed with other traffic
Minor arterial	60 - 100km/h	$q_{peak} < 2000$ veh/s	Separated (by lanes)
Major arterial	60 - 110km/h	$q_{peak} > 2000$ veh/h	Separated (by paths)

Figure 4.4: Road classification applied to the current road network. Black is mixed, yellow is separated and red is not suitable for cycling

4.5. Setup of the model

4.5.1. Coverage per link

As for every link, the coverage is calculated and added as an attribute. This will be used to classify the roads further than the classification made in section 4.4.4. It adds the importance of a road relatively to other roads. This will be further discussed in section 4.5.

Coverage of the road is defined as the number of inhabitants that are within reach of the bicycle network. Reach has been defined as the distance one is willing to travel to the nearest bicycle infrastructure. The distance that people are willing to travel without being on dedicated bicycle infrastructure is around four blocks - which is around 350 metres (Lin & Yu, 2012).

The coverage is formulated as a buffer around the link with an offset of 350 metre. In QGIS this is implemented by use of the *buffer* function that creates the buffer zone.

The buffer areas intersect with the layer that holds population data. An example of a selection of links with their corresponding buffer can be seen in figure 4.6. The purple coloured background is the layer with population data - darker colour stands for a higher number of population in that area.

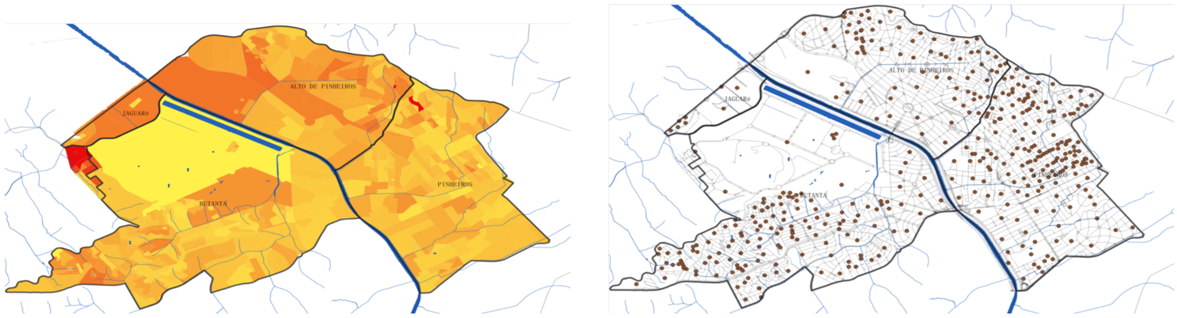
The *join attributes by location (summarised)* function makes an intersection of the buffer zone with the population data and adds up the population number. This last step is important since the 350-meter buffer intersects with more than one population area and the coverage is the total population. The use of a buffer with a big radius leads to a smaller drop off due to areas that only partly intersect with a buffer. This leads to better results since in case where a buffer partly overlaps with a region near the 'edge' the total population amount is less influenced.

4.5.2. Demand points

This section describes the selection of demand points and consists of three parts. These points form the basis and indicate which points in the area need to be connected by the bicycle network. The selection of demand points based on the population areas (1), the selection of demand points of high interest, such as public transport stations (2) and the reduction of the total amount of points.

Population aggregation points

From Prefeitura de Sao Paulo (2019), a map of population areas has been used. This map contains aggregated population numbers, this is visualised in figure 4.5. Red areas have a higher population that yellow areas.



(a) Areas (gradient filled) (b) Nodes

Figure 4.5: Map of populations in area of interest

To be able to use this data as input for the model, all areas are converted to nodes, so-called centroids. This results in a map with 409 nodes.

High demand points

Besides the classification of the roads and the coverage of the design area there are also points that have a high demand; i.e. metro stations and the university. These demand nodes are an important part of the multi-modal transport chain, where people i.e. (first) use public transport and use a bicycle for last mile transport. Section 3.10 also emphasises that stakeholders greatly value the connectivity of public transport stations to the bicycle network and see it as an important part of the success of a bicycle network.

The high demand points are listed in table 4.3 and include all important bus terminals and metro stations which are in total 11 nodes.

The combined selection result contains 409 population points and eleven terminals within the study area.

Table 4.3: Public transport stations in the study area

Station	**Mode**	**District**	**GIS data**
Morumbi	Metro	Butantã	Metrô estacão
Butantã	Metro	Butantã	Metrô estacão
Pinheiros	Metro	Pinheiros	Metrô estacão
Faria Lima	Metro	Pinheiros	Metrô estacão
Fradique Coutinho	Metro	Pinheiros	Metrô estacão
Villa Lobos	Train	Jaguaré	Trem estacão
Cidade Universitària	Train	Alto de Prinheiros	Trem estacão
Prinheiros	Train	Pinheiros	Trem estacão
Estacão Hebraica	Train	Pinheiros	Trem estacão
Estacão Cidade Jardim	Train	Pinheiros	Trem estacão
Pinheiros	Bus	Pinheiros	Terminal de ônibus

Demand point selection

Connecting 409 nodes from the previous two sections by a bicycle network leads to a bicycle network that will include almost every node. This is not a result that is practical nor feasible.

However, it is safe to assume that if an inhabitant travels by bike they need a dedicated bicycle network to be available within a certain distance. In other words, within a certain distance of every possible trip starting point must be able to enter dedicated bicycle infrastructure. Also the selected neighbourhoods need to be covered. This assumption is the basis to reduce the number of nodes that have to be connected by the bicycle network.

Finding the minimum needed demand points, whilst covering the total area, is an example of a MCLP, that is often used for facility location selection.

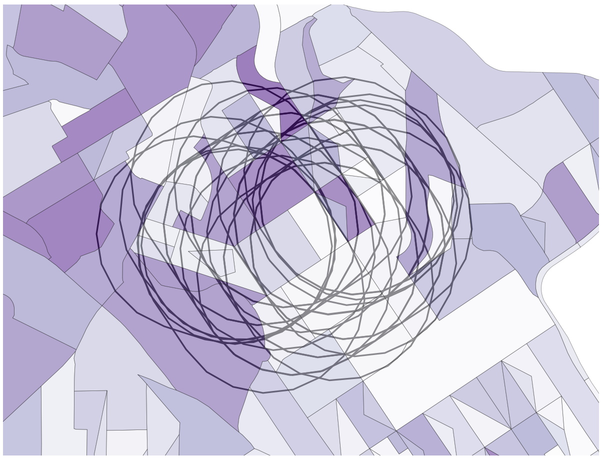


Figure 4.6: Example of buffers of 350 metres and the intersection with population areas

To do so, the same assumption has been made as in section 4.5.1. An area has a coverage of 350 metres, but this time centred around the area's centroid, as shown in figure 4.5. A layer with the provided nodes is needed as input, the coverage distance (Eucledian) is set on 350m. The results are in chapter 4.7 and the selected demand points are shown in figure 4.8.

TransCAD has a built-in plugin to solve this problem and will be applied in section 4.6.

4.5.3. Network routing model

There are three commonly-applied network routing models. One is evaluating the bike-use suitability of various locations quantitatively and establishing the network by connecting those points with high suitability. One method gives the geometrical design on the basis of the existing road network and traffic data of cars, public transits and other motor vehicles with the aim of vehicle mobility and pedestrian safety were not adversely affected. The other way of cycling network design is to identify the optimal layout of bikeway networks in built-up urban areas by algorithms. The first two methods are applicable at the stages when there is no road infrastructure and the bicycle is just taken into account as the new transportation mode. The last model can be used after some preliminary construction of cycling infrastructure. Because São Paulo exits some bicycle lanes distributed in the varied districts shown in figure 4.2 with unsatisfied connectivity described in section 3, this study uses the third one, which is essentially a route selection problem.

The route selection model is based on the current road network and the costs of each link to find the optimal paths from the determined departure locations to the destinations. The optimal objective is minimising the total link costs. The link costs are determined by the utility function in chapter 4.5.4. The routing model is special in the way of considering the demands. The relevant explanation is in section 4.5.2 about demand points determination and in chapter 4.5.4 about the utility calculation.

The selection approach is a greedy algorithm as it is a classic algorithmic paradigm intends to a global or local optimum that follows the problem-solving heuristic of making the locally optimal choice at each step. A greedy strategy for the travelling route problem of a high computational complexity follows the approach of at each step of the journey, visiting the nearest unvisited city. This heuristic terminates in a countable number of steps, and give the optimal solution to a complex problem. In mathematical optimisation, greedy algorithms optimally solve combinatorial problems having the properties of matroids and give constant-factor approximations to optimisation problems with the sub-modular structure.

Minimum Spanning Tree

Minimum spanning tree (MST), as one greedy algorithm, is used to select the cycling routes through the demand points from the candidate links. The algorithm is chosen because it is well-developed and broadly applied to many transportation network design problems. In TransCAD, Kruskal's algorithm is applied for MST module.

Kruskal's algorithm (Kruskal, 1956) has the classic result that is a subset of the candidate network and a cost-weighted undirected graph that connects all the nodes together, without any cycles. The computation process runs in O $\log_M N$ time, where N and M denote, respectively, the number of the connection components and the candidate links in the case. The algorithm starts at any one vertice and then go throughout the whole network. At each step, it requires the minimal link costs so that the final spanning tree will give the result of the less total costs with the weighted points.

4.5.4. Formulation of the utility function

To apply a MST a generalised cost is of importance. This cost is an arbitrary value for, in our case, every link that indicates how suitable the link is to be included in the network.

In literature most of the times this is expressed as a monetary value. Mostly by costs, such as construction costs, and travel time reduction multiplied by the value of time (VoT). However, this is extremely hard in our case. In this case, on the one hand, the road classification and on the other hand, the coverage are not directly monetary costs and are also hard to express as such.

Another approach is to express the 'costs' of a link as a likelihood to change that road out of all roads. This is a common approach in choice behaviour sciences. The model includes factors of link type, steepness and the risk classification of the link. In Dey, Anowar, Eluru, and Hatzopoulou (2018) a stated preference collected data from 695 commuter cyclists. It incorporated heterogeneity in discrete choice models with respect to exogenous variables and decision rules (Dey et al., 2018) by using state of the art RUM-models, based on regret minimisation.

This research is very applicable to solve the aforementioned problem regarding the cost function. One of the conclusions of this research is that cyclists value road attributes, when making route choices. Such road attributes include, amongst others, i.e. steepness, risk profile, road type. Values and variation in attributes are listed in table 4.4 and are derived from Dey et al. (2018). To be able to exclude roads from cycling where another variant called 'no cycling allowed' is introduced. This is, for example, the case for rural roads that are on private property, which are not suitable for the bicycle network.

Another requirement is the use of current bicycle infrastructure. This is implemented by the attribute 'current cycling infrastructure', which behaves as a Boolean term.

Table 4.4: Utility function, attributes and values

Attribute	**Variation**	**Utility**
Road type	no cycling allowed	-99
	residential	0
	minor arterial	-0.398
	major arterial	-1,29
Risk type	no cycling allowed	-99
	shared	0
	exclusive	0,939
Current cycling infrastructure	no	0
	yes	99

By using a function and including the factors road type, risk type and steepness it is possible to give the probability of choosing a link from the whole set of links. This probability can then be multiplied with the potential coverage of every link. In other words, what percentage of people would choose this link out of all links. As a base the general multinomial logit function is used, as shown in equation 4.1.

$$P(i) = \frac{e^{V_i}}{\sum_{j=1...j} e^{V_j}} \tag{4.1}$$

Where V_i correspondent with the so-called utility of link i. This link utility consists of the road type, the risk type and the current availability of bicycle infrastructure. The denominator of this function is the sum of all possible attribute variation combinations.

The function V_i is the summation of the three attributes (types), and can be rewritten as shown in equation 4.2.

$$V_i = road_i + risk_i + current_i \tag{4.2}$$

To be able to link the probability of choosing a link to the coverage of a link, the probability $P(i)$ is multiplied by the coverage. In other words, the correspondent with the number of people that would potentially choose a link. This is called the ‘cost’ of a link, since this is the common term for MST solving problems. For the sake of completeness, this is shown in equation 4.3.

$$Cost^*(i) = P(i) \cdot Coverage(i) \tag{4.3}$$

Since the MST minimises the cost function, one last step is needed. The cost function now gives a higher value to roads that are better suited for cycling, however, the MST minimises costs. To achieve this, the function is inverted, as shown in equation 4.4.

$$Cost(i) = \frac{1}{P(i) \cdot Coverage(i)} \tag{4.4}$$

4.5.5. Validation

The model is validated by checking the value for the cost function for 3 cases:

1. A rural road that has no bicycle infrastructure
2. A major arterial road that has bicycle infrastructure
3. A highway through a highly populated area

The attribute values and results are listed in table 4.5. One assumes the coverage for case 1 and 2 to be 1,000 and for the highly populated area 5,000.

Table 4.5: Three cases to validate the model

Case	Road type	Risk type	Infra	Coverage	Cost
1	0	0	0	1000	0.0139
2	-1.29	0.939	99	1000	~ 0
3	-99	-99	0	5000	∞

The last column of table 4.5 shows us for case three a cost that is infinitely high, which is what was expected, since the highway should never be included in the bicycle infrastructure. The high coverage doesn’t change this.

Another edge case is case two, where there is a bicycle infrastructure present. However, it is a major arterial road, which is not the most suited. Since current bicycle infrastructure should always be included in the network this value is, as expected, near zero.

Case one is a rural road, where one can drive with the bike-mixed traffic that is very suited for inclusion in the bicycle network, leading to a rather low cost.

Based on these validations it seems that the utility function works as intended.

4.6. Application of the model

The first step for the model application is transferring QGIS map to TransCAD, because the two GIS platforms edit and storage the data in different forms. QGIS can edit the database of SHP file, but the standard map layer in TransCAD is CGF (compact geographic file). To solve the problem, TransCAD provides "export" module It should be noticed that in QGIS, the link and the endpoints of the link are separated as two layers, but in

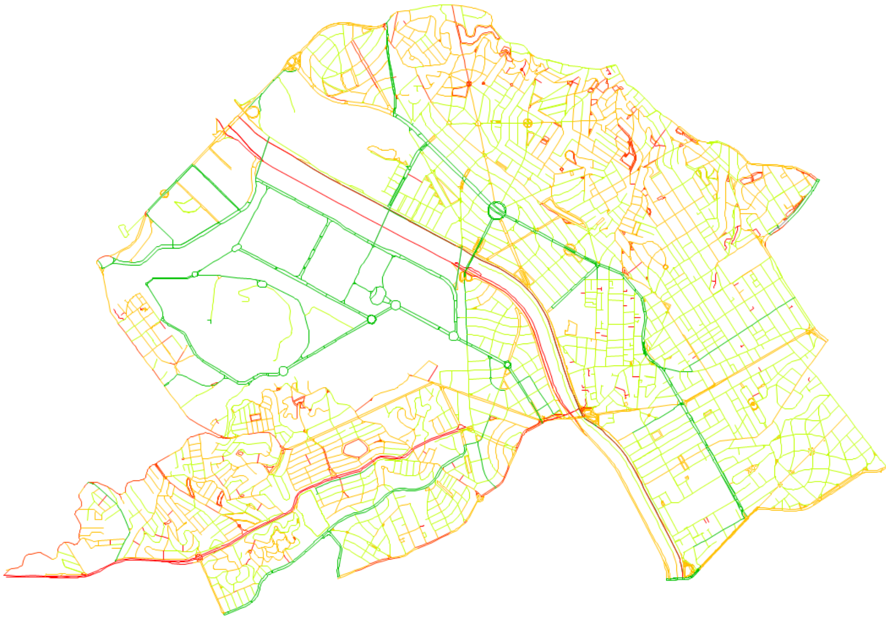


Figure 4.7: The safety and comfortable map for cyclists

TransCAD they are aggregated as a line map. So it is enough to only import the link maps in TransCAD and the endpoints will be autonomously generated.

The second step is solving MCLP explained in section 4.5.2 by "facility location" module in TransCAD. Firstly, we should define two node maps. The one is a facility layer with one candidate set of the population-aggregated points (409 nodes) and the existing set that contains 11 public transit stations and 4 demand locations in USP campus. The second is a client layer of 409 nodes with the weights as the population. And then calculate the cost matrix of the distance between nodes. The selection process is finding the new facilities as many as needed with the objective of the minimum average cost of service based on the cost matrix. And explained in chapter 4.5.2 the constraints of 350m (0.217 miles) is used as the constraints for MCLP. As a result, 21 nodes in figure 4.5.2 are selected as the new facilities.

The last and main approach is running the "routing" module in TransCAD. Firstly, create the network of the street layer with the setting of "length field" as the utilities of links and "type field" as the street ID. The network will be stored separated from the nodal layers. MST is a calculation package in the software. The set of selected points, a network file as well as its link cost matrix should be called when running the model. The result will be a tree-shaped network in which every node is reachable with the objective of minimising the total link costs. In the application phase, the set contains 21 new facilities and 15 high demand nodes. The matrix of link costs is computed by the utility functions in section 4.5.4. The result is the new cycling network design in the next chapter.

4.7. Model results

This chapter gives the results of the pre-modelling and the modelling of MCLP and MST. The analysis result of pre-modelling shown in map 4.7 indicates that the highways and the districts in Lapa and Jardim Bonfigliolo are not expected to attach the cycling network. The more dangerous and the steeper the road is, the closer the colour in the map 4.7 is red, and vice verse, the closer the colour is to green.

The result of demands points in figure 4.8 has 21 population demand points (blue) and 15 high demand points (red as PT stations and yellow as USP demand points). The 21 demand points can connect 407 original sets within the average walking distance as 320 metres out of 409 candidate nodes in total.

The new cycling network covers 24.2% of the whole road infrastructure, while the existing one only accounts for 17.3%. Thus, in the new design, the coverage is increased by 39.8%. As shown in figure 4.9, the new

Figure 4.8: Reduced demand points

network expands to the demands points and connect some independent bicycle lanes. It is composed of 21 new lanes (12 access roads, 7 distributor roads, and 2 through roads) listed in table 4.6. Aggregated with the present network, which contains 11 access roads, 19 distributor roads and 1 highway), 44% of the total network is the access roads, while the distributor roads account for 50% and the through roads for 6%. It is worthy noticed that in the current bikeways, the proportion of the distributor roads as 61% is larger than the access road as 35%. But the new design of the study improves the share of the access roads apparently. The result is logical because in the context that São Paulo has developed some cycling ways, the access roads will be potentially chosen to reach the last mile of the destinations.

Table 4.6: New cycling lanes

Street	**Road type**	**District**
R. Ariqueme	AR	Alto de Pinheiros
R. Pio XI	AR	Alto de Pinheiros
R. Pedralva	AR	Alto de Pinheiros
Rua Dona Elisa de Moraes Mendes	DR	Alto de Pinheiros
Rua Tonelero	DR	Alto de Pinheiros
R. Padre Carvalho	AR	Alto de Pinheiros
R. Natingui	AR	Pinheiros
Rua Henrique Schaumann	DR	Pinheiros
R. Joao Moura	AR	Alto de Pinheiros
Av. Dr. Arnaldo	DR	Pinheiros
Rua Gumercindo Saraiva	DR	Pinheiros
R. Belgica	AR	Pinheiros
R. Alemanha	AR	Pinheiros
R. Franca	AR	Pinheiros
Av. Jaguaré	T	Jaguaré
Av. Corifeu de Azevedo Marques	DR	Butantã
Av. Eng. Heitor Antonio Eiras Garcia	DR	Butantã
R. Francisco dos Santos	AR	Butantã
R. Bernardo Alvarenga	AR	Butantã
R. Roquete Pinto	AR	Butantã
Av. Prof. Francisco Morato	T	Butantã

MST results derived from the current road facilities (left) and the system with the addition of a cycling and

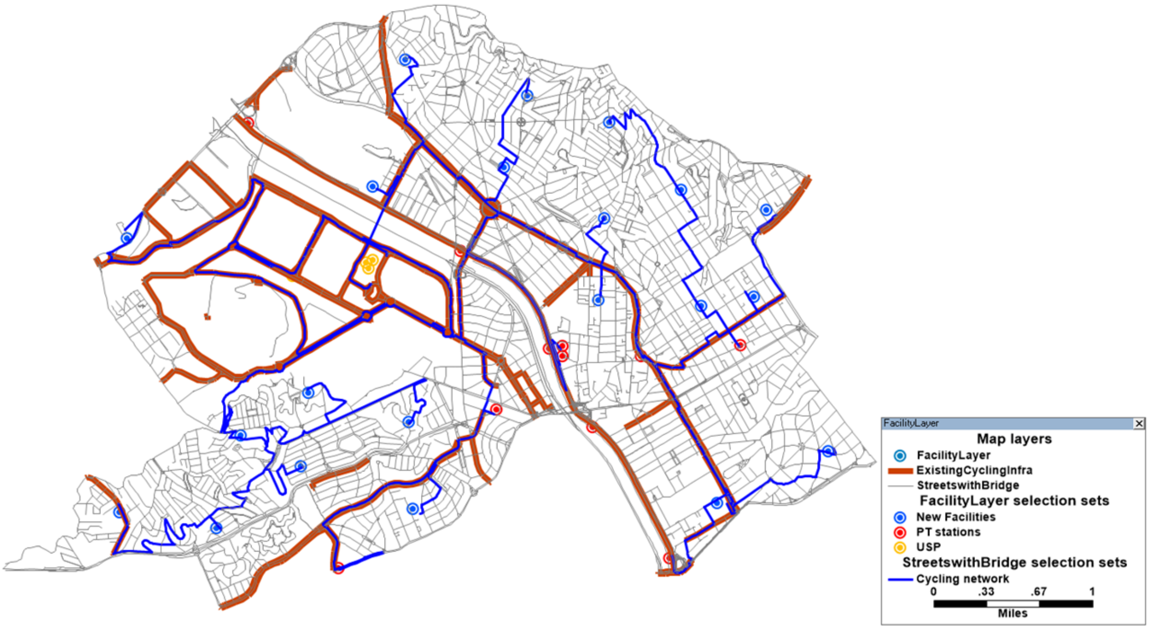


Figure 4.9: Result of the application of the MST

Figure 4.10: Minimum spanning tree (left: no cycling bridge; right: with a cycling bridge)

pedestrian bridge (right) are shown in figure 4.10. Intuitively, the right image is like a mesh, and the left image is the aggregation of the scattered branches. Travelling from one end of a branch to another end of the other branch follows the path through branch A, trunk and branch B. But when the branches are connected and the meshes generate, it greatly shortens the distance. Therefore, the road network with bicycle bridges has better accessibility.

5

Parametric design of bicycle and pedestrian bridges

In appendix F information about parametric design, bicycle bridges and pavement engineering has been gathered. This chapter deals with the conceptual and parametric design of bicycle and pedestrian bridges, which will be discussed in 5.1 and 5.2 respectively. In section 5.3 checks will be made between the results of the hand calculations and the results from Grasshopper. The chapter finalises with the visualisations (section 5.4) and execution methods (section 5.5).

5.1. Conceptual design

5.1.1. Situation and boundary conditions

Directly next to both sides of the Pinheiros and the Tietê river are the SP-015 and the BR-116 motorways situated (see figure 2.2a). Therefore, the bicycle and pedestrians will also have to cross these motorways. To minimise the change of collision of a truck with the bridge a minimum clearance of 6m is required. The water elevation in both rivers barely fluctuates which will give a navigation clearance of approximately 12m when a clearance of 6m with respect to the top of the asphalt layer of the motorways is maintained (Skaf & Oyamada, 2019c). According to Google Maps, the navigation clearance of 12m is larger than the minimum height of existing bridges crossing the Pinheiros and Tietê rivers and is therefore assumed to be sufficient. The situation is sketched in figure 5.1.

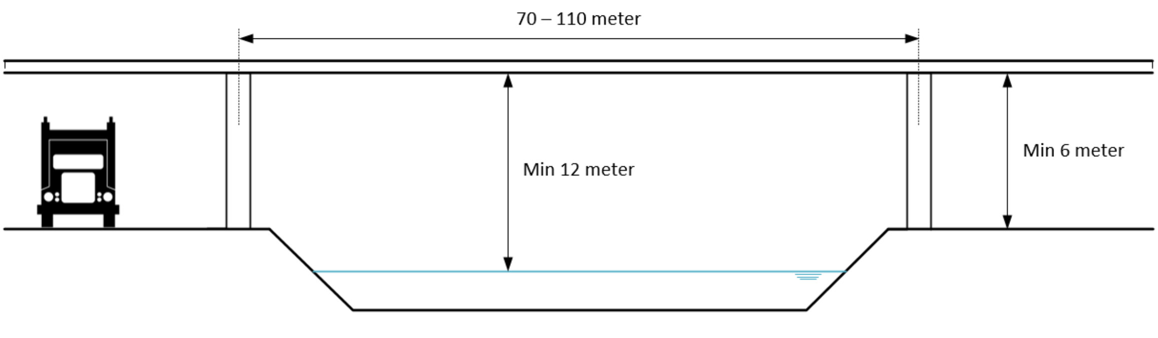


Figure 5.1: Sketch of a cross section of the Pinheiros and Tietê rivers, the motorways next to these rivers and the bridge (figure is indicative and not to scale).

For the width of bicycle lanes there are no regulations, only recommendations. According to the *Ontwerpwijzer Fietsverkeer* the minimum width of a bicycle lane, including motorised traffic, is 2m. For major lanes a minimum width of 2.5m is recommended (CROW, 2016), hence a width of 3m will be applied. According to USP, for the with of the pedestrian path a recommended value in Brazil is 3m (Skaf & Oyamada, 2019c).

5.1.2. Bridge type and applied materials

Due to the very limited space (range 10-30m) next to the Tietê and Pinheiros rivers, a bridge type need to be applied which requires the least amount of space next to its main span. Therefore a cable-stayed bridge and suspension bridge cannot be applied in a standardised design since their anchorages occupy space in the range of 20-30m, see figure 5.2. This range is based on bridges build with similar spans (≈ 110m) in the Netherlands like the Nesciobridge and the Daphne Schippersbrug (measured with Google Earth).

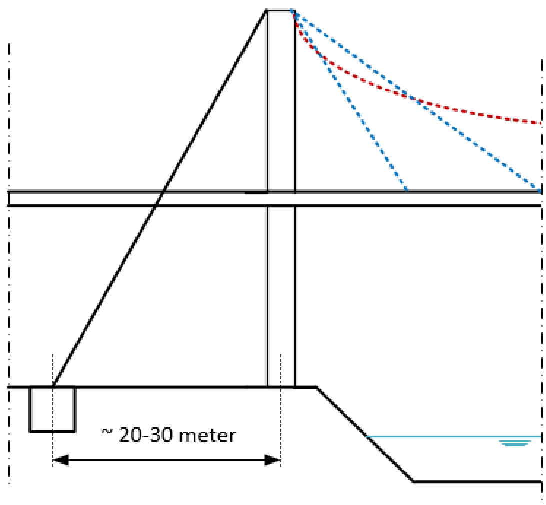


Figure 5.2: Area needed for anchorage varies roughly from 20-30m.

Moreover, the project team strives to design a slender bridge. The arch bridge is much more slender than a box girder or truss bridge. Therefore, an arch bridge will be applied. The bridge will be build of steel which allows for the most slender bridge. Steel class S355 will be used.

5.1.3. Design choices

Arch bridges are conceived to stand permanent loads. The performance of an arch bridge under moving loads is less, which requires a high flexural deck stiffness. For arch type bridges the dynamic amplification factor (for vertical displacement) along the span is butterfly shaped. This means that the value is low at midspan but high at the quarters of the span. There are three different type of arches:

- Type A: the basic arch bridge
- Type B: the basic tied arch bridge
- Type C: the tied arch bridge with stiffening girder

The arch of type A has a predominating arch with the thrust transmitted directly to the foundation (see figure 5.3 (a)). Because of this the elongation of the deck supporting structure can be neglected. The change of temperature can result in extra bending moments on the arch. For type B, the stiffness of the arch still dominates, but tying the ends of the arch through the deck system resists the thrust. The change in temperature doesn't result into an extra bending moment. With type C the stiffening girder is predominating and is subjected to bending moments and axial forced induced by the arch. The arch is mainly loaded in compression. Since the foundation of the arch will be onto piers instead of an abutment we discard the arch type A due to the high thrust load on the foundation. The types B and C can be called tied arch bridges. The primary structural elements of a tied arch bridge are the arch itself, the hangers, the bracing between arches, the deck and the piers which will be discussed in the next paragraphs. (Romeijn, 2006b)

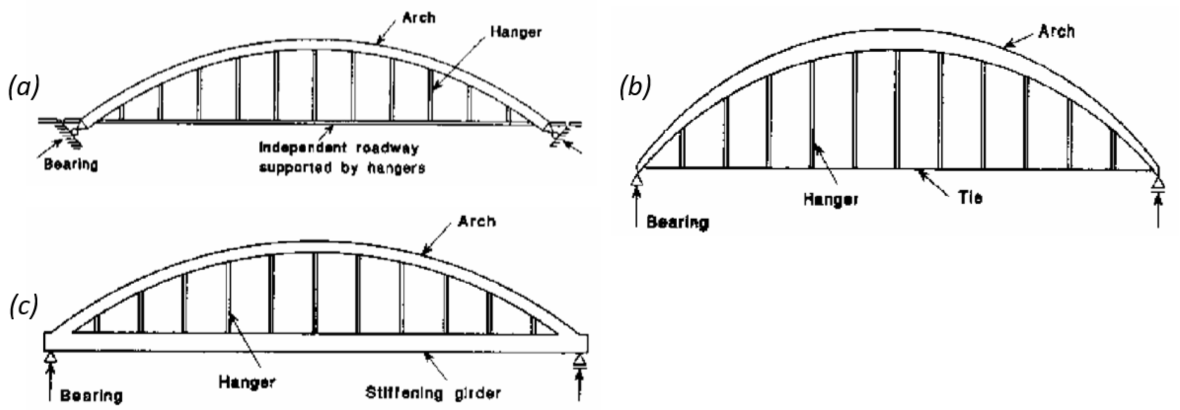
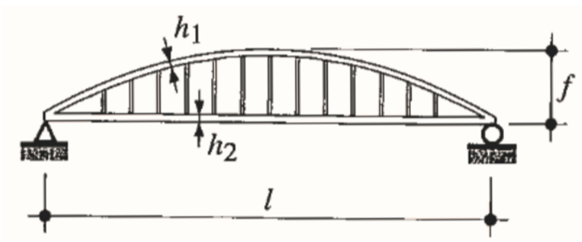


Figure 5.3: (a) Type A, basic arch bridge, (b) Type B, basic tied arch bridge (c) Type C, tied arch bridge with stiffening girder (Romeijn, 2006b)

Arch

For the arch itself the options are either a truss, box girders, plate girder or hollow sections. An arch can consist of a series of short straight chords, but ideally the arch will follow a smooth curved profile for aesthetic reasons. Besides stiffening girders, the arches themselves in an inclined position like figure 5.4a is also a solution to obtain a minimum buckling force on the arches. This solution will be included for this design. It is decided to make the arches with circular hollow sections, because of the aesthetically appealing look of this kind of section. A positive effect of circular hollow sections is that water accumulation on the arch is not possible (Romeijn, 2006b).

(a) Shin-Hamadera Bridge, Japan(Tawashi2006, 2010)



(b) Arch dimensions (Jean-Paul Lebet, 2013)

An arch bridge can be expressed in slenderness λ_1. The slenderness is given by the ratio of the span length L and the total rise of the arch f (see figure 5.4b):

$$\lambda_1 = \frac{f}{l} \tag{5.1}$$

When the slenderness λ_1 decreases the flexibility of a bridge increases. However a high slenderness is often more aesthetically appealing. For both road and railway bridges the slenderness is often chosen between 1/5 and 1/6. The distribution of material between the deck and arch decides if the arch bridge is of type B or C. The slenderness λ_2 depends on the span length L, the depth of the cross section of the arch member h_1 and the depth of the deck h_2 (see figure 5.4b) and generally lies between 1/30 and 1/45 (Jean-Paul Lebet, 2013):

$$\lambda_2 = \frac{h_1 + h_2}{l} \tag{5.2}$$

Hangers

For hangers different configurations can be considered. Besides vertical configuration also a network, a trussed and a fan arrangement is possible (see figure 5.5). If inclined arches are combined with a network hanger configuration in stead of a vertical configuration it is called the Nielsen-Lohse bridge. An example is the Shin-Hamadera bridge in figure 5.4a. The fan configuration of the hangers are becoming more popular because of aesthetic reasons. For now the vertical hangers are considered to simplify our hand calculation and the model further on (Romeijn, 2006b).

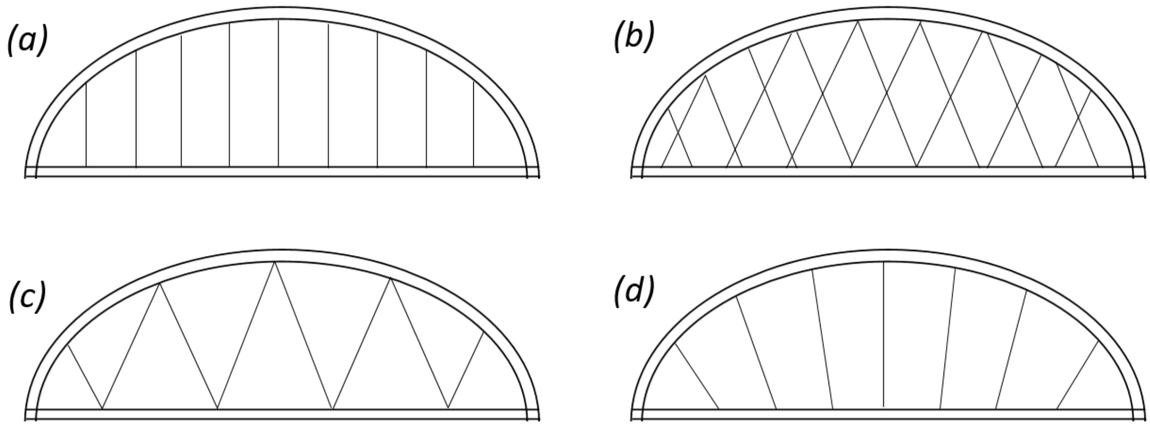


Figure 5.5: (a) vertical (b) network (c) truss (d) fan

For the hangers itself I-sections (welded or rolled), circular hollow sections, bars or cables can be considered. Hollow sections and cables can be sensitive with respect to vortex shredding while I-section hangers can be sensitive with respect to flutter. If slender hanger members are used, damping systems like mass dampers and energy absorbing dampers can be necessary. Another option is to limit risks on rain-wind induced vibrations by a certain minimum on roughness on the outer surface of circular shaped hangers. To reduce the problems on flutter with I-section members the hangers can be connected horizontally (Romeijn, 2006b).

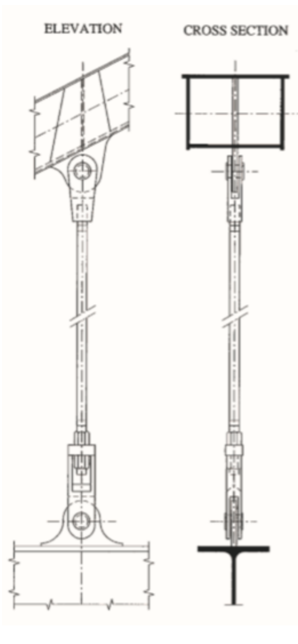


Figure 5.6: Hanger with a pinned joint (Jean-Paul Lebet, 2013)

Rolled sections are rarely used for hangers, this option is mainly used when additional stiffness is needed in case of only a single arch or lack of stiffening girders. For I-section hangers the possibility exist that horizontal connections are needed. With bars welding needs to be considered for long hangers which is not preferable with respect to fatigue and brittle failure aspects. Therefore the cable option will be used for this design. The ideal situation is that a hanger is pinned at both ends, so no bending stresses are present in the cable. For cables standard pinned joints can be used (see figure 5.6). Another advantage of pinned joints is that they lend themselves for replacement of a hanger because of the pin that can be removed temporarily (Jean-Paul Lebet, 2013).

Bracing

Bracing between the arch members is used to support the arch laterally and to reduce the buckling length of the arch. When only steel structures are considered, the girder can be made of an I-section, box girder / hollow section or an open "top hat" section. Different examples of bracing between arches are given in figure 5.7. In our design the arches will be inclined and extra stiffened with only horizontal braces (Vierendeel truss). With the Vierendeel truss the stability will be less than the other two bracing types, but it is aesthetically more appealing. There is already an additional stiffness due to the inclined arches. Since the arches are made of circular hollow sections, one decides to make the bracing also with circular hollow sections so the bridge will have an uniform design.

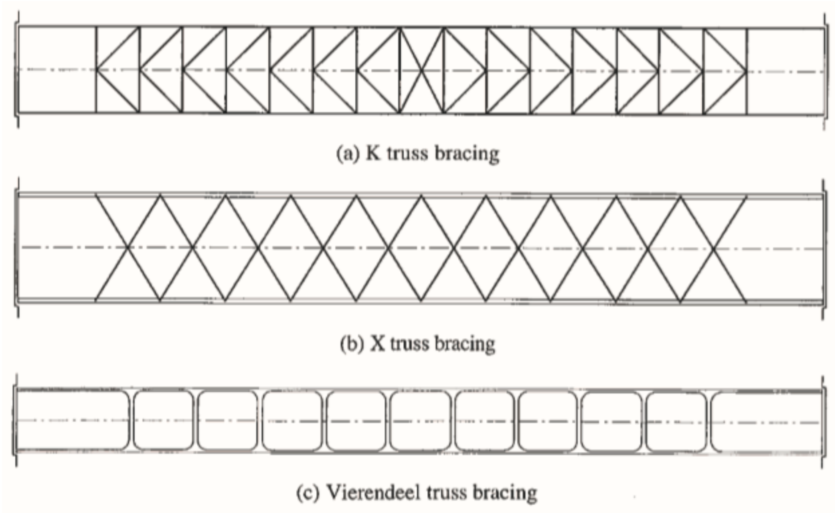


Figure 5.7: Top view of different bracing types between arches (Jean-Paul Lebet, 2013). (a) K-truss bracing (b) X-truss bracing (c) Vierendeel truss bracing

Deck

Examples of deck types are a concrete slab, an orthotropic steel plate and a composite deck. Concrete decks are usually more economic, but with a width of approximately 7m for the bridge a composite deck is preferred. The orthotropic steel deck is more expensive than a composite deck, which is also an argument to choose this option. For the composite deck sheer connectors are needed to connect the concrete slab to the steel plate (Romeijn, 2006a).

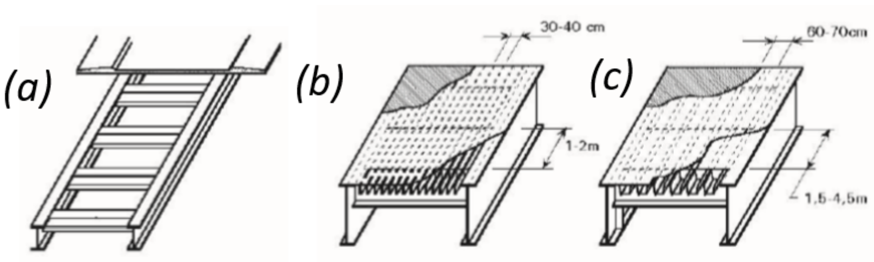


Figure 5.8: (a) main beams with girders (b) concrete slab configuration (c) composite deck configuration (Romeijn, 2006a)

The deck of the bridge transfers the loads to the supports. It must be taken into account that the deck contributes as a part of the tie for a tied arch bridge. A modern deck configuration will be used in which the concrete slab is working with the lateral beams to resist tension. This option has the advantage of allowing shorter cross girders and also the lateral beams are protected from the weather. Extra detailing of the slab at the ends of the bridge is required to carry some tension. There is sufficient longitudinal reinforcement needed to limit the opening of cracks in the slab due to the tension forces. The hangers will be connected to the lateral beams. Figure 5.9 presents a sketch of the bridge deck. (Jean-Paul Lebet, 2013)

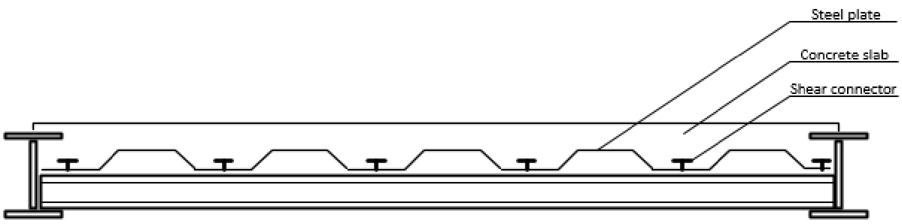


Figure 5.9: Sketch of the bridge deck

Piers

Since the bridge has an arch structure, the vertical load of the bridge will be divided over four points. These are the points where the arches itself cross the deck. A pier needs to be designed to bear the load of the bridge. Also the collision of highway traffic against a single pier needs to be taken into account, since at least one pier will always be located next to a highway. To bear both the vertical and horizontal load the piers will have a design like figure 5.10. The columns are inclined with a slope of $\frac{5}{1}$ for aesthetic reasons.

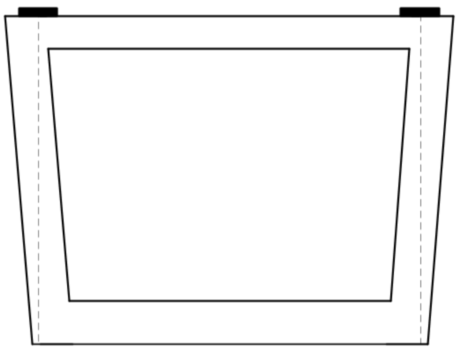


Figure 5.10: Sketch of the pier

Estimation of dimensions

To calculate the exact dimensions of the bridge a first assumption has to be made to determine the selfweight of the bridge. Since there is no fixed length of the span, we consider a span of 110 meter at first. With a span of 110 meter and a slenderness λ_1 of 1/6 the height of the arch will be 18.33 meter according to formula 5.1. For the lateral girders a height of 700 mm is assumed. The circular hollow sections are considered to have a diameter of 1300 mm so it is possible to execute maintenance work from the inside of this section. With formula 5.2 the slenderness λ_2 will be 1/55. This is outside of the range 1/35 and 1/45 as stated at the part arches in this subsection 5.1.3. This is due to the fact that this range is given for railway and motorway bridges. Since this design is for cyclists and pedestrians the design can probably be more slender.

5.1.4. Structural system

The type of the bridge is an tied arch. As a first assumption it is assumed that the bending stiffness of the main beams is small compared to the arch, therefore the ends of the arch are schematised as hinges. The ends of the arch are tied together by the main beams and the deck.

At one side the deck is free to deform, at the other side is fixed. Therefore the structure is outwards statically determinate.

Furthermore, as a first indication the bending stiffness of the arch is assumed to be infinite, i.e. axial deformation is neglected. Also the deck is schematised as a continuously girder over multiple supports (representing the hangers). In reality the supports need to be translational springs since the axial stiffness of the hangers is not infinite and the arch itself will deform also.

The static scheme is visualized in figure 5.11.

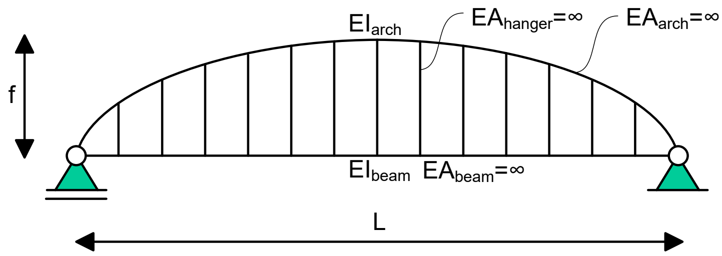


Figure 5.11: Static scheme of the bridge. The bicycle and pedestrian bridge is a tied-arch bridge. In the design it is assumed that the stiffness of the arch is large compared to the main beams. So the deck will transfer the loads to the main beams, the main beams to the hangers, the hangers to the arch and the arch to the piers.

5.1.5. Loads

In this section the static loads will be considered. Due to the self weight of the deck, it is assumed that dynamic loads is negligible. There are three types of loads:

- Permanent loads - P
- Variable loads - V
- Accidental loads - A

Where relevant, a lower and an upper bound is calculated, which are based on the range of the span between 70 and 110m respectively.

P1.01 - Self weight

The following self-weights for the bridge are used:

- **Deck**: for the deck structure an initial thickness of 200 mm is assumed. Hence the own weight of the deck yields $0.2 \cdot 25 = 5$ kN/m^2. Since the deck is made from composite slabs and profiled steel sheeting, the average thickness of the deck is somewhat thinner. Therefore a self-weight of 4 kN/m^2 will be used in the calculations. Furthermore, the additional weight of the main and transverse beams and wind bracings are assumed to be 2 kN/m^2 (Skaf & Oyamada, 2019e).
- **Arch**: the arch consists of a tubular structure with an initial diameter of 1.3m and a thickness of 25mm. This leads to a self weight of $\pi \cdot 1.3 \cdot 0.025 \cdot 78.5 = 8.02$ kN/m^1 for a single arch. Therefore a self-weight of 8 kN/m^1 is assumed.
- **Hangers**: for the hangers one assumes a self-weight of 1 kN/m^1.

P1.02 - Shrinkage and Creep

These forces are not taken into consideration.

P1.03 - Settlements

The bridge is statically determinate with respect to the bridge deck and the arches. Therefore settlements are not taken into consideration.

V2.01 - Uniformly distributed load (UDL)

According to NEN-EN 1991-2-C1/NB, art. 5.3.2.1(3), the equal distributed load $q_{f;k}$ can be described by:

$$q_{f;k} = 2 + \frac{120}{L+30} \quad \text{with:} \quad 2.5 \leq q_{f;k} \leq 5.0 \tag{5.3}$$

Lower bound:

$$q_{f;k} = 2 + \frac{120}{70+30} = 3.20 \quad \text{kN/m}^2 \tag{5.4}$$

Upper bound:

$$q_{f;k} = 2 + \frac{120}{110+30} = 2.86 \quad \text{kN/m}^2 \tag{5.5}$$

V2.02 - Service vehicles

Service (emergency and maintenance) vehicles need to make use of the bridge. According to NEN-EN 1991-2+C1, art. 5.3.2.3(1) this load consist of 25 kN per axle, hence $Q_{serv} = 2 \cdot 25 = 50$ kN. However, the replacement of the hangers (during maintenance) have to be done from the bridge deck itself. A small telescope crane will be used with an own weight of 135 kN in total (Cranes, 2019).

To prevent an excessive design, the load of 135 kN will only be used in maintenance combinations. The load of 50 kN will be used for all the other combinations, since emergency vehicles need to be able to enter the bridge at all times.

The lifting capacity of the crane is 135 kN. So the total vertical load in the lifting configuration then yields $2 \cdot 135 = 270$ kN.

V2.03 - Braking and acceleration forces

According to NEN-EN 1991-2-C1, art. 5.4(1) a horizontal load q_{hor} need to be taken into account along the middle axis of the bridge with respect to the top of the pavement layer. The characteristic value of this horizontal force equals the maximum value of:

- A load that corresponds with 10% of the UDL. By assuming a deck width of 7m, the total load then becomes $110 \cdot 7 \cdot 0.1 \cdot 3.2 = 247$ kN for the lower bound and $70 \cdot 7 \cdot 0.1 \cdot 2.86 = 140$ for the upper bound.
- 60% of the total weight of the service vehicle, hence $0.6 \cdot 25 = 15$ kN.

So the horizontal load is a longitudinal distributed load with a value for lower bound (longest span):

$$q_{hor} = \frac{247}{110} = 2.25 \quad \text{kN/m}^1 \tag{5.6}$$

And as an upper bound (shortest span):

$$q_{hor} = \frac{140}{70} = 2.00 \quad \text{kN/m}^1 \tag{5.7}$$

V2.04 - Force on parapet

According to NEN-EN 1991-2-C1, art. 4.8(1) both a horizontal and a vertical force of 1 kN/m^1 need to be considered.

V2.05 - Temperature loads

In this conceptual design temperature loads will not be considered.

V2.06 - Wind loads

For calculation of the wind force coefficients one made use of the approximation method conform NEN-EN 1991-1-4+A1+C2, art. 8.3.2. The applied decktype according to figure 8.3 is a) III. D_{tot} is assumed to be 0.7m, b is 8m. According to art. 8.3.2 (1) it is assumed that the dynamic response calculation is not necessary.

The distributed values of the wind is calculated for the x-direction (transversal direction, perpendicular to the bridge deck) and the z-direction (vertical direction, perpendicular to the bridge deck) in appendix G.1. The wind force in x-direction equals 5.61 kN/m^1 and in z-direction 21.25 kN/m^1 and the basic wind speed of 40 m/s is determined according to Back and Correa (2013). Horizontal wind loads are not considered in the conceptual design since these are very small compared to the vertical ones.

V2.07 - Building loads

According to (RBO, 2019) one needs to take into account an additional load due to the pouring of concrete. The value of this load lies between 0.75 kN/m^2 and 1.75 kN/m^2 and depends on the thickness of the floor. In this project one assumes a pouring load of 1 kN/m^2 projected on an area of 3×3m. This load is not governing.

A3.01 - Collision forces at the piers

According to NEN-EN 1991-1-7-C1, table 4.1, for motorways collision forces of $F_{dx} = 1,000$ and $F_{dy} = 500$ kN need to be taken into account. F_{dx} and F_{dy} are the collision forces parallel and perpendicular to the motorway respectively. Furthermore, F_{dx} cannot occur simultaneously with F_{dy}. A further reduction $\sqrt{1-\frac{d}{d_0}}$ is not applied to guarantee that in the future roads can be expanded and still fulfill the Eurocodes.

A3.02 - Collision forces at the bridge deck

These forces are not acting on the mainspan and therefore not considered but it will lead to forces in the piers. However, the height of the bridge is determined based on a free profile of at least 6.0m. This profile is based on NEN-EN 1991-1-7-C1, art. 4.3.2, remark 3: h_1 *is the free profile between the road surface and the bottom of the bridge deck, where no colission force need to be considered. The recommended value of* h_1 *is 6.0m.*. However, the Brazilian codes recommend a collision force of 100kN.

A3.03 - Collision forces due to ships

According to NEN-EN 1991-1-7+C1/NB the value an equivalent static force is 1,000 kN and be projected on an area of 0.25×3.0m on the bridge deck. Since almost no naviagtion is present on the Pinheiros and Tietê rivers, this force is not taken into account.

A3.04 - Accidental presence of vehicles on the bridge

If there is no permanent obstacle to prevent driving vehicles on the bridge, an accidental presence of vehicles on the bridge have to be taken into account according to NEN-EN 1991-2-C1, art. 5.6.3. It consists of two axle loads of 80kN and 40kN, with a wheel basis of 3m and a width of 1.3m with contact areas of 0.2×0.2m. The accompanying braking force is equal to 60% of the weight of this vehicle, hence $0.6 \cdot 120 = 72$kN. If A3.04 is present, no variable loads need to be taken into account. In the meeting of (Skaf & Oyamada, 2019b) the access of the bicycle and pedestrian bridges for motorised vehicles will be blocked by using removable poles, which allows service vehicles to enter the bridge (they can turn down the poles).

Table 5.1: Combination factors for the ULS, valid for limit states STR/GEO. Table is obtained from NEN-EN 1990-A1-A1-C2, table NB.13-A2.4(B).

Gevolgklasse	β	G			Verkeer (met ψ = 1)	Overig veranderlijk (met ψ = 1)
		$\gamma_{G,j,sup}$		$\gamma_{G,j,inf}$		
		6.10a	6.10b (incl. ξ)	6.10a en 6.10b		
CC1	3,3	1,20	1,10	0,9	1,20	1,35
CC2	3,8	1,30	1,20	0,9	1,35	1,5
CC3	4,3	1,40	1,25	0,9	1,5	1,65

γ = 0 voor gunstig werkende veranderlijke belastingen

Voor γ_P zie de aanbevelingen in de desbetreffende materiaalgebonden Eurocodes 1992 t.m. 1999.

Voor de berekening van het effect van ongelijkmatige zettingen geldt dat $\gamma_{G,set}$ = 1,20 in het geval van een lineaire berekening en $\gamma_{G,set}$ = 1,35 in het geval van een niet lineaire berekening. Gunstig werkende zettingsverschillen worden niet in rekening gebracht. De grootte van de zettingen is bepaald op basis van de karakteristieke belastingscombinatie en de karakteristieke waarden voor de grondeigenschappen.

OPMERKING De factor K_{Fi} volgens B 3.3 is in de waarden van γ verwerkt; voor de zettingsberekening blijft de betrouwbaarheidsdifferentiatie achterwege.

A3.05 - Accidental loads due to Earthquakes

Earthquakes are not frequent in Brazil, since it lies in the middle of the South American plate (Program, n.d.). According to the United States Geological Survey, in São Paulo there have been no earthquakes with a magnitude of ≥ 3.5 on the Richter Scale between 1955 and 2012 (Igor Zolnerkevic, 2013). Furthermore, according to (Sergio Hampshire C. Santos, 2008), São Paulo is placed in a zone of zero seismic activity. Therefore, the forces of earthquakes are not taken into account.

5.1.6. Load combinations

Choice of the Consequence Classes

NEN-EN 1990-A1-A1-C2, table B1, gives definitions of consequence classes. Since a collapse of the bridge have large consequences, one chooses a consequence class CC3. The accompanying partial factors for the STR/GEO limit states are presented in table 5.1.

The momentary factors are presented in table 5.2.

Overview of load combinations

Table 5.3 presents an overview of the used load combinations and the items which are calculated.

Ultimate limit state (ULS)

NEN-EN 1990-A1-A1+C2, article 6.4 distinguishes the following ultimate limit states:

- **EQU**: loosing equilibrium of the structure.
- **STR**: internal collapse or extensive deformations of the structure or its elements.
- **GEO**: collapse or extensive deformation of the ground in which the strength of the ground or rock is determining the resistance.
- **FAT**: collapse of the structure or its structural elements due to fatigue.
- **UPL**: loosing equilibrium due to water pressure or other vertical forces.
- **HYD**: hydraulic collapse, erosion and erosion due to concentrated ground water flow due to hydraulic gradients.

Table 5.2: Momentary factors. Table is obtained from NEN-EN 1990-A1-A1-C2-NB, table NB.10-A2.2

Belasting	Symbool		ψ_0	ψ_1	ψ_2
Verkeersbelastingen	gr1	Gelijkmatig verdeelde belasting q_{fk}	0,4	0,8 [c]	0,4
		Horizontale belasting Q_{flk}			
	gr 2	Gelijkmatig verdeelde belasting q_{fk}	0,4	0,8 [b]	0
		Dienstvoertuig Q_{serv}			
		Horizontale belasting Q_{flk}			
	Geconcentreerde belasting Q_{fwk}		0	0,8 [b]	0
	Onbedoeld voertuig (zie 5.6.3)		0	0,8 [b]	0
Windkrachten	F_{Wk}	blijvende ontwerpsituatie	0,3	0,6 [b]	0
		Uitvoering	0,8	0	
Thermische belastingen	T_k		0,3	0,8	0,3 [a]
Sneeuwbelastingen	$Q_{Sn,k}$	blijvende ontwerpsituatie	0	0	0
		Uitvoering	0,8	0	
Belastingen tijdens de bouw	Q_c		1,0	0	1,0

[a] In de uiterste grenstoestand kan voor ψ_2 voor thermische belasting 0 worden aangehouden.

[b] Voor aanrijding op of onder de brug en aanvaring is ψ_1 = 0.

[c] Voor aanrijding op of onder de brug en aanvaring is ψ_1 = 0,4.

OPMERKING Groepen verkeersbelastingen hoeven niet met elkaar te zijn gecombineerd.

Table 5.3: Overview of all load combinations including their description

Load comb.	Description / combiation used for
ULS-1.01	Max. moment in complete deck, V2.02 is dominating.
ULS-1.02	Max. moment in complete arch, V2.01 is dominating.
ULS-1.03	Max. normal force in arch, V2.01 is dominating.
ULS-1.04	Max. moment in 1 arch, V2.01 is dominating.
ULS-1.05	Max. normal force in arch, V2.01 is dominating.
ULS-1.06	Max. normal force in deck, shear force in pier, V2.03 is dominating.
ULS-1.07	Max. shear force in pier, accidental combination.
ULS-1.08	Max. normal force in hanger, V2.02 is dominating.
ULS-1.09	Uplifting of the deck, only wind as variable load
ULS-1.10	Building combination, V2.02 is dominating.
ULS-1.11	Maintenance combination, only service vehicle as variable load.
SLS-2.01	Max. deflection deck, V2.01 is dominating.
SLS-2.02	Max. deflection deck, V2.01 is dominating.
SLS-2.03	Max. deflection deck, V2.01 is dominating.

Table 5.4: Overview of load combinations of load combinations in the ULS, based on (5.8)

Load comb.	Load case								
	P1.01	**V2.01**	**V2.02**	**V2.03**	**V2.04**	**V2.06A**	**V2.06B**	**A3.01**	**A3.02**
ULS - 1.01	1.4	$0.4 \cdot 1.5$	$0.8 \cdot 1.5$	0	$0.4 \cdot 1.65$	0	$0.4 \cdot 1.65$	0	0
ULS - 1.02	1.4	$0.8 \cdot 1.5$	$0.4 \cdot 1.5$	0	$0.4 \cdot 1.65$	0	$0.4 \cdot 1.65$	0	0
ULS - 1.03	1.4	$0.8 \cdot 1.5$	$0.4 \cdot 1.5$	0	$0.4 \cdot 1.65$	0	$0.4 \cdot 1.65$	0	0
ULS - 1.04	1.4	$0.8 \cdot 1.5$	$0.4 \cdot 1.5$	0	$0.4 \cdot 1.65$	0	$0.4 \cdot 1.65$	0	0
ULS - 1.05	1.4	$0.8 \cdot 1.5$	$0.4 \cdot 1.5$	0	$0.4 \cdot 1.65$	0	$0.4 \cdot 1.65$	0	0
ULS - 1.06	1.4	0	0	1.5	0	0	0	0	0
ULS - 1.08	1.4	$0.4 \cdot 1.5$	$0.8 \cdot 1.5$	$0.4 \cdot 1.5$	$0.4 \cdot 1.65$	0	$0.4 \cdot 1.65$	0	0
ULS - 1.09	0.9	0	0	0	0	0	1.65	0	0
ULS - 1.10	1.4	0	1.5	0	0	0	$0.4 \cdot 1.65$	0	0
ULS - 1.11	1.4	0	1.5	0	0	0	0	0	0

Table 5.5: Overview of load combinations in the ULS, based on (5.10)

Load comb.	Load case								
	P1.01	**V2.01**	**V2.02**	**V2.03**	**V2.04**	**V2.06A**	**V2.06B**	**A3.01**	**A3.02**
ULS - 1.07	1	0.8	0.4	0	0.4	0	0.4	1	0

In this conceptual design only the equilibrium limit state (EQU) is taken into account.

The deck, hangers, arches and piers will be checked by fundamental combinations according to NEN-EN 1990-A1+C2, art. 6.4.3.2. The most inconvenient ones need to take into account.

- 6.10a: the permanent load is dominant: the existing load will be fully implementend and all other variable loads will be combined with the accompanying combination factors ψ_i.
- 6.10b: the variable load is dominant: one variable load case will be fully implemented and all other variable load cases are combined with the accompanying combination factors ψ_i.

Equations 6.10a and 6.10b of the ULS according to NEN-EN 1990-A1+C2, art. 6.4.3.2 are presented in 5.8 and 5.9 respectively.

$$6.10a: \quad \sum_{j\geq 1} \gamma_{G,j} G_{k,j} \text{"}+\text{"} \gamma_p P \text{"}+\text{"} \gamma_{Q,1}\psi_{0,1} Q_{k,1} \text{"}+\text{"} \sum_{i>1} \gamma_{Q,i}\psi_{0,i} Q_{k,i} \tag{5.8}$$

$$6.10b: \quad \sum_{j\geq 1} \xi_j \gamma_{G,j} G_{k,j} \text{"}+\text{"} \gamma_p P \text{"}+\text{"} \gamma_{Q,1} Q_{k,1} \text{"}+\text{"} \sum_{i>1} \gamma_{Q,i}\psi_{0,i} Q_{k,i} \tag{5.9}$$

In which " + " means to be combined with. An overview of load combinations in the ULS is presented in table 5.4.

The accidental load combinations need to be taken into account according to (5.10):

$$6.11b: \quad \sum_{j\geq 1} G_{k,j} \text{"}+\text{"} P \text{"}+\text{"} A_d \text{"}+\text{"} (\psi_{1,1}+\psi_{2,1}) Q_{k,1} \text{"}+\text{"} \sum_{i>1} \psi_{2,i} Q_{k,i} \tag{5.10}$$

It is assumed that the permanent load is dominant, since the only variable loads are wind loads and vehicle loads which are small with respect to the own weight of the bridge. Hence for the ULS only (5.8) will be used.

NEN-EN 1990+A1+A1/C2/NB, table NB.16 indicates how the load cases need to be combined. However this is only valid for (5.9). The accidental load combiantions are presented in table 5.5.

Besides the combinations in the final phase (when the bridge is in use, ULS-1.01 t/m ULS-1.09), also a combination in the building phase (ULS-1.10) is considered.

In the building phase (see also section 5.5) parts of the deck are transported by barges. It is assumed that a service vehicle with a characteristic weight of 50 kN have to make use of the bridge and the deck already has its full weight (to be variable in the construction method).

Table 5.6: Overview of load combinations in the SLS, based on (5.11)

Load comb.	Load case								
	P1.01	**V2.01**	**V2.02**	**V2.03**	**V2.04**	**V2.06A**	**V2.06B**	**A3.01**	**A3.02**
SLS - 2.01	1	0.8	0.4	0	0.4	0	0.4	0	0
SLS - 2.02	1	0.8	0.4	0	0.4	0	0.4	0	0
SLS - 2.03	1	0.8	0.4	0	0.4	0	0.4	0	0

Furthermore, the replacement of hangers need also be taken into account. This stage is not critical since only the own weight of the deck and a service vehicle need to be taken into account. The normal force in a hanger in that stage will be less than the combination ULS-1.08).

Serviceability limit state (SLS)

For the serviceability limit state the frequent loading combination need to be taken into account: this combination needs to be applied for reversible limit states to check deformations and comfort of the structure. The frequent combination is obtained by appling equation 6.15b of NEN-EN 1990-A1+C2:

$$6.15b: \quad \sum_{j\geq 1} G_{k,j}\text{"}+\text{"}\psi P\text{"}+\text{"}\psi_{1,1}Q_{k,i}\text{"}+\text{"}\sum_{i>1}\psi_{2,i}Q_{k,i} \tag{5.11}$$

In which " + " means to be combined with. The SLS load combinations are presented in table 5.6.

5.1.7. Force distribution

The applied bridge type is an arch. An arch acts like an inverted cable under an equally distributed load. Since the shape of an cable is a parabola, the shape of the arch has to be an inverted parabola. A parabola loaded under an equally distributed load will lead to only to normal forces into the arch. Point loads and non-eccentric loads do lead to bending moments into the arch.

To determine the force distribution in the arch, there are a few options (Welleman, 2017):

- **The classical approach**: this method is based on the force method, see (5.12). The arch is made statically determinate by removing one of the supports. To satisfy the boundary conditions, an redundant horizontal force H is applied. By applying the deformation conditions (zero horizontal movement in the supports) the horizontal force can be calculated. The application area of this method is limited to zero movement of the supports.
- **Applying the differential equations**:

By using the first approach (force method) one ends up with

$$H = -\frac{\int_{\text{arch}} \frac{M^a\, z}{EI} dx}{\int_{\text{arch}} \frac{z^2}{EI} dx + \frac{L}{EA}} \tag{5.12}$$

The moment distribution in the arch can now be determined according to

$$M = M^a + Hz \tag{5.13}$$

In which M^a are the moments in the statically determinate system and $H \cdot z$ the additional moments due to the redundant H. z is the shape of the undeformed arch.

The second approach is based on the ordinary differential equations which allows for a large variety of boundary conditions; for example horizontal translated supports. The differential equation yields:

$$EI\frac{d^4 w}{dx^4} = q - H\frac{d^2 z}{dx^2} \tag{5.14}$$

In which w is the deformation of the arch which need to be solved, q the distributed load and z the shape of the undeformed arch. The horizontal force is unknown but can be determined by using the boundary conditions. When horizontal displacements are neglected, the horizontal forces can be found according to:

$$\int_{x=0}^{x=L} \frac{dz}{dx}\frac{dw}{dx}dx = 0 \tag{5.15}$$

When axial deformations of the arch cannot be neglected, (5.15) gets more complicated and transforms into:

$$\frac{HL}{EA} = -\int_{x=0}^{x=L} \frac{dz}{dx}\frac{dw}{dx}dx \tag{5.16}$$

By applying a parabolic arch, (5.15) and (5.16) can be simplified due to the properties of a parabolic arch and these transforms into

$$\int_{x=0}^{x=L} w dx = 0 \tag{5.17}$$

And

$$\frac{HL}{EA} = \frac{8f}{L^2}\int_{x=0}^{x=L} w dx \tag{5.18}$$

In this conceptual design one will only make use of (5.17). The force distribution calculation is based on the following assumptions:

- The bending stiffness of the arch is large compared to the bending stiffness of the main beams. Therefore, the arch can be modelled as a pinned arch.
- Axial deformation of the deck and the arch will influence the force distribution in the arch but in this conceptual design this effect is neglected.
- The longitudinal beams are modelled as continuous beams over a rigid support (for a first indication). This is not the reality since the arch and the hangers act as a continuously elastic support.
- Hand-made structural analysis is based on a linear elastic analysis only.

The conceptual force distribution in the deck, hangers and arches are calculated in appendix G.3 and the results are presented in table 5.7.

5.1.8. Deck calculation

Design checks

According to (Prof. ir. J.W.B. Stark, 2010), the following design checks have to be performed:

- Bending resistance (hogging and sagging)
- Punching shear resistance
- Vertical shear resistance (not considered)
- Vertical displacements (not considered)

Design assumptions

For the deck a composite slab with profiled steel sheeting (ComFlor® 80 (Steel, 2017)) will be used. The initial thickness is assumed to be 200mm. The concrete deck (C30/37) is supported by the main girders and secondary longitudinal girders. The latter distributes the vertical load to transverse girders and the main girders.

The characteristic cylindrical compression strength is $f_{ck} = 30$ MPa. This is the characteristic strength after 28 days. It is assumed that the piers are poured some weeks before the deck is lifted into position so the piers

Table 5.7: Overview of governing forces per structural item in the ULS, based on a span of 110m.

Load comb.[1]	Element	Force	Unit	Remarks	Structural check
ULS-1.01	Main beams	−177	kNm	Stage 3	Moment resistance
		111	kNm	Stage 3	Moment resistance
ULS-1.02	Arch	2940	kNm		Moment resistance
ULS-1.03	Arch	−6295	kN		Buckling resistance
ULS-1.06	Main beams	165	kN		Max. normal force
ULS-1.08	Hanger	323	kN		Max. normal force in hanger
ULS-1.09	Deck	1.37	kN		Prevent uplifting
ULS-1.10	Deck	1176	kNm		Moment resistance
	Main beams	−1176 [2]	kNm	Stage 0a	Moment resistance
		1176	kNm	Stage 0b	Moment resistance
	Main beams	−106	kNm	Stage 1b	Moment resistance
	Main beams	53	kNm	Stage 1b	Moment resistance
ULS-1.11	Hanger	467	kN		Max. normal force in hanger
	Main beams	−426	kNm	Stage 2	Moment resistance
		327	kNm	Stage 2	Moment resistance

[1] Load combinations ULS-1.04 and ULS-1.05 are not governing since there effects are already covered in ULS-1.02 and ULS-1.03 respectively.
[2] Based on a transportation length of $\frac{110}{3}$ = 36.7 m. For more information about the calculation of the main beams and the execution is referred to sections 5.1.9 and 5.5.

can carry the own weight of the deck. The concrete deck is also made of C30/37. This deck is poured after the complete bridge is installed. The largest moments in the deck will occur due to the crane on top of the deck, but only after 28 days so the concrete regains its full strength.

For the deck a X-bracing plan will be used to resist the horizontal forces in the bridge deck. This plan can relatively be easy implemented in the current deck configuration.

It is assumed that when the crane is driving over the deck the total vertical load is divided over four wheels. Thus, the total load for each wheel then becomes 135/4 = 33.75 kN.

In case the crane is lifting it's maximum capacity, the combined load becomes 135 + 135 = 270 kN. This load is divided over two outriggers of the crane (just before the overturning point). This load is governing for both the moment resistance as for the punching shear resistance.

For the slab a rigid plastic analysis has been applied.

Bending moment resistance

For the case of simplicity, it is assumed that the neutral axis is positioned above the steel decking. In this case, the complete steel decking acts as reinforcement. The resistance of the concrete in tension is neglected (just as for ordinary reinforcement calculations).

For hogging bending moment resistance, reinforcement in the top layer is required. The compressive strength of the steel decking is neglected since it is susceptible for buckling.

After the calculations of the deck, the geometry of the deck has changed according to table 5.8.

Bending stiffness

According to Prof. ir. J.W.B. Stark (2010) the recommended value for the maximum deflection equals:

- $\frac{L}{250}$ for permanent loads

Table 5.8: Properties of the steel-concrete deck.

Symbol	Value	Unit	Remarks
h_c	140	[mm]	
h_p	80	[mm]	
A_p [1]	1864	[mm^2]	
A_s	2000	[mm^2]	To resist hogging moments [2]
	400	[mm^2]	To resist sagging moments [3]
f_{ck}	30 (C30/37)	[N/mm^2]	
f_{ys}	500	[N/mm^2]	
f_{yp}	350	[N/mm^2]	
EI	$1.68 \cdot 10^{12}$	[Nmm^2]	

[1] Applied steel decking: ComFlor® 80, nominal thickness 1.20 mm.
[2] Applied reinforcement configuration: Ø16-100.
[3] Applied reinforcement configuration: Ø8-125.

- $\frac{L}{300}$ for variable loads

The deflection of the sheeting due its own weight is not included in the verification of the composite slab. The effects of slip on the deflection need not to be taken into account if the end slip is 0.5mm for a load exceeding 1.2 times the desired design service load. The bending stiffness of the slab is based on a cracked calculation of the steel-concrete slab. This calculation is valid for the bending stiffness in the SLS and based on a cracked cross section. For the sake of simplicity this value is also adopted in the ULS.

5.1.9. Main beam calculation

Load phases

The configuration of the main beam largely depends on the construction stage in the execution of the bridge, see section 5.5. For the values of the force distribution is referred to table 5.7.

- **Stage 0a**: the main beams of the bridge are transported to its final location and lifted from the barge to the temporary supports. This stage is characterised by large hogging bending moments. Furthermore, the concrete slab is not poured yet, therefore all the hogging bending moments need to be carried by the steel main beams. The force distribution of this stage is considered in load combination ULS1-10.
- **Stage 0b**: this stage considers the large sagging bending moments when the main beams are lifted into position onto the temporary supports and piers. Again, the concrete slab is not poured yet, all the sagging bending moments need to be carried by the steel main beams. The force distribution of this stage is considered in load combination ULS1-10.
- **Stage 1a**: the hangers are installed and the temporary supports removed, but the concrete slab is not poured. This stage is not governing in the analysis and therefore not part of any of the load combinations.
- **Stage 1b**: the hangers are installed and the temporary supports removed, and the concrete slab is poured but not yet hardened, so no composite action is presented but the full dead load is present. Therefore, this stage could be dominant (Pauletti, 2019).
- **Stage 2**: the hangers are installed and the concrete slab is poured hardened. One hanger needs to be removed, which requires a mobile crane with a weight of 135kN. No other variable loads are considered since maintenance operations will only be carried out when there is no other variable load on the bridge (to obtain an economical design). This stage is considered in load combination ULS1-11.
- **Stage 3**: the final or using stage. In this stage the regular load combinations according to NEN-EN 1990+A1+A1/C2 are considered.

The bending moments of stage 0 are governing and based on a transportation length of $\frac{110}{3} = 36.7$m. The absolute maximum moment is equal for stage 0a and 0b, since

$$\frac{1}{8}qL^2 = \frac{1}{2}q\left(\frac{1}{2}L\right)^2 \tag{5.19}$$

With the aforementioned transportation length stage 0 is governing. If the segmental deck length is reduced to

$$L = \sqrt{\frac{8 \cdot M_{max}}{q}} = \sqrt{\frac{8 \cdot 427}{7}} = 22 \quad \text{m} \tag{5.20}$$

Then the transportation phase is not governing anymore. However, the deck parts are transported by barges. These barges need to centrically loaded. A reduction of transportation length would result in too small space for navigate the barges and deck parts to the final location. Therefore a transportation length of 36.7m will be still used in further calculations.

Design checks

According to (Prof. ir. J.W.B. Stark, 2010), the following design checks have to be performed:

- Bending strength
- Strength of the longitudinal shear connection
- Longitudinal shear strength
- Shear strength of the web including buckling
- Sagging of the cross section

The latter will not be performed since the main beams are restrained at the top by the concrete slab and in the webs by the transverse girders.

Design assumptions

For the determination of the bending resistance the following assumptions have been made:

- The main beam is a class 1/2 profile, so a plastic calculation (without redistribution of moments) may be performed.
- For the sake of simplicity there is a full interaction between the steel beam and the concrete slab.
- The distribution of compression stresses is uniform and equal to $\frac{0.85 f_{ck}}{\gamma_c}$. This factor allows for the difference between test cilinder strength and the real strength observed in experiments.
- The concrete parts loaded in tension does not add to the resistance.
- The reinforcement in the slab yields with a stress of $\frac{f_{ck}}{\gamma_s}$.
- The steel part of the slab and the reinforcement in compression is neglected.
- Assumed concrete type: C30/37, $E_{cm} = 32,800$ N/mm^2 (Betonvereniging, 2010).
- Assumed steel decking: ComFlor® 80 (Steel, 2017).

Calculation results

The calculation results are presented in table 5.9.

Table 5.9: Properties of the steel-concrete main beam.

Symbol	Value	Unit
t_1	15	[mm]
t_2	15	[mm]
t_3	15	[mm]
t_4	15	[mm]
t_5	10	[mm]
t_6	10	[mm]
A_a	$43,000$	[mm^2]
h_w	500	[mm]
h_c	140	[mm]
h_p	80	[mm]
b_{eff}	3250	[mm]
I_{zz}	$1.71 \cdot 10^9$	[mm^4]
n_r	2	[-]
$M_{Rd;no,slab}$	2755	[kNm]
$M_{Rd;slab;sag}$	4503	[kNm]
$M_{Rd;slab;hog}$	3105	[kNm]
n_{req} [1]	25	[-]

[1] The centre-to-centre distance between each rib is 300 mm, leading to 20 ribs between each hanger connection point in a single rib. 25 shear connectors in a single row are required to guarantee ductility. For a more elaborate explanation is referred to appendix G.5.

5.1.10. Longitudinal beams

Geometry and design assumptions

For the longitudinal beams a profile HEA240, steel class S355 is assumed. The highest load on the secondary longitudinal beams will occur if the maintenance vehicle is lifting a load and is positioned above these beams. The support conditions depends on the execution method; a bolted connection is assumed to be a hinge, a welded connection a clamped one. To have freedom in the execution choice, the beam is assumed to be simply supported since this will lead to the largest bending moments.

Stability checks are not performed since the top flange (which is in compression) is supported transversely by the steel-concrete deck. Therefore it is not assumed that lateral torsional buckling is governing.

Design checks

The following checks are performed:

- Bending moment resistance
- Displacement

Since in the middle of the profile bending moments and shear forces are acting at the same time, one has to check if the bending moment resistance need to be reduced due to the shear force. The bending moment resistance check is based on a fully plastic calculation since the profile is a class-1 profile according to (ArcelorMittal, 2017). A reduction is not needed if

$$V_{Ed} \leq 0.5 \cdot V_{Pl,Rd} \tag{5.21}$$

$$112 \leq 0.5 \cdot 518 \tag{5.22}$$

$$112 \leq 259 \quad \text{kN} \tag{5.23}$$

Table 5.10: Properties of the longitudinal beam HEA240.

Symbol	Value	Unit
M_{Ed}	210	[kNm]
V_{Ed}	225	[kN]
L	3000	[mm]
I_{zz}	$7763 \cdot 10^4$	[mm^4]
$W_{z,pl}$	$744.6 \cdot 10^3$	[mm^3]
b	240	[mm]
A	7680	[mm^2]
t_f	12	[mm]
t_w	7.5	[mm]
r	21	[mm]

Since this criterion is fulfilled, the fully plastic moment resistance can be used. The forces and properties are tabulated in table 5.10 and the calculations are presented in appendix G.6. The connection between the longitudintal and transverse beam is designed in appendix G.12 (Eurocode Applied, 2019).

5.1.11. Transversal beams

Geometry and design assumptions

For the transversal beams a profile HEA300, steel class S355 ($f_y = 355\ \mathrm{N/mm^2}$) is assumed. The highest load on a transverse beam occurs when the maintenance vehicle is lifting directly above the transverse girder.

Stability checks are not performed since the transverse beams are supported laterally by the longitudinal beams. Therefore it is not assumed that lateral torsional buckling is governing.

Design checks

The following checks are performed:

- Bending moment resistance
- Displacement

The dimensions of the profile are chosen in such a way that the longitudinal beams can fit into the transversal ones. The web of the HEA300 profile is just enough to enable a connection with the longitudinal girders. Just like the longitudinal girders, it has to be checked if the plastic bending moment resistance need to be reduced due to the shear forces.

A reduction is not needed if

$$V_{Ed} \leq 0.5 \cdot V_{Pl,Rd} \tag{5.24}$$

$$55.1 \leq 0.5 \cdot 767 \tag{5.25}$$

$$55.1 \leq 767 \quad \mathrm{kN} \tag{5.26}$$

Since this criterion is fulfilled, the fully plastic moment resistance can be used. The forces and properties are tabulated in table 5.11 and the calculations are presented in appendix G.6.

5.1.12. Plan bracing deck

To resist the horizontal forces acting perpendicularly the concrete slab will act as plan bracing (Jean-Paul Lebet, 2013). However during the building phase this bracing is not present. Therefore, to maintain the geometry of the deck, during the construction, lifting and installing of the deck a plan bracing (X-shape) will be used.

Table 5.11: Properties of the transversal beam HEA300

Symbol	Value	Unit
M_{Ed}	469	[kNm]
V_{Ed}	55	[kN]
L	7000	[mm]
I_{zz}	$18260 \cdot 10^4$	[mm^4]
$W_{z,pl}$	$1383 \cdot 10^3$	[mm^3]
b	300	[mm]
A	11250	[mm^2]
t_f	14	[mm]
t_w	8.5	[mm]
r	27	[mm]

Table 5.12: Properties of a single steel tubular arch

Symbol	Value	Unit
I_{zz}	0.0204	[m^4]
E	210,000	[N/mm^2]
f_y	355	[N/mm^2]
A	0.1	[m^2]
t	25	[mm]
EA	$2.103 \cdot 10^7$	[kN]
EI	$4.2748 \cdot 10^6$	[kNm^2]

5.1.13. Hanger calculation

The hangers need to be attached to the deck where the transverse girders are placed to prevent bi-axial bending of the main girders of the bridge. The hangers will be placed with a center-to-center distance of 6m.

According to table 5.7 the maximum normal force in the hanger equals 467 kN. The hangers need to be adjustable to allow a redistribution of forces, prestressing or to adjust the geometry. One will apply a double hanger configuration, so the force in each hanger then equals

$$\frac{467}{2} = 233.5 \quad \text{kN} \tag{5.27}$$

One can use the Adjustable Prolite Sockets from CBSI Clodfelter. To guarantee extra safety (unsafety of the bridge cable), one uses a cable safety factor of 2 (of Bridge Engineering, 1997). According to the brochure, one can use a cable diameter of 29mm ($\approx$ 1.25 inch).

The corresponding sockets are the adjustable prolite sockets of type OPA30 which are adjustable in length (CBSI, 2019).

5.1.14. Arch calculation

Geometry and design assumptions

The arch consists of tubular steel section with a outer diameter of 1,300mm and a thickness of 25mm. For aesthetic reasons (to create an open design as possible), a vierendeel bracing will be used. The transverse bracing also consists of tubular sections. The cross section properties of the arch are presented in table 5.12.

The shape of the arch is an parabola (see figure 5.12). For assuming a $\frac{f}{L}$-ratio of $\frac{1}{6}$, the crest height of the arch becomes $\frac{55}{3}$m. By assuming the origin of the coordinate system at midspan at top of the deck, the shape $z(x)$ of the arch can be described by

$$z = \frac{x^2}{165} - \frac{55}{3} \tag{5.28}$$

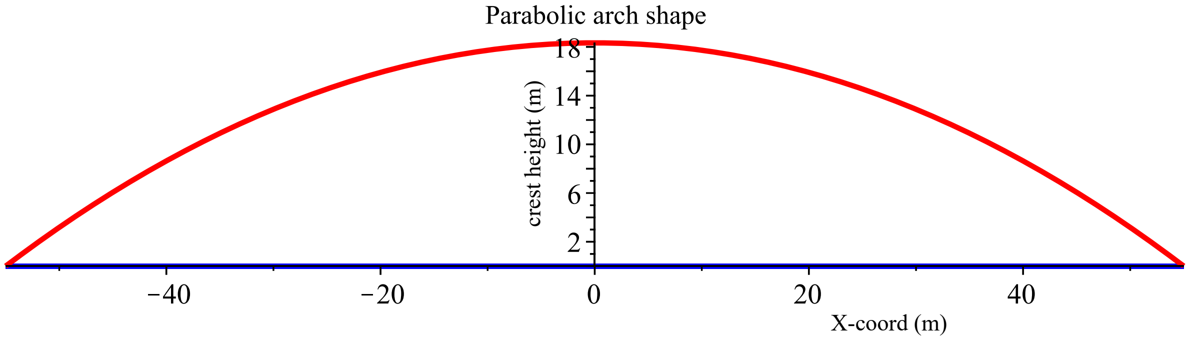


Figure 5.12: Geometry of the arch. The arch has the shape of a parabolato minimize the moments in the arch.

Design checks

The following design checks of the model are performed:

- Bending strength
- In-plane buckling

The calculations are performed in appendix G.7.

Check in-plane buckling

The in-plane buckling is checked by two separate methods:

- Approximate the parabola of (5.28) by a circular arch, according to (of Japan, 1971).
- According to NEN-EN 1993-2+C1, appendix D.3 - arch bridges.

The approximate radius of (5.28) can be obtained by computing the curvature and take the inverse of this value. Hence,

$$R = \frac{1}{\kappa} \tag{5.29}$$

In which R is the approximate radius of the parabola and κ the curvature. The curvature is defined as

$$\kappa = \frac{d^2 z(x)}{dx^2} \tag{5.30}$$

Applying (5.30) to (5.28) yields

$$\frac{d^2}{dx^2}\left(\frac{x^2}{165} - \frac{55}{3}\right) = \frac{2}{165} \tag{5.31}$$

The critical buckling force equals 17,301 kN. This is more than the maximum normal force in the arch according to table 5.7. Therefore, the arch is sufficient.

The second approach is based on NEN-EN 1993-2+C1, appendix D.3. The critical in-plane buckling force can be obtained by

$$N_{cr} = \left(\frac{\pi}{\beta\, s}\right)^2 EI_y \tag{5.32}$$

In which EI_y is the bending stiffness for in-plane buckling (equals to EI_z in TU-Delft convention), β the buckling length factor according to table D.4, s the half length of the arch which can be calculated by using the arclength formula and N_{cr} is the buckling force at the supports. Elaborating of (5.32) yields

$$N_{cr} = \left(\frac{\pi}{0.95 \cdot 58.99}\right)^2 4.275 \cdot 10^6 = 13{,}434 \quad \text{kN} \tag{5.33}$$

Again, this is more than the critical buckling force and therefore sufficient. The Eurocode approach is used (Skaf & Oyamada, 2019a).

This value is checked by using the approach according to (Jean-Paul Lebet, 2013). The critical buckling force according to this approach (see Appendix G.7) is 11,765 kN.

Temporary checks of the model

The load distribution as presented in G.3 are complex due to the additional point loads of the service vehicle. Therefore a temporary check of the output of Maple need to be performed. The accompanying horizontal force of load combination ULS-1.03, which consist out of a uniformly distributed load of 53.3 kN/m^1 and a point load of 50kN (service vehicle) equals 4,433 kN.

The load of the service vehicle is small compared to the UDL. The horizontal load can therefore by easily calculated by neglecting the UDL:

$$H = \frac{q\,L^2}{8\,f} \tag{5.34}$$

In which H is the horizontal force in the arch, L the span and f the crest height of the arch. Elaborating (5.34) yields

$$H = \frac{63.1 \cdot 110^2}{8 \cdot 18.3} = 5{,}215 \quad \text{kN} \tag{5.35}$$

The latter is almost the same as the value of 5,242 kN obtained from the Maple calculation (load combination ULS-1.03) and therefore assumed to be correct.

5.1.15. Pier calculation

Design checks

The following design checks of the model have been performed:

- Bending moment resistance (around strong axis)
- Bending moment resistance (around weak axis)
- Shear force check

For the piers concrete class C30/37 is assumed. The dimensions of the piers are presented in figure 5.13 The force distribution is calculated in SCIA Engineer with an assumed cracked E-modulus of

$$E_{crack} = \frac{E_{cm}}{3} = \frac{32{,}800}{3} = 10{,}933 \quad \text{N/mm}^2 \tag{5.36}$$

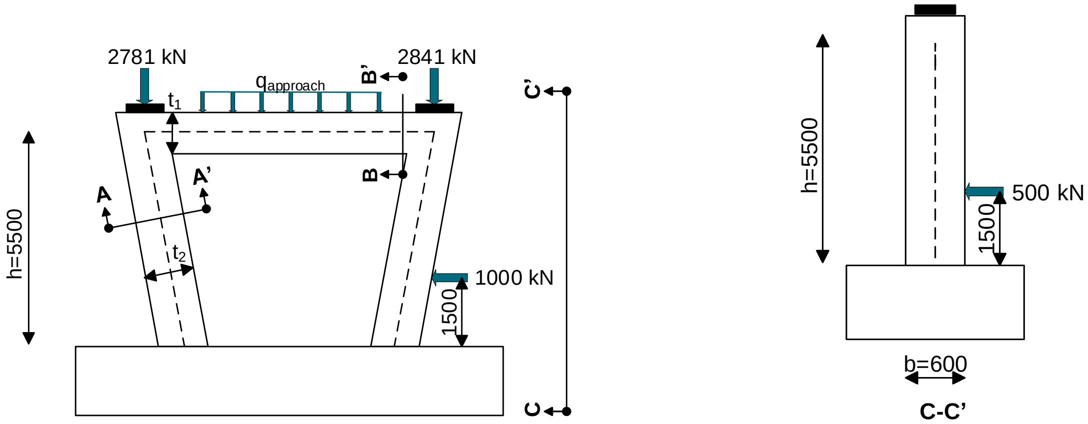
For the static model is referred to figure 5.13.

The bending moment resistance need to be checked as an interaction with normal force and bending moment. (Betonvereniging, 2010) gives interaction tables which take into account these interactions. However, to keep a parametric model, an exact calculation has been performed.

An amount of reinforcement steel is assumed and the normal force is known. By assuming that the reinforcement steel is yielding, by applying a vertical equilibrium check the height of the concrete compression zone can be calculated. Next, by applying the bending moment equilibrium equation the bending moment resistance M_{Rd} is calculated, in which M_{Rd} has to be larger than M_{Ed}.

Reinforcement configuration

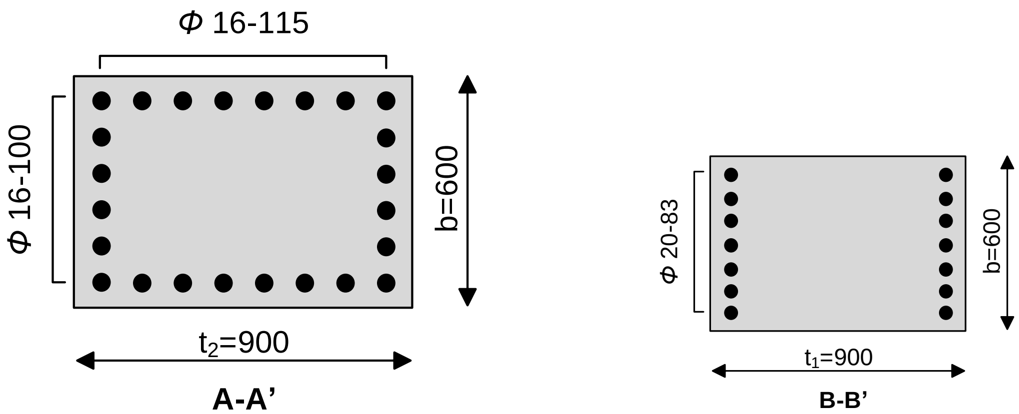
Based on the bending moment resistance analysis, the reinforcement configurations according to figure 5.14 will be applied.



(a) Front view of the pier, including forces according to load combination ULS-1.07 (see appendix G.8). The load $q_{approach}$ is taken as 20% of the total load at the main span.

(b) Side view of the pier.

Figure 5.13: Dimensions of the piers.



(a) Reinforcement configuration in cross-section A-A' according to figure 5.13.

(b) Reinforcement configuration in cross-section B-B' according to figure 5.13.

Figure 5.14: Reinforcement configurations.

Table 5.13: Properties of the piers.

Symbol	Value	Unit
h	5,500	[mm]
t_1	900	[mm]
t_2	900	[mm]
b	600	[mm]
a	1,500	[mm]
$M_{Rd,y,N,max}$	1,492	[kNm]
$M_{Rd,y,N,min}$	1,393	[kNm]
$M_{Rd,x,N,max}$	961	[kNm]
$M_{Rd,x,N,min}$	889	[kNm]

[1] Point of origin of the collision force is located 1.2m above the road level according to NEN-EN 1991-1-7-C1/NB, art. 4.3.1. It is assumed that the bottom of the column is located 0.3m below the ground surface. Therefore the value of a yields $1.2 + 0.3 = 1.5$m.

Calculation results

The calculation results of the piers are presented in table 5.13.

5.1.16. Detailing

Expansion joints

The expansion joints at the end of the bridge need to accommodate the elongation of the bridge deck. The elongation is due to:

- Temperature differences
- Introduced axial normal force in the bridge deck

According to the Brazilian Standards *NBR-6118/2013* a temperature difference ΔT of 15 °C is assumed (Skaf & Oyamada, 2019d). Then the elongation can be computed by

$$\Delta L_{temp} = L\,\alpha\,\Delta T \tag{5.37}$$

In which ΔL is elongation of the bridge deck, L the length of the span, α the linear expansion coefficient $1 \cdot 10^{-6}$ and ΔT the difference in temperature.

Elaboration of (5.37) yields

$$\Delta L_{\text{temp}} = 110 \cdot 10^3 \cdot 12 \cdot 10^{-6} \cdot 15 = 19.8 \quad [\text{mm}] \tag{5.38}$$

Additional elongation will occur due to the introduced axial force in the bridge deck. This elongation equals

$$\Delta L_{force} = \frac{H_{axial,max} - H_{axial,min}}{EA} \tag{5.39}$$

In which L is the length of the bridge deck in mm, $H_{axial,max}$ the maximum normal force in N, $H_{axial,min}$ the minimum normal force in N and EA the axial resistance of the main girders and bridge deck combined.

Elaboration of (5.39) yields

$$\Delta L_{\text{force}} = \frac{5242 \cdot 10^3 - 1848 \cdot 10^3}{210 \cdot 10^3 \cdot 43{,}000} = 41.34 \quad [\text{mm}] \tag{5.40}$$

So the total elongation yields:

$$\Delta L_{tot} = 2 \cdot 19.8 + 41.43 = 81 \quad [\text{mm}] \tag{5.41}$$

A sufficient expansion joint is the ULS Transflex bridge joint model, type 400 (BridgeCare, 2019). The movement accommodation equals 102mm. This type can be applied at one side of the bridge and has a limited cosntruction height so it will fit in the concrete slab completely. At the other side, a small expansion joint (flexible plug joint) can be applied.

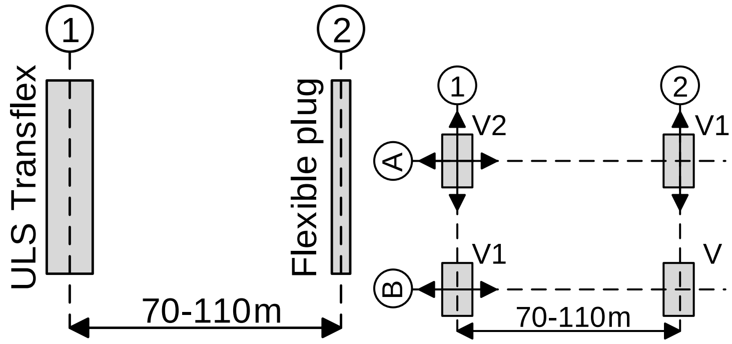
For the calculation of the expansion joints is referred to appendix G.9.

Bearings

Elastomeric bearings 450×600mm will be applied due its low costs with respect to spherical and pot bearings. Three different types of bearings will be used (Bearings, 2019):

- Type V2: horizontally free-deforming in all directions
- Type V1: horizontally free-deforming in one direction and fixed in the other direction
- Type V: horizontally fixed in all directions

Figure 5.15: Expansion joints and bearings



(a) Expansion joints. At axis 1, where the deck can deform freely, a ULS Transflex bridge joint model, type 400 will be applied. At axis 2, where the deck is horizontally restrained, a plug joint can be applied.

(b) Bearings. Type V: horizontal movement is restrained in all directions. Type V1: horizontal movement is restrained in one direction. Type V2: horizontal movement is restrained in both directions. The arrows indicate in which direction the deck can deform freely. Dimensions of the bearings: 450 × 600mm.

Dewatering

For dewatering purposes, a raingutter will be applied in the bridge slab, at one side of the deck. An applicable type is the Roostergoot Multiline HV100S/G. The height of this gutter is 6cm so it can be build into the slab (ACO, 2019).

Parapet

According to (fib, 2005) the minimal recommended height of the parapet equals 1.15m and where cycle traffic is present 1.20m. Therefore, a height of 1.20m will be applied.

Approaching bridges

The approaching bridges are not in the scope of this project. However, these bridges need to fulfil some requirements regarding the longitudinal and lateral slopes (fib, 2005):

- Maximum longitudinal slope: 6%
- Maximum lateral slope: 2%

Wheel-chair users need to be able to enter the bridge, as well as the gantry.

5.2. Parametric modelling

5.2.1. Introduction

The parametric model is made with Grasshopper, which is a Rhinoceros plugin. A parametric model means that not all parameters are constant. It gives the freedom to variate chosen parameters so the model can easily be adapted. Since the main span of the bridge is variable, the parametric model is an effective tool for this project.

5.2.2. Variables and constraints

The first step of the parametric model is to determine the variable and constant parameters of the bridge. Figure 5.16 shows most of the parameters of the bridge. The main variable parameter is the the main span of the bridge L. The rise of the arch f varies linearly due to the main span since the slenderness of the bridge is constant. The width of the bridge w_1 is constant since the bicycle lanes width and pedestrian path width are known. The inclination of the arches is determined with parameter w_2 which can not exceed the value of w_1. The number of girders of the bridge is also variable which gives the spacing of the girders s_1 as output. It is determined that the spacing of the girders should approximately be around 3 m. The hangers are placed where the girders connect with the lateral beams. For the sequence of the hangers there are two options. For the first option a hanger will be present at every connection of a girder with the lateral beam. In the second option the placement of a hanger will skip one girder - lateral beam connection in lateral direction. The number of bracing between the arches is also variable in the model. The diameter of the arch h_1 and the height of the lateral beam h_2 are constants determined with the calculation in appendix G. The height of the piers of the bridge is a constraint of 6 m.

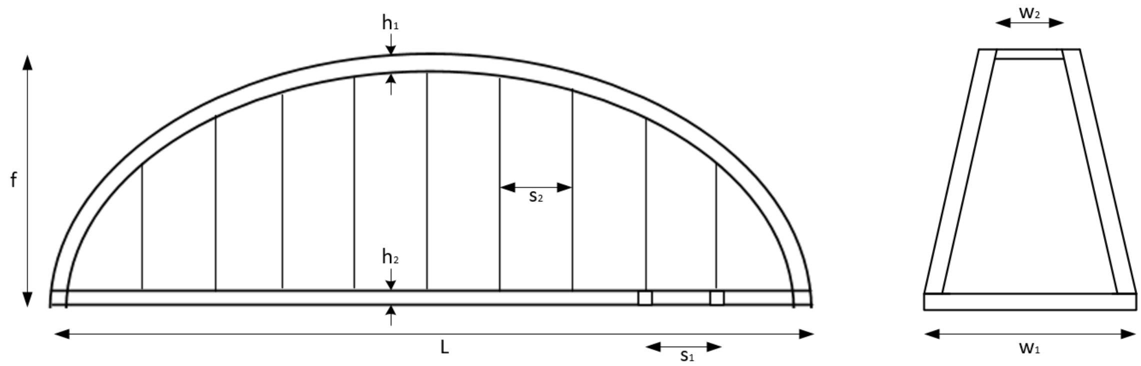


Figure 5.16: Sketch of the bridge with parameters

5.3. Comparison of results

To validate the model, different checks have been performed. To compare the model the variables needs to be set to the same values as the calculation. Therefore the length of the bridge span L is set to 110 m, the inclination width w_2 is 2 m, the number of girders is 37, the number of bracings is 13 and the hanger sequence is 2. The checks are performed based on the deflections, normal forces, moments and shear forces. The results are shown in table 5.14.

There are some differences in the results, but in general the results of the model are not completely different from the calculations. The results are mostly in the same order. It is very likely to observe some differences, because for the calculations some assumptions were taken into account to simplify the calculation. An example are the hangers. In the calculation the hangers are assumed to be uniformly distributed whereas in the parametric model they have a constant spacing and are not uniformly distributed. This difference will show in the results of the moment distribution and shear distribution in the lateral beams and arches. Load Case 14 (LC14) shows that the deflection calculated with Maple and the deflection determined with Karamba3D are quite similar, see table 5.14. Hereby is determined that the model is verified to give a good overview of the results of the load cases on the bicycle bridge. The model can be used with different parameters to gain needed information for a bridge design with a various span.

Table 5.14: The results of the calculations and the parametric model

		Maple		Model	
		Min	Max	Min	Max
LC0					
-Deflection Arch	[m]	-	-	-0.037	0.0012
-Deflection Main Beam	[m]	-	-	-0.057	0.0012
LC1					
-Moments Main Beam	[kNm]	-177	111	-180	188
-Shear force Main Beam	[kN]	-	-	-164	149
LC2					
-Moments Arch	[kNm]	-2804	2940	-3343	2288
-Deflection Arch	[m]	-0.210	0.210	-0.277	0.147
-Normal force Arch	[kN]	-5699	-4647	-5721	-4614
LC3					
-Moments Arch	[kNm]	-84	180	-686	208
-Normal force Arch	[kN]	-6295	-5242	-6369	-5226
LC7					
-Normal force Bearing	[kN]	-	2841	-2868	-2826
LC8					
-Normal force Hanger	[kN]	-	323	270	300
LC14					
-Deflection Arch	[m]	-	-	-0.178	0.092
-Deflection Main Beam	[m]	-	-	-0.211	0.074
-Difference Arch - Beam	[m]	-0.033	-	0.033	

5.4. Visualisations

When the Grasshopper file is made Rhinoceros will show some visualisations of the bridge. The overview of the Grasshopper file with the Karamba3D plugin is showed and explained in appendix E. The complete model with the supports and joints is shown in figure 5.17.

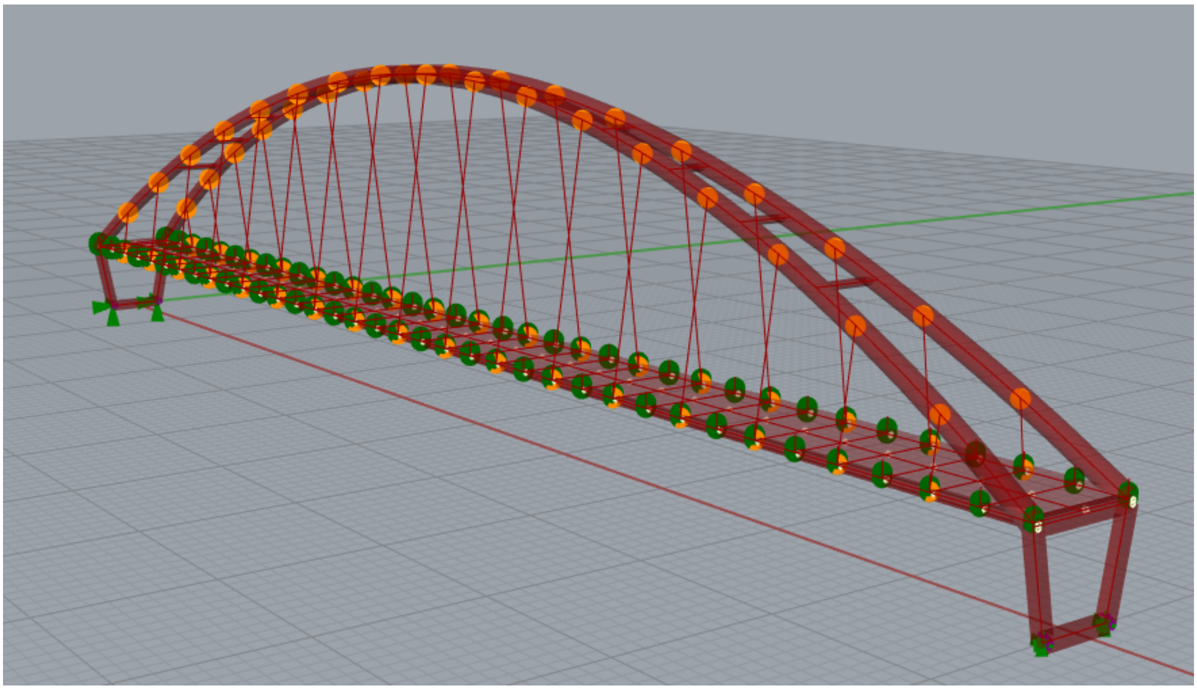


Figure 5.17: Bridge model with supports and joints made with Grasshopper and Karamba 3D

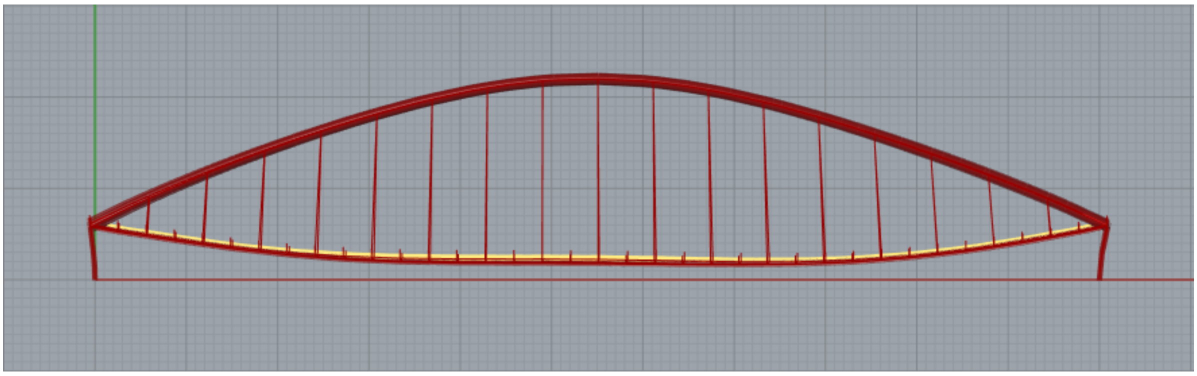


Figure 5.18: The deflection of the bridge (scale factor is 77)

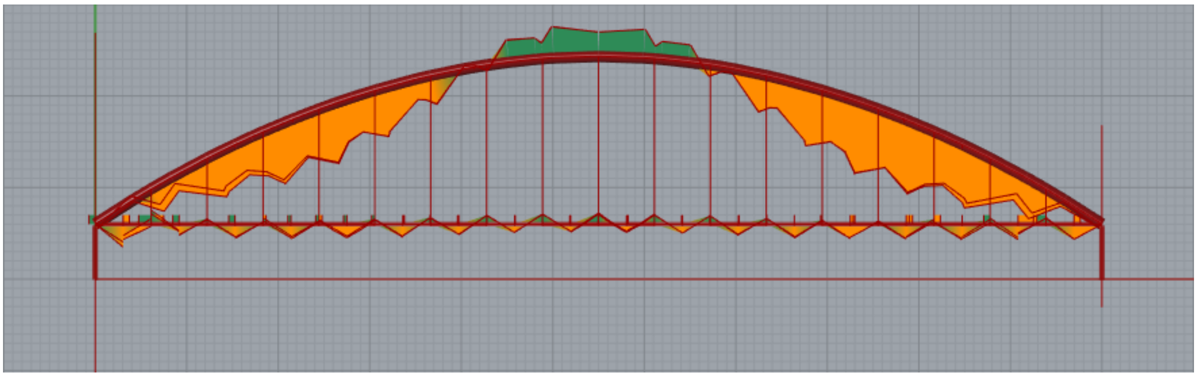


Figure 5.19: The moment around y axis in the model

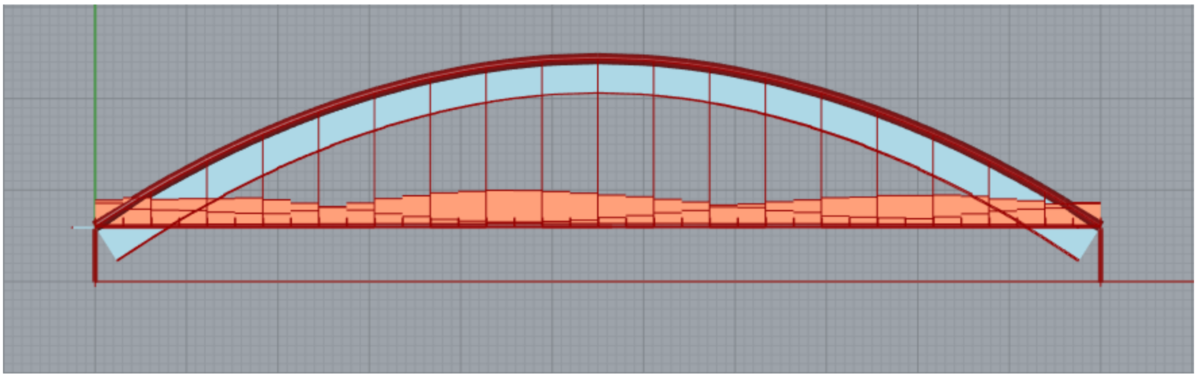


Figure 5.20: The normal forces in the model

5.5. Execution methods

In the design it is very important to consider the execution methods. Different designs lead to different execution methods and not all methods are suitable in such a dense city as São Paulo.

Method 1

Building phases:

- Pre-assembly the parts of the deck and the arch for all the bridges at a central location.
- Build the piers and intermediate supports.

- Place the deck and the starts of the arch.
- Build temporary supports for the top of the arch.
- Install the hangers.
- Remove the temporary supports in the river (cut the prestressing cables) and the arch.
- Construct the deck and pour the concrete.

Method 2

Building phases:

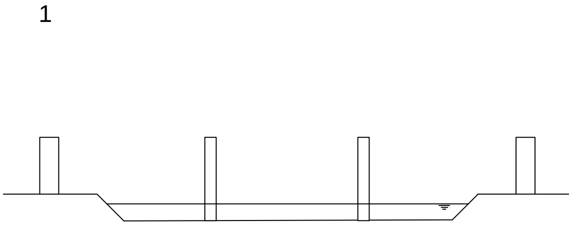
- Pre-assembly the parts of the deck and the arch for all the bridges at a central location.
- Build the piers and intermediate supports.
- Construct the complete arch on a barge by using temporary support.
- Navigate the complete arch to its final location and place it on the final supports.
- Install the hangers by using a scaffolding or mobile crane on a barge next to the final bridge to prevent excessive loads in the building stage.
- Remove the temporary supports of the arch.
- Construct the deck and pour the concrete.

Method 3

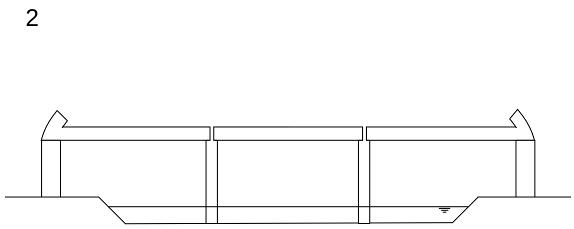
Building phases:

- Pre-assembly the parts of the deck and the arch for all the bridges at a central location.
- Build the piers and intermediate supports.
- Construct the arch into three parts on a barge and transport them to the final location.
- Install the hangers.
- Remove the temporary supports in the river (cut the prestressing cables) and the arch.
- Construct the deck and pour the concrete.

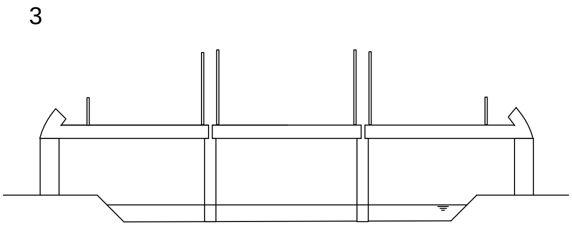
After the meeting of (Skaf, 2019) execution method 2 will be applied. In the prefabricated stage, all the parts are welded but when the different parts of the bridge deck and arch will be combined together, bolted connections will be used. Besides, the concrete deck will be poured after the complete bridge installed to prevent excessive cracking of the concrete. The execution method is visualised in figure 5.21.



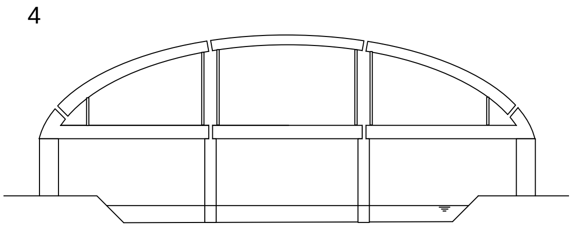
(a) Building phase 1: installation of the temporary supports, building of the piers, prefabrication of the steel deck and arch parts.



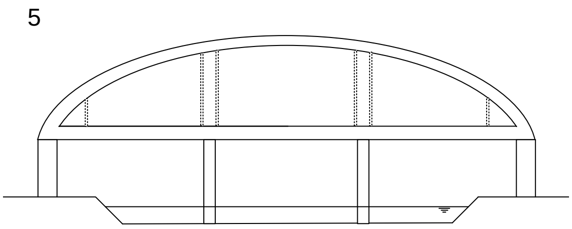
(b) Building phase 2: transportation, lifting and installation of the deck parts.



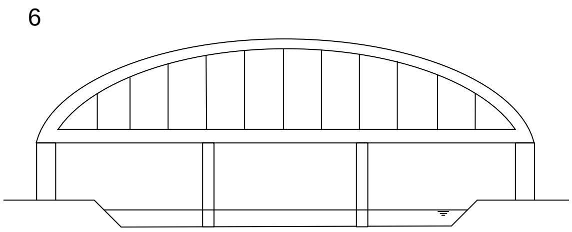
(c) Building phase 3: building of the temporary arch supports.



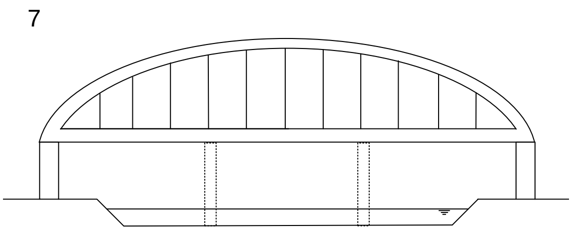
(d) Building phase 4: lifting and installation of the arch parts.



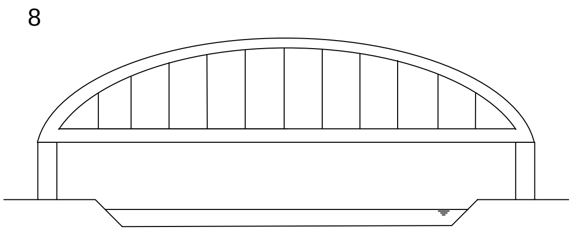
(e) Building phase 5: bold the deck and arch parts together.



(f) Building phase 6: installation of the hangers.



(g) Building phase 7: removal of the temporary supports.



(h) Building phase 8: pouring of the concrete deck.

Figure 5.21: Building phases of the arch bridge

6

Conclusions and recommendations

6.1. Conclusions

The aim of this report is to develop a standardised way of designing a bicycle network in São Paulo. Through investigation by three disciplines, the problem was tackled from different sides in order to create a solid network design. In Chapter 3, the most important stakeholders were established and analysed in three ways. The most important conclusion to be drawn from this analysis, is that the small associations do not cooperate, but are only aware of the other associations‘ actions. This holds back progress immensely, since separately they are less powerful. When these associations start to cooperate, they will shift to cooperation in a process, where decisions are made in consultation and negotiation with all external parties. This shift results in one combined approach with more chance of success in reaching their goal.

Interviews were held with stakeholders, which were also treated as locals to gather a more personal point of view. However, the results from the personal interviews need to be questioned, since the interviewees might have a biased opinion due to their predilection towards cycling. No locals were interviewed with a negative or neutral opinion on cycling.

The whole stakeholder analysis is combined to develop a list of requirements for the bicycle network to fulfil. The list of requirements is separated into three categories: infrastructure network, incentives for use and long-term guidelines and recommendations. The second category was created due to the outcome that cycling is not a usual practice and is mostly used for leisure. If only a bicycle network is created without people making use of it, the traffic problem would still not be solved. It must be noted that changing the locals‘ perspectives on cycling might take some time and effort, especially due to the car-based society in São Paulo, and is therefore linked to the long-term guidelines and recommendations as well.

One of the biggest problems concerning the current network turned out to be the connectivity, which is absent on most locations. The list of requirements was therefore used as input for the algorithm to determine where the best location is for extension of the current network and creation of a new network, in order to optimise connectivity. This is done while trying to have a minimal impact on the existing infrastructure for motorised vehicles, to minimise opponents. A new bicycle infrastructure is then designed with an availability that 99.51% of the inhabitants of the chosen areas of São Paulo can access the network within a walking distance of 320 metres. This is less than the constraint of the availability of the network within 350 metres, which was determined from the interviews with locals. The new network does not include roads that are classified as not suitable for cycling, such as the highways along the Pinheiros river.

To improve the connectivity, the new cycling network demands cycling bridges to cross the rivers, which will shorten travelling distances and mitigates some detours. The best location that came out of the network is the connection of Av. Arruda Botelho to Conjunto Residencial da USP. This is the location for which a bicycle bridge design was then developed, so the cyclists are able to cross the Pinheiros river.

Due to the fact that this is a pilot-plan, not only a bridge for this specific location is designed. A parametric design is therefore created, with amongst others the parameters of span, height and geometry of the arch.

This model is verified and these parameters can be adjusted along the demand of the specific location to create a conceptual design for a bicycle bridge. The parametric design connects well to the goal of having a design that can be extended through São Paulo. However, the approaching bridges and the design of the foundation were excluded, because they cannot be standardised. Not the complete bridge can therefore be standardised, because the approaching bridges depends on the local situation.

The report has shown a connected network design that takes into account stakeholders‘ wishes and demands and creates incentives for use. This network is created for only a pilot area of São Paulo, but is designed to be implemented within multiple areas in the city. This report is therefore only a piece of the puzzle that solves the traffic problems in São Paulo, but at least it is a start.

6.2. Recommendations

During the study, some limitations and boundaries have been found, and thus the recommendations are stated here to help the further research. The approach for the classification is to exclude the most dangerous roads, like highways and major arterial roads with very high volumes. However, it can be argued that for policymakers those roads are the most interesting. If bicycle paths are built along those roads they can increase the traffic safety the most.

First of all, the location of the pilot-study was determined partly on the fact that our research took place at USP. For further research it might be interesting to research the neighbourhoods beforehand, to create a combination of neighbourhoods that is more diverse. This would suit São Paulo more closely, since all neighbourhoods are very diverse in terms of landscape but also in terms of residents.

With respect to the stakeholder analysis and the determination of the requirements, the interviews held were limited in numbers. Besides, all interviewees were in favour of the bicycle path, leading to only positive answers. Furthermore, there were no interviews held with local people due to a language barrier. Therefore the results might have been one-sided, leading to one-sided conclusions. Corporate companies were also excluded, due to the lack of time and where not part of the pilot-plan. However, they are essential for a network that covers the entire city.

Regarding the created network, it seems to be fulfilling its purpose. However, in the southern part, with respect to the Universidade de São Paulo, the chosen path seems rather wibbly. The algorithm has chosen small roads, where it would be more comfortable to select one long continue road, with fewer intersections. For future research, it is very interesting to see that this will be implemented to increase the comfort of cyclists.

The elevation as a filtering factor is used to filter out the links that locate at the steep locations, without taking into account the direction of those links, since the available topological data was insufficient due to the low resolution. Future research should look at the correct and more detailed calculation of the steepness of the links, and possibly even include it in the cost function as an attribute.

This research determined the demand points and used them to connect the network properly. However, these demand point can also be used as an indication of the addition of bicycle sharing docks. Since the use of the coverage in this model, it can be used to indicate important demand points as, for example, pick-up and return locations for shared bicycle systems. This would also create incentives for use since not much locals have their own bicycles.

The design of the bicycle bridge is very conceptual due to the limited time span of eight weeks of this project. After a conceptual design a more detailed design is needed which first of all includes the arriving slopes of the bridge since only the main span is considered. The design of the slopes highly depend on the current infrastructure and available space at the destination of the bridge. Secondly, more details are needed for the design of the bearings of the bridge, for the connections and for the foundation of the bridge. Thirdly, a more detailed plan for the construction phase would be needed which also depends highly on the determined location of the bridge.

Besides the structural linear analysis also a non-linear analysis is needed. Considering that a bicycle bridge is quite a slender structure, a dynamic analysis is very important due to the occurrence of vibrations which eventually can be compensated with dampers.

If these recommendations are taken into account in further research, the design for the bicycle network would be more solid and fit the demands of the different areas of São Paulo better.

I

Appendices

A

Interview transcripts

All interviews were recorded and then transcripted afterwards. The transcripts serve as means of a source and are used for analysis. The numbered and bold sentences are our questions, followed by the answers of the interviewees.

A.1. CicloCidade - Flavio Soares

Friday March 15, 02.00 pm

A.1.1. Background information

CicloCidade is the association for urban cyclists in São Paulo. They are the voice for people that cycle or want to cycle in the city. CicloCidade works on analysing the existing bicycle infrastructure and monitoring the ongoing projects from the city hall.

A.1.2. Questions about CicloCidade

1. Could you give us a brief introduction of yourself?
My name is Flavio and I have been working for CicloCidade for 4 years. I used to be the head of communications from the association and now I coordinate projects with the initiative of road safety, it is called GRSP, Global Road Safety Partnership, which is funded by the Bloomberg Initiatives. It is a 2 year project, at the end of it we would have gathered a lot of data, to use it to go to the policymakers to show them the data and try to change the policies, not only regarding cyclists but also pedestrians.

2. What is the main goal of CicloCidade and how do they plan to achieve this?
I will first give some information about how it all started. It starts here on Paulista avenue. CicloCidade is already 9 years old, so when it started with the critical mass on Paulista Avenue. The cyclists would come here and it started growing. It grew and grew until it was really a critical mass. At this moment the administration started asking us: "guys, you are making a lot of noise, what do you want?". Then we sat at the table with the government in order to do policy making. And this is the moment where the grassroot movements started to become institutions. So at this moment 3 institutions were born at pretty much the same year: CicloCidade, BikeAnjo and CicloBR. So these 3 organisations were pretty much born at the same moment, all with a different focus. At that moment it was a little blurred in the sense of what we would do. But what we eventually got up to was that BikeAnjo started training people to use bicycles and created a whole network in Brazil. CicloBR eventually started to defend that the open roads would be used as open to cyclist and be made safer. But eventually they ended up doing the leisure lanes on Sunday. These are the guys that operate the maintenance stands on the leisure days.

CicloCidade operates in 3 fronts: Bicycle culture: different manifestations of the culture of the bicycle. We do have a partnership with the government where we have a bike garage where people can learn how to fix their own bicycle 2 times per week. We also do research on the state of cycle lanes, bicycles etc. Third is trying to change the policy making, trying to talk with the municipality to try to change the policies to improve the policies for biking in São Paulo. The cityhall is like our second home, we cooperate with them a lot. Not a daily basis but almost this.

3. So you do feel like they are taking you very seriously at the moment?
They do take us very seriously currently. It starts to get better. During the last 2 years we were in the middle of the bike clash with the previous mayor, but now it is starting to be better. They do listen to us. The new vice mayor is a bit slow but he does listen to us. We only operate in the city of São Paulo right now. Not yet including the surroundings of São Paulo, because it is already so big.

4. Does CicloCidade cooperate with other bicycle activist groups? Who are they? Or are there any other companies you cooperate with?
We are on the same page as CicloBR and BikeAnjo. Whenever it is important we tend to get together. in 2005, if I remember well, we made a major event on the bicycle culture. We occupied a major area of the centre for 4 days. There were about 10.000 people to participate. Whenever things are in danger or when it is important, we always get together. We are in close contact to all of them. Either with associations of bicycles, or with organsations in the urban mobility to see how everything connects. Because we would like to see the bigger picture and look at how everything connects.

5. Can you tell us something more about the public opinion on biking in São Paulo? Do you notice negative opinions, and if yes, what are they about?
We did in 2015 a major research of who are cyclists, for which we were talking to cyclists in São Paulo. One group was circulating in the central cyclists, that have more income, they cycle because it is an option. They can choose to take a bicycle instead of the car and metro. And this one is centre and the western part, this is where Tembici and Yellow are (in the west part), there is a kind of boom of cycling here. It is a flat terrain, which is very good for cycling and therefore there are a lot of bicycle sharing systems. People that would normally not cycle are starting to cycle now. North east and southern parts are low incomes cyclists. They will take the bicycle and cycle for an hour to get to their job or bike to mass transportation to get further. There is only one way to visualise this group. They have released their first data this year, they will release the microdata this June. So they can see if the other parts are improving or not, because monitoring in the other areas is very hard.

Once the last mayor Haddad implemented the 400km of cycle lanes, when there was the change to the next major, there was a bikeclash, which came from business from the commercial association. We realised that this was coming with a whole narrative that cycling is bad etc. So we tried to raise the voices of bike friendly data, so we used it from other cities like New York and so. We did not have the data from here so we used other. We did interviews with these guys to try to create a better image.

We started to study a street were cycling was used for deliveries. Then we partnered with the federal university of Rio de Janeiro, which had a master student that did a research to the economic effects of cycling. It was a cycle lane of 500m connecting 2 parts, connecting a bus and train terminal to another part of a cycle lane which would pass through a commercial street. She wanted to measure the impact that cycling there had on the street.

We have been waiting for the infrastructure to be implemented already since 2016, but the perception from the local business owners is misrepresented. They misrepresent the people that come by car. They think it is 80 percent, but it is the opposite. Still the business owners have the perception that most people come by car but this is not the case. We want to go back now to measure it again to see if the perception has changed, a few years later. And how much they are expending now. It is focused on research, so we can change a narrative through research. We do our advocacy through combining knowledge and research, for which we have to go after data to use this to change people‘s minds. Data based advocacy.

6. What do you think is the main problem at the moment that is holding the development of biking in São Paulo back?
Its vision and political problems. It is a complex development, but there is nothing now. Politics are holding it back. There should be more pressure behind it. I will give you an example. I used to be director for CicloCidade. We sued the municipality when they raised speeds on the marginal streets. We could stop them for 4 days, but we never received so many hater emails. So I think the Brazilians are in an interesting political way. When the new mayor came the bikeclash was there. It took us as technicians of planning, as CicloCidade, it

took us about 2 years not to only focus on the lanes and the bicycles but also on the safety. We are building it for safety, not for other things. The new mayor avoided this whole rejection from this kind of things. If you go another way instead of the other, he could do major changes. It is heading in this direction but it is not on the streets yet so we are never sure.

7. We have created a list of stakeholders, do you think there are relevant stakeholders missing?
It really depends on what you want, but I think it is a nice list. SPTrans operates the busses. They kill most cyclists historically. You will probably not be able to find someone from them to talk to. The train and metro are not really related to bicycles. Viaquatro is a private one, this one has a parking spaces, but you have to log in and everything, very bureaucratic. Viaquatro did not really know how to do this. Tembici operates a 24h parking space near Paulista in the eastern zone, the parking spaces are very heavily used because everyone has to use this.

There are also the night riders, as a crew during the night. If you want a different view. they do this for leisure. Their minds are very car based during the day. They do not use the cycle lanes because at night the roads are less busy. Might be interesting.

A.1.3. Personal questions

At last, we would like to ask you some personal questions, about your opinion on biking.
8. What is your view on the current situation of the bicycle network on the campus and in the city?
From my point of view it is start, it has already improved. We do have plans since São Paulo is a major city, we do have plans to grow in the next 20 years. We have the director plan. He was the one that leads the cycling in the director plan. We do have a mobility plan. Now we have a road safety plan as well. If you do not look at it as a whole, you will always think it is a mess and it is not connected. I do have these maps, if you look at them together you see how everything connects. We need to go to the data always, we always have to find the data if we do not have it. There is no data on making connections yet. We can look at different data, and maybe looking at everything you can come up with something. But there is no data on making connections. It should have been done yet.

At the moment we need to fill in the blanks, we need to connect. We need to build the new cycle lanes and in 5 years we can have a new fresh vision on what works and what not. Brazil can keep on researching. But you also have to implement otherwise nothing ever happens.

9. Could you rank the following parameters for us from most important to least important (1 is most important, 3 is least important):

1. Comfort (pavement conditions, slope, shade)
2. Risk (by interacting with motorised traffic)
3. Commute time (compared to other traffic modes)

For me, as the situation is now, it would be that risk and traffic time could be equally important and comfort is last. I have been in all situations, but not under a car yet. I do go for time, but I not neglect safety. For example the path that comes here. I could take a safe route to chose a partly connected lane, which is uphill. So as an experienced cyclist, maybe I would choose for travel time before risk. But because i am experienced. But if i am with someone else for example, risk would always come first. Comfort is a far third!

A.2. Yellow - Leila von Dreifus

Friday March 8 2019, 09.30 am

A.2.1. Background information

Yellow is one of the bicycle sharing systems that operates in São Paulo. They are one of the largest companies and are seen through the city centre. They do not work with bicycle docks, so their bikes can be picked up and placed anywhere.

1. Could you give us a brief introduction of yourself and your work right now and in the past at Yellow?
I am an engineer graduate since 2016, I worked also at 99 and after that joined Yellow. We are also going to launch electric bike, merged with green (last month). Head of global strategy planning. 7 countries in Latin America. Joined forces to be Latin player.

2. What is the main goal of Yellow and how do they plan to achieve this?
Aggressive, to change cities, by changing how people transport themselves. Think by offering people public transport and car, offer different kind of micro mobility vehicles (from bikes to small electric cars), shared and non polluted. Electric or do it yourself (bike). But in order for people to use it, we need to change the city. The city is not prepared for this yet in terms of infrastructure and connections.

3. Has Yellow been growing in São Paulo during the last years? Do you know how much?
We just merged, so yes. 6 months ago, we had 2.7 million rides globally. That is all I can say.

4. What are the future plans for Yellow? Are there plans to expand?
Launch pilots of new vehicles; electric bikes next week. Test other vehicles. Have more cities, be in all the cities that have transportation problems in Latin America. Aggressive plan to have more vehicles on the streets (bikes, scooters, electric cars) Electric bikes how would it work in São Paulo. In same areas that are already bikes that are there. Bit safer. More bikers on the street, streets become safer. Drivers become more aware, used to cyclists. Chicken and egg. Increase little bit demand and than the offer.

5. Does Yellow cooperate with other bicycle sharing companies, or are the others considered competitors? In case of the first, in what way do they cooperate and with whom? And in the case of the latter, who is the main competitor?
We do work together sometimes. As an example, the Marginal street bridge fell. We joined Tembici, for a temporary bike lane to a metro station. We operated the bike lane together. We proved to the government that we can do things like that. We used the movable things, the cones on street. There was enough demand, and make it real bike lane with paint. Run for 2 months (from December) and gather data. Initiative from the government and joined with BikeSampa. The goal to change to city, so we need to join forces so we have competitors.

6. We have created a list of stakeholders (which we sent you by email), do you think there are relevant stakeholders missing?
Talk to public transportation users, the microbility. Distances in São Paulo are very huge. Microbility is not the only way to transport themselves. The combination of micromobility with public transport is really the key.

A.2.2. Personal questions

At last, we would like to ask you some personal questions, about your opinion on biking.
7. What is your view on the current situation of the bicycle network in the city?
There is still room to improve. More room for pedestrians and bikers is needed. Micro mobility overall scooters, bikes, etc. In São Paulo is everything for cars , bridges for cars, etc. More people on micromobility on these roads, change the way the government thinks. For example. Parking space for bikes, dedicated parking spaces. City hall does not want to lose parking space for cars. Not everyone is going to support it. Since we already launched it, it becomes easier.

8. Could you rank the following parameters for us from most important to least important (1 is most important, 3 is least important):

1. Comfort (pavement conditions, slope, shade)
2. Risk (by interacting with motorised traffic)
3. Commute time (compared to other traffic modes)

Risk is most important, comfort second, commute time third. For me my home is 10 or 11 km of the office.I could come to electric bike. There are all the way bike lanes. I won't have risks. But I am not comfortable with the path. The bike lanes close by my house are very empty. Late at night I would bicycle alone. Same commute time as today, but be more comfortable. What I do today, use public transport, because I prefer that. I am not stuck in traffic, I can do other things like reading a book, one block away from my house and go to the train station near the office.

9. Consider, you are living in a street where no dedicated bicycle infrastructure is present. What would be an acceptable distance to ride your bicycle without dedicated bicycle infrastructure such as a bike path or bike lane (a bike path is separated from the road, a bike lane is on the same road as cars)? In other words: how many blocks are you willing to travel to reach dedicated bike infrastructure?
Depends on how busy the street is. If it is not busy, maybe 5 or 6 blocks. But on a busy street not more than 1 block on sidewalk and not on the street. I am a little bit scared of riding bike in the middle of the cars.

A.3. BikeAnjo - JP Amaral

Tuesday March 12 2019, 06.00 pm

A.3.1. Background

JP is cofounder of Bike Anjo Network in São Paulo, which has more than 7100 volunteers right now. He is currently coordinating the "Bicycle in the Plans" project. He has a bachelor degree on Environmental Management at the University of São Paulo, works for a sustainable urban mobility since 2008, is certified as an auditor on the BYPAD methodology - Bicycle Planning Audit, and is the Bicycle Mayor of São Paulo through Bycs. He is also fellow member of the Red Bull Amaphyko network for social entrepreneurs and of the German Chancellor Fellowship program for tomorrow's leaders from the Alexander von Humboldt Foundation, working with international cooperation on cycling promotion, especially between Brazil and Europe.

A.3.2. Questions about Bike Anjo

1.Could you give us a brief introduction of yourself and your work right now and in the past at Bike Anjo?
I am JP, I am born in São Paulo, lived abroad in many places. I studied environmental management. In my second year in uni I started participating in urban mobility activism, and within this group that I created we discussed a lot about urban mobility and then I started cycling. I used to drive the car a lot. So i found out the huge movement of cycle activists. In the critical mass movement, we created the concept Bike Anjo, which helps other people who want to start cycling, to help them out. We have a website, platform to match people that already cycle with newbies.

2.What is the main goal of Bike Anjo and how do they plan to achieve this?
It's an NGO. It has as a goal to mobilise people and change cities. We are not focused on having bike spaces, but to change cities through biking. we also focus on the environmental part to create better environment for cyclists. With this community of cyclists we organise campaigns such as bike to work and bike to school and activities with taxi drivers and bus drivers and we also focus on advocacy campaigns and how to implement public policies into the cities.

3. On the website of Bike Anjo the growing number of the network is shown. Have you seen difference in growth over the years (with political changes for example)?
We started in 2010, and we started with 30 friends in São Paulo only, and in a couple of months we already had 3 cities interested in Bike Anjo. in 6 months we already had 100 volunteers. In 2 years we already had 100 cities. We have a growth of 120 new members per month.

We had some data and we could correlate the period when the bike lanes come at the same time at Paulista, at that time the growth was way bigger. also the volunteers but also the people that wanted to start biking. also natural to see on the streets. 10 years ago drivers would always say that I had to go off the street and you would recognise each other cyclist. Nowadays it's not the same, cars are not that rude anymore, but still a bit.

4.What are the future plans for Bike Anjo? Are there plans to expand?
My role in Bike Anjo is more like a councillor, I am not in the team. We don't want to grow much but engage in the community. we want to work on the connections in the community, not per se grow so much. Second we are looking a lot at health, physical activity. Especially in the context of the politics in Brazil. Not only for Brazil but also for São Paulo, we are not talking about transportation so more but there is not so much interest. But

talking about health, quality of life gets more to the people and there is also more budget for public policies. we are World Health Organisation, global for physical activity. global goal to reduce the physical activity, Brazil has 65 percent has the condition of physical inactivity. We are looking a lot to focus on this.

We at bike activists only look at transportation, but it is more a interdisciplinary way. We should be independent of political changes. That is why we are changing the focus to health instead of leisure. Bicycles are more for mobility/comfort/urban use.

5. Does Bike Anjo cooperate with other bicycle promoting companies, or are the others considered competitors? In case of the first, in what way do they cooperate and with whom? And in the case of the latter, who is the main competitor?
No, we work with a lot of them, we do not have competitors as a small NGO. We always need to work together to have better results.

6. You are also the bicycle mayor of São Paulo for Bycs. What does this mean?
I was invited by Bycs to become the mayor. We created a 2 year plan on 3 main goals:

1. Focus on positive image of cycling in São Paulo. because when i became the new mayor, the new mayor came in which brought a negative view on biking.
2. Engaging the business and the private sector to promote cycling. not only bike shops but the whole bike sector, the big companies.
3. Improve the dialogue between civil society and the city hall in practice.

We did a bicycle fashion show, during the bike expo, to show the diversity of cyclists. To show that everyone can be a cyclists, much diversity! Everyone can do it. Big bicycles, small ones, everything. For the second goal, I helped on a campaign on a bike-to-work, to create an award and promoted cycling through a big event. For the third, we brought a professor from NHTV in the Netherlands, she came here and we did a workshop. She did some workshops together on solutions for the city and what to do for São Paulo, together with the city hall to cocreate the solutions together.

I am trying to get a junior bicycle mayor in São Paulo, to have some drawings on biking in São Paulo and then the best one will be the bicycle mayor.

7. Itaú and UCB are considered partners on your website. How does this partnership work, or are they mainly sponsors?
Itaú is a sponsor, they give us support for our institutional work to run the platform, the communication, the finances etc. UCB is such as Fietsersbond which connects all involved companies.

8.We have created a list of stakeholders, do you think there are relevant stakeholders missing?
I think that's it.

A.3.3. Personal questions

At last, we would like to ask you some personal questions, about your opinion on biking.

9. What is your view on the current situation of the bicycle network in the city?
It's better than 10 years ago. I still think we have some progress to do, there is a lot to do still, but have advanced a lot of course. We have new perspectives on the new mayor, which i think will do more on cycling.

10. What is your view on cycling as a way of transportation within São Paulo? Do you use the bike yourself?
It's much better to cycle now in São Paulo, it is as a capital one of the best cities in Brazil to bike. once you are in traffic you are respected. I do not have much trouble with that.

11.Could you rank the following parameters for us from most important to least important (1 is most important, 3 is least important):

1. Comfort (pavement conditions, slope, shade)
2. Risk (by interacting with motorised traffic)

3. Commute time (compared to other traffic modes)

When I have control of my time:

1. Comfort, low traffic streets with lots of trees and good pavement
2. Safety
3. Time

In the end I will be more efficient than a car anyway, because i go inside the neighbourhoods and will be on time anyway. New cyclists care more about time, because they cannot stand being stuck in traffic anymore. You want a lane to be safe but you also want it to be more efficient.

12. Could you describe your itinerary from home to work in terms of distance and way of transportation? From which area in São Paulo do you need to come?
I never calculated, it is about 4-5 km it is about 20min. I come from Vila Mariana, park Iberapuera until Pinheiros/Fradique, I always drive through neighbourhoods with trees. about 70 percent is on bicycle lanes. It is a very good route. There are not a lot of cyclists either. I would hate to drive on Faria Lima, with a cycling traffic jam.

13. Consider, you are living in a street where no dedicated bicycle infrastructure is present. What would be an acceptable distance to ride your bicycle without dedicated bicycle infrastructure such as a bike path or bike lane (a bike path is separated from the road, a bike lane is on the same road as cars)? In other words: how many blocks are you willing to travel to reach dedicated bike infrastructure?

For me there is no certain criteria because I cycle without them anyway. I would recommend a bike lane within 4 or 5 blocks from the house, it is not just the blocks but also within the neighbourhood. If you do not have to cross a bridge or a big road, that would not be nice. It would motivate to cycle and make it much safer. There is a research from ITDP says that there is a rate that people tend to cycle more if there is a cycle lane in front of their house.

A.4. Mêtro - Haydee Svab

Thursday March 14 2019, 07.00pm

A.4.1. Background

Metrô, the Companhia do Metropolitano de São Paulo, is a public transport company that operates in São Paulo. They are responsible for the planning and operation of the metro system. Haydee Svab is a former USP student and also a former Metrô employee.

A.4.2. Questions about Metrô

1.Could you give us a brief introduction of yourself and your work right now and in the past at Metrô?
I am Haydee Svab. I am a former employee of Metrô, but I do not work there anymore. I cannot help you a lot concerning Metrô, but I think I have useful information for you about the cycling infrastructure.

Then we will skip the questions concerning Metrô, and continue with other questions.

2. What is your view on the current situation of the bicycle network in the city?
The bike lanes now are also in the rich parts of the city. They mess with the mindset of people, the rich people are going to look at it and most people with money did not like it a lot but in the last years they started to accept it more. There are also bike lanes in the periphery, it is very important how many people cross there. There is another one that is not exactly constructed by the mayor but by Metrô but it was required by the mayor. The Metrô company built line 15, the silver line, it's on a rail and we have some urban impact. When we do this kind of interventions in urban planning, we have to do some activities that can be paid with money or can be delivered with something. We have to do something back, so we did a cycle lane. We did the

construction of the bicycle lane. We did rethink all the crossing paths (zebras), we rethought all intersections and considered all things including people walking. The neighbourhood that walked nearby. And also all the plans to make it a more sustainable environment. With the authorised plans that did not damage the street, a lot of bureaucracy. We also did some rest areas. Not just a cycle lane. But it was rethinking of the public space. The first part was already constructed and the second part just finished. Metrô is constructing a monorail until the east zone, and to compensate we create some public space. Which was a cycle path, benches and everything. The mayor has a cycle plan, but is not already done. But the great discussion at the time was why did we start at that part and not another one. It was a choice to try to earn some support from certain groups or certain parts of the city that were symbolic. That would start to change the public opinion. You always have to compensate for any construction in São Paulo. The silver lane was finished in 2016. The previous administration had specific coordination for bicycles. That does not exist anymore, due to then new mayor. It is not a priority anymore, which is very evident. But the infrastructure that was installed, is being used by people now that did not want to use it then. People thought it was a waste of money but at this time they do use it. Faria Lima is super crowded. When the lane was constructed, there was no Yellow yet. They came afterwards, Green as well. Yellow and Green just merged. And now you also see the scooters all around. It is being used more and they also use the cycle lanes. Yellow would have never been able to exist if the infrastructure was not there. Yellow wants now to show the government that people do use bicycles by creating demand. Rafael or Hannah from Bloomberg Felantropy: they do a great job about mapping the safety of people that walk or bike. They have a lot of data on this. Daniel Guth also mentioned this.

3. Do you think a combination of Metrô and bike stations would be a good idea, so that people can use the metro and then bike?
It does not work very well, because they are only allowed to enter the metro system after 8 pm. Nobody uses it because the opening times are not ok. And it is also too crowded in the metro: 9 people per square meter in the metro during the peak. If you already have a backpack people are already not happy with you because it is too crowded. It is not possible. There is no capacity anymore.

3.1 That is the case when people take their bikes into the metro. But what about placing bikes at the stations?
It depends on the neighbourhood. The exchange could be done. CicloCidade made a research about the profile of the people that use bikes. And it was less than 6 percent of woman. There is a lot of things involved. We have to think about our safety. It also rains a lot, which is another factor. It got worse during the last years. The normal in the summer was at 5/6 pm it rains, right now at 2 or 3pm. I would not take a bike in the afternoon because of the rain. In the morning I would. Not comfortable, totally wet. I would not do this instead of a bus. If I have to take the metro or a bus or 2 buses, or I have the cycle lanes such as in Paulista, I would take it. But I would not take all the hills. And the lanes are not the better way when it comes to hills. Other ways make you less tired but then you don't have the infrastructure. In Consolaçao you have the infrastructure, but nobody uses this one, they try alternative ways to make the hill less steep and make it less tiring. But then you don't have infrastructure. The question for cyclists is: I am ok with taking that risk or I will suffer on the hills. I tried it once and will never try again. The steep hills are not ok. Metrô is not so much chaining with bike. But with train in the suburbs there is. Because Metrô shut down some bike shelters, but SPTM goes into the perisphery and there are some of these that are super busy. They go to the station by bike and then go to work by train. There are some places that are overly crowded. But this is a feeling/opinion: but I don't think it is a walkable way, they have to take a bike because they live far from the station. They could also take a bus but this is more expensive and this happens mostly in the poorer neighbourhoods. The bus here is not cheap. Going to work is about 8 reais to go by bus, and they earn about 1000 reais per month. If you count this it is a big part of their wage. That is not an option. There is another class of people, they use it because it is cheaper. They do not care about health and sustainability but only because it is cheaper. They have to count their money. This is a different target group. They have no choice. There was a guy that cleaned in Paulista metro, he lives very far away but always used to bike to work and then took the metro to work. The money is the only argument for this people. It can be a side benefit, but not the main reason. People that come from the outskirts of the city, they have pretty much all this reason. This is what I heard from talking to people. I lived in west and working in east so it took me 50min by car without any traffic because I did the night shifts. It would have been not doable if I had to work during the day. It was almost 30km. If I had to work at 10pm I took the subway, I took it at Butantã, then change twice, and then was in the east. And then 40min driving to get to the point of construction. For many people this is a daily routine.

A.4.3. Personal questions

At last, we would like to ask you some personal questions, about your opinion on biking.

9. What is your view on cycling as a way of transportation within São Paulo?
I do not use the cycle lanes a lot. The part that I would use it is on Paulista, I always walk it because it is not necessary. I have a folding bicycle that I can take into a Uber or my car to go cycle somewhere. If I talk to people that use the infrastructure, you have some very good ones like silver line, Paulista really good, but there are some that are not really cycle lane built for that. It is just a part of the street that was painted. Paulista and silver line are cycle paths, built for cyclists. I am not enthusiastic about the cycle lanes. Our asphalt is bad and we have maintenance problems, during the rain period it gets worse. The cycle lanes that are on the street are not a priority to fix it. If you have a small hole in a road its not the same as for the cycle lane. A small hole is very bad for a bicycle. It is a bigger problem than for a car, but the bike lanes are not fixed. The maintenance problem also exists for the road but in comparison is worse for the cyclists. Painting itself also gets slippery when it rains. That's what I heard from other people. When I do use them I always use the sidewalk. It is not the best way but sometimes I don't want to share the street with cars. We need more cycle routes. In streets where street limits are about 30-40km/h. the cycle lane getting out of USP is the largest avenue that you have to cross. But if you go to the more calmer one, there is a cycle route there which is more calm. It is better to use. When the bus passes I don't like it because you feel the buss passing. I prefer a calm street, without busy busses and everything. The busses stop on the right, not in the middle, cycle lanes are also there so the busses cross the bicycle lane. This is not safe. The largest vehicle is just behind you. This is not safe. To have it the Dutch way with the busses, we don't have enough space for this to have the bicycle lane on the other side of the bus lane. Urban planning is different here. The infrastructure is not only looked at from the cycle point of view.

10. Could you rank the following parameters for us from most important to least important (1 is most important, 3 is least important):

1. Comfort (pavement conditions, slope, shade)
2. Risk (by interacting with motorised traffic)
3. Commute time (compared to other traffic modes)

For me, that would be:

1. Risk
2. Comfort
3. Commute time

Sometimes I spend more time but it's more comfortable so then it's more important. People that do not put risk at first they might be more used to biking. It also depends on where you live what your options are. I used to cycle more when I lived in a neighbourhood and not so much in the centre. It is much busier in the centre. In the centre it is much more difficult to find a calm streets to cycle in. so that is very different concerning the traffic pattern. And that makes me use less the bike. Only getting more afraid now.

A.5. Tembici - Renata Rabello

Tuesday March 12 2019, 02.30 pm

A.5.1. Background

Renata is projectmanager at Tembici since 2 years. She studied a bachelor degree of architecture and urbanism at USP, has a master degree in architecture, education and society and did a double degree on civil engineering.

1. Could you give us a brief introduction of yourself?
We are from the design team from Tembici, we are urbanists and architects and we want to think of the

location for each bike station in Brazil and also in Latin America. We study the city and see where is the best area to place a bike station.

2 What is the main goal of Tembici and how do they plan to achieve this?
The main goal is to be the bigger and the best quality bike sharing company. Our biggest goal is to have a billion trips in 5 years. We want to have the best system to have more trips.

3. Has Tembici been growing in São Paulo during the last years?
Yes, Tembici started in 2010 with Mauricio which was a student PedalUSP was his master thesis, a system for bikes on the USP campus. Then he opened the company of Tembici. 2 years ago we bought another company which used to be the operator (like BikeRio, BikeSampa, BikeSalvador), then we changed all the technology, we took all old stations and bought the stations from a company in Canada en then redesigned all the system. We studied the whole city again and researched the best places in the city and how many docks were needed in which location in the city. In the last year we have a cite in Buenos Aires and in Santiago in Chili. We have 800 employees at the moment.

4. What are the future plans for Tembici? Are there plans to expand?
We are talking about expanding to other cities and we are talking about electric bikes. We are starting a pilot project next week with electrical bikes in São Paulo.

4.1. Do you also take into consideration where the bike lanes are?
We always study where the bike lanes are. We study:

1. The infrastructure
2. The transport system, because intermodality is really important. We study bus stops, metro stations, train stations.
3. The service areas, attractive regions where people go to work or study. University is a good example.

Then we decide which area we want to cover with the system. Density is very important, at least 500m between the docks. We started with a small part because we cannot cover the whole city. Where there are bike lanes, the usage of bikes is bigger. We are trying to see with the government how we could

Government asked us to cooperate in the development of new bike lanes. But we do not know yet how to prioritise yet because we have to find where they need to be planned. The connections of the lanes are very bad, because the development of bike lanes is only recent. So there is a big challenge there. I don't know how the government is going to put the effort in this. Many people are against it, because the car here is very important. My thesis was about public bike sharing systems and the urban dispute of space. We always have to take a few parking spaces to put a bike station. People think that their cars own the street. So imagine constructing bike lanes on the whole street. We have some maps to show you where you can see where the bicycle lane near Faria Lima is the most used, it is about 15km and the connections are good. This data is always used, to show that people are going to use it and there is a demand. This proves the need for them to place more stations.

5. Does Tembici cooperate with other bicycle sharing companies, or are the others considered competitors? In case of the first, in what way do they cooperate and with whom? And in the case of the latter, who is the main competitor?
We had to cooperate when the bridge fell down, so we met with Yellow. The permits in São Paulo are always going way too slow. So we had to work with Yellow to work on temporary permits for a shared bicycle lane, and combined our maps. We also combined a bike lane somewhere else, which we placed every time the orange cones for, this was more as a test. They are our competitors, but sometimes we have to cooperate. We both want more bike lanes because it is better for us. We want to improve bike mobility and for people to see that biking in São Paulo is possible. Dockless and station based companies are very different though.

6. Do you collaborate with Itaú on certain levels or is it mostly the sponsor of the bicycles?
They give money and with that it is possible to buy the stations and bikes. But they also help in other ways. People can buy the plans in order to use the bikes. We are very close to Itaú because they sponsor us and it is on all bikes. They want the system to be good and working. We have to prove that it works. They do not participate in anything, but we have to show them. We are responsible for the technical issues, they do not check on this. We also have systems in other cities with other sponsors.

7. We have created a list of stakeholders to create an overview of all stakeholders involved in the bicycle network development in São Paulo, do you think there are relevant stakeholders missing?
Thiago is from CicloCidade and now from ITDP, I will give his email. He knows everything about biking. Daniel Haze is a cyclist. He is from CET in a department of active modes, he is responsible for analysing all projects for bike lanes and bike stations. Could be helpful. He was responsible for the workshops. I will give you his email. You have to talk to someone from CicloCidade! A cycle activist group, that is really important.

I think you should talk to Aline. Do you know the document "car versus bikes"? She participates in the documentary. It was filmed in São Paulo and also Amsterdam, multiple cities. It is really nice. I will give you her email.

We were in touch with SPTrans. ViaQuatro is operator of Yellow Line from metro, they have the Butantã station at USP. I think we have someone here, I will try to give the email. This could be important because it is at USP.

A.5.2. Personal questions

At last, we would like to ask you some personal questions, about your opinion on biking.
8. What is your view on the current situation of the bicycle network in the city?
I think that the connections are really bad. I used to cycle more, but not anymore since I work further from home. I always think that when you are on a bike lane, you have mental therapy, you can think of anything. But when on the street, you always have to think of your life, it is amazing and not positive. Yesterday I was cycling and a kid yelled to me to get of the street, the culture really has to change a lot! You have to be very careful. It is possible but you need to be careful. I always lived in another region in the north of São Paulo, at the other side of the river. It was so hard for me to reach other places because I had to cross the river and this was horrible. It is not possible on all placed. It is getting better and safer though, drivers get a bit more careful so it is improving.

9. What is your view on cycling as a way of transportation within São Paulo? Do you use the bike yourself?
I cycle a lot, I live quite close so I come to work by bike almost every day.

10. Could you rank the following parameters for us from most important to least important (1 is most important, 3 is least important):

1. Comfort (pavement conditions, slope, shade)
2. Risk (by interacting with motorised traffic)
3. Commute time (compared to other traffic modes)

Person 1: Is comfort not linked to risk?

1. Risk
2. Comfort
3. Time

I do not use a lot of bike now because I have to cross a bridge with a big slope, which is not nice. When I have to cross a bridge that is dangerous I do not go. If the time is better by bike I would take the bike, unless I have to take a big slope to get here, because then it is annoying and we don't have a bathroom here to shower. I prefer to go somewhere that is less fast but safer and with a bike lane.

Person 2:

1. Risk
2. Time
3. Comfort

Costs for transportation is also important! I have two ways to come, one with bike lane and one without. The one without bike lane is less safe but is faster, so I will take that one. To come here I have to drive uphill so back home I have to go downhill. Maybe safety is not my priority. When I take the one without bike lane it is 25minutes and the one with bike lanes it is 35minutes. So I prefer the one without bike lane so I can be quicker. I am always late. So then it would be:

1 Time 2 Risk 3 Comfort

11. Could you describe your itinerary from home to work in terms of distance and way of transportation? From which area in São Paulo do you need to come?
Person 1: I come by bus, 30-40 minutes. It is about 8km. I came by bike a few times but it takes one hour. And I don't have the slope then. Sometimes I go to a club via public transport to FariaLima and then take a bike from the bike sharing systems to reach my destination.

Person 2: By bike 25-30 minutes, about 4km. By subway same time. By bus it takes like 40-45 minutes, so way more. Sometimes I come walking, it is about 50minutes.

12. Consider, you are living in a street where no dedicated bicycle infrastructure is present. What would be an acceptable distance to ride your bicycle without dedicated bicycle infrastructure such as a bike path or bike lane (a bike path is separated from the road, a bike lane is on the same road as cars)? In other words: how many blocks are you willing to travel to reach dedicated bike infrastructure?

Person 1: Nowadays I live 1,5km from the bike lane, and for me that is ok. Maybe more I would not accept it. But the street is not very busy.

Person 2: I used to take 20minutes to get to a bike lane. It was very difficult, about 3km with a lot of hills up and down and it was very difficult. Sometimes I tried to take a bike but very hard.

It depends on the amount of hills there. If there is a plan maybe 1km maximum. Because I was not comfortable when it was 3km.

Person 1: We have some cycle routes, with signs, but nobody cares about it.

In Liberdade people do not use the bikes a lot, but we are still trying to understand why. Bike sharing users are normally not used to biking. So they prefer places where there is bicycle lane.

A.6. Prefeitura do Campus USP - Douglas C. Costa

Wednesday March 13 2019, 03.00 pm

A.6.1. Background information

Douglas C. Costa studied at USP and works as an engineer for the Prefeitura do Campus USP. This is a separate municipality than the one from the city of São Paulo, with their own laws and rules.

A.6.2. Questions about Prefeitura do Campus USP

1. Could you give a brief introduction of yourself and your work?
I am a civil engineer and nowadays I am a project manager for the prefeitura, the municipality. On projects for USP campus, but not only for mobility. That is the problem, I have to work on multiple projects. We do not have departments like a normal municipality. Here we don't, I have to take care of everything. The electrical engineer takes care of the infrastructure and we work together. We have to do everything together. If we take vacation it is quite a chaos.

2. What kind of authority does the municipality of USP have? Do they make all decisions for the area on their own?
We have administrative autonomy, the university belongs to the state of São Paulo. All surroundings belong to the municipality. CET does not have authority over our campus at all. They do some educational events from time to time because we do not have any fees, and we try to use some traffic calming things but they are

not enough. We do have a lot of problems with accidents over the years. We are trying to reduce that, 10 year ago we did not have any speed limit. It came from 60 to 40 but not everybody does this. The solution is the project, because the space of the roads will be reduced so the cars are obligated to drive slower. I think that's a great solution and its not a massive investment. We have 3 years for this.

2.1 Do you have some kind of CET for the campus?
No we do not. We do not have a police force so we cannot fine people etc. Problem is we do not have a legal fee to send to people, we have a limitation on sending fees so we cannot fine them. So if we have this project we can implement the municipality to check on people. A lot of bureaucracy and politics is involved. I have been here for 5 years. They cannot fine anyone so that is why people can drive as fast as they want and park wherever they want. If the CET starts to control the campus, and charge infractors, then the problem will be solved. The professors actually run the campus. They keep changing every 4 years. That makes it chaotic and a long process to change things.

We have the university campus that has 4 million square km, quite huge, 100.000 people that come in and out everyday. We are in a huge city, the biggest on the southern hemisphere. Very chaotic. Our mobility problems are unbelievable. We should have an underground station inside the campus. But the subway station was started to build 10 years ago but for politics it did not happen, so they put it outside the campus. We do not have a mass system on the campus. The majority that comes here comes by car. In 2014 we hired a company that made a countage of the vehicles that entered the campus and exiting, 24 hours on 3 days in the end of November. We know how many vehicles come in and out of the campus. Peaks in the morning and evening. We have an idea of the busses but we do not know anything about the cycling. The infrastructure is surrounding the campus, built by the last mayor, Haddad. Some Dutch consultants helped with that, because they have a lot of knowledge. The cities there are smaller but the principles are the same.

The campus is different, there are a lot of professors that are cyclists and they keep demanding a cycling infrastructure, but they never could do it. I have been working for 5 years and also studied here and never understood why. That project came to my lab and I wanted to buy the infrastructure for the campus. It was really hard because we have 9 roundabouts and we hired TC Urbis. They used most of the research about the principles of cycling inside the campus. The problem was not money, not technical but it was politics.The administration is different than abroad. We have a relationship with the state of São Paulo, the municipality is another kind of administration so the politics are different from others. This rector wants to put the project up and build it. He has 3 years so we are revising the project, looking up the problems that there in here and implement it in the problem, they studied the roundabouts, they used dutch solutions. Because the dutch have the only solutions for roundabouts. Roundabouts are dangerous for pedestrians and cyclists. We are improving the transportation infrastructure, with guidelines: take care of pedestrians, then cyclists, then busses and mass transportation and then cars. There are three major entrances, called one, two and three. Those are the points that had the countage, we have a lot of data on the busses and cars. We never count the amount of cyclists. We have 6 entrances for pedestrians.

The projects consists of cycle ways, so just painted on the roads. The recourse to implement 60 km of cycling infrastructure would be 4 million reais, we can solve the problems on the roundabouts on the pedestrians, fix the cycle lanes on campus and attract cyclists and solve the problems with the parking lots because people park wherever they want. Another professor said cars should not be allowed to enter the campus. They are thinking on charging cars for parking there so they can get a lot of money from it to benefit the campus. 40-50 million reais a year revenues only for charging. The cars right now have all benefits.

Rede estrutual de circulacao de bicicletas (powerpoint): bicycle lanes around the campus which they want to link to the bicycle lanes within the campus. But right now there is a black area around the campus where there is no link. The cycle lane along the water from CET is horrible because it is shared with pedestrians. It was decided by politics and not by engineers. Cycle path is completed segregated, they wanted this on the campus but the investments would be very expensive. Right now they want cycle lanes painted on the ground and then change it over the years if they receive more money. I said to the mayor and rector, we have only project, we don't have any other ideas.

The surroundings: a lot of students live inside the campus, I have the data for hat, in a residential complex. We have some neighbourhoods that people live, republicas (flat where students live together). Multiple areas. We have an underground station at Butantã. We have a mass transportation system brings 20.000 in 30 minutes and we have to bring all people to the campus. We have the buses that we spent 70 million reais on as a campus, to bring all the people to campus. These buses circle the campus, all students get a free card, from the budget from the university.

3. Do you cooperate with the municipality of São Paulo?
We do have some contact, for example the water supply system SABESP works over the state and we need contact with this company all the time. We also have contact with CET and with the construction company for the municipality.

If we want to build a new building we have total autonomy for that. We hire specialists to do that. My responsibility is to hire the company that can build everything to our requirements. I make the requirements for that. we contract the best company via tendering. That is really hard in Brazil. This discussion is taking place in the capital because this needs to be improved. Brazil is a country that still needs to be built. We need more agility to build things. Huge problems for engineers.

4. Can you explain us something more about the Plano Cicloviário that was created in 2014? Was it all implemented?
We are still working on bureaucracy and decisions, it should be about 6 months but I think it will be finished at the end of 2020 it could be finished. The last years they did not do anything so it is very frustrating.

A.6.3. Personal questions

At last, we would like to ask you some personal questions, about your opinion on biking.

5. What is your view on the current situation of the bicycle network on the campus and in the city?
It is absolutely necessary to build an infrastructure and change the culture gradually. I am 37 years old but the young people, like 25, don't care about cars and they want to cycle. They will need infrastructure for them to use it. The industrialisation process from the 50's was the B master of our economy. Gave lots of employment in the car industry. Now we are on a crisis on the sector, the 4th biggest company is now bankrupt. All the economic system of this city and metropolitan region, we are always dependent on cars. I don't care about cars but i don't cycle either, because i cannot do it because of my leg. But i will again. I used to love to cycle. I would love to see a campus and even city that is more pleasant to live and be in. There is a lot of of traffic and people are rough. The city is so amazing but the traffic drivers makes it aggressive. We lose 5-7 of our GTP just due to the traffic. If we have investment on subway and cycle paths could be a huge thing for our city. I have no doubt about it. And we are working on that way, but everything changed suddenly due to politics. One problem of the policies is only for 4 years, so only short-term projects and those projects demand a long time to come through. In 4 years it is very short-sided. The strategic master plan was planned to be long-term but the next administration burned it and did not want to use it anymore. It was from the administration before so they do not have to follow this.

Important to know is that a lot of people do use the roads in campus just to cross, not to go to campus! They avoid the traffic by using the campus, so they drive very fast.

6. What is your view on cycling as a way of transportation within São Paulo? Do you use the bike yourself?
It's definitely fantastic, a lot of people say it is a civilisation process, it is to be a real citizenship decision to use a bicycle because you don't do harm to the environment in terms of pollution and noise. And for yourself so good because the relationship with the city changes, because you do exercise and see people and see the city differently. The future generations are definitely going to use it, they will see the benefits of it. It will be the decision for short term trips, door-to-door transportation. from for example from the train or metro systems. The mind of the conductors is a problem here, they are really aggressive. When they get in the car it changes their mind. The last mayor tried to change that, it is a process, it takes time, we had lots of critics. The decisions he took to change the transportation are very good. If you do not change anything you are not going to change their mentality.

7. Could you rank the following parameters for us from most important to least important (1 is most important, 3 is least important):

1. Comfort (pavement conditions, slope, shade)

2. Risk (by interacting with motorised traffic)
3. Commute time (compared to other traffic modes)

First risk, because there are a lot of deaths in the traffic systems. Only with the motorcyclists we have about 2 guys killed everyday only in the city. Second comfort. Third commute time. Not for me because I live nearby. When I studied here it was like 25km from here and I took about 2 hours to come here. I hate to waste time on the traffic system so its a nightmare to live here.

8. Could you describe your itinerary from home to work in terms of distance and way of transportation? From which area in São Paulo do you need to come?
I always come by car even though I live nearby. If they started to charge monthly to park here, I would probably start to walk or take the bus. If I take the car I am here in 10 minutes. I come here alone. I have been doing that for 3-4 years, quite selfish and I am conscious about it and that's worth the comfort. I live about 3,5km from here. When I studied here I lived 25km away.

9. Consider, you are living in a street where no dedicated bicycle infrastructure is present. What would be an acceptable distance to ride your bicycle without dedicated bicycle infrastructure such as a bike path or bike lane (a bike path is separated from the road, a bike lane is on the same road as cars)? In other words: how many blocks are you willing to travel to reach dedicated bike infrastructure?

I stopped using bikes about 5 years ago. I would say like 4km, it depends on the slopes. I think 4km is ok. Does it also depends on the risk? Yes a lot. Inside my neighbourhood it's calm so that's why 4km is fine. If it is busy i would be less. I do not bike on big avenues, only if they have bicycle paths.

A.7. Aliança Bike - Daniel Guth

Monday March 11, 2019, 11.00 am

A.7.1. Background information

Daniel Guth has been working with the public board on the management of projects and the municipal government policy. He has been working on the implementation of the leisure-based bicycle network in São Paulo and facilitated the mapping of the ciclorrotas (special bicycle routes with designated bicycle lanes alongside the road) within the city centre, in collaboration with Cebrap. He also coordinated a bicycle program for schools. He works for Aliança Bike.

A.7.2. Questions about Aliança Bike

1. Could you give us a brief introduction of yourself?
I work in Aliança Bike, a national bicycle industrial association. We have already 100 companies affiliated. We do a lot of work about bicycles: promoting, good lobby, research studies, economic studies, special projects, debate, etc. My story with bicycles began in 2006, when I bought a folding bicycle (one of the first from China), and I got super happy. That was because I could ride and get into the bus and into subway stations and all around the city with this bicycle. I sold my car in 2007 because I didn't need it anymore. The bicycle and public transportation combination were okay for me for everything I was doing at that time. Moreover, I moved to an apartment that had no garage, so parking in the street was a bad thing since it had a blue zone. This means that you can only park your car for 2 hours and there was no private garage for me, so I sold my car. In 2007 I was invited by the secretary from Sports, Leisure and Entertainment from São Paulo to work with them. So, I went there and the first job I got was the coordination of a Virada Esportiva, 24 hours of leisure and sports in the whole city. This is an important, yearly, event in São Paulo. Besides the 24-hours event for sports and leisure, there is another one, on a different date, for culture.

I helped to coordinate this event and there were a lot of bicycle events involved. Since I was working with bicycles and commuting by bicycle, people in the secretary referred to me whenever there was something bicycle related. They were like: “Talk to Guth, he's the cyclist guy.” In 2008 I had a meeting with the ex-mayor Gilberto Kassab (mayor of São Paulo from 2006 – 2013, red.) and the secretary of sports. In this meeting I talked about an old law from 1989 that told the city hall they should organise bicycle paths, leisure paths, between parks in the city. The mayor agreed to execute this plan and that's what they did. With the help of a friend that worked at a publicity agency they involved Bradesco Insurance. Bradesco was really interested in sponsoring the initiative and we did not have any money from the government, because it wasn't planned for us to do this that year. To make use of the public money in São Paulo you have to plan it the one year before to implement it the next year. Now with the money from Bradesco it was possible to execute the plan. In 2008 we launched the leisure bike lanes in São Paulo. In the beginning it was a network of 6 km and nowadays it's 120 km. Every Sunday more than 100.000 people cycle on these leisure bike lanes. Because I planned and implemented this policy, I got to know everybody that was talking about bicycles in São Paulo and in Brazil.

Then I got to know "Critical Mass". You probably don't have this in the Netherlands, because you don't need it. It is a thing from San Francisco in the early nineties they organised cyclists one day in the month to shout for something, against capitalism, etc. Like a protest, to talk about urban mobility but also to address other issues like capitalism or social inequality. So, it is comparable to a protest, but every month they gather. In 2007/2008 it was like ten people over here. In 2009 it grew to 100/200 people and came together every month to talk about bicycles, bicycle infrastructure, etc. In 2008 it was an important start, not really a beginning because it started way earlier, but it was important nevertheless because due to the policies there was more talking in the city hall about bicycles and bicycle infrastructure. In 2010 we organised, and I was the coordinator as well, first cycle route map of the city. We got 10 urban cyclists together for 2 months to cycle all the city to see all the best bike routes in the city, without physical infrastructure. There were only 32 physical bike lanes, leisure lanes, implemented at that time. So, the map contained the best and safest routes, without infrastructure, for kids, elderly, everyone.

In 2011 I got out from the city hall because it is hard to work there, with policymakers and decision making, etc. In 2012 a friend of mine was invited to be the secretary of education in the city hall and he invited me to work with him. So then again, I worked in the city hall. I worked to make dialogue with the parliament, with the congressmen in São Paulo and worked furthermore with special projects. One of these special projects I coordinated was the bike-to-school project. We worked with 46 educational centres, the all over the city. These public educational centres have everything, pools, theatres, etc., and the age of the children attending these schools range from kindergarten until 18 years old. We worked with these centres to have bicycles and bicycle infrastructure for the kids within the centres, but also to have safe cycle routes to school. Every morning the students go in groups from 10-30 students by bicycle to school.

In 2013 we had a political change due to the elections and this program was discontinued. So, it only worked for 1 year. At the end of 2012 I quit the city hall again. In 2013 I organised a private company working with cycling projects: communication, of all sorts regarding bicycles. I got an invitation from the urban cyclist's association in São Paulo. It was not a paid job, it was voluntary. It was great for organising data and lobbying, to make bicycles grow in São Paulo. From 2013 until 2017 I was working with the urban cyclist's association from São Paulo, it is called CicloCidade. In 2013 Aliança Bike invited me to be a consultant of a huge project they started on bicycle taxes on a national level. We organised this huge campaign to decrease bicycle taxes on the national level. In 2017 I left CicloCidade, because Aliança Bike invited me to be the executive director of the organisation. That's where I am now.

Parallel, in 2018, I started my master's degree in urban planning at the Federal University of Rio de Janeiro and right now I'm in the second year and doing my final project, my thesis. I have a degree in social communication and now I'm working on getting my master's degree on urban planning, focusing on bicycles. It is more about travel behaviour and a dialogue with urban planning systems, like the director plan of a city. How travel behaviour can help these tools regarding land use and others, help to implement to circulate urban mobility better

I used to write, still do, a lot about bicycles. I used to write for Folha de São Paulo, it is a huge newspaper in Brazil. Two years I had this column about bicycles in São Paulo and every week there was an article to talk about São Paulo and bicycles in São Paulo. I wrote 3 books: one about bicycles in capitals in Brazil, one about animal rights and one book, recently launched, about bicycles in small cities in Brazil. I also have a book for you about bicycles in small cities of Brazil. Small cities have about 100.000 inhabitants, medium cities range from 100.000 to 500.000 inhabitant and big cities are bigger than 500.000 inhabitants.

In small cities it is what makes bicycle culture in Brazil important. That is because, on average, 13-14% of all trips in the city are made by bicycles. However, it is changing in the last years due to the motorcycles. Many cyclists are migrating to motorcycles.

2. What is the main goal of Aliança Bike and how do they plan to achieve this?
Our mission is to promote and stimulate the grow of the bicycle economy in Brazil. Last year we did a study about bicycle economy in Brazil. First to answer the question: What is bicycle economy? What represents bicycle economy? It is not only industry, import and export, it is more. It is about the many factors that involve bicycles, like bike sharing, the whole industry. It is not only producing, but also selling, using, cycle tourism, people travelling with bicycles, bicycle events, sports, etc. This study is also available in English and online.

Our mission is to make all this bicycle economy grow in Brazil. Of course, it is about industry, about the increase of popularity of the bicycle. Making bicycles more affordable, so you have to lower the taxes, make the infrastructure better, more bike lanes, etc. All the policies help the bicycles to grow and also help to make people buy bicycles and this helps the whole bicycle economy system.

We have complex problems, because we have social economic problems in the past. Of course, you cannot segregate bicycles from this, you cannot segregate urban mobility from this. We have historical social and structural economic inequalities in the city as well as in the whole country. Rich people in São Paulo live near their jobs and use more cars than public transportation and bicycles. Poor people live a long distance from their work and they don't have cars to use and depend on the bad public transportation.

You're looking at Pinheiros. All people working in Pinheiros do not live in Pinheiros, they live like 30km away. How do they get there? How can we make jobs closer to people's homes? How can we can public transportation and bicycles to them? 30 – 40km within the city, that kills more than a 1000 people in a year, is not doable. It is a complex thing.

I ride my bike in São Paulo since 2006 and I think São Paulo is, from the capitals, is one of the best cities to ride a bicycle right now in Brazil. If you ride in Rio de Janeiro, it is a mess. Drivers are crazy. Since the 90's traffic is congested in São Paulo. All drivers know that the problem of the traffic jams over here is the number of cars. The main problem is that we have to many cars. In other cities they do not know this, because the traffic jams are more recent. That's why the drivers are crazy over there. Everyone and everything that is in front of the driver is a problem. If it is a cyclist, it is a problem. If it a pedestrian, it is a problem. So, it is really dangerous.

Since the beginning we hat to share to roads in São Paulo. Drivers are used to share the roads with kids, pedestrians, cyclists, dogs, everything. So, you have to be aware, because suddenly a cyclist can pop up in front of you. The average speed on the roads in São Paulo is lower than in other cities of Brazil. That is why it is much safer for cyclists here.

I'm not saying São Paulo is good, it is the worst. Car drivers are still rough against bicycles. It is just better than the other cities. I can compare because I rode in all different sized cities and also the numbers can compare this. São Paulo has a 1000 deaths in a year, but compared to other cities we heave one of the lowest rates. This is about 7.x per 100.000 inhabitants. If you take Recife for example, this number is like 12/13 per 100.000 inhabitants. São Paulo is low compared to this, but high if you compare that number to cities as Amsterdam, New York or Berlin.

In Brazil we have this organisation called ANTP, the National Association of Public Transportation. Last year we launched a book on the last 20 years about urban mobility in Brazil. I was responsible for writing about bicycle policies in Brazil in the last 20 years.

The first bicycle lane is from 1975 which was destroyed later on in 1982-something, to replace it by a tunnel for cars. Then in 1980 the city hall made a huge bicycle network plan for the whole city, connecting 14 sectors of the city. It was a network from over 200km of bicycle lanes, that was planned. They planned this due to a huge oil crisis that was happening in the seventies. The oil prices went up and they needed another way of transportation. On national level, from 1976 until 1980, the federal government made a lot of plans regarding bicycles network, pedestrians, public transportation, active transportation, etc. The oil crisis never got to Brazil because they have oil, so it was not a problem here. In 1984 there was another bike lane network plan from the city hall and in 1994 some of the environmental laws changed because of the Eco-92 (Earth Summit, a major United Nations conference, red.) in Rio de Janeiro.

Every infrastructure for cars (road projects, tunnels, bridges, etc.) needed an environmental compensation and therefore they started with the bicycle lanes, in addition to their road projects. In 1994 there was a bad mayor in São Paulo, Paulo Maluf (tenure 1993 – 1997, red.) who made the big car fly over in the seventies. Now there is a discussion going on to make it into park, like the highline in New York, or demolish it. In 1994 he started to build the first bike lanes, segregated from the car roads, in the city. There were a few, amongst which were Ibirapuera bike lane and the first lane in Pinheiros, now it's a main part of Faria Lima. However, the part they built in 1994 was a bike and pedestrian lane in the centre of the avenue. That year they built a total of 30 km of segregated bicycle lanes in the city, because of environmental compensation for tunnels and bridges they built. They also approved in 1994 the Faria Lima plan, changing all land use and obligating the city hall to make bike lane all over it. However, only in 2012 the first kilometre of this bike lane was made and then further in 2016 some more and also some more in 2017. Now it is 25 km long and 9000 cyclists there every day. It's a mess.

In 2013 Fernando Haddad was elected to be mayor. We made a protest in front of his house, because one cyclist was hit by a car. He was not killed, but he lost his arm because the driver was drunk. The son of the mayor got to talk to us and he told us that the mayor would meet us next week. So we arranged the time, date and place for the meeting and we eventually talked to the mayor. In this meeting we told him the whole story and it was the beginning of a collaboration with us and the mayor. We got out of this meeting and started to organise a new bike lane plan for the city, a new urban plan for the city, not only for bicycles, was the start of this collaboration. Haddad was great. He didn't know anything about bicycles, but he was listing. From the start he was listening. Both the secretary of transportation and one governmental secretary were great, because they were working along with the mayor.

The new mayor (João Doria, red.) is terrible. He, however, was elected for the government of the state. His vice-mayor (Bruno Covas, red.) took over. We don't know what he will be like. I think he is better than João Doria, because Doria is the worst guy ever. That's because he is a wealthy man, only listening to the elite group of people in São Paulo and he is a car-minded person. He increased the speed limit in all the cities, less than one year after Haddad got out of the city hall. He didn't destroy all the bicycle lanes, but he didn't make any effort to make them better or maintain them. So, there are huge holes in the paths. Now we don't know if the vice-mayor, Bruno Covas, will be any better. He is telling he wants to make something good for bicycles. However, we don't know yet. To say is one thing, to do is another. He has plans, but he has only less than 2 years to execute them. It is not so much time and the last year of the tenure is election year. So, there is only 6 months left in that year, because the last 6 months you cannot spend money on investments on infrastructure. That's because it's the electoral window. Only 1.5 year he has left to show something. I don't think he is going to do anything. He is going to talk, but he is not going to do.

3. We have created a list of stakeholders. Do you think there are relevant stakeholders missing?
ITDP is very important because they have a lot of materials on evaluating bicycle network in São Paulo. Thiago Beniccio is a former employee. He is not working there anymore, but he is still important. He worked on the plans for São Paulo. I will write down his email address.

If you talk about road safety, you could talk to Bloomberg Philanthropies. They have the big picture of the road safety in São Paulo. The Bloomberg Foundation in New York have an office in São Paulo, with 3 people working here only on road safety. You can reach Hannah Machado, I will also give you her email. BIGRS (Bloomberg Philanthropies Initiative for Global Road Safety, red.) is an organisation working with Bloomberg Philanthropies, and they have a cooperation with the city hall on road safety. They have a monthly meeting the with mayor, just to talk about road safety.

If you talk to CET, you can talk to André Castro. He is the advisor for the transportation secretary, he knows about CET and municipal public transportation, not about the metro or the subway, but about the buses.

Bradesco is not very useful because they only do the leisure bike lanes on Sunday. I already talked to you about that and I can give you extra material if you want. UCB on national level is good to have on your list.

Itaú is actually the same as Tembici. Only if you want to talk about money, it is the main bank from Brazil. If you want to talk about this or the private sector, then you can talk to them. Tembici has the operational point of view, Itaú has the money point of view. If you want to talk to Itaú: Guilherme Monacelli. I will write down his email. Bike Anjo should be great. They have a lot of projects, initiate people to cycle the city. It is great project. I think you got them all.

A.7.3. Personal questions

At last, we would like to ask you some personal questions, about your opinion on biking.
4. What is your view on the current situation of the bicycle network in the city?
That's a tricky question. If you talk about numbers of kilometres, of course we have the largest network in Brazil. However, if you talk per person per capital, Rio Branco is on the top of the list on bicycle network/ person. If you talk about investments: Vitoria is the best. In terms of quality of the bicycle network, perhaps Rio Branco is the best one. But they are not all good. Of course, São Paulo is making a huge effort in 3 or 4 years, but it stopped there. We saw that the bicycle culture gained more people, but since the bad mayor it stopped. It was gaining muscle and then the whole development stopped. I don't think we are in a bad situation compared to other cities in Brazil, but we are the largest city in Latin America and we can do more, we have to do more.

We have civil society organised. Cyclists that are always making protests, organise ourselves and push the policy makers, to make better, to make more infrastructure for bicycles. Even when we are in a situation where I am, in a national industry association, we always use our strength to push all these policies forward. You will talk to JP tomorrow. He will tell you the same thing. Everywhere we are, we are trying to make these bicycle policies to go further.

5. How do you think this will develop? You mentioned that it kind of stopped now, but you're still trying to work on it. Do you think there will come a new boost?
I think that it will. The thing about this period, the period where the city hall implemented 400 km of bike lanes. There was of course a bike clash from some sector of the society. People are addicted to cars. There was a bike clash. People were shouting against the new infrastructure. Now it's pacifying. They got used to it and saw opportunities from this infrastructure. People ride the bike more, people walk more, etc. The traffic gets calmer eventually. There are many, many benefits. I think they began to see the bike lanes in a different way. The shouting calmed down. I think a new boost is coming, in a different way. People see the benefits of the bicycles. Yellow and Tembici help a lot, to make sure that the bicycle is visible, to be seen, to be touched. It is about creating demand, creating mass. Right now, they are even talking about making Faria Lima larger, because if you go there now there are huge bicycle traffic jams, like in Amsterdam. That's something new for us.

Instead of talking about how people be more natural in the traffic, let's talk about making the bicycle network larger. Let's talk about taking a road, a space from the cars, to get to bicycles. That's the discussion we are going to have. That's new. All the bike lanes that we have, are built on car parking. Only in 1 or 2 cases, the city hall took driving space from the cars. But the main areas where bicycle lanes where built were in parking spaces or in the space left.

6. We read a lot of positive reactions on the bicycle development in São Paulo, but how do you see this? Is everyone that positive or are the internet articles biased?
There is still some negativity, of course. We have 80 years of car policies in Brazil, tax policies, road infrastructure, statues, publicity for cars, etc. It's 80 years of car policy, of course we cannot change that 3 to 4 years. We have to think on the long-term. We have to work on passing this bike clash, showing data, showing researches, showing the benefits, dialoguing. It is not cars vs. bicycles, drivers vs. cyclists, it is not about that. It's about showing the benefits to people that there is more than a car, there are other ways of transportation, you can think on a life beyond cars.

You can also use an electric bicycle for example. It's a more natural way of transferring out of cars and be with us in the active transportation. With an electric bike you do not sweat, you can ride hills, that's ok. Now we have three bicycle sharing systems. We have electric scooters. I think all these policies address one thing that is the multi-model way of transportation. You have opportunities, you have more offers than just your car. There are trains, busses, electric busses, subways, bicycles, bicycle sharing, electric bicycles, scooters, your feet, etc.

50% of all drivers in the city, 50% of all trips made by cars, are trips lower than 5km. That's a distance you could walk, well not walk, but you can easily drive it by bike. Of course, we are addressing and talking to these people, they are addicted to their cars. When they go to the bakery or the pharmacy, 500m from their homes, they drive their cars. That's a thing we need to change. If we change even half of these trips made by cars, we could take 5 or 6 million cars out of the street. That is a game changer.

Another problem is the transportation of goods, more than 50% of all transport of products is done by cars and trucks that enter São Paulo, could easily made by cargo bicycles or tricycles. That could change real things for pollution, but also for bicycles. That's because we have a major company for delivering of documents and small goods and we are beginning to have more tricycles and cargo bicycles for goods. We did a research on the area next to here. It is a 400 squared km and we entered every shop and retailer, with a questionnaire about the deliveries they make. We discovered that every day they deliver, only in this neighbourhood, 2300 deliveries by cargo bicycles or tricycles. Every day 2300 deliveries. Just using normal cargo bicycles or tricycles, they were not electric. This is something, that if we work with this data and policies and motivate people, not just shop owners, but also commuters, to make to make more use of bicycles, tricycles, etc. We could change the whole city. So we have lot's to do.

7. Could you rank the following parameters for us from most important to least important (1 is most important, 3 is least important):

1. Comfort (pavement conditions, slope, shade)
2. Risk (by interacting with motorised traffic)
3. Commute time (compared to other traffic modes)

What would be the most important for me? In 2015 we did a research on cyclist's profiles. The main issue for cyclists to begin cycling in the city was in the first place, speed and practicality, in the second-place health and in the third-place economy. Bicycle as a speed vehicle and a practical vehicle that's the most important reason to start cycling.

Then there are the problems cyclists face in the city:

- Lack of infrastructure
- Safety and driver's behaviour

It's a mixed question. Because travel time is in our research speed and practical. Risk is here the problems they faced in the daily times in the city and comfort. I don't think comfort is a thing. Bicycle is speed and practical, that's more important than the comfort.

8. We also talked to people who mentioned that if they have to use a bike that they sweat, and they are wet when they arrive at their destination. Comfort would also include weather and pavement conditions.
That is an important question for non-cyclists. Because I think if you interviewed actual cyclists, like me, all these thinks like sweat and other things, we are already beyond that. I already had this discussion with myself. Most of the people use the car, because it's comfortable. Say, your destiny is 5 km from your house. Why endure 40 minutes of traffic jam, why are you still in your car? It's because it's comfortable, there is air-conditioning. But that is just what I think, I don't have any data about that.

For me it would be:

- commute time
- comfort
- risk (because I'm already a cyclist)

9. Could you describe your itinerary from home to work in terms of distance and way of transportation? From which area in São Paulo do you need to come?
I always use my bicycle. I just moved, my new house is 15/20 minutes from here, in kilometres I think it's 6 or 7. But I ride fast, and I love to ride it. I have this light, simple bicycle. Of course, I have 7 bicycles for different purposes. One for daily use, grocery trips, cycle trips, mountain bike, another one that I don't use and a folding one. I use that one when I have a plane to catch. To take a bicycle with you on the plane is expensive. However, with this folding bicycle you put it inside a bag and you say it's a bag, so you don't pay that much. Moreover, I have a bicycle from the seventies. It is an old bicycle, just for fun, for Sundays.

If I have a meeting, like for example this afternoon, that is 10 kilometres from here, I go by bicycle. Even if I sweat, I don't care. The meeting will be about bicycles, I talk about bicycles, so yeah. This Thursday I will be in Brasilia and I have a bicycle over there. I'll have to go to meetings and I have to wear a tie and everything, but

I still use my bicycle. I got the bicycle in my life, I don't change my life, my clothes, etc. I don't wear cyclists' clothes or helmets, like you in the Netherlands. Only a helmet for mountain biking.

10. Consider, you are living in a street where no dedicated bicycle infrastructure is present. What would be an acceptable distance to ride your bicycle without dedicated bicycle infrastructure such as a bike path or bike lane (a bike path is separated from the road; a bike lane is on the same road as cars)? In other words: how many blocks are you willing to travel to reach dedicated bike infrastructure?
This is not a good question for me, because I'm used to ride my bicycle without bicycle paths. I don't have a bicycle path near my home. From my home to here (work, red.), is 6 kilometres and I only get like 500 metres of bicycle infrastructure.

Of course, when you are in an avenue with a highspeed limit, when you get to a bicycle infrastructure you feel relieved, safe, warm. However, these types of infrastructure are not built for me, they are built for new cyclists. For creating demand for new cyclists.

I cycle in Rio de Janeiro, it is the most awful place to cycle. If you are outside the south zone (not Copacabana or Ipanema), it is like a warzone. Busses, cars, all are crazy while driving like 100 km/h. It is the only place I fear for my life. But I still go by bike.

B

Extensive stakeholder research

An extensive research is done through literature study to create an overview of all stakeholders, who they are and what they do. The short version is discussed in the report, the longer version can be found here.

Prefeitura de São Paulo

The Municipal Chamber of São Paulo is the unicameral legislative body of the city of São Paulo. The municipality of São Paulo has launched its Master Plan in 2014, with as subgoals to incorporate the environmental agenda, improve urban mobility, guiding growth near public transportation and improving urban life in neighbourhoods. Regarding urban mobility, it was stated that 30 percent of the investments funds should be going to public transport, pedestrians and cyclists Haddad, Campeão, De Mello Franco, Herling, and Slutti (2014). This plan was constructed together with inhabitants and shows that the municipality is actively involved in the bicycle issues.

CET

Companhia de Engenharia de Tráfego (CET), or the Traffic Engineering Company in English, is a mixed company focused on traffic safety and education. It is responsible for the management, operation and supervision of the city's road system (Prefeitura Municipal de São Paulo, 2006). The ministry of Mobility and Transportation uses the information gathered by the CET. Their stakes in the project come from the Strategic MasterPlan and regulations and guidelines set by the Municipality of São Paulo. Therefore they aim to minimise the growing problems of congestion and harmful emission of polluting gases (CET, n.d.).

Prefeitura do Campus USP

The campus of USP has its own municipality, which means that the city's municipality does not have anything to say in this area. They have full authority over the area and make all decisions on themselves.

Inhabitants of São Paulo

The inhabitants of São Paulo represent a vast variety of income scales. Resulting from the previous literature review, it is decided that combining all inhabitants into one group is not possible. Therefore they have been decided into two groups. Low income scale: people with lower incomes usually have to travel farther to work, as seen in the literature review. Using public transport results in extremely long voyages to reach their destination. The main reason behind these long voyages is that they have to use multiple forms of transportation to reach their end destination. Different forms of public transportation never connect perfectly, resulting in even longer trips. People that are dependent on this forms of transportation are not free to travel whenever they want because they are always dependent on public transport schedules. This last factor is a very important one for this category.

High income scale

At this moment, most bicycle networks are implemented into the wealthier neighbourhoods. However, cars are seen as a status symbol and therefore the high income scale might not be interested in using bicycles as means of transportation. Due to this status symbol, which is an important factor in Brazil, incentives need to be created for them to use it. Since they have the luxury of their cars, health improvement could a reason for them to start using it as means of leisure or eventually as transportation.

Road users

We distinguish 3 types of road users: the ones that travel to work, the ones that do it for leisure and the ones that travel from A to B. Leisure and home-work commute are the main types of road usage that is noticed. The A to B group contains all the other types of activities that requires road usage. This can range from grocery shopping to a dentist appointment, all that isn't work or leisure related. Below they are explained in some detail.

- **A to B**: these are the users of the road, either car, motorbike or bicycle, that travel from A to B to and/or through the city. Therefore this category can be both inhabitants of São Paulo, but also inhabitants of the suburbs. The goal of travelling from A to B is to reach the destination, in the shortest period of time possible and in a safe way.
- **Leisure**: these are the users of the road, either car, motorbike or bicycle, that use the city roads for leisure. This group concerns only inhabitants of São Paulo. They do not need to reach a certain destination, but desire to cross the roads for fun.
- **House-to-work**: these are the users of the road, either car, motorbike or bicycle, that use the roads to reach their work. Therefore this category can be both inhabitants of São Paulo, but also inhabitants of the suburbs. Work always starts at a certain time and therefore their main goal is to reach their destination as soon as possible.

Bycs

Bycs is a social enterprise that is based in the Netherlands, who believes that bicycles transform cities, and cities transform the world. They work internationally with non-profit organisations, other businesses and governments to initiate ideas around cycling. They believe cycling is not just transportation, but transformation.

Bycs is active within São Paulo with their Bicycle Mayor Program, which aims to accelerate the progress of cycling in cities. A bicycle mayor is appointed to serve as a catalyst by bringing together public and private organisations. They work on new ideas related to biking and break down barriers to enable people to bike for the first time. JP Amaral is the bicycle mayor of São Paulo.

Bike Anjo

Bike Anjo means "Bike Angel" in Portuguese, and is a network that desires to spread the word of benefits of cycling. It is all based on volunteers who want to promote, mobilise and help people to get started with cycling as means of transportation. They see it as a tool for social change and to improve cities. JP Amaral is co-founder of this organisation, besides being the bicycle mayor of São Paulo.

Bicycle sharing companies

- **Yellow**: Yellow has started their bicycle sharing network in a small part of the city as can be seen in figure B.1. This is the Faria Lima - Berrini axis, which involves very busy streets. The decision to start with a small area was made to be able to offer high quality service: provide quick maintenance and reassure there are enough bikes available. However they plan on extending their network to other areas of São Paulo. Their stake in the project is to create a larger group of users, meaning they can extend their network. They have areas in multiple cities in Brazil and are now also extending to other Latin American countries.

- **Mobike** is a bicycle sharing company from China, enlarging their scope to the whole world. They are a dockless sharing company, meaning the bicycles can be placed anywhere, as long as the destination is inside the area of usage. Mobike wants to place their first 10.000 bikes on the Faria Lima - Berrini axis, which is the same area as Yellow, and eventually wants to expand to 100.000 bikes.
- **Tembici / BikeSampa**: Tembici is the Brazilian version from the Public Bike System Company (PBSC). It was the first bicycle sharing network in São Paulo. PBSC‘s goal is to implement their urban solution on a large scale, one city at a time. They are investing in research and development and tend to enlarge their scope. They stand for sustainability, easy implementation and smart technologies. They scattered 2600 bikes and 260 bike stations through São Paulo in 2018. They work on a rent basis: They can be rented for one hour, for one day, for 3 days, for a month or for a year.
- **CicloSampa**: CicloSampa is an initiative from the bank Bradesco, which is the other main bank of Brazil. They want to be the perfect link between sustainability, mobility and the quality of life. They work the same as Tembici, using bicycle stations, however they only operate during the weekend. They started at Avenida Paulista but have been growing slightly since then, leading to 17 stations nowadays. see B.2. They work on a rent-basis, paying a certain amount of money per 30 minutes. it is required to register and download the app in able to use the bikes.

Figure B.1: The current area of Yellow. The yellow lines represent the bicycle area, while the black lines represent the motorised scooter area. The latter is out of our scope and will not further be taken into account.

Environmental groups

They have a stake in the sense that the environmental impact will be decreased when using more bikes instead of cars, busses and motorbikes. However, based on literature, it is concluded that environmental groups bicycle stations.PNG

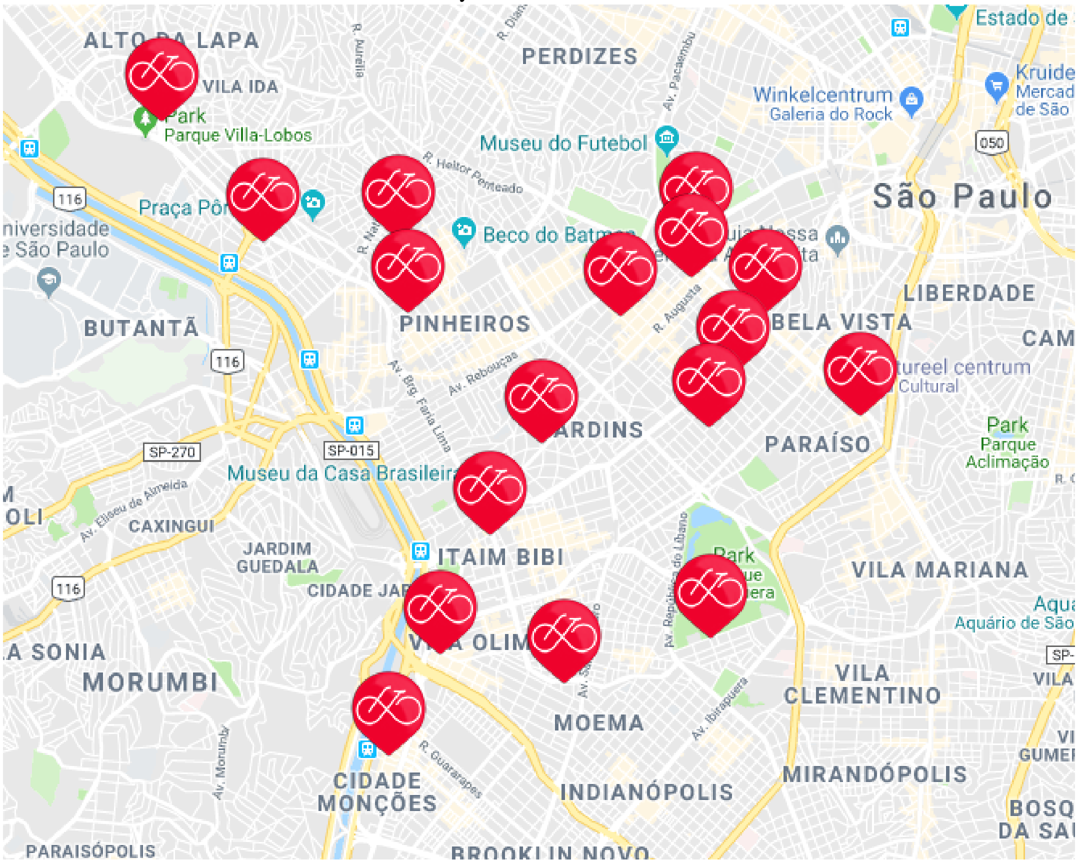


Figure B.2: The CicloSampa bicycle stations.

are not actively working on this matter.

Public transport companies

SPTrans: as discussed in Chapter 1, literature review, busses are a common mode of transport in São Paulo, sharing the road with cars on most streets. The bus system is governed by the São Paulo Transporte (SPTrans), which is responsible for the planning and management of the busses, including setting paths, operation hours and demanded fleet. The bus can be paid for by cash or by a contactless smart card called Bilhete Único. The executive company is Empresa Metropolitana de Transportes Urbanos de São Paulo (EMTU), owned by the Secretaria de Estado dos Transportes Metropolitanos (STM). They have a fleet scattered over all 39 municipalities within the Greater São Paulo area and carry over 1,6 million people per day.

- **Metrô** The Companhia do Metropolitano de São Paulo, or Metrô, is responsible for the planning and operation of the metro system and its extension. As discussed in the literature review, there are 6 metro lines within the city: blue, red, green, yellow, lilac and silver. Together they have a length of 96 km and they process more than 4 million passengers each day. Line 1 and line 3 are the lines with the most programmed trips per day. The metro network can be seen in figure B.3.

  The blue line is the oldest, and connects the Southern and Northern regions of São Paulo. The red line is the most extensive and crowded line, and connects the Western and Eastern regions. This line is operated by ViaQuatro. The green line connects the Western and Eastern regions. The yellow line was the first one to be operated by the private sector and the first driverless system. it connects downtown‘s Luz neighbourhood to the Western neighbourhood of Butantã. The lilac line is the shortest line, and connects the Southern area of Santo Amaro to the extreme Southwestern neighbourhood of Capão Redondo. This line is operated by ViaMobilidade.

  There are 7 main transfer stations, allowing passengers to transfer from one line to the other. Most metro lines operate from 4.40 am till midnight, and on Saturdays until 1 am. Metrô states that bicycles are welcome within their vehicles, however not at all times and under strict rules. Bicycles are allowed from Monday till Friday after 08.30h pm, Saturday after 2 pm and only on Sundays and holidays during the whole day. They are advertising to promote leaving the car at home and use a combination of bicycle and public transport to reach the destination. From 2008, the Caminho Verde Cycle Lane connects the station of Tatuapé to the Corinthians-Itaquera station. The cycle path follows the Metrô line along the Radial Leste. The cycling path can be seen in figure B.3 along Linha Vermelha, by the orange and yellow dotted line. The same figure also shows all guarded bike parking terminals and bicycle attachments points on the stations. The parking terminals are not open to everyone and one should first register in order to use them.

- **Train** The lines of the CPTM, the train company, were constructed on the location where the previous CBTU lines were. These tracks used to be cargo and long-distance passengers transportation lines. The CPTM is responsible for the planning and operation of the train lines. There are 6 CPTM lines, that cover 19 out of 39 municipalities in the Greater Area of São Paulo, with 89 stations. They process over 1.6 million passengers per day. All of the CPTM lines have a physical connection with the Metrô lines. The six train lines are:

  – **Linha 7-Rubi**, Luz-Francisco Morato-Jundiaí;

  – **Linha 8-Diamante**, Júlio Prestes-Itapevi-Amador Bueno;

  – **Linha 9-Esmeralda**, Osasco-Grajaú;

  – **Linha 10-Turquesa**, Luz-Rio Grande da Serra;

  – **Linha 11-Coral**, Luz-Guaianases-Estudantes;

  – **Linha 12-Safira**, Brás-Calmon Viana.

  Along with Metrô, CPTM also advertises for the combination of cycling and public transport to reach your destination. Bicycles are welcome on Saturdays after 2pm and Sundays and holidays during the whole day. This means reaching work by a combination of train and bicycle is not possible. All stations that have a Bike Parking Terminal available are shown in figure B.3.

Figure B.3: The Metrô and CPTM network including Bike Parking Terminals shown in green dots.

Emergency services (ambulance, fire fighting department, police)

Emergency services have limited times to reach their destination, because delays in their journey can have fatal consequences. The maximum time that each emergency service has is stated by law, and should always be met. Their main stake is to be able to reach their destination as quick as possible.

UCB (cycling federation)

União de Ciclistas do Brasil is an association that is in partnership with local organisations to promote the use of bicycles as a means of transport, leisure and sports in urban and rural areas. They operate throughout the whole country.

ITDP Brasil (consultancy)

The Institute for Transportation and Development Policy works around the globe to design and implement high quality transport systems and policy solutions in cities. For Brazil this means creating innovative solutions for issues on public transportation, sustainable growth and urban form. They had a great influence in the city's Strategic Masterplan 2014.

Instituto CicloBR

CicloBR is an Institute of Sustainable Mobility Promotion, that was created to represent cyclists in the whole country of Brazil. They aim to promote the use of bicycles as means of transportation, leisure, tourism and sports. Since the headquarters are in the city of São Paulo, most of their work is based there. Examples of their work are the creation of the Municipal Council of Traffic and Transport of São Paulo and the Thematic Chamber of the Bicycle (Instituto CicloBR, 2019). By having a connected bicycle network through the city, incentives are created for locals to use cycling as means of transportation, leisure, tourism and maybe even sports.

Aliança Bike

They aim to stimulate the use of bicycles as an effective means of transportation within Brazil, lowering the barriers of access that currently exist. Following, one of their goals is "to bring together companies among manufacturers, importers, suppliers, distributors and retailers of bicycles, accessories and parts, as well as associations, institutions and individuals that promote the use of bicycles."

Itaú

Itaú is the sponsor of BikeSampa and Tembici. Itaú is the largest private bank in Latin America, and they are an active promoter of sustainable mobility. They note that the initiative of sponsoring bicycles work on 3 axes: community, customers and collaborators. They want to promote the bike as a sustainable means of transportation, leisure and healthy habits.

Bradesco

Bradesco is one of the biggest financial services companies in Brazil. It was the largest bank in Latin America, until Itaú merged with Unibanco. Their mission is to contribute people's achievements and to sustainable development via provision of accessible solutions, products and services. This also corresponds with their value regarding socio-environmental responsibility (Bradesco, n.d.). Bradesco is the sponsor of CicloSampa project, with shared bicycles and stations (CicloSampa, n.d.).

C

Stakeholder Typology

Following (Murray-Webster & Simon, 2006), this is the meaning of the 8 labels from the advanced stakeholder typology map:

- **Saviour** – powerful, high interest, positive attitude or alternatively influential, active, backer. They need to be paid attention to; you should do whatever necessary to keep them on your side – pander to their needs.
- **Friend** – low power, high interest, positive attitude or alternatively insignificant, active, backer. They should be used as a confidant or sounding board.
- **Saboteur** - powerful, high interest, negative attitude or alternatively influential, active, blocker. They need to be engaged in order to disengage. You should be prepared to 'clean-up after them'.
- **Irritant** – low power, high interest, negative attitude or alternatively insignificant, active, blocker. They need to be engaged so that they stop 'eating away' and then be 'put back in their box'.
- **Sleeping Giant** - powerful, low interest, positive attitude or alternatively influential, passive, backer. They need to be engaged in order to awaken them.
- **Acquaintance** –low power, low interest, positive attitude or alternatively insignificant, passive, backer. They need to be kept informed and communicated with on a 'transmit only' basis.
- **Time Bomb** - powerful, low interest, negative attitude or alternatively influential, passive, blocker. They need to be understood so they can be 'defused before the bomb goes off'.
- **Trip Wire** – low power, low interest, negative attitude or alternatively insignificant, passive, blocker. They need to be understood so you can 'watch your step' and avoid 'tripping up'.

D

Road classification

The appendix gives the results of the road classification (class_risk), the elevation classification (slope), the number of people who can be served (populacao_), whether the road has the cycling lanes or not (exists), the utilities (utility), and the link costs (link_costs) with regard to the existing roads. Limited by the length of the report, here only shows the part of the total network.

ID	lg_tipo	lg_nome	class_risk	populacao_	slope	exists	utility	link_costs
49685		Bridge1	1	0.000000	0	0	0.000000000000000	0.0000000000
92362		Bridge2	1	0.000000	0	0	0.000000000000000	0.0000000000
95571		Bridge3	1	0.000000	0	0	0.000000000000000	0.0000000000
36316	R	ALFREDO TIANCA BRAGA	1	9660.000000	2	0	0.019671718255722	0.0052618150
18589	R	ALFREDO TIANCA BRAGA	1	9660.000000	2	0	0.019671718255722	0.0052618150
18604	R	ALFREDO TIANCA BRAGA	1	11146.000000	2	0	0.019671718255722	0.0045603660
118935	R	LUIS AUGUSTO Q ARANHA	1	4679.000000	1	0	0.052519366259712	0.0040685030
119098	R	LUIS AUGUSTO Q ARANHA	1	5276.000000	1	0	0.052519366259712	0.0036082230
18505	TV	LUIS C VIOTTI S VINTE ZERO NOVE	1	10480.000000	2	0	0.019671718255722	0.0048501470
33584	R	ORLANDO MARQUES PAIVA	1	3482.000000	1	1	83290000000.000000000000000	0.0000000000
33593	R	ORLANDO MARQUES PAIVA	1	4020.000000	1	1	83290000000.000000000000000	0.0000000000
33614	R	ORLANDO MARQUES PAIVA	1	3990.000000	1	1	83290000000.000000000000000	0.0000000000
17947	PS	ASSOCIACAO DOS A SAO REMO	0	12272.000000	1	0	0.000000000000000	96.7082000000
36912	R	DEZESSEIS (J UNIVERSIDADE)	1	1804.000000	2	0	0.019671718255722	0.0281631020
35485	R	DEZESSEIS (J UNIVERSIDADE)	1	3364.000000	2	0	0.019671718255722	0.0151068050
35524	R	DEZESSEIS (J UNIVERSIDADE)	1	3364.000000	2	0	0.019671718255722	0.0151068050
42570	TV	E SETOR OITENTA E DOIS Q VINTE QUARENTA E UM	1	35.000000	1	0	0.052519366259712	0.5289054240
47204	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47218	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47235	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47514	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47520	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47539	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47561	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47585	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47675	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47684	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47690	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47696	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47702	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47711	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47720	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47731	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47792	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47798	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47804	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47811	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
47817	PC	HERMAN CAPPELEN	2	2420.000000	1	0	0.036972780609631	0.0111717980
110032	R	INHATIUM	1	9841.000000	2	0	0.019671718255722	0.0051650470

Figure D.1: The matrix of the road utilities (Part I)

ID	lg_tipo	lg_nome	class_risk	populacao_	slope	exists	utility	link_costs
180995	R	ARCOVERDE	1	11230.000000	2	0	0.019671718255722	0.0045262570
181011	R	ARCOVERDE	1	11394.000000	1	0	0.052519366259712	0.0016709600
181053	R	ARCOVERDE	1	10696.000000	2	0	0.019671718255722	0.0047522100
161286	R	ARCOVERDE	1	8009.000000	1	0	0.052519366259712	0.0023771030
161303	R	ARCOVERDE	1	9558.000000	1	0	0.052519366259712	0.0019919020
160043	R	ARCOVERDE	1	9548.000000	1	0	0.052519366259712	0.0019939880
180479	R	ARCOVERDE	1	13355.000000	1	0	0.052519366259712	0.0014256210
180489	R	ARCOVERDE	1	13355.000000	1	0	0.052519366259712	0.0014256210
180495	R	ARCOVERDE	1	12533.000000	2	0	0.019671718255722	0.0040557200
180502	R	ARCOVERDE	1	12533.000000	2	0	0.019671718255722	0.0040557200
25705	R	FLAVIO CESCON	1	10408.000000	2	0	0.019671718255722	0.0048836960
29631	R	FLAVIO CESCON	1	8612.000000	2	0	0.019671718255722	0.0059020550
15438	R	ARI APS	1	10482.000000	2	0	0.019671718255722	0.0048492220
15450	R	ARI APS	1	11691.000000	2	0	0.019671718255722	0.0043477930
18647	R	ARI APS	1	13310.000000	2	0	0.019671718255722	0.0038189760
18713	R	ARI APS	1	12025.000000	2	0	0.019671718255722	0.0042270410
18744	R	ARI APS	1	12180.000000	2	0	0.019671718255722	0.0041732530
22508	R	ARI APS	1	11282.000000	1	0	0.052519366259712	0.0016875470
22032	R	ARI APS	1	12156.000000	2	0	0.019671718255722	0.0041814920
20409	R	ARI DOS SANTOS	1	12423.000000	1	0	0.052519366259712	0.0015325650
20440	R	ARI DOS SANTOS	1	12565.000000	1	0	0.052519366259712	0.0015152470
106920	R	ARIQUEME	1	8084.000000	2	0	0.019671718255722	0.0062874950
106926	R	ARIQUEME	1	8084.000000	2	0	0.019671718255722	0.0062874950
107023	R	ARIQUEME	1	8708.000000	2	0	0.019671718255722	0.0058369960
107038	R	ARIQUEME	1	8708.000000	2	0	0.019671718255722	0.0058369960
107073	R	ARIQUEME	1	9010.000000	2	0	0.019671718255722	0.0056413710
107109	R	ARIQUEME	1	11791.000000	1	0	0.052519366259712	0.0016147040
134458	R	ARMANDO PINTO	1	11413.000000	2	0	0.019671718255722	0.0044536880
134487	R	ARMANDO PINTO	1	13354.000000	2	0	0.019671718255722	0.0038063940
185510	AV	ARNALDO	2	8852.000000	2	0	0.013848570062453	0.0081565140
185527	AV	ARNALDO	2	8852.000000	2	0	0.013848570062453	0.0081565140
185542	AV	ARNALDO	2	7789.000000	2	0	0.013848570062453	0.0092695270
185555	AV	ARNALDO	2	7789.000000	2	0	0.013848570062453	0.0092695270
185564	AV	ARNALDO	2	7789.000000	2	0	0.013848570062453	0.0092695270
185616	AV	ARNALDO	2	8275.000000	3	1	199870000000.000000000000000	0.0000000000
185703	AV	ARNALDO	2	7789.000000	2	0	0.013848570062453	0.0092695270
185717	AV	ARNALDO	2	8275.000000	2	0	0.013848570062453	0.0087251830
185735	AV	ARNALDO	2	7658.000000	3	1	199870000000.000000000000000	0.0000000000
92461	AV	ARRUDA BOTELHO	2	3100.000000	1	1	200190000000.000000000000000	0.0000000000

Figure D.2: The matrix of the road utilities (Part II)

ID	lg_tipo	lg_nome	class_risk	populacao_	slope	exists	utility	link_costs
50291	AV	NACOES UNIDAS	2	3066.000000	1	0	0.036972780609631	0.0088186900
50305	AV	NACOES UNIDAS	2	3066.000000	1	0	0.036972780609631	0.0088186900
50319	AV	NACOES UNIDAS	2	3066.000000	1	0	0.036972780609631	0.0088186900
50328	AV	NACOES UNIDAS	2	3066.000000	1	0	0.036972780609631	0.0088186900
50552	AV	NACOES UNIDAS	2	3101.000000	1	0	0.036972780609631	0.0087191890
112247	AV	NACOES UNIDAS	2	3656.000000	1	1	200190000000.000000000000000	0.0000000000
112300	AV	NACOES UNIDAS	2	2830.000000	1	0	0.036972780609631	0.0095538410
112376	AV	NACOES UNIDAS	2	1745.000000	1	0	0.036972780609631	0.0154907920
146708	AV	NACOES UNIDAS	2	3299.000000	1	0	0.036972780609631	0.0081960370
146734	AV	NACOES UNIDAS	2	6459.000000	1	1	200190000000.000000000000000	0.0000000000
146820	AV	NACOES UNIDAS	2	4983.000000	1	0	0.036972780609631	0.0054267500
146832	AV	NACOES UNIDAS	2	4983.000000	1	0	0.036972780609631	0.0054267500
146968	AV	NACOES UNIDAS	2	4199.000000	1	1	200190000000.000000000000000	0.0000000000
72318	AV	NACOES UNIDAS	2	2970.000000	1	1	200190000000.000000000000000	0.0000000000
72325	AV	NACOES UNIDAS	2	3305.000000	1	1	200190000000.000000000000000	0.0000000000
72331	AV	NACOES UNIDAS	2	3305.000000	1	0	0.036972780609631	0.0081811620
72351	AV	NACOES UNIDAS	2	3384.000000	1	0	0.036972780609631	0.0079902280
80626	AV	NACOES UNIDAS	2	5485.000000	1	1	200190000000.000000000000000	0.0000000000
80717	AV	NACOES UNIDAS	2	3691.000000	1	0	0.036972780609631	0.0073258190
80723	AV	NACOES UNIDAS	2	3691.000000	1	0	0.036972780609631	0.0073258190
80761	AV	NACOES UNIDAS	2	3691.000000	1	0	0.036972780609631	0.0073258190
80773	AV	NACOES UNIDAS	2	3691.000000	1	0	0.036972780609631	0.0073258190
80783	AV	NACOES UNIDAS	2	3691.000000	1	0	0.036972780609631	0.0073258190
80789	AV	NACOES UNIDAS	2	3691.000000	1	0	0.036972780609631	0.0073258190
80805	AV	NACOES UNIDAS	2	3163.000000	1	0	0.036972780609631	0.0085483320
80914	AV	NACOES UNIDAS	2	2571.000000	1	0	0.036972780609631	0.0105159110
80926	AV	NACOES UNIDAS	2	2143.000000	1	0	0.036972780609631	0.0126151690
80962	AV	NACOES UNIDAS	2	2672.000000	1	0	0.036972780609631	0.0101185650
81057	AV	NACOES UNIDAS	2	2672.000000	1	0	0.036972780609631	0.0101185650
81383	AV	NACOES UNIDAS	2	3938.000000	1	0	0.036972780609631	0.0068664440
81572	AV	NACOES UNIDAS	2	2352.000000	1	1	200190000000.000000000000000	0.0000000000
81584	AV	NACOES UNIDAS	2	2352.000000	1	1	200190000000.000000000000000	0.0000000000
81609	AV	NACOES UNIDAS	2	2868.000000	1	1	200190000000.000000000000000	0.0000000000
81615	AV	NACOES UNIDAS	2	2868.000000	1	1	200190000000.000000000000000	0.0000000000
81622	AV	NACOES UNIDAS	2	2868.000000	1	1	200190000000.000000000000000	0.0000000000
81628	AV	NACOES UNIDAS	2	2868.000000	1	1	200190000000.000000000000000	0.0000000000
81637	AV	NACOES UNIDAS	2	2868.000000	1	0	0.036972780609631	0.0094273000
81690	AV	NACOES UNIDAS	2	2868.000000	1	0	0.036972780609631	0.0094273000
81729	AV	NACOES UNIDAS	2	2868.000000	2	1	199870000000.000000000000000	0.0000000000

Figure D.3: The matrix of the road utilities (Part III)

ID	lg_tipo	lg_nome	class_risk	populacao_	slope	exists	utility	link_costs
73512	AV	FRANCISCO MORATO	2	2715.000000	2	0	0.013848570062453	0.0265867520
73037	AV	FRANCISCO MORATO	2	1724.000000	1	0	0.036972780609631	0.0156793760
73043	AV	FRANCISCO MORATO	2	2003.000000	1	0	0.036972780609631	0.0134964690
73067	AV	FRANCISCO MORATO	2	2003.000000	1	0	0.036972780609631	0.0134964690
73098	AV	FRANCISCO MORATO	2	2003.000000	1	0	0.036972780609631	0.0134964690
73104	AV	FRANCISCO MORATO	2	2003.000000	2	0	0.013848570062453	0.0360327440
73110	AV	FRANCISCO MORATO	2	2338.000000	2	0	0.013848570062453	0.0308720050
73116	AV	FRANCISCO MORATO	2	2338.000000	1	0	0.036972780609631	0.0115634560
73123	AV	FRANCISCO MORATO	2	2338.000000	2	0	0.013848570062453	0.0308720050
73135	AV	FRANCISCO MORATO	2	2338.000000	2	0	0.013848570062453	0.0308720050
73158	AV	FRANCISCO MORATO	2	2338.000000	2	0	0.013848570062453	0.0308720050
73164	AV	FRANCISCO MORATO	2	2338.000000	2	0	0.013848570062453	0.0308720050
58249	AV	FRANCISCO MORATO	2	8405.000000	2	0	0.013848570062453	0.0085902470
58259	AV	FRANCISCO MORATO	2	6231.000000	2	0	0.013848570062453	0.0115869090
57618	AV	FRANCISCO MORATO	2	8817.000000	2	0	0.013848570062453	0.0081888880
57633	AV	FRANCISCO MORATO	2	9139.000000	1	0	0.036972780609631	0.0029591820
57705	AV	FRANCISCO MORATO	2	8584.000000	1	0	0.036972780609631	0.0031504860
57717	AV	FRANCISCO MORATO	2	8214.000000	1	0	0.036972780609631	0.0032923820
57726	AV	FRANCISCO MORATO	2	8214.000000	1	0	0.036972780609631	0.0032923820
57732	AV	FRANCISCO MORATO	2	8214.000000	1	0	0.036972780609631	0.0032923820
57738	AV	FRANCISCO MORATO	2	8543.000000	1	0	0.036972780609631	0.0031656040
57753	AV	FRANCISCO MORATO	2	8543.000000	1	0	0.036972780609631	0.0031656040
57854	AV	FRANCISCO MORATO	2	7177.000000	2	0	0.013848570062453	0.0100598520
74450	AV	FRANCISCO MORATO	2	2748.000000	2	0	0.013848570062453	0.0262675950
74460	AV	FRANCISCO MORATO	2	2748.000000	2	0	0.013848570062453	0.0262675950
74474	AV	FRANCISCO MORATO	2	2748.000000	2	0	0.013848570062453	0.0262675950
74485	AV	FRANCISCO MORATO	2	2748.000000	2	0	0.013848570062453	0.0262675950
74491	AV	FRANCISCO MORATO	2	2748.000000	2	0	0.013848570062453	0.0262675950
74511	AV	FRANCISCO MORATO	2	2748.000000	2	0	0.013848570062453	0.0262675950
74527	AV	FRANCISCO MORATO	2	2748.000000	2	0	0.013848570062453	0.0262675950
74545	AV	FRANCISCO MORATO	2	2748.000000	2	0	0.013848570062453	0.0262675950
74563	AV	FRANCISCO MORATO	2	2748.000000	2	0	0.013848570062453	0.0262675950
74576	AV	FRANCISCO MORATO	2	2748.000000	2	0	0.013848570062453	0.0262675950
74593	AV	FRANCISCO MORATO	2	2115.000000	2	0	0.013848570062453	0.0341255290
74599	AV	FRANCISCO MORATO	2	3276.000000	2	0	0.013848570062453	0.0220352820
74813	AV	FRANCISCO MORATO	2	3019.000000	2	0	0.013848570062453	0.0239104700
74822	AV	FRANCISCO MORATO	2	3019.000000	2	0	0.013848570062453	0.0239104700
74871	AV	FRANCISCO MORATO	2	2643.000000	2	0	0.013848570062453	0.0273107490
74877	AV	FRANCISCO MORATO	2	2116.000000	2	0	0.013848570062453	0.0341094090

Figure D.4: The matrix of the road utilities (Part IV)

ID	lg_tipo	lg_nome	class_risk	populacao_	slope	exists	utility	link_costs
25766	R	LAYR COSTA REGO	1	4074.000000	1	0	0.052519366259712	0.0046725380
19493	R	LAYR COSTA REGO	1	5255.000000	1	0	0.052519366259712	0.0036226390
19511	R	LAYR COSTA REGO	1	6642.000000	1	0	0.052519366259712	0.0028662640
132344	R	LEAO COROADO	1	7690.000000	1	0	0.052519366259712	0.0024756980
132368	R	LEAO COROADO	1	10519.000000	1	0	0.052519366259712	0.0018099420
130899	R	LEAO COROADO	1	7818.000000	2	0	0.019671718255722	0.0065013940
131067	R	LEAO COROADO	1	7690.000000	1	0	0.052519366259712	0.0024756980
131103	R	LEAO COROADO	1	7690.000000	1	0	0.052519366259712	0.0024756980
125195	R	LELIS VIEIRA	1	6869.000000	1	0	0.052519366259712	0.0027715560
125238	R	LELIS VIEIRA	1	7816.000000	1	0	0.052519366259712	0.0024357930
125253	R	LELIS VIEIRA	1	7816.000000	1	0	0.052519366259712	0.0024357930
124552	R	LELIS VIEIRA	1	9161.000000	1	0	0.052519366259712	0.0020782130
123962	R	LELIS VIEIRA	1	6853.000000	1	0	0.052519366259712	0.0027780260
131028	R	LEMOS CONDE	1	7415.000000	2	0	0.019671718255722	0.0068546920
131077	R	LEMOS CONDE	1	7690.000000	1	0	0.052519366259712	0.0024756980
131092	R	LEMOS CONDE	1	7690.000000	1	0	0.052519366259712	0.0024756980
131114	R	LEMOS CONDE	1	7690.000000	1	0	0.052519366259712	0.0024756980
75935	R	LEMOS MONTEIRO	1	2754.000000	2	0	0.019671718255722	0.0184516870
76059	R	LEMOS MONTEIRO	1	2475.000000	1	0	0.052519366259712	0.0076900620
76278	R	LEMOS MONTEIRO	1	2694.000000	1	1	183290000000.000000000000000	0.0000000000
42534	R	LEONARDO MOTA	1	4792.000000	2	0	0.019671718255722	0.0106059670
103829	AV	LEOPOLDINA	2	4869.000000	1	0	0.036972780609631	0.0055537830
59045	R	LUIS ALBERTO MARTINS	1	6262.000000	2	0	0.019671718255722	0.0081166210
59058	R	LUIS ALBERTO MARTINS	1	6733.000000	2	0	0.019671718255722	0.0075489160
59128	R	LUIS ALBERTO MARTINS	1	6262.000000	1	0	0.052519366259712	0.0030401710
59188	R	LUIS ALBERTO MARTINS	1	4772.000000	2	0	0.019671718255722	0.0106504080
59197	R	LUIS ALBERTO MARTINS	1	5254.000000	2	0	0.019671718255722	0.0096735300
174220	R	LUIS ANHAIA	1	8689.000000	1	0	0.052519366259712	0.0021910920
136076	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	6717.000000	1	0	0.052519366259712	0.0028342650
136082	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	5530.000000	1	0	0.052519366259712	0.0034425230
136094	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	5530.000000	1	0	0.052519366259712	0.0034425230
118923	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	4679.000000	1	0	0.052519366259712	0.0040685030
118948	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	5764.000000	1	0	0.052519366259712	0.0033027910
119089	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	5276.000000	1	0	0.052519366259712	0.0036082230
119156	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	7515.000000	1	0	0.052519366259712	0.0025333410
119648	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	6717.000000	1	0	0.052519366259712	0.0028342650
136463	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	6280.000000	1	0	0.052519366259712	0.0030314590
136523	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	9299.000000	2	0	0.019671718255722	0.0054660640
138161	R	LUIS AUGUSTO DE QUEIROS ARANHA	1	8549.000000	2	0	0.019671718255722	0.0059455430

Figure D.5: The matrix of the road utilities (Part V)

E

Parametric model flow

Figure E.1 shows the grasshopper file of the parametric model of the bridge. The model is divided into different parts with different colours to have a clear overview of the flow of the model. The colour yellow stands for constraints, orange for output, red for variable parameters, blue for geometry, purple for modifying input and pink for the use of Karamba3D. The model is explained as following:

Yellow

1. Geometry constraints
2. Cross-section constraints
3. Loads and safety factors constraints

Orange

1. Geometry output
2. Self-weight output
3. Forces and deflections output

Red

1. Geometry parameters

Blue

1. Constructing of centrelines of geometry

Purple

1. Modifying geometry to input for Karamba3D
2. Modifying cross-sections to self-weight input for Karmaba3D
3. Modifying loads and safety factors to input for Karamba3D

Pink

1. Application of materials and cross-sections with Karamba3D
2. (a) Application of supports and connections with Karamba3D
   (b) Application of load cases with Karamba3D
   (c) Analyze model with Karamba3D

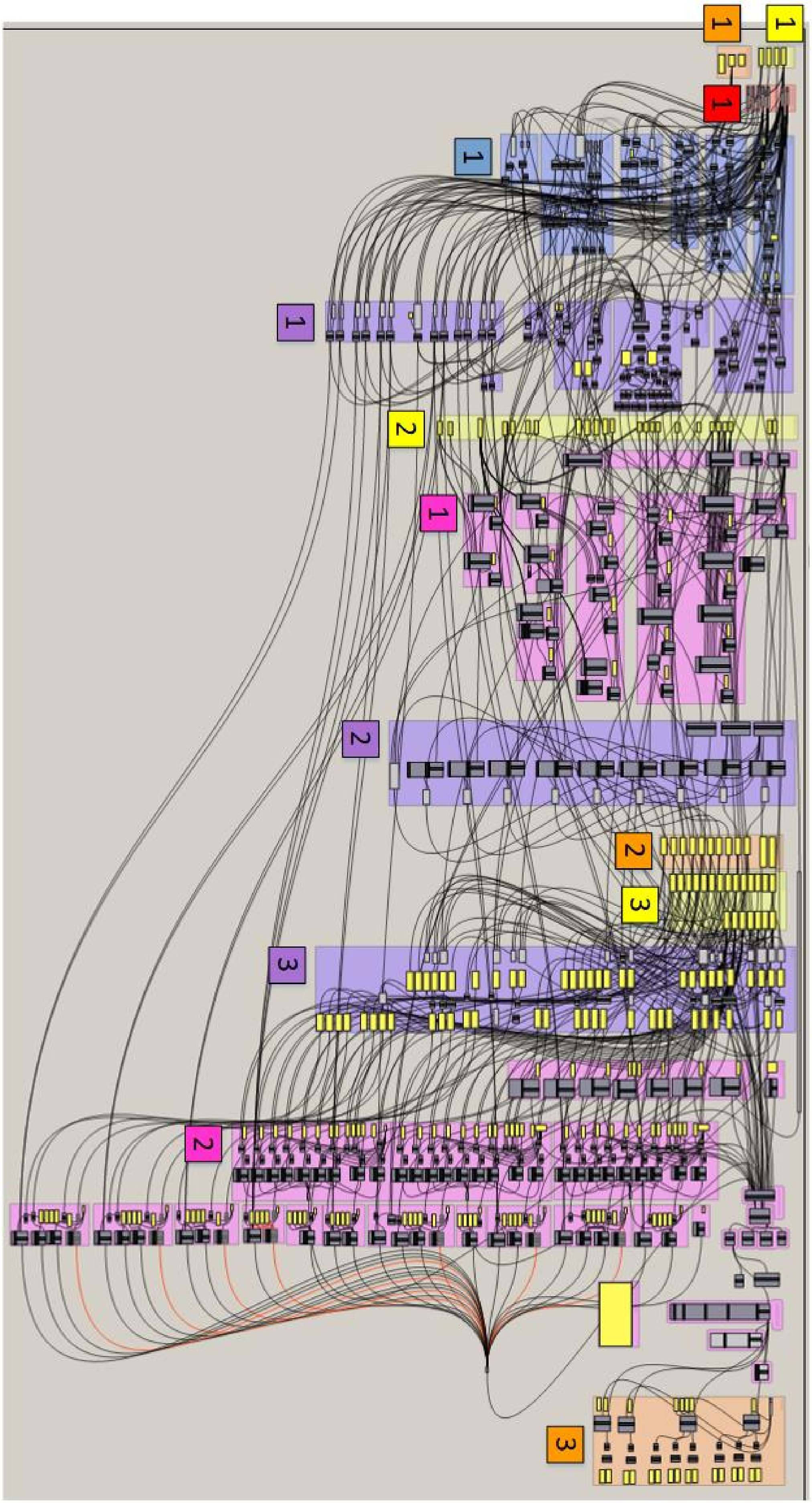


Figure E.1: The parametric model in Grasshopper

F

Literature study

F.1. Introduction

To be able to design a bicycle and pedestrian bridge parametrically, knowledge about bridge design need to be gathered. Therefore in this appendix a literature study has been performed.

F.2. Bridge layout

Figure F.1 shows the bridge layout divided in a superstructure and a substructure. Each superstructure consists of a longitudinal structural system with main girders, cross beams and bracings. Besides there is also a transverse structural system which involves a cross section and a deck type. The substructure includes the piers, abutments and foundations. Besides the superstructure and substructure there are other components like bearings, expansion joints, parapets and rainwater system (Pavlovic, 2018; van der Veen, 2019).

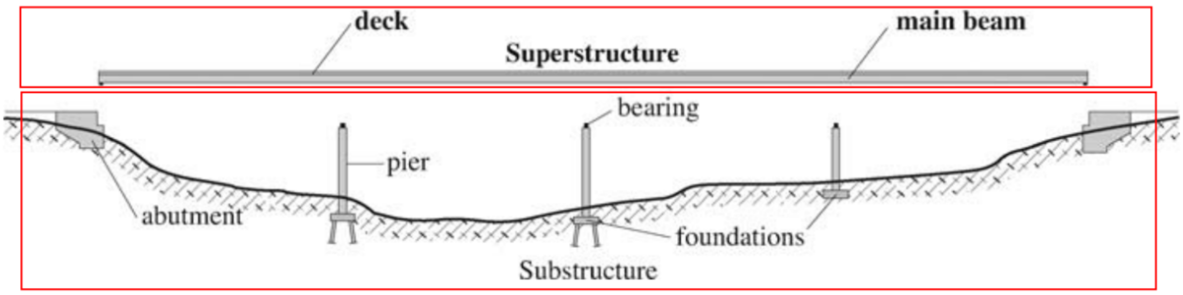


Figure F.1: Bridge layout (Pavlovic, 2018)

F.3. Bridge types

There are different bridge types. Figure F.2 presents an overview for each type of bridge and their common used main span. They can be divided in the following categories (Pavlovic, 2018; Romeijn, 2006b):

- **Plate and box girder bridges**: these bridges types are mostly used for relatively small spans and the structural system do not use space next to its main span. The construction depth increases largely if the span increases, which makes it difficult to obtain a slender deck design. Box girders have a large torsional rigidity and possible spans goes up to 250m.
- **Truss / tubular bridges**: these bridges allows for larger spans in the range of 50-100m for simple supported structures and 70-200m for continuous structures. This bridge type is characterised by very

efficient use of material since almost only normal forces are present. The truss design have a slenderness of 10-12 for simple supported trusses and 12-16 for continuous trusses and is therefore, compared to arch bridges and plate and box girder bridges, not a slender design.

- **Arch bridges**: arch bridges allows for a very slender design and do not require area next to its main span which is important in a densely build city like São Paulo. The possible span varies from 200-500m.
- **Cantilever bridges**: allows for large spans up to 500m, but like truss bridges these types are not slender.
- **Cable stayed and suspension bridges**: often used for large spans, however they occupy a relatively large area next to the main span of the bridge due to the anchorage of the towers and main cables. These bridge types are hard to apply as a standardisation since the available building space at the possible bridge locations is limited.

The decision for a bridge type depends not only on the possible length of the main span, but also on the applied materials (and local expertise of different material types), available (construction) area, maintenance, detailing, purpose of the bridge / type of loads and soil conditions.

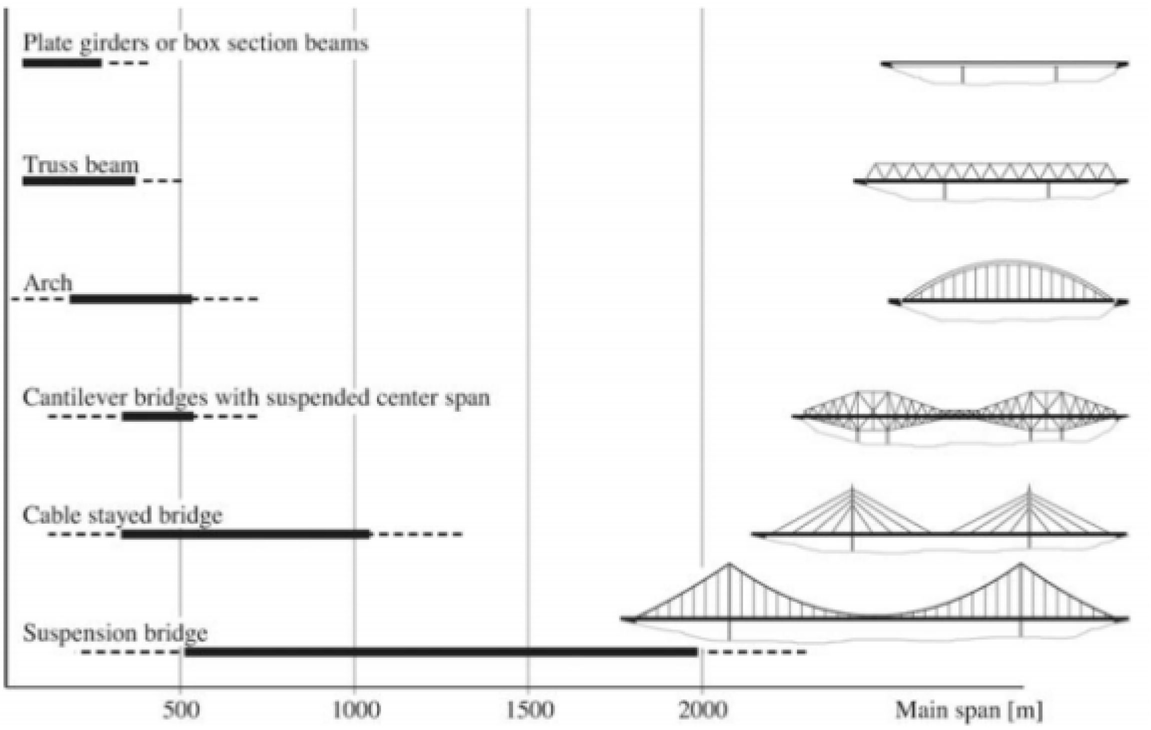


Figure F.2: Overview of the bridge types and their common used main span (Pavlovic, 2018). Plate girders and truss beams are mostly applied for relatively small spans, while cable-stayed bridges and suspension bridges often are used for relatively large spans. Cable-stayed bridges and suspension bridges use a lot of space.

F.4. Material of the bridge

Since the development of prestressed concrete and composite structures it is not straightforward to decide between a steel or concrete solution for medium and long span bridges. A span varying from 40-100m is considered as an intermediate span and between 200-400m as a long span. Steel bridges have some advantages with respect to concrete bridges, namely reduced dead loads which results in more economic foundations, easier erection procedures and shorter execution times. Also much more slender and open structures are possible (Romeijn, 2006a).

However the expertise and experience in steel constructions in Brazil is limited (Romeijn, 2006a) and steel bridges are prone to fatigue and higher material and maintenance costs since the structure needs to be preserved and prevented for dirt accumulation. Furthermore today still most bridges in São Paulo are made out of (prestressed) concrete.

According to Batista (2005), up to 1980 there was a lack of specifications and courses at universities and technical colleges. This leads to no basis of analysis and design of steel structures and most steel structures in buildings and bridges were constructed with specialists from outside Brazil. For the last two decades there is an relatively rapid increase in the application of steel structures for buildings and modern bridges in Brazil. This is due the extensive effort of the steel producers and the improvement of steel courses and research programs in institutions and universities. Due to this transition, nowadays steel structures for buildings and bridges are used frequently. The option of timber bridges is not considered since in general these bridges are applied in the range of 5 to 75m (da Vinci Pilot Project, 2008), which is less than the maximum width of 110m of the Tietê and Pinheiros rivers. Therefore, in the material choice only (prestressed) concrete and steel is considered.

F.5. Cross section types

All cross sections can be categorised (Pavlovic, 2018) according to table F.1 and figure F.3:

Table F.1: Cross section types, for a visualisation is referred to figure F.3.

Class	**Type**	**Subfigure**	**Description**
Open cross section	Twin girder	a	-Simple form, easy detailing, limited deck width of 13m
2-4	Multi girder	b	-Same type as twin girder, allows for wider decks
2-4	Twin box girder	c	-Limited height of girders, better distribution of loads
Closed cross section	Box girder	d	-Better torsional stiffness, suitable for eccentric loads
2-4	Multiple box girder	e	-Better torsional stiffness, suitable for wide decks and cable stayed and suspension bridges
2-4	U shaped box girder	f	-Better torsional stiffness, reduced weight of bottom flange
Truss cross section	Twin planar trusses	g	-Large stiffness, top chord sensitive for out of plane buckling
2-4	Spatial trusses	h	-Better torsional stiffness
2-4	Multiple spatial trusses	i	-Suitable for wide decks, connected by truss cross beams

F.6. Deck types

Besides cross section types one can distinghuish different deck types (Romeijn, 2006a):

- **Concrete deck**: often applied for small and intermediate spans. The construction is relatively easy and fast to construct and this type is cheaper than orthotropic steel decks.
- **Orthotropic steel deck**: contains difficult detailing and welding parts and therefore is more expensive. This type is often applied for traffic bridges.
- **fibre reinforced polymer (FRP)**: FRP is a relatively new material, allows for the least weight deck structure.
- **Timber deck structure**: this type is easy and fast to construct and has a light deck structure. The lifespan of timber deck structures is limited and in general less than their steel and concrete counterparts.

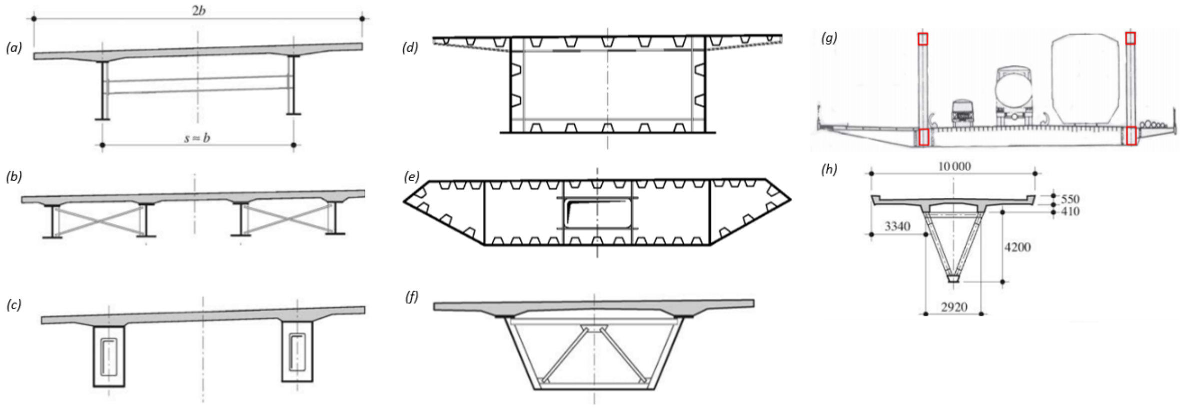


Figure F.3: (a) twin girder bridge, (b) multi girder bridge, (c) twin box girder, (d) box girders, (e) multiple box girders, (f) U-shaped box girder, (g) twin planar trusses, (h) spatial trusses. (Pavlovic, 2018)

Lifespan varies from eight (da Vinci Pilot Project, 2008) to fifteen years (*How will we pay for a new bridge?*, 2019).

- **Composite deck, steel and concrete deck combined**: often used for traffic bridges with large variable loads and less fast to construct than concrete decks.

The bridge deck can be applied above the girders (upper deck) or between the girders (lower deck). The former has the advantage that the span is balanced, the latter solution leads to a smaller construction height but creates (some) torsion in the main girders. (Pavlovic, 2018)

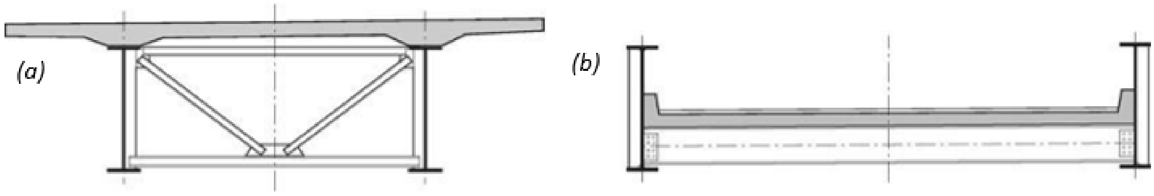


Figure F.4: (a) upper deck (b) lower deck (Pavlovic, 2018)

F.7. Pier types

Piers are mostly made of concrete but can also be made of steel. For the concrete piers there are multiple options according to the cross section of the superstructure and the plan geometry (Pavlovic, 2018; Romeijn, 2006a), see figure F.5:

- **Type A, Wall type pier**: generally less economical and less pleasing from an esthetical point of view. This type is often applied in box girder bridges.
- **Type B, Capped pile pier**: consists of multiple piles driven into the ground in a straight line. The top of the piles are capped with a beam (capping beam). It is economical and easy to construct. Most times it consists of three or more piles, so the system do not collapse in case one pile fails.
- **Type C, T-type pier**: consist out of one column and a capping beam to transfer the forces from the deck into this pile. As discussed for type (b), this type is vulnerable for collisions, so a concrete barrier has to be applied.
- **Type D, Multiple columns without cap**: same type as (b), but now without a capping beam but with columns. The deck is directly supported by the columns. This type is frequently used for girder bridges where each column supports a girder.
- **Type E, Cap and column pier**: same as type (d), but now a capping beam is present to prevent too high concentrated forces in the bridge deck.

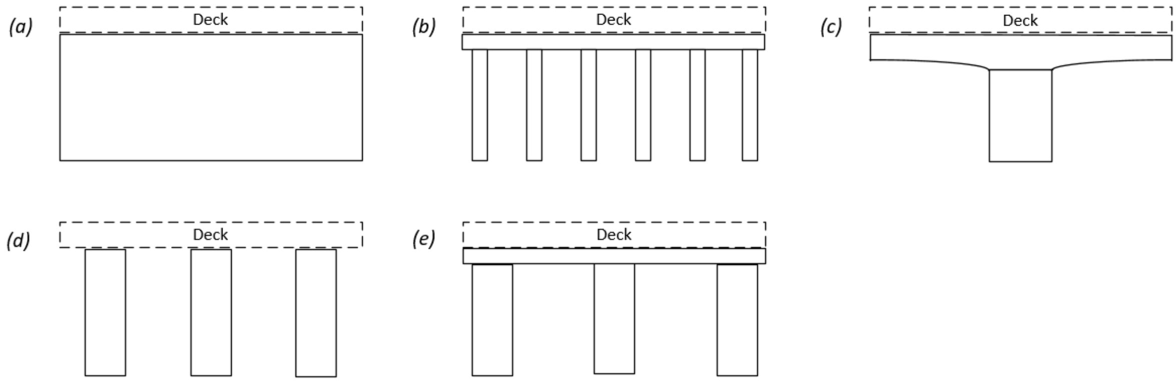


Figure F.5: (a) Wall type (b) Capped pile (c) T-type (d) Multiple columns without cap (e) Cap and column

F.8. Regulations

The ABNT is a non-profit organisation which prepare national standards. They are written in Portuguese (CROW, 2019a). To create a more efficient design process (prevent struggles with language), the Eurocodes will be applied for structural design. The use of the Eurocodes is approved by our professors from the Universidade São Paulo (Skaf, Oyamada, & Balbo, 2019).

Regarding the bicycle lanes itself, design recommendations of CROW will be applied. CROW is a Dutch standardisation organisation for e.g. road and bicycle construction, traffic control and public transport (CROW, 2019b).

G

Calculations parametric design bridge

G.1. Calculation wind speed

Determination of the wind load on the bridge

General info

I.A. van der Esch
d.d. 2019-03-01

Assumptions

-Determination of the wind load on the bridge, calculation according to NEN-EN 1991-1-4+A1+C2.
-According to the approximation method of the Eurocode.

```
> restart;
```

Geometry and wind properties

Parameters

Deck width [m]
```
> deck_width:=7.5:
```
Deck height [m]
```
> deck_height:=0.7:
```
Air density [kg/m3]
```
> Air_density:=1.25:
```
Basic wind speed [m/s]
```
> Basic_wind_speed:=40:
```
Reference height [m]
```
> Ref_height:=6.5:
```
Exposure factor [-]
```
> c_e:=3.32:
```
Slope approaching wind [deg]
```
> Slope_wind:=5:
```

Output

Approximate calculation wind force perpendicular to bridge deck (transversal direction)

Total height [m]
```
> d_tot:=deck_height+0.6:
```
Ratio 1[-]
```
> r1:=deck_width/d_tot:
```
Exposure factor [-]
```
> c_fx0:=1.3:
```
Wind load factor x-direction [-]
```
> C_x:=c_e*c_fx0:
```
Reference area [m2]
```
> Ref_area_x:=d_tot:
```

Approximate calculation wind force perpendicular to bridge deck (vertical direction)

Slope bridge deck [deg]
```
> Slope_bridge_deck:=evalf(arctan(1,50)*(180/Pi)):
```
Total angle of wind force [deg]
```
> theta:=Slope_bridge_deck+Slope_wind:
```
Ratio 2 [-]
```
> r2:=r1:
```
Exposure factor [-]
```
> c_fz0:=0.8:
```
Wind load factor x-direction [-]
```
> C_z:=c_e*c_fz0:
```
Reference area [m2]
```
> Ref_area_z:=deck_width:
```

Results

Wind force perpendicular to bridge deck, x-direction (transversal direction) [kN/m1]
```
> q_wind_x:=(1/2)*Air_density*Basic_wind_speed^2 * C_x*Ref_area_x*10^(-3);
```
$$q\_wind\_x := 5.610800000 \tag{1}$$

Wind force vertical to bridge deck, z-direction (vertical direction) [kN/m1]
```
> q_wind_z:=(1/2)*Air_density*Basic_wind_speed^2 * C_z*Ref_area_z*10^(-3);
```
$$q\_wind\_z := 19.92000000 \tag{2}$$

Figure G.1: Calculation of wind load acting on the bridge

G.2. Load combinations

This section presents the load combinations on the bridge, determining the governing forces in the ULS and SLS. An overview of all the load combinations are presented in table 5.3.

For the calculation is referred to appendix G.3.

G.2.1. ULS combinations

The ULS considers the maximum load in each bridge part. The obtained force distribution is used to set up a conceptual design for the different elements.

Load combination ULS 1.01

This load combination (see figure G.2) considers the maximum moments in the main beams.

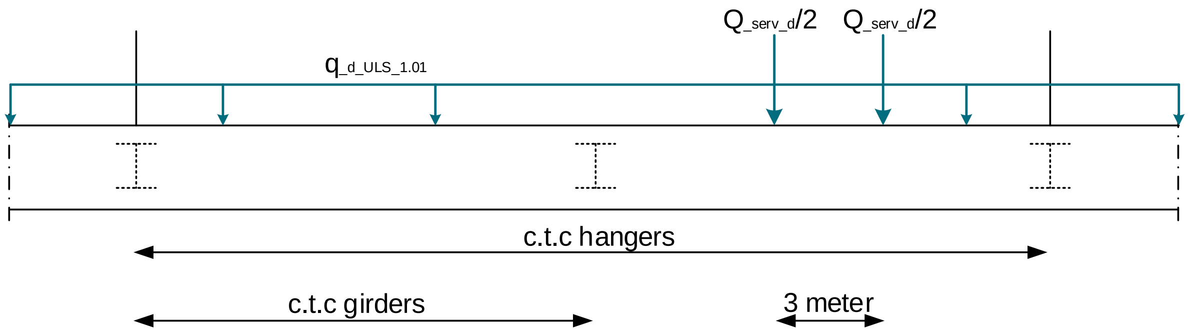


Figure G.2: Load combination ULS-1.01

Load combination ULS 1.02

This load combination (see figure G.3) considers the maximum moments in the arch.

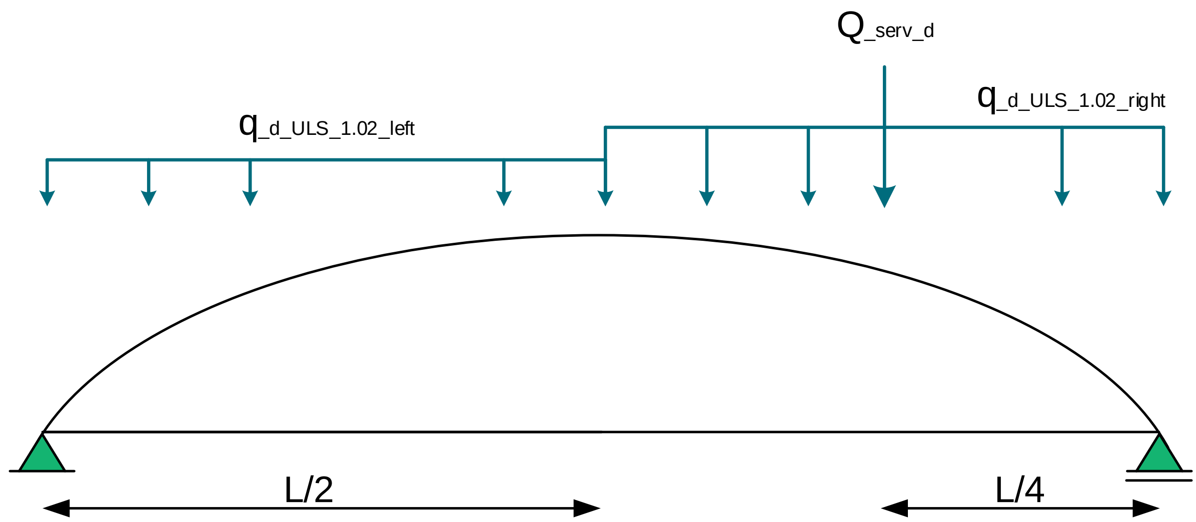


Figure G.3: Load combination ULS-1.02

Load combination ULS 1.03

This load combination (see figure G.4) considers the maximum normal force in the arch.

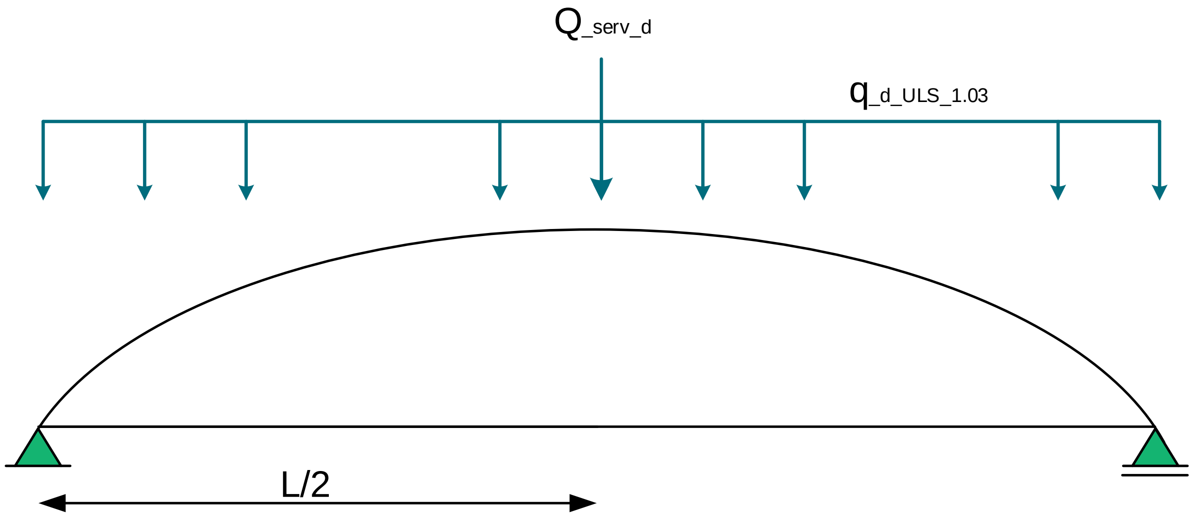


Figure G.4: Load combination ULS-1.03

Load combination ULS 1.04

This load combination (see figure G.5) considers the maximum moments in the arch. Only a quarter of the deck is loaded.

Load combination ULS 1.05

This load combination (see figure G.6) considers the maximum normal forces in the arch. Only a half of the deck is loaded.

Load combination ULS 1.06

This load combination (see figure G.7) considers the maximum horizontal forces (braking and acceleration forces) acting on the bridge deck. Since the horizontal forces are acting at the top of the bridge deck, it creates an eccentricity (bending moments) in the main beams.

Load combination ULS 1.07

This load combination (see figure G.8) considers the collision force acting at the piers of the bridge, combined with the vertical reactions from the weight of the bridge acting on the piers.

Load combination ULS 1.08

This load combination (see figure G.9) considers the maximum vertical forces acting in the hangers of the bridge in the usage stage. The maximum forces occurs if the bridge is fully loaded and there is a service vehicle at the position of one of the hangers.

Load combination ULS 1.09

This load combination (see figure G.10) considers whether the deck can be uplifted by wind or not. Only the own weight of the deck is considered in combination with an uplifting wind force.

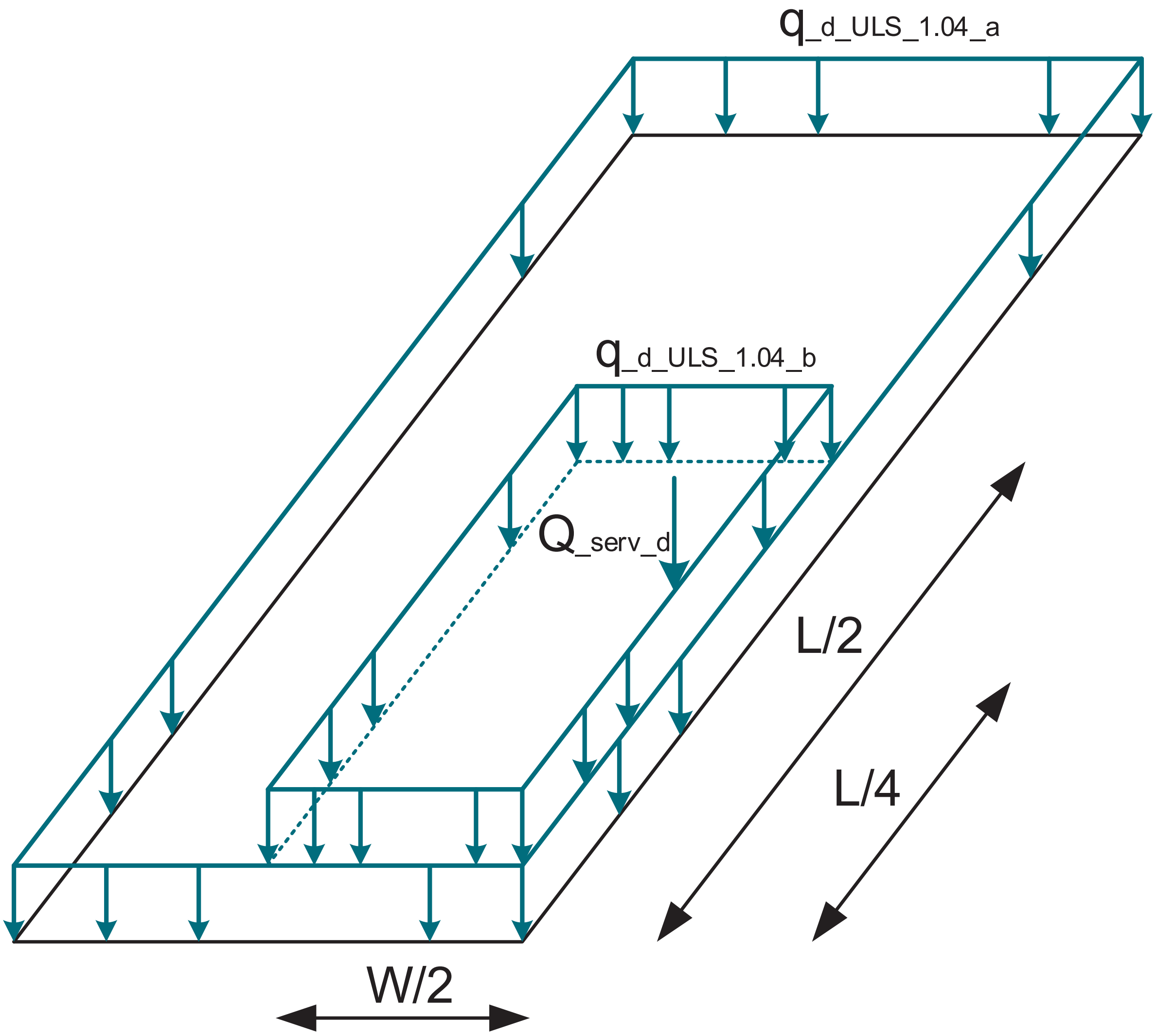


Figure G.5: Load combination ULS-1.04

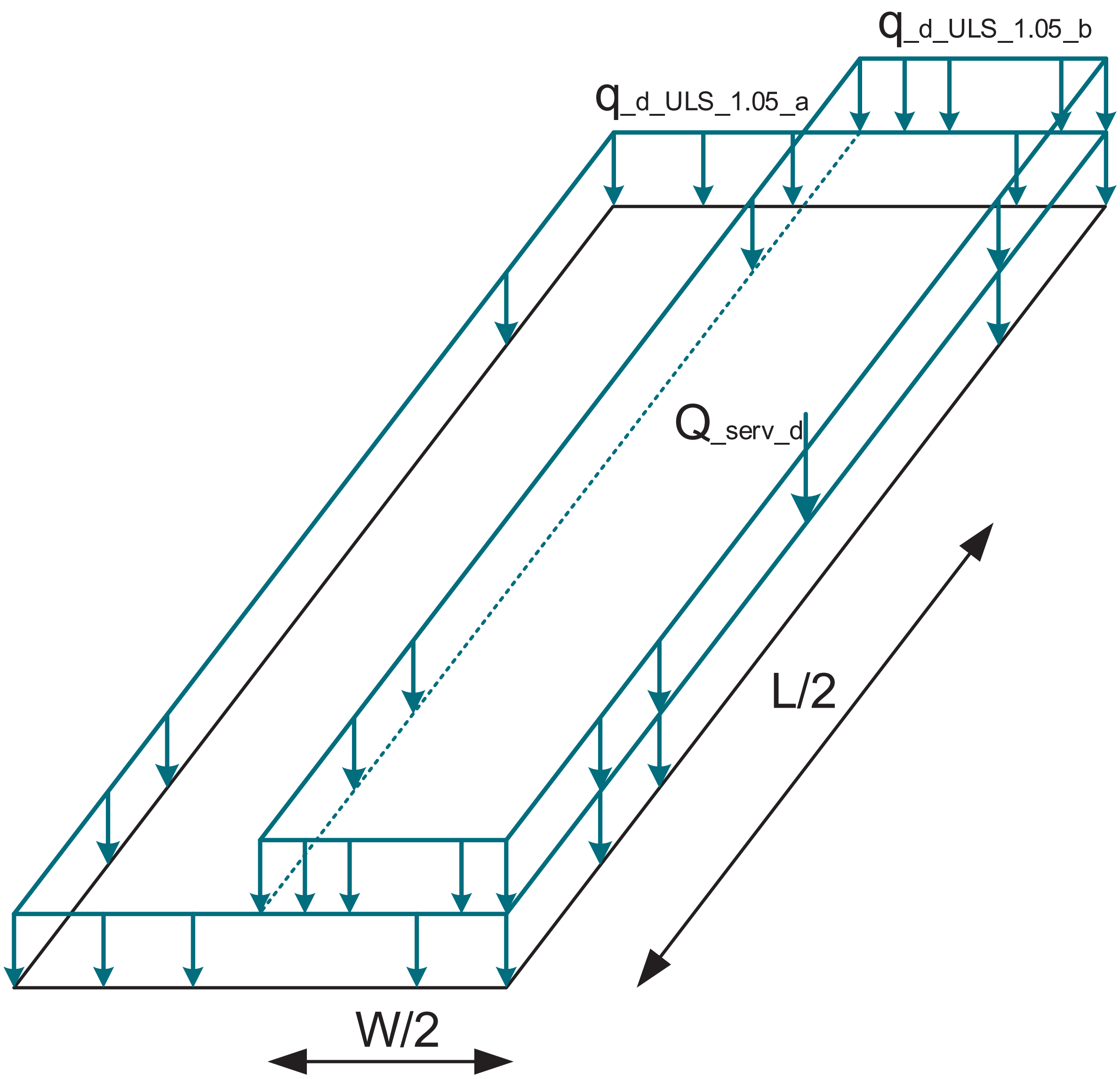


Figure G.6: Load combination ULS-1.05

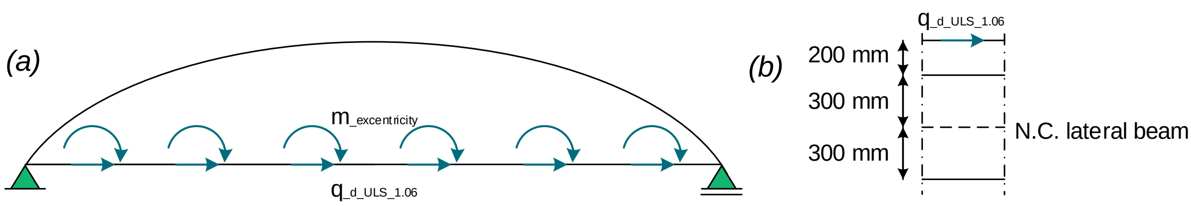


Figure G.7: Load combination ULS-1.06

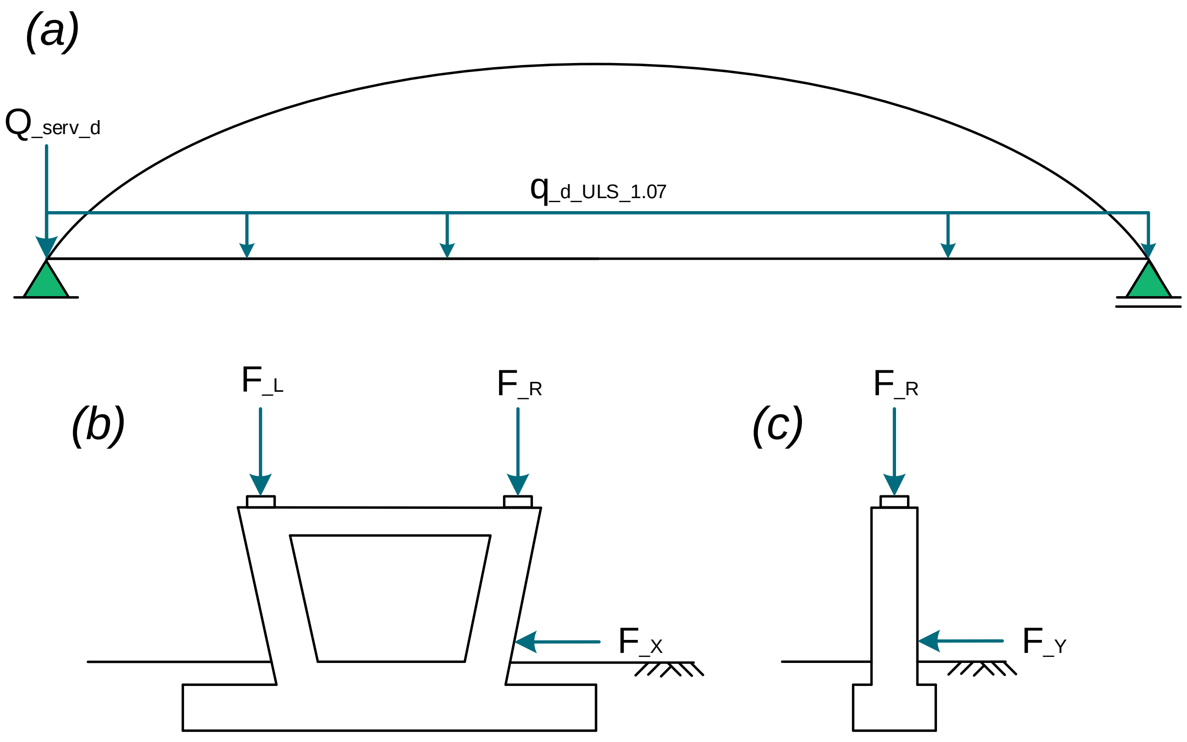


Figure G.8: Load combination ULS-1.07

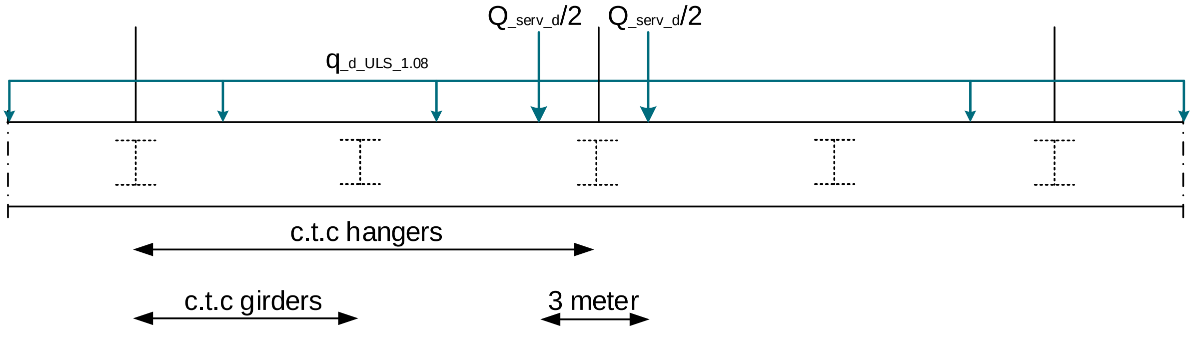


Figure G.9: Load combination ULS-1.08

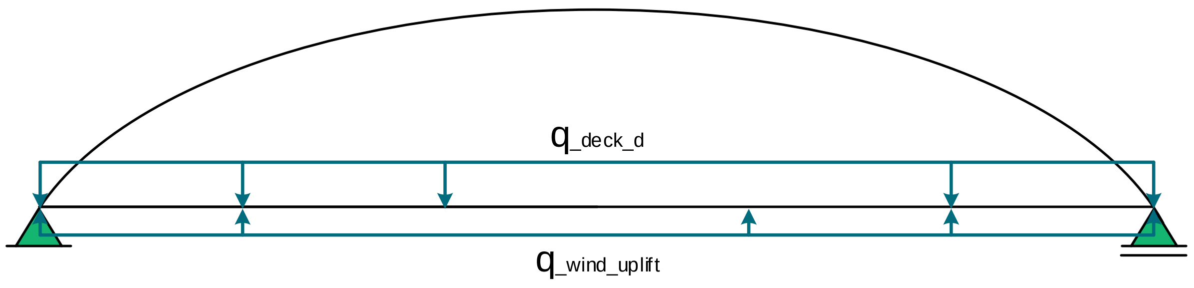


Figure G.10: Load combination ULS-1.09

Load combination ULS 1.10

This load combination (see figure G.11) considers the following stages (see also subsection 5.1.9):

- **Stage 0a**: transportation phase
- **Stage 0b**: lifting phase
- **Stage 1a**: building phase, hangers are installed, concrete slab is not poured yet
- **Stage 1b**: building phase, hangers are installed, concrete slab is poured but not hardened yet

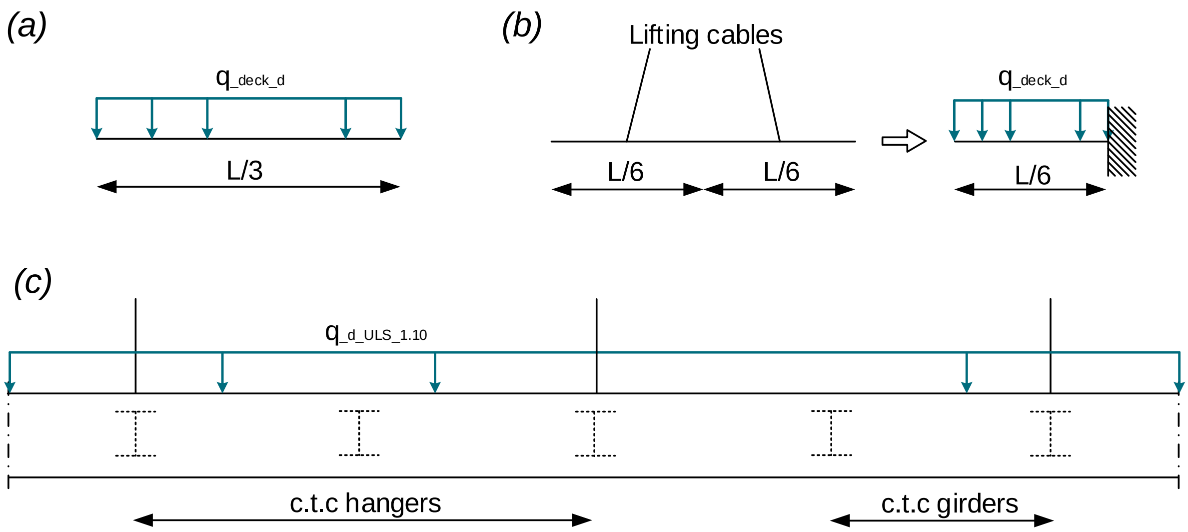


Figure G.11: Load combination ULS-1.10

Load combination ULS 1.11

This load combination (see figure G.12) considers the maintenance operation: a cable is temporary removed and that will lead to additional normal forces in the adjacent hangers. The total equivalent load of the two axes of the service vehicles is placed exactly at the position of an hanger.

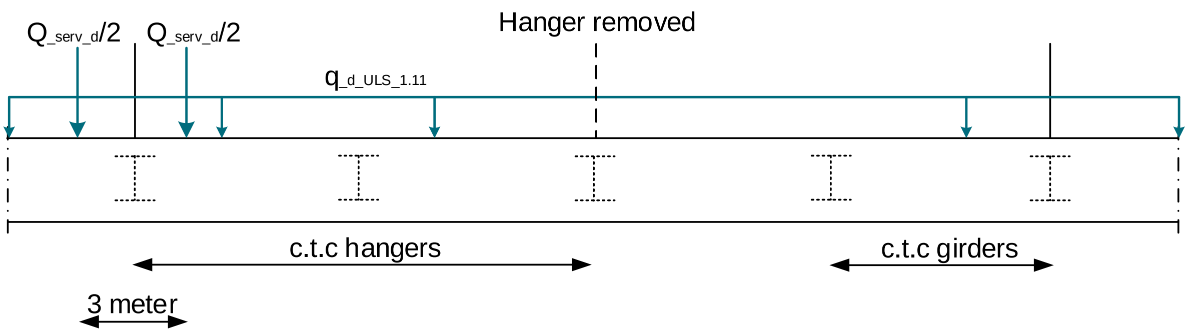


Figure G.12: Load combination ULS-1.11

G.2.2. SLS combinations

The SLS load combinations are used for the determination of maximal deflections of the bridge deck.

Load combination SLS 2.01

This load combination (see figure G.13) assumes a fully loaded deck with in the middle a service vehicle.

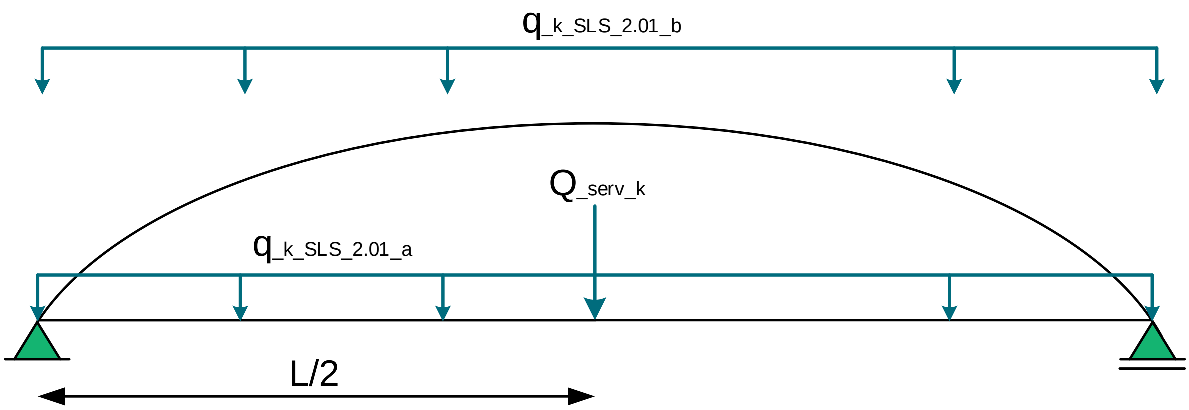


Figure G.13: Load combination SLS-2.01

Load combination SLS 2.02

This load combination (see figure G.14) assumes a chess-board loading pattern which lead to large deformations of the deck.

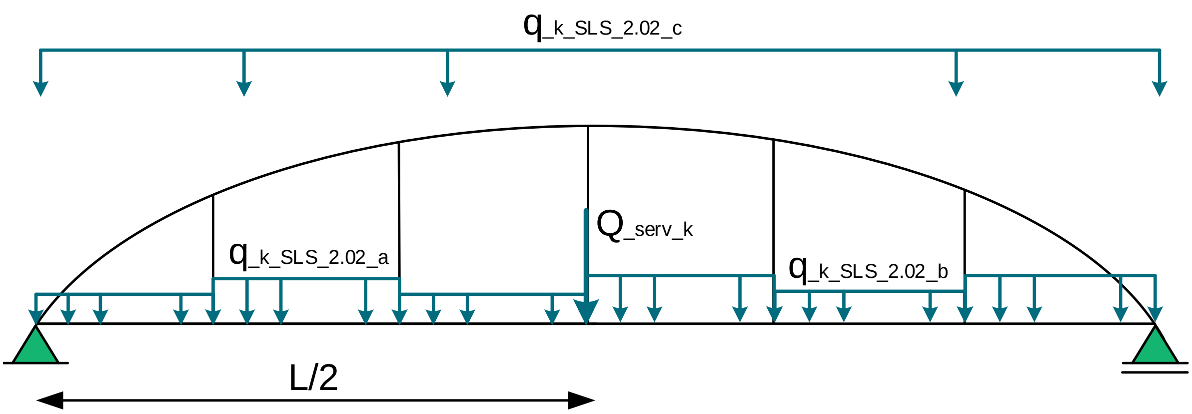


Figure G.14: Load combination SLS-2.02

Load combination SLS 2.03

This load combination (see figure G.15) assumes an unequal load distribution: at the left half of the deck also UDL and the parapet forces are present in addition to the own weight and wind load (which acts only at the right half of the deck).

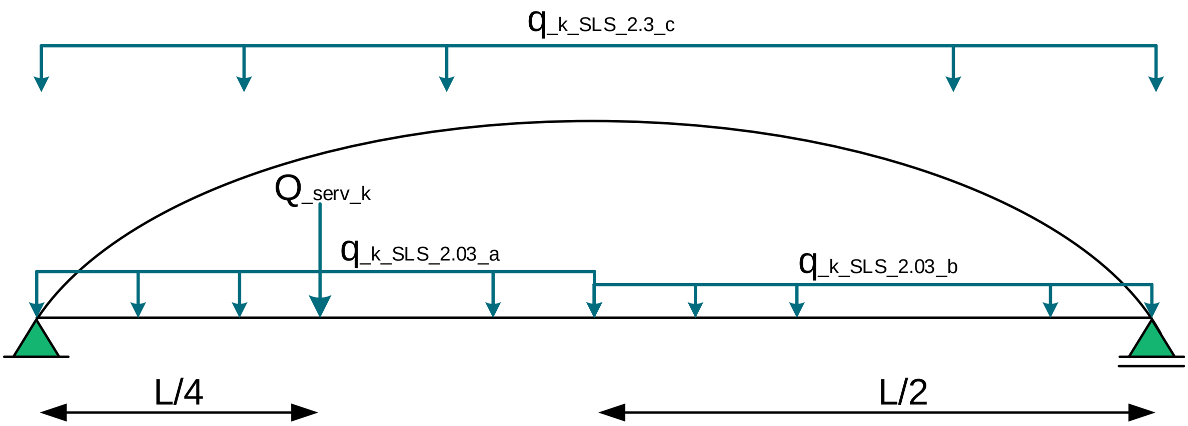


Figure G.15: Load combination SLS-2.03

G.3. Force distribution

Force distribution of the structural elements of the bridge

General info
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d.d. 2019-04-01

Assumptions
-Determination of the wind load on the bridge, calculation according to NEN-EN 1991-1-4+A1+C2.
-According to the approximation method of the Eurocode.
-Based on slides Slender Structures (CIE4190)
-Arch design based on equally distributed load --> parabola design --> least amount of bending moments
-Rule of thumb: arch height is 1/6 of span

General

```
> restart;
> with(plots): with(plottools): with(Student[Calculus1]):
```
Build-in distance error to overcome problems with undefined Heaviside and Dirac functions:
```
> err:=0.01:
```

Loads

Vertical loads

Own weight deck - total [kN/m2]:
```
> q_deck_k:=6: q_deck_k_maintenance:=1: q_deck_k_build:=2: q_deck_k_pour:=1:
```
Own weight arch [kN/m1]:
```
> q_arch:=8:
```
Own weight hangers [kN/m1]:
```
> q_hanger:=1:
```
Load parapet [kN/m1]:
```
> q_parapet:=1:
```
UDL [kN/m2]:
```
> UDL_lower:=3.20: UDL_upper:=2.86:
```
Wind load [kN/m1]:
```
> q_wind_hor:=5.61: q_wind_ver:=21.25:
```
Service vehicle [kN]:
```
> q_serv:=50: q_install:=135:
```
Colision force [kN]:
```
> F_coll_x:=1000:
```
Momentary factors [-]:
```
> psi1:=0.4: psi2:=0.8:
```
Safety factors [-]:
```
> saf1:=1.5: saf2:=1.65: saf3:=1.4: saf4:=0.9: saf5:=1:
```

Horizontal loads [kN/m1]:
```
> q_hor_short_span:=hoh_main_beam_cross*0.1*UDL_lower;
```
$$q\_hor\_short\_span := 0.320\ hoh\_main\_beam\_cross \tag{4.1}$$
```
> q_hor_long_span:=hoh_main_beam_cross*0.1*UDL_upper;
```
$$q\_hor\_long\_span := 0.286\ hoh\_main\_beam\_cross \tag{4.2}$$

Properties of the arch

Shape of arch: circular hollow section
Thickness of the arch wall [m]:
```
> t:=0.025:
```
Outer diameter [m]:
```
> D_outer:=1.3:
```
Second moment of intertia Izz [m4] of a single arch:
```
> I_zz:=(1/64)*Pi*(D_outer^4 - (D_outer-2*t)^4):
```
E-modulus [kN/m2]:
```
> E:=210*10^6:
```

Bending stiffness of a single arch [kNm2]:
```
> EI:=E*I_zz;
```
$$EI := 4.274808691\ 10^6 \quad (5.1)$$

Area of a single arch [m2]:
```
> A:=(1/4)*Pi*(D_outer^2 - (D_outer-2*t)^2):
```
Axial stiffness of a single arch [kN]:
```
> EA:=E*A;
```
$$EA := 2.102903582\ 10^7 \quad (5.2)$$

Geometry

Coordinate info of the arch [m]
```
> hoh_main_beam_cross:=7: hoh_hanger:=6: deck_width:=7:
> L_shortest:=70: L_longest:=110:
> L_transport:=L_longest/3:
> hoh_hanger_maintenance:=9:
```

Ratio span / arch height [-]:
```
> r3:=6:
```
Arch length [m]:
```
> L:=110:
> Margin:=0:
```

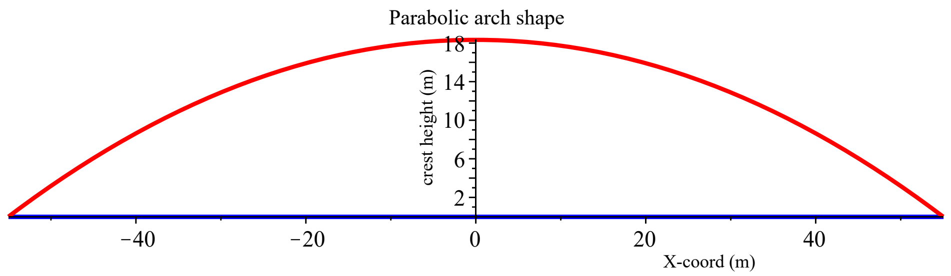
Point coordinates (Bottom Left (x-coord), Bottom Right (x-coord), Top (y-coord)) [m]:
Coordinate convention: origin is at midspan deck, positive z-axis is downwards, negative upwards.
```
> P1:=-L/2: P2:=L/2: P3:=-L/r3:
```

With three points and three unknowns the shape of the parabola can be determined uniquely.
```
> eq0:=a*x^2 + b*x + c:
> eq1:=subs(x=P1,eq0)=0:
> eq2:=subs(x=P2,eq0)=0:
> eq3:=subs(x=0,eq0)=P3:
> sol1:=solve({eq1,eq2,eq3},{a,b,c}): assign(sol1):
```

Plot of the arch

The parabola of the arch now yields:
```
> z:=eq0;
```
$$z := \frac{x^2}{165} - \frac{55}{3} \quad (6.1)$$

```
> AA:=line([P1,0], [P2,0], color=blue,thickness=3):
> BB:=plot(-z,x=P1-Margin..P2+Margin,thickness=3,color=red,title="Parabolic arch shape",
  titlefont = ["ARIAL", 12],labels = ["X-coord (m)","crest height (m)"],labeldirections=
  ["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,200]):
> display(AA,BB);
```



Load combination ULS-1.01 - Maximum moment in deck beam

Design loads

Design load deck [kN/m1]:
```
> q_deck_d:=saf3*q_deck_k*hoh_main_beam_cross/2;
```
$$q\_deck\_d := 29.40000000 \quad (7.1)$$

Design load UDL [kN/m1] (use half deck width):
```
> q_UDL_d:=UDL_lower*psi1*saf1*deck_width/2;
```
$$q\_UDL\_d := 6.720000000 \quad (7.2)$$

Wind load [kN/m1] (use half deck width):

```
> q_wind_d:=q_wind_ver * psi1*saf2/2;
```

$$q\_wind\_d := 7.012500000 \quad (7.3)$$

Design load parapet [kN/m1]:

```
> q_parapet_d:=q_parapet*psi1*saf2;
```

$$q\_parapet\_d := 0.660 \quad (7.4)$$

Total design load on beam, combination ULS-1.01 [kN/m1]:

```
> q_d_ULS:=q_deck_d + q_UDL_d + q_wind_d + q_parapet_d;
```

$$q\_d\_ULS := 43.79250000 \quad (7.5)$$

Design point load service vehicle [kN]:

```
> q_serv_d:=q_serv*psi2*saf1;
```

$$q\_serv\_d := 60.00 \quad (7.6)$$

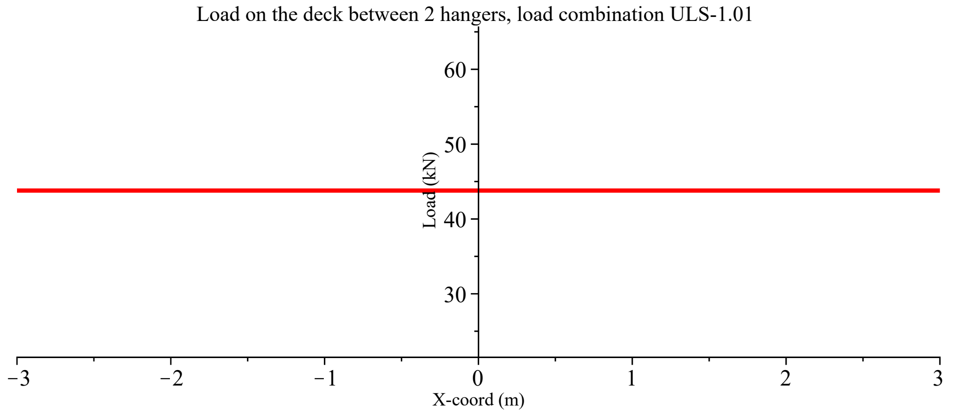
Force distribution

Total load function in MAPLE description:

```
> q_101:=q_d_ULS + q_serv_d*Dirac(x-err):
```

Plot of the load

```
> plot(q_101,x=-hoh_hanger/2-Margin..hoh_hanger/2+Margin,thickness=3,color=red,title="Load on the deck between 2 hangers, load combination ULS-1.01",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Load (kN)"],labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



Mathematical relations

Now the differential equation for the beam has to be used.

```
> DV0:=EI*diff(w0(x),x$4) = q_101:
> sol0:=dsolve(DV0,w0(x)): assign(sol0): w0:=w0(x):
> phi0:=-diff(w0,x): kappa0:=diff(phi0,x): M0:=EI*kappa0: V0:=diff(M0,x):
```

Boundary conditions

The girder is assumed as an inifinite long girder, resting on fixed supports (in reality it is an elastic support).

```
> x:=-hoh_hanger/2: eq50:=phi0=0: eq51:=w0=0:
> x:=hoh_hanger/2: eq52:=phi0=0: eq53:=w0=0:
> x:='x':
```

Solve for the unknowns

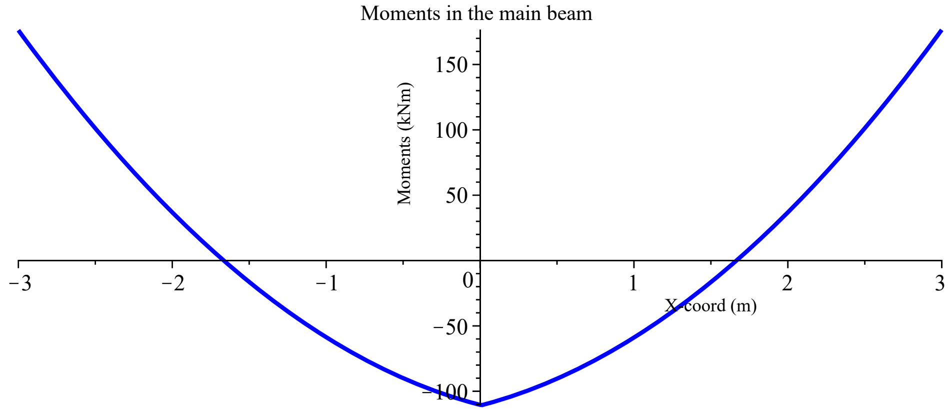
```
> sol50:=solve({eq50,eq51,eq52,eq53},{_C1,_C2,_C3,_C4}): assign(sol50):
```

Output

-Moment of the arch, projected on the deck.
-Added a minus sign because this is the real direction of the projected displacement.

Moment distribution

```
> plot(-M0,x=-hoh_hanger/2-Margin..hoh_hanger/2+Margin,thickness=3,color=blue,title="Moments in the main beam",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Moments (kNm)"],labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```




```
> maximize(M0,x=-hoh_hanger/2..hoh_hanger/2);
```
110.6855604 **(7.7)**

```
> minimize(M0,x=-hoh_hanger/2..hoh_hanger/2);
```
−176.5269983 **(7.8)**

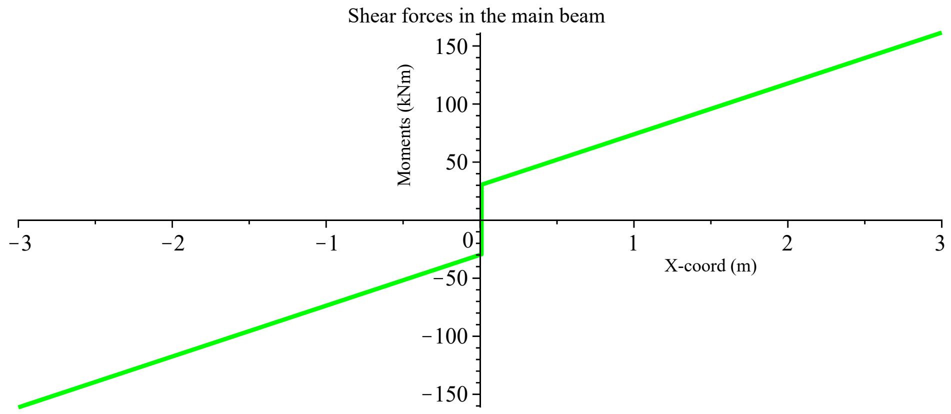
```
> x_root:=Roots(M0,-hoh_hanger/2..hoh_hanger/2);
```
$x\_root := [-1.664879989, 1.665855321]$ **(7.9)**

Distance in the span between two points of zero bending moment:

```
> L_e:=x_root[2]-x_root[1]
```
$L\_e := 3.330735310$ **(7.10)**

Shear force distribution

```
> plot(-V0,x=-hoh_hanger/2-Margin..hoh_hanger/2+Margin,thickness=3,color=green,title="Shear
  forces in the main beam",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Moments (kNm)"],
  labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



Load combination ULS-1.02 - Maximum moment in arch

Assumptions

-Regarding side view.
-Right half of the deck is loaded with UDL, left half without UDL.
-Maintenance vehicle is located at right half of deck.
-Wind load is distributed over the complete length of the deck.

Design load deck [kN/m1]:

```
> q_deck_d:=saf3*q_deck_k*hoh_main_beam_cross/2;
```
$q\_deck\_d := 29.40000000$ **(8.1)**

Design load hangers [kN/m1]:

```
> q_hanger_d:=q_hanger*saf3;
```
$q\_hanger\_d := 1.4$ **(8.2)**

Design load arch [kN/m1]:
```
> q_arch_d:=q_arch*saf3;
```
$q\_arch\_d := 11.2$ (8.3)

Design load UDL [kN/m1] (use half deck width):
```
> q_UDL_d:=UDL_lower*psi2*saf1*deck_width/2;
```
$q\_UDL\_d := 13.44000000$ (8.4)

Wind load [kN/m1] (use half deck width):
```
> q_wind_d:=q_wind_ver * psi1*saf2/2;
```
$q\_wind\_d := 7.012500000$ (8.5)

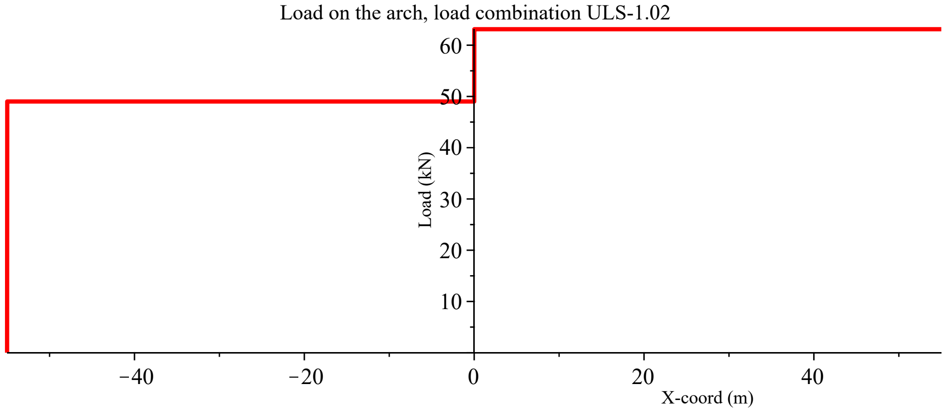
Design load parapet [kN/m1]:
```
> q_parapet_d:=q_parapet*psi1*saf2;
```
$q\_parapet\_d := 0.660$ (8.6)

Total design load on arch right part, combination ULS-1.02 [kN/m1]:
```
> q_d_ULS_right:=q_deck_d + q_hanger_d + q_arch_d + q_UDL_d + q_wind_d + q_parapet_d;
```
$q\_d\_ULS\_right := 63.11250000$ (8.7)

Total design load on arch left part, combination ULS-1.02 [kN/m1]:
```
> q_d_ULS_left:=q_deck_d + q_hanger_d + q_arch_d + q_wind_d;
```
$q\_d\_ULS\_left := 49.01250000$ (8.8)

Design point load service vehicle [kN]:
```
> q_serv_d:=q_serv*psi1*saf1;
```
$q\_serv\_d := 30.00$ (8.9)

Force distribution

Total load function in MAPLE description
```
> q_102:=q_d_ULS_left*Heaviside(x-P1-err)-q_d_ULS_left*Heaviside(x-err) + q_d_ULS_right*
  Heaviside(x-err)-q_d_ULS_right*Heaviside(x-P2-err) + q_serv_d*Dirac(x-0.5*P2-err):
```
Plot of the load
```
> plot(q_102,x=P1-Margin..P2+Margin,thickness=3,color=red,title="Load on the arch, load
  combination ULS-1.02",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Load (kN)"],
  labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```


Mathematical relations
```
> DV1:=EI*diff(w1(x),x$4) = q_102-H*diff(z,x$2):
> sol2:=dsolve(DV1,w1(x)): assign(sol2): w1:=w1(x):
> phi1:=-diff(w1,x): kappa1:=diff(phi1,x): M1:=EI*kappa1: V1:=diff(M1,x):
```

Boundary conditions
```
> x:=P1: eq100:=M1=0: eq101:=w1=0:
> x:=P2: eq102:=M1=0: eq103:=w1=0:
> x:='x':
```

Extra condition to found horizontal force H

-This formula is only valid for parabolic arches in which axial deformation is neglected!
```
> eq104:=int(w1,x=P1..P2)=0:
```

Solve for the unknowns
```
> sol3:=solve({eq100,eq101,eq102,eq103,eq104},{_C5,_C6,_C7,_C8,H}): assign(sol3):
> H;
```
4650.032729 (8.10)

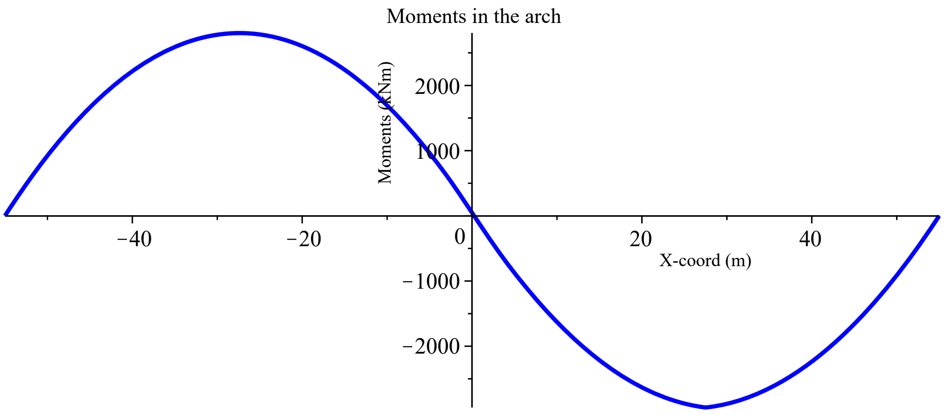
Output

-Moment in the arch, projected on the deck.

-Added a minus sign because this is the real direction of the projected displacement.

Moment line
```
> plot(-M1,x=P1-Margin..P2+Margin,thickness=3,color=blue,title="Moments in the arch",titlefont =
```

```
["ARIAL", 12],labels = ["X-coord (m)","Moments (kNm)"],labeldirections=["horizontal",
"vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```




```
> maximize(M1,x=P1..P2);
```

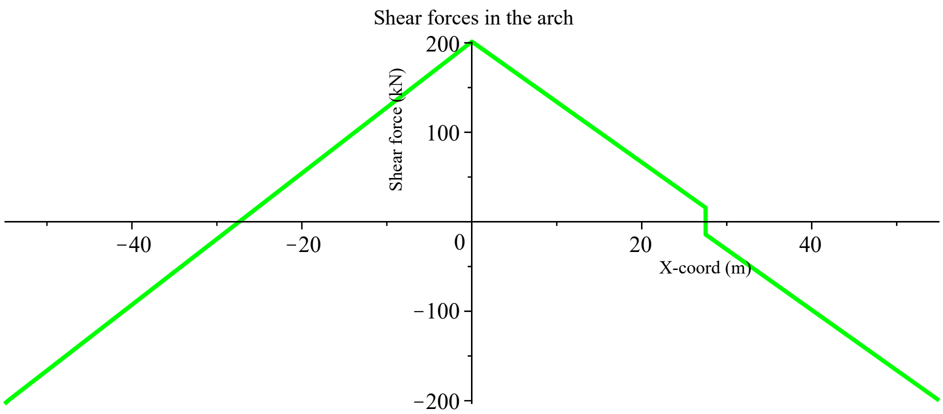
2940.473383 **(8.11)**

```
> minimize(M1,x=P1..P2);
```

−2803.649172 **(8.12)**

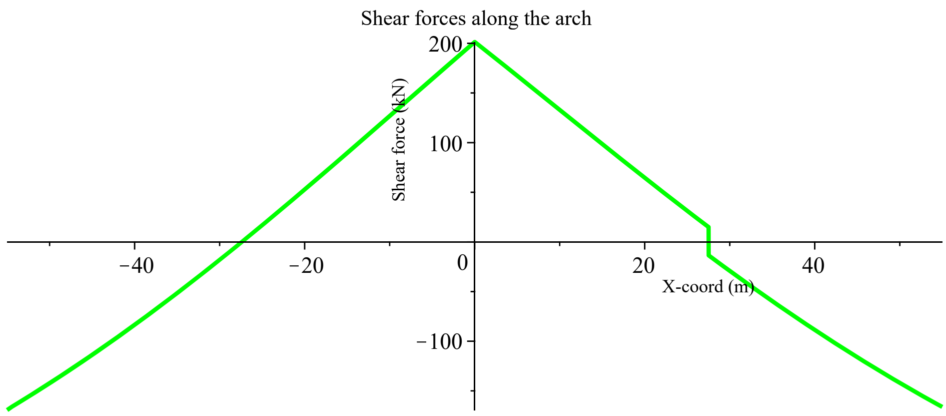
Shear force line arch projected on the deck

```
> plot(V1,x=P1-Margin..P2+Margin,thickness=3,color=green,title="Shear forces in the arch",
  titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Shear force (kN)"],labeldirections=
  ["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



Shear force line along the arch

```
> alpha1:=arctan(diff(z,x)):
> V1_arch:=H*sin(alpha1) + (-EI*diff(w1,x$3)-H*diff(z,x))*cos(alpha1):
> plot(V1_arch,x=P1-Margin..P2+Margin,thickness=3,color=green,title="Shear forces along the
  arch",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Shear force (kN)"],labeldirections=
  ["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



Displacement (not governing for this combination, just for an indication!):

```
> plot(-w1,x=P1-Margin..P2+Margin,thickness=3,color=blue,title="Displacements in the arch (just for indication)",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Displacements (m)"],labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]):
```

```
> maximize(w1,x=P1..P2);
```

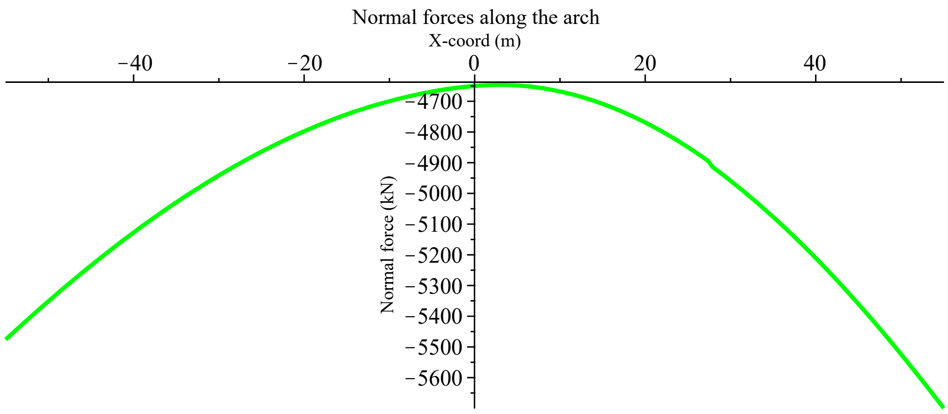
0.2094963667 **(8.13)**

```
> minimize(w1,x=P1..P2);
```

−0.001517578275 **(8.14)**

Normal force line, along the arch

```
> alpha1:=arctan(diff(z,x)):
> N1_arch:=-H*cos(alpha1) + (-EI*diff(w1,x$3)-H*diff(z,x))*sin(alpha1):
> plot(N1_arch,x=P1-Margin..P2+Margin,thickness=3,color=green,title="Normal forces along the arch",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Normal force (kN)"],labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```




```
> maximize(N1_arch,x=P1..P2);
```

−4646.515395 **(8.15)**

```
> minimize(N1_arch,x=P1..P2);
```

−5699.430131 **(8.16)**

Load combination ULS-1.03 - Maximum normal force in arch

-Regarding side view.

Design load deck [kN/m1]:

```
> q_deck_d:=saf3*q_deck_k*hoh_main_beam_cross/2;
```

$q\_deck\_d := 29.40000000$ **(9.1)**

Design load hangers [kN/m1]:
```
> q_hanger_d:=q_hanger*saf3;
```
$$q\_hanger\_d := 1.4 \tag{9.2}$$

Design load arch [kN/m1]:
```
> q_arch_d:=q_arch*saf3;
```
$$q\_arch\_d := 11.2 \tag{9.3}$$

Design load UDL [kN/m1] (use half deck width):
```
> q_UDL_d:=UDL_lower*psi2*saf1*deck_width/2;
```
$$q\_UDL\_d := 13.44000000 \tag{9.4}$$

Wind load [kN/m1] (use half deck width):
```
> q_wind_d:=q_wind_ver * psi1*saf2/2;
```
$$q\_wind\_d := 7.012500000 \tag{9.5}$$

Design load parapet [kN/m1]:
```
> q_parapet_d:=q_parapet*psi1*saf2;
```
$$q\_parapet\_d := 0.660 \tag{9.6}$$

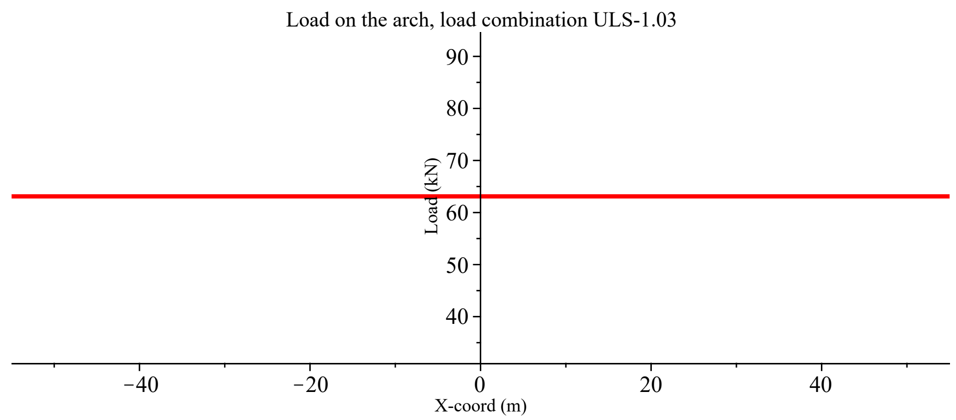
Total design load on arch, combination ULS-1.03 [kN/m1]:
```
> q_d_ULS:=q_deck_d + q_hanger_d + q_arch_d + q_UDL_d + q_wind_d + q_parapet_d;
```
$$q\_d\_ULS := 63.11250000 \tag{9.7}$$

Design point load service vehicle [kN]:
```
> q_serv_d:=q_serv*psi1*saf1;
```
$$q\_serv\_d := 30.00 \tag{9.8}$$

Force distribution

Total load function in MAPLE description
```
> q_103:=q_d_ULS + q_serv_d*Dirac(x-err):
```

Plot of the load
```
> plot(q_103,x=P1-Margin..P2+Margin,thickness=3,color=red,title="Load on the arch, load
  combination ULS-1.03",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Load (kN)"],
  labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



Mathematical relations
```
> w:='w': H:='H': phi:='phi': kappa:='kappa': M:='M': V:='V':
> DV2:=EI*diff(w2(x),x$4) = q_103-H*diff(z,x$2):
> sol12:=dsolve(DV2,w2(x)): assign(sol12): w2:=w2(x):
> phi2:=-diff(w2,x): kappa2:=diff(phi2,x): M2:=EI*kappa2: V2:=diff(M2,x):
```

Boundary conditions
```
> x:=P1: eq110:=M2=0: eq111:=w2=0:
> x:=P2: eq112:=M2=0: eq113:=w2=0:
> x:='x':
```

Extra condition to found horizontal force H

-This formula is only valid for parabolic arches in which axial deformation is neglected!!
```
> eq114:=int(w2,x=P1..P2)=0:
```

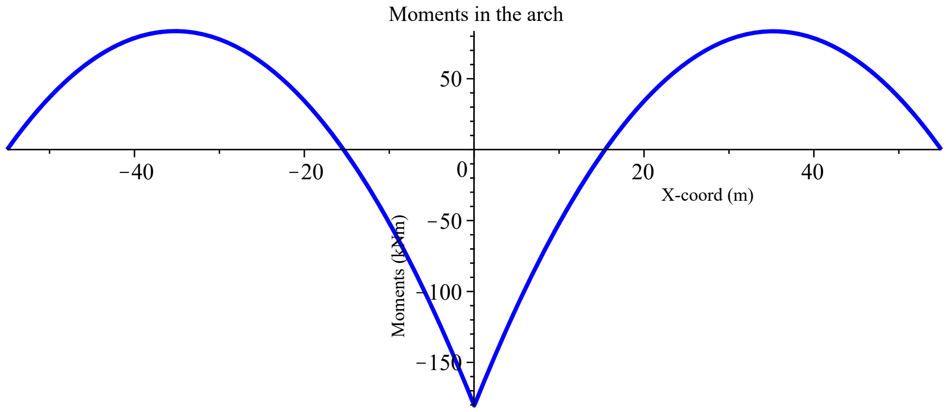
Solve for the unknowns
```
> sol13:=solve({eq110,eq111,eq112,eq113,eq114},{_C9,_C10,_C11,_C12,H}): assign(sol13):
> H;
```
$$5241.937500 \tag{9.9}$$

Output

-Moment of the arch, projected on the deck.
-Added a minus sign because this is the real direction of the projected displacement.

Moment line, projected on the deck
```
> plot(-M2,x=P1-Margin..P2+Margin,thickness=3,color=blue,title="Moments in the arch",titlefont =
  ["ARIAL", 12],labels = ["X-coord (m)","Moments (kNm)"],labeldirections=["horizontal",
```

```
"vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```




```
> maximize(M2,x=P1..P2);
```

180.4687654 **(9.10)**

```
> minimize(M2,x=P1..P2);
```

−83.58523965 **(9.11)**

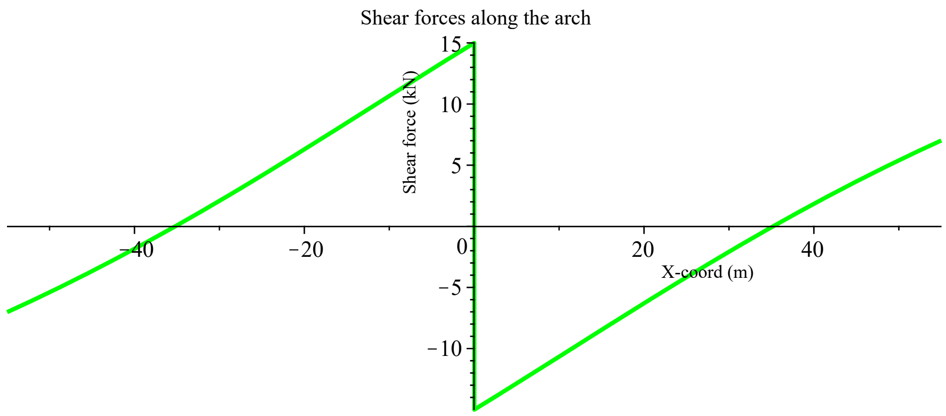
Shear force line, projected on the deck

Shear force of the arch, projected on the deck

```
> plot(V2,x=P1-Margin..P2+Margin,thickness=3,color=green,title="Shear forces in the arch",
  titlefont = ["ARIAL", 20],labels = ["X-coord (m)","Shear force (kN)"],labeldirections=
  ["horizontal","vertical"],labelfont=["ARIAL",16],size=[1400,300]):
```

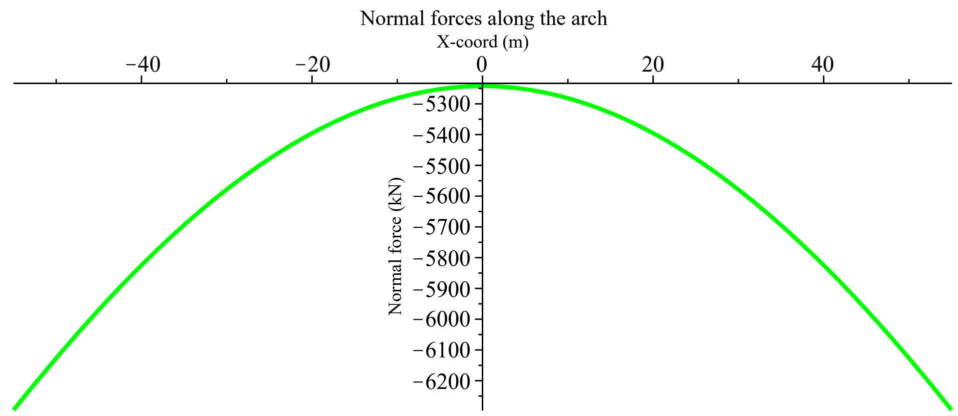
Shear force line, along the arch

```
> alpha2:=arctan(diff(z,x)):
> V2_arch:=H*sin(alpha2) + (-EI*diff(w2,x$3)-H*diff(z,x))*cos(alpha2):
> plot(V2_arch,x=P1-Margin..P2+Margin,thickness=3,color=green,title="Shear forces along the
  arch",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Shear force (kN)"],labeldirections=
  ["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



Normal force line, along the arch

```
> N2_arch:=-H*cos(alpha2) + (-EI*diff(w2,x$3)-H*diff(z,x))*sin(alpha2):
> plot(N2_arch,x=P1-Margin..P2+Margin,thickness=3,color=green,title="Normal forces along the
  arch",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Normal force (kN)"],labeldirections=
  ["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```




```
> maximize(N2_arch,x=P1..P2);
```

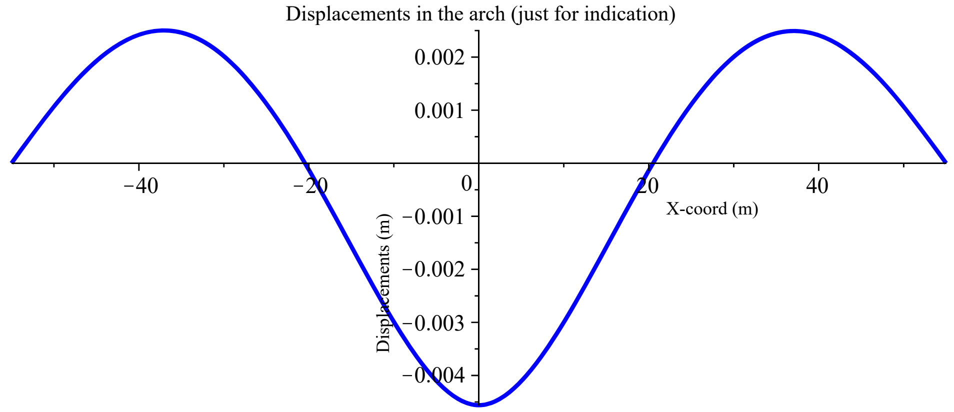
-5241.935720 **(9.12)**

```
> minimize(N2_arch,x=P1..P2);
```

-6295.346043 **(9.13)**

Displacement (not governing for this combination, just for an indication!):

```
> plot(-w2,x=P1-Margin..P2+Margin,thickness=3,color=blue,title="Displacements in the arch (just
  for indication)",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Displacements (m)"],
  labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



Load combination ULS-1.06 - Maximum normal (horizontal) force in deck

-Regarding side view, required for horizontal force on pier and max. normal force in deck
-The distrubted moments are neglected.
-Only variable force, hence no momentary factors used.

Distributed horizontal forces along deck, short span [kN/m1]

```
> q_hor_d_short_span:=q_hor_short_span/2*saf1;
```

$q\_hor\_d\_short\_span := 1.680000000$ **(10.1)**

Distributed horizontal forces along deck, long span [kN/m1]

```
> q_hor_d_long_span:=q_hor_long_span/2*saf1;
```

$q\_hor\_d\_long\_span := 1.501500000$ **(10.2)**

The total horizontal force on the bridge piers then equals for the short span [kN]:

```
> F_wind_d_short:=q_hor_d_short_span*L_shortest;
```

$F\_wind\_d\_short := 117.6000000$ **(10.3)**

The total horizontal force on the bridge piers then equals for the long span [kN]:

```
> F_wind_d_long:=q_hor_d_long_span*L_longest;
```

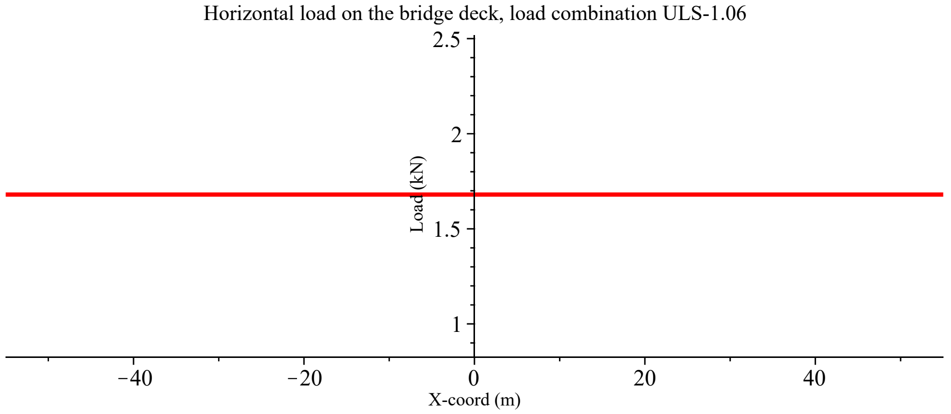
$F\_wind\_d\_long := 165.1650000$ **(10.4)**

Horizontal force distribution in bridge deck

-Total load function in MAPLE description

Plot of the load

```
> plot(q_hor_d_short_span,x=P1-Margin..P2+Margin,thickness=3,color=red,title="Horizontal load on
  the bridge deck, load combination ULS-1.06",titlefont = ["ARIAL", 12],labels = ["X-coord (m)",
  "Load (kN)"],labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



Mathematical relations

```
> DV6:=EA*diff(u(x),x$2)=-q_hor_d_long_span:
> sol106:=dsolve(DV6,u(x)): assign(sol106): u:=u(x):
> eps:=diff(u,x): N_normal:=EA*eps:
```

Boundary conditions

-Assumptions for the boundary conditions:

-Left: horizontal restraint

-Right: free to move

```
> x:=P1: eq220:=u=0:
> x:=P2: eq221:=N_normal=0:
```

Solve for the unknowns

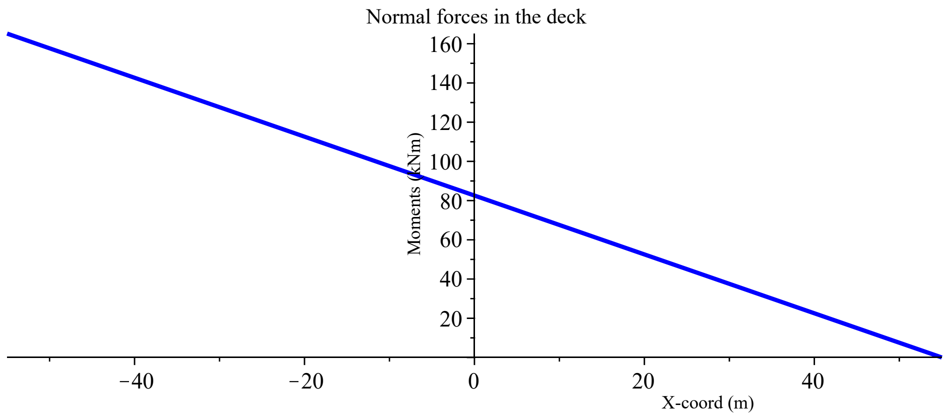
```
> sol107:=solve({eq220,eq221},{_C13,_C14}): assign(sol107):
> x:='x':
```

Output

* Normal force in the deck.
* The distributed horizontal load is pointed from left to right.

Normal force line, projected on the deck

```
> plot(N_normal,x=P1-Margin..P2+Margin,thickness=3,color=blue,title="Normal forces in the
  deck",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Moments (kNm)"],labeldirections=
  ["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



Load combination ULS-1.07 - Collision force on bridge pier

-In this combination the permanent load has to be taken into account as a characteristic load.

Characteristic load deck [kN/m1]:

```
> q_deck_k_distr:=q_deck_k*hoh_main_beam_cross/2;
```

$$q\_deck\_k\_distr := 21 \tag{11.1}$$

Characteristic load hangers [kN/m1]:

```
> q_hanger_k_distr:=q_hanger;
```

$$q\_hanger\_k\_distr := 1 \tag{11.2}$$

Characteristic load arch [kN/m1]:

```
> q_arch_k_distr:=q_arch;
```

$$q\_arch\_k\_distr := 8 \tag{11.3}$$

Design load UDL [kN/m1] (use half deck width):

```
> q_UDL_d:=UDL_lower*psi2*saf1*deck_width/2;
```

$$q\_UDL\_d := 13.44000000 \tag{11.4}$$

Wind load [kN/m1] (use half deck width):

```
> q_wind_d:=q_wind_ver * psi1*saf2/2;
```

$$q\_wind\_d := 7.012500000 \tag{11.5}$$

Design load parapet [kN/m1]:

```
> q_parapet_d:=q_parapet*psi1*saf2;
```

$$q\_parapet\_d := 0.660 \tag{11.6}$$

Total design load on arch, combination ULS-1.07 [kN/m1]:

```
> q_d_ULS:=q_deck_k_distr + q_hanger_k_distr + q_arch_k_distr + q_UDL_d + q_wind_d +
  q_parapet_d;
```

$$q\_d\_ULS := 51.11250000 \tag{11.7}$$

Design point load service vehicle [kN]:

```
> q_serv_d:=q_serv*psi1*saf1;
```

$$q\_serv\_d := 30.00 \tag{11.8}$$

Design support reaction at pier [kN]:

```
> Support_pier_d_long:=q_d_ULS*L_longest/2 + q_serv_d;
```

$$Support\_pier\_d\_long := 2841.187500 \tag{11.9}$$

Design collision force [kN]:

```
> F_coll_x_d:=F_coll_x;
```

$$F\_coll\_x\_d := 1000 \tag{11.10}$$

The columns of the piers are inclined (slope 5:1). Since the vertical forces act at the centerlines of the piers, they do not introduce additional bending moments.

A more extensive calculation is performed by Karamba3D.

Load combination ULS-1.08 - Max. normal force in a hanger

-Especially based on combination ULS-1.01.
-The additional forces due to horizontal wind are neglected (slope of hangers with respect to deck is relatively large).

Design load deck [kN/m1]:

```
> q_deck_d:=saf3*q_deck_k*hoh_main_beam_cross/2;
```

$$q\_deck\_d := 29.40000000 \tag{12.1}$$

Design load UDL [kN/m1] (use half deck width):

```
> q_UDL_d:=UDL_lower*psi1*saf1*deck_width/2;
```

$$q\_UDL\_d := 6.720000000 \tag{12.2}$$

Wind load [kN/m1] (use half deck width):

```
> q_wind_d:=q_wind_ver*psi1*saf2/2;
```

$$q\_wind\_d := 7.012500000 \tag{12.3}$$

Design load parapet [kN/m1]:

```
> q_parapet_d:=q_parapet*psi1*saf2;
```

$$q\_parapet\_d := 0.660 \tag{12.4}$$

Total design load on beam, combination ULS-1.01 [kN/m1]:

```
> q_d_ULS:=q_deck_d + q_UDL_d + q_wind_d + q_parapet_d;
```

$$q\_d\_ULS := 43.79250000 \tag{12.5}$$

Design point load service vehicle [kN]:

```
> q_serv_d:=q_serv*psi2*saf1;
```

$$q\_serv\_d := 60.00 \tag{12.6}$$

Design load on the hanger [kN]:

```
> F_hanger_d:=q_d_ULS * hoh_hanger + q_serv_d;
```

$$F\_hanger\_d := 322.7550000 \tag{12.7}$$

Load combination ULS-1.09 - Uplifting of the deck

-Only present variable load is the wind load. Hence no momentary factors needed.

Design load deck [kN/m1] (works positive, hence need a partial safety factor of 0.9):

```
> q_deck_d:=saf4*q_deck_k*hoh_main_beam_cross/2;
```

$q\_deck\_d := 18.90000000$ (13.1)

Wind load [kN/m1] (use half deck width) [kN/m1]:

```
> q_wind_d:=q_wind_ver*saf2/2;
```

$q\_wind\_d := 17.53125000$ (13.2)

```
> q_deck_d-q_wind_d;
```

1.36875000 (13.3)

```
> res9:=piecewise(q_deck_d-q_wind_d>0,"Own weight is sufficient to prevent uplifting",q_deck_d-
  q_wind_d<0,"Own weight is not sufficient to prevent uplifting");
```

$res9$:= "Own weight is sufficient to prevent uplifting" (13.4)

Load combination ULS-1.10 - Building combination

Main beam (phase 0a and phase 0b - building phase, hangers not installed)

-The deck will be transported to it's final location into three parts.
-The only load in the transportation phase is a limited own weight (only steel main beams and transverse beams).
-The applied partial safety factor is 1.

Own weight of the deck in the transportation phase [kN/m1]:

```
> q_deck_d:=saf5*q_deck_k_build*hoh_main_beam_cross/2;
```

$q\_deck\_d := 7$ (14.1)

This lead to the following moments in a deck beam [kNm]:

```
> M_max:=evalf((1/8)*q_deck_d*L_transport^2);
```

$M\_max := 1176.388889$ (14.2)

Main beam (phase 1a - hangers installed, no concrete slab)

* At this phase the hangers are installed from a barge next to the bridge.

Main beam (phase 1b - hangers installed, concrete slab is poured but not hardened yet)

Own weight of the deck [kN/m1]:

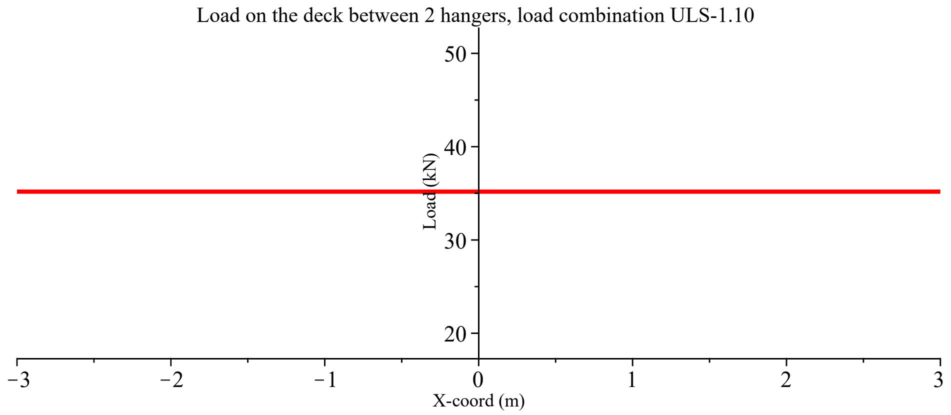
```
> q_deck_d:=saf3*q_deck_k*hoh_main_beam_cross/2 + saf2*q_deck_k_pour*hoh_main_beam_cross/2;
```

$q\_deck\_d := 35.17500000$ (14.3)

```
> q_110:=q_deck_d;
```

$q\_110 := 35.17500000$ (14.4)

```
> plot(q_110,x=-hoh_hanger/2-Margin..hoh_hanger/2+Margin,thickness=3,color=red,title="Load on
  the deck between 2 hangers, load combination ULS-1.10",titlefont = ["ARIAL", 12],labels = ["X-
  coord (m)","Load (kN)"],labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=
  [1400,300]);
```



-Important! Now the differential equation for the beam has to be used.

```
> DV10:=EI*diff(w10(x),x$4) = q_110:
> sol10:=dsolve(DV10,w10(x)): assign(sol10): w10:=w10(x):
> phi10:=-diff(w10,x): kappa10:=diff(phi10,x): M10:=EI*kappa10: V10:=diff(M10,x):
```

Boundary conditions

* The girder is assumed as an inifinite long girder, resting on fixed supports (in reality it is an elastic support).

```
> x:=-hoh_hanger/2: eq300:=phi10=0: eq301:=w10=0:
> x:=hoh_hanger/2: eq302:=phi10=0: eq303:=w10=0:
> x:='x':
```

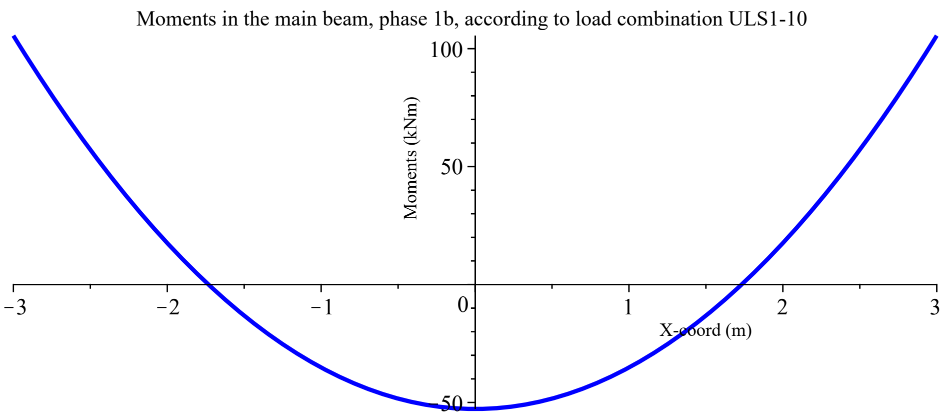
Solve for the unknowns

```
> sol300:=solve({eq300,eq301,eq302,eq303},{_C15,_C16,_C17,_C18}): assign(sol300):
```

Plot of the moment line

```
> plot(-M10,x=-hoh_hanger/2-Margin..hoh_hanger/2+Margin,thickness=3,color=blue,title="Moments in
```

```
the main beam, phase 1b, according to load combination ULS1-10",titlefont = ["ARIAL", 12],
labels = ["X-coord (m)","Moments (kNm)"],labeldirections=["horizontal","vertical"],labelfont=
["ARIAL",10],size=[1400,300]);
```




```
> maximize(M10,x=-hoh_hanger/2..hoh_hanger/2);
```

52.76250000 **(14.5)**

```
> minimize(M10,x=-hoh_hanger/2..hoh_hanger/2);
```

−105.5250000 **(14.6)**

Load combination ULS-1.11 - Maintenance combination

Hangers

-In this combination the effect of hanger replacement is considered.
-In a very simple way the effect of a temporary removal of 1 hanger is considered.
-Loads that are taken into account: own weight and service vehicle.
-No maintence will be executed during crowd loads (UDL) or stormy weather (wind loads).
-The service vehicle is the only variable load. Therefore, no momentary factors are used

Own weight of the deck [kN/m1]:

```
> q_deck_d:=saf3*q_deck_k*hoh_main_beam_cross/2;
```

$q\_deck\_d := 29.40000000$ **(15.1)**

Design load of the maintenance vehicle [kN]:

```
> q_serv_d:=q_install*saf1;
```

$q\_serv\_d := 202.5$ **(15.2)**

In the maintenance stage this lead to the following forces in the hangers next to the temporary removed one [kN]:

```
> F_hanger_maintenance:=q_deck_d * hoh_hanger_maintenance + q_serv_d;
```

$F\_hanger\_maintenance := 467.1000000$ **(15.3)**

Main beam (phase 2 - maintenance phase, including concrete slab)

-During this phase, a hanger is removed and need to be replaced by using a small telescope crane (type Grove, self weight = 135 kN).
-The lifting capacity of this crane is 135 kN. It is assumed that the weight of the total load (=270 kN) is devided over both main beams.
-It is assumed that maintenance is carried out when there is no wind load of UDL, only self weight. Therefore no partial factors have been used in this combination.
-Girder is assumed to be a continuous beam on rigid supports.
-Therefore the maximum moments follows from an elastic calculation, thus:

Minimum moment at hanger points in main beam (hogging bending moment, negative) [kNm]:

```
> M_max_phase2:=-(1/8)*q_install*saf1*hoh_hanger_maintenance - (1/12)*q_deck_d*
hoh_hanger_maintenance^2;
```

$M\_max\_phase2 := -426.2625000$ **(15.4)**

Maximum moment, middle span of hanger points (sagging bending moment, positive) [kNm]:

```
> M_min_phase1:=(1/8)*q_install*saf1*hoh_hanger_maintenance + (1/24)*q_deck_d*
hoh_hanger_maintenance^2;
```

$M\_min\_phase1 := 327.0375000$ **(15.5)**

Load combination SLS-2.01 + SLS-2.02 - Max. deflection in a deck

Assumptions

-Own weight already calculated at combination ULS-1.07.

Design load deck [kN/m1]:

```
> q_deck_k_distr;
```

$$21 \tag{16.1}$$

Characteristic load hangers [kN/m1]:

```
> q_hanger_k_distr;
```

$$1 \tag{16.2}$$

Characteristic load arch [kN/m1]:

```
> q_arch_k_distr;
```

$$8 \tag{16.3}$$

Design load UDL [kN/m1] (use half deck width) [kN/m1]:

```
> q_UDL_d:=UDL_lower*psi2*deck_width/2;
```

$$q\_UDL\_d := 8.960000000 \tag{16.4}$$

Wind load [kN/m1] (use half deck width):

```
> q_wind_d:=q_wind_ver*psi1/2;
```

$$q\_wind\_d := 4.250000000 \tag{16.5}$$

Design load parapet [kN/m1]:

```
> q_parapet_d:=q_parapet*psi1;
```

$$q\_parapet\_d := 0.4 \tag{16.6}$$

Total design load on beam, combination ULS-1.01 [kN/m1]:

```
> q_d_SLS:=q_deck_k_distr + q_UDL_d + q_wind_d + q_parapet_d;
```

$$q\_d\_SLS := 34.61000000 \tag{16.7}$$

Design point load service vehicle [kN]:

```
> q_serv_d:=q_serv*psi1;
```

$$q\_serv\_d := 20.0 \tag{16.8}$$

Karamba3D will be used to obtain the deflection of the deck, since the calculation in Maple is too difficult.

Load combination SLS-2.03 - Max. deflection in a deck

-Own weight already calculated at combination ULS-1.07.
-Right half of the deck is loaded with UDL, left half without UDL.
-Maintenance vehicle is located at right half of deck.
-Wind load is distributed over the complete length of the deck.

Design load deck [kN/m1]:

```
> q_deck_k_distr;
```

$$21 \tag{17.1}$$

Characteristic load hangers [kN/m1]:

```
> q_hanger_k_distr;
```

$$1 \tag{17.2}$$

Characteristic load arch [kN/m1]:

```
> q_arch_k_distr;
```

$$8 \tag{17.3}$$

Design load UDL [kN/m1] (use half deck width) [kN/m1]:

```
> q_UDL_d:=UDL_lower*psi2*deck_width/2;
```

$$q\_UDL\_d := 8.960000000 \tag{17.4}$$

Wind load [kN/m1] (use half deck width):

```
> q_wind_d:=q_wind_ver*psi1/2;
```

$$q\_wind\_d := 4.250000000 \tag{17.5}$$

Design load parapet [kN/m1]:

```
> q_parapet_d:=q_parapet*psi1;
```

$$q\_parapet\_d := 0.4 \tag{17.6}$$

Total design load on beam, left part:

```
> q_d_SLS_left:=q_deck_k_distr + q_UDL_d + q_wind_d + q_parapet_d;
```

$$q\_d\_SLS\_left := 34.61000000 \tag{17.7}$$

Total design load on beam, right part:

```
> q_d_SLS_right:=q_deck_k_distr + q_wind_d;
```

$$q\_d\_SLS\_right := 25.25000000 \tag{17.8}$$

T

Design point load service vehicle [kN]:

```
> q_serv_d:=q_serv*psi1;
```

$$q\_serv\_d := 20.0 \tag{17.9}$$

Karamba3D will be used to obtain the deflection of the deck, since the calculation in Maple is too difficult.

G.4. Steel concrete deck calculation

Calculations steel-concrete slab

```
> restart; with(ListTools): with(plots):
```

General info

I.A. van der Esch
d.d. 2019-03-13

Assumptions

-Considered slab width: 1m
-Sagging bending moment resistance: PNA located in the concrete slab - - > making calculations easier!
-Own weight of the gantry: 135 kN.

Geometry

Thickness of the concrete slab [mm]:
```
> h_c:=140:
```
Thickness view of steel stiffener [mm]:
```
> h_p:=80:
```
Nominal thickness of the steel decking [mm2] - - > based on a nominal thickness of 1.2 mm:
```
> A_p:=1864:
```
Considered slab width [mm]:
```
> b:=1000:
```
Distance from top of slab to centroid of reinforcement to resist hogging bending moments [mm]:
```
> c_s_hog:=25:
```
Distance from top of slab to centroid of reinforcement to resist sagging bending moments [mm]:
```
> c_s_sag:=45:
```
Distance b_0 (mean width of 1 rib) [mm]:
```
> b_0:=135:
```
Average height d in the slab [mm]:
```
> d_gem:=h_c+h_p-0.5*(c_s_hog+c_s_sag):
```
2nd moment of inertia of the steel plate [mm4]:
```
> I_p:=213*10^4:
```
E-modulus of steel decking [N/mm2]:
```
> E_p:=210000:
```
Secant modulus of the concrete [N/mm2]:
```
> E_cm:=32800:
```
Long term modulus of the concrete [N/mm2]:
```
> E_cm_long:=E_cm/3:
```
Span [m]:
```
> L:=3.5:
```

Chosen reinforcement configuration

Diameter of chosen reinforcement [mm]:
```
> diam_trans:=16:
> diam_long:=12:
```

Material properties

Yield stress of the steel decking [N/mm2]:
```
> f_yp:=350:
```
Partial factor steel decking [-]:
```
> gamma_ap:=1:
```
Characteristic concrete strength [N/mm2]:
```
> f_ck:=30:
```
Partial factor concrete [-]:
```
> gamma_c:=1.5:
```
Amount of area of tansversal reinforcement in the slab [mm2]:
```
> A_s:=2000:
```
Characteristic yield strength of reinforcement [N/mm2]:
```
> f_ys:=500:
```
Partial factor of reinforcement [-]:
```
> gamma_s:=1.15:
```
Design yield strength of reinforcement [N/mm2]:
```
> f_ysd:=f_ys/gamma_s:
```
Design yield strength of steel decking [N/mm2]:
```
> f_ypd:=f_yp/gamma_ap:
```

Load properties

Partial safety factors [-]:
```
> saf1:=1.5: saf2:=1.4: psi1:=0.4: psi2:=0.8:
```
Load of gantry in driving configuration [kN]:
```
> F_driving:=saf1*135/4:
```
Load of outrigger of gantry in lifiting configuration [kN]:
```
> F_lifting:=saf1*135:
```
Spanning length of the slab [m]:
```
> L:=3.5:
```
Distance between wheels in driving configuration [m]:

```
> dist_wheel_drive:=1.75:
```
Distance between outriggers in lifting configuration [m]:
```
> dist_wheel_lifting:=4.27/2:
```
Distances for calculating the force distribution [m]:
```
> b_1:=L-a_1: a_2:=a_1+dist_wheel_drive: b_2:=L-a_2:
```
Design load of the deck [kN]:
```
> q_deck_d:=saf2*6:
```

Output - Strength check

Sagging bending moment resistance - -> governing for driving

Design yield strength of the steel decking (acts as reinforcement) [N/mm2]:
```
> f_y:=f_yp/gamma_ap:
```
Design concrete strength [N/mm2]:
```
> f_cd:=f_ck/gamma_c:
```
Effective height [mm]:
```
> d_sag:=h_c + h_p/2:
```
Concrete compression zone [mm]:
```
> x_pl_sag:=(A_p*f_ypd)/(0.85*b*f_cd);
```
$$x\_pl\_sag := 38.37647058 \quad (1)$$

Is the calculated concrete compression zone still in the concrete slab (i.e.: is case 1 valid)?
```
> if x_pl_sag < h_c then OUTPUT="VALID" end if;
> if x_pl_sag > h_c then OUTPUT="INVALID"; end if;
```
$$OUTPUT = \text{"VALID"} \quad (2)$$

Tension force in the steel decking [N/mm2]:
```
> N_p:=A_p*f_ypd:
```
Internal lever arm [mm]:
```
> z_sag:=d_sag-0.5*x_pl_sag:
```
Sagging moment resistance [Nmm]:
```
> M_pl_sag_Rd:=N_p*z_sag:
```
Sagging moment resistance [kNm]:
```
> M_pl_sag_Rd:=M_pl_sag_Rd/10^6;
```
$$M\_pl\_sag\_Rd := 104.9135953 \quad (3)$$

Hogging bending moment resistance - -> governing for lifting

Design resistance of the reinforcement bars [N]:
```
> N_s:=A_s*f_ysd:
```
Height of the compression zone [mm]:
```
> x_pl_hog:=N_s/(0.85*b*f_cd):
```
Effective height [mm]:
```
> d_hog:=h_p + h_c - c_s_hog:
```
Internal lever arm [mm]:
```
> z_hog:=d_hog-(1/2)*x_pl_hog:
```
Hogging moment resistance [Nmm]:
```
> M_pl_hog_Rd:=N_s*z_hog:
```
Hogging moment resistance [kNm]:
```
> M_pl_hog_Rd:=-1*M_pl_hog_Rd/10^6;
```
$$M\_pl\_hog\_Rd := -147.3256977 \quad (4)$$

Maximum sagging bending moment: due to moving point loads - - > governing for driving

-Maximum moment is under left point load: thus the maximum moment in the beam is the combination of the left point load and a linear interpolation of the right one (the latter one is taken into account with an interpolation factor).

-The position of the maximum load is found by using an influence-line generator, created by a for-loop with 100 increments.

```
> beta:=a_1/a_2:
> M_max:=((F_driving*a_1*b_1)/(4*(L^3))) * (4*L^2 - a_1*(L+a_1)) + beta*((F_driving*a_2*b_2)/(4*
  (L^3))) * (4*L^2 - a_2*(L+a_2)):
```
Upper bound for a_1, at that the point the right load is at the mid support.
```
> ub_a_1:=L-dist_wheel_drive:
> incr:=100:
> a_norm:=(ub_a_1/incr)*i:
> M_sag_tot:=subs(a_1=a_norm,M_max):
> A_sag:=Array(0..incr):
> for i from 0 to incr do:
  A_sag[i]:=M_sag_tot:
  end do:
> B_sag:=convert(A_sag,list);
```
B_sag := [0., 1.235614318, 2.450791940, 3.645584693, 4.820045735, 5.974229550, 7.108191953, 8.221990086, 9.315682421, 10.38932876, 11.44299023, 12.47672929, 13.49060973, 14.48469667, 15.45905655, 16.41375713, 17.34886754, 18.26445820, 19.16060086, 20.03736864, 20.89483593, 21.73307848, 22.55217338, 23.35219903, 24.13323516, 24.89536284, 25.63866446, 26.36322374, 27.06912573, 27.75645680, 28.42530468, 29.07575838, 29.70790829, 30.32184608, 30.91766480, 31.49545879, 32.05532373, 32.59735662, 33.12165581, 33.62832098, 34.11745311, 34.58915453, 35.04352890, 35.48068119, 35.90071772, 36.30374614, 36.68987541, 37.05921583, 37.41187904, 37.74797796, 38.06762694, 38.37094153, 38.65803872, 38.92903675, 39.18405525, 39.42321513, 39.64663865, 39.85444942, 40.04677233, 40.22373364, 40.38546092, 40.53208307, 40.66373034, 40.78053428, 40.88262778, 40.97014506, 41.04322167, 41.10199448, 41.14660172, 41.17718289, 41.19387889, 41.19683188, 41.18618540, 41.16208431, 41.12467476, 41.07410429, 41.01052172, 40.93407721, 40.84492228, 40.74320973, 40.62909373, 40.50272975, 40.36427461, 40.21388644, 40.05172472, 39.87795024, 39.69272512, 39.49621284, 39.28857815, 39.06998720, 38.84060741, 38.60060755, 38.35015772, 38.08942936, 37.81859522, 37.53782939, 37.24730728, 36.94720564, 36.63770255, 36.31897739, (5)

35.99121092]

```
> Max_M_sag:=FindMaximalElement(B_sag,position):
```

Maximum hogging bending moment: due to moving point loads - - > governing for lifting

-The maximum hogging moment will occur if both point loads are placed symmetrical regarding mid-support B.
-This situation can easily be solved by using the forget-me-knots:

```
> a_hog:=L-dist_wheel_lifting/2:
> b_hog:=L-a_hog:
> eq1:=F_lifting*a_hog*b_hog*(L+a_hog)/(6*EI*L) - Max_M_hog*L/(3*EI) = 0:
> Max_M_hog:=-1*solve(eq1,Max_M_hog):
```

Force distribution due to own weight of the deck: sagging bending moment

```
> M_q_hog:=-1*(1/8)*q_deck_d*L^2:
> M_q_sag:=M_q_hog/2 + (1/8)*q_deck_d*L^2:
```

So the total bending moments become:

```
> M_tot_sag:=Max_M_sag[1] + M_q_sag;
```

$$M\_tot\_sag := 47.62808188 \quad (6)$$

```
> M_tot_hog:=Max_M_hog + M_q_hog;
```

$$M\_tot\_hog := -140.1885958 \quad (7)$$

Checks - sagging moment resistance:

```
> res_sag:=piecewise(abs(M_pl_sag_Rd)>abs(M_tot_sag),"Sufficient",abs(M_pl_sag_Rd)<abs(M_tot_sag),
  "Insufficient");
```

res_sag := "Sufficient" **(8)**

```
> res_hog:=piecewise(abs(M_pl_hog_Rd)>abs(M_tot_hog),"Sufficient",abs(M_pl_hog_Rd)<abs(M_tot_hog),
  "Insufficient");
```

res_hog := "Sufficient" **(9)**

Applied reinforcement

Reinforcement in transverse direction:

```
> n_trans:=ceil(A_s/(0.25*Pi*diam_trans^2));
```

$$n\_trans := 10 \quad (10)$$

Reinforcement in longitudinal direction:

Min. wap. 0.2% of concrete above steel plate. Used is a poisson ratio of 0.2

```
> nu:=0.2:
> A_s_long:=nu*A_s:
> n_long:=ceil(A_s_long/(0.25*Pi*diam_long^2));
```

$$n\_long := 4 \quad (11)$$

Output - Punching shear check of the steel-concrete slab

In lifting position:

Rectangular size of the crane pad to distribute the pressure of the gantry outrigger to the deck [mm]:

```
> crane_pad:=1000:
```

Factor [-]:

```
> k:=min(1+sqrt(200/d_gem),2):
```

Minimum shear capacity [N/mm2]:

```
> nu_min:=0.035*k*sqrt(f_ck):
```

Circumference of the pressure distribution area [mm]:

```
> Circ_lift:=2*Pi*h_c + 4*crane_pad:
```

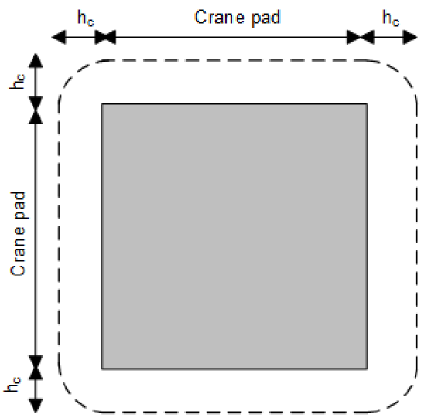
Resistance against punching shear [kN]:

```
> V_Rd_lift:=evalf(nu_min*Circ_lift*d_gem)/1000:
```

Checks - punching shear:

```
> res_punch_lift:=piecewise(abs(V_Rd_lift)>abs(F_lifting),"Sufficient",abs(V_Rd_lift)<abs
  (F_lifting),"Insufficient");
```

res_punch_lift := "Sufficient" **(12)**



In transport position:
Lower bound for punching shear (rectangular area assumed) [mm]:

```
> crane_tire_area:=250:
```

Circumference of the pressure distribution area [mm]:

```
> Circ_driving:=2*Pi*h_c + 4*crane_tire_area:
```

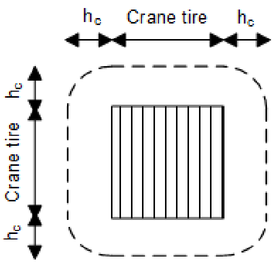
So the resistance against punching shear equals [kN]:

```
> V_Rd_driving:=evalf(nu_min*Circ_driving*d_gem)/1000:
```

Checks - punching shear:

```
> res_punch_driving:=piecewise(abs(V_Rd_driving)>abs(F_driving),"Sufficient",abs(V_Rd_driving)<abs
  (F_driving),"Insufficient");
```

$$res\_punch\_driving := \text{"Sufficient"} \tag{13}$$



Calculation of the bending stiffness of the slab

-According to "Steel Structures 3 - Part: composite constructions", lecture 4, blz. 9, the recommanded value for the maximum deflection equals:
-L/250 under permanent loads
-L/300 under variable loads
-The deflection of the sheeting due its own weight and the wet concrete need not to be included in the verification for the composite slab.
-Since the composite slab is a continious slab spanning two spans, it is considered as an external slab. In general no account need to be taken if the end slip is 0.5mm for a load exceeding 1.2 times the desired design service load.

Bending stiffness for the service-ability limit state:
Cracked cross section:
-The formulas below is only valid for cracked sagging bending moments in the SLS.

Ratio [-]:

```
> n:=E_p/(0.5*(E_cm+E_cm/3)):
```

Height of concrete compression zone [mm]:

```
> x_c:=((n*A_p)/b) * (sqrt(1 + (2*b*d_sag)/(n*A_p)-1)):
```

Moment of inertia [mm4]:

```
> I_cc:=evalf(((b*x_c^3)/(12*n)) + ((b*x_c*(x_c/2)^2)/n) + A_p*(d_sag-x_c)^2 + I_p):
```

The bending stiffness of the steel-concrete slab now becomes [Nmm2]:

```
> EI_cc:=((b*x_c^3)/(12*n))*(E_p/n) + ((b*x_c*(x_c/2)^2)/n)*(E_p/n) + (A_p*(d_sag-x_c)^2)*(E_p) +
  (I_p)*(E_p);
```

$$EI\_cc := 4.732670706\ 10^{12} \tag{14}$$

Calculation of the deflections of the slab

-For the calculations of the slab only the wind load and variable load (regular maintenance vehicle) is taken into account. This to prevent an too excessive design.
-The deflections of the load in the SLS are calculated by using the differential equations for bending. The maximum deflection occurs if 1 field is fully loaded. 1 wheel load of the service vehicle equals:

Load of the service vehicle [kN]:

```
> q_serv:=50:
```

Load for each wheel [kN]:

```
> load_wheel_k:=q_serv/4:
```

Loads [kN/m2]:

```
> q_UDL:=3.2: q_wind:=2.66*psi1; load_wheel_d:=load_wheel_k*psi2;
```

$$q\_wind := 1.064$$

$$load\_wheel\_d := 10.00000000 \quad (15)$$

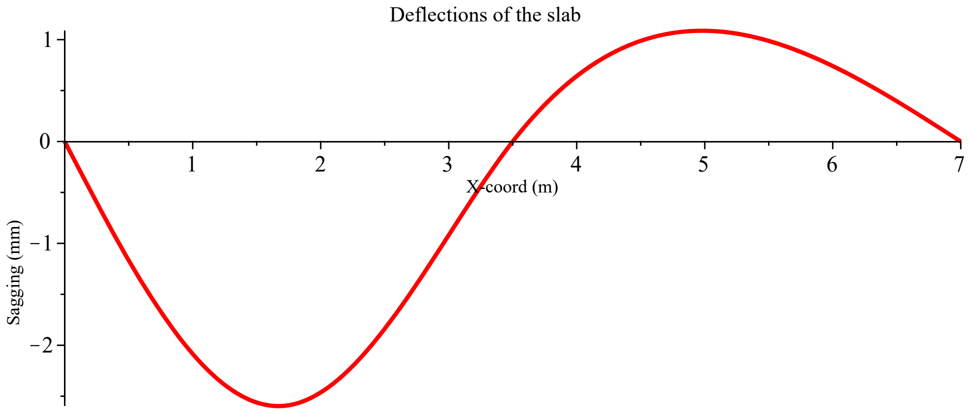
```
> q_sls1:=q_UDL + q_wind + load_wheel_d*Dirac(x-dist_wheel_drive): q_sls2:=0:
```

Determine the force distribution by solving the differential equations:

```
> DV1:=EI_cc/(10^9)*diff(w1(x),x$4)=q_sls1: DV2:=EI_cc*diff(w2(x),x$4)=q_sls2:
> sol1:=dsolve({DV1,DV2},{w1(x),w2(x)}): assign(sol1): w1:=w1(x): w2:=w2(x):
> phi1:=-diff(w1,x): kappa1:=diff(phi1,x): M1:=EI_cc*kappa1: V1:=diff(M1,x):
> phi2:=-diff(w2,x): kappa2:=diff(phi2,x): M2:=EI_cc*kappa2: V2:=diff(M2,x):
> x:=0: eq1:=w1=0: eq2:=M1=0:
> x:=L: eq3:=w1=0: eq4:=w2=0: eq5:=M1=M2: eq6:=phi1=phi2:
> x:=2*L: eq7:=w2=0: eq8:=M2=0:
> sol2:=solve({eq1,eq2,eq3,eq4,eq5,eq6,eq7,eq8},{_C1,_C2,_C3,_C4,_C5,_C6,_C7,_C8}): assign(sol2):
> x:='x':
```

Plot of the deflections:

```
> AA:=plot(-w1*1000,x=0..L,color=red,thickness=3,title="Deflections of the slab",titlefont =
  ["ARIAL", 12],labels = ["X-coord (m)","Sagging (mm)"],labeldirections=["horizontal","vertical"],
  labelfont=["ARIAL",10],size=[1400,300]):
> BB:=plot(-w2*1000,x=L..2*L,color=red,thickness=3,title="Deflections of the slab",titlefont =
  ["ARIAL", 12],labels = ["X-coord (m)","Sagging (mm)"],labeldirections=["horizontal","vertical"],
  labelfont=["ARIAL",10],size=[1400,300]):
> display(AA,BB);
```



The maximum deflection equals:

```
> w_max:=max(maximize(abs(w1),x=0..L),maximize(abs(w2),x=L..2*L));
```

$$w\_max := 0.002596932159 \quad (16)$$

```
> check:=piecewise(w_max<(L/300),"Sufficient",w_max>(L/300),"Insufficient");
```

$$check := \text{"Sufficient"} \quad (17)$$

G.5. Main beam calculation

Calculations main beams

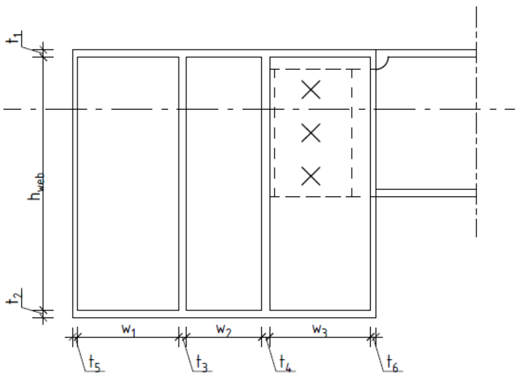
```
> restart;
```

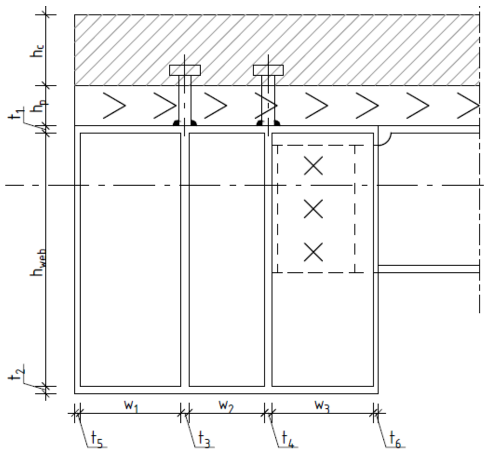
General info
I.A. van der Esch
d.d. 2019-03-11

Assumptions
-Profile based on meeting with professor Kalil, d.d. 2019-03-04.
-Calculation based on 3 different stages as mentioned in report.
  -Stage 0: transportation (a) and lifting (b).
  -Stage 1a: installation of hangers, no concrete slab present (this stage is not considered).
  -Stage 1b: concrete slab present, but concrete not yet hardened (No Composite action!!!).
  -Stage 2: hangers are installed, concrete slab is poured and hardened, maintenance performed (Composite action!!!).
  -Stage 3: final or using stage.
-Initial dimensions of main beams based at initial dimensions of Course Steel Bridges, lecture 2.
-Calculations based on the ULS, only strength checks.
-Stability not checked (assumed not to be governing):
  -Global stability assumed to be not governing: due to horizontal support of top flange and bracing system during the building stage.
  -Local stability not considered: plate buckling, shear buckling, flange induced buckling of the web
-Fatigue not considered.
-Ductile studs: studs are considered as ductile if:
  -The overall length of the stud should not be less than four times its diameter.
  -The stud diameter should not be less than 12mm and not greater then 25mm.
  -Addtional check: eta

```
> tol:=100:
```

Geometry
Below the geometry of the main beams. Left image: stage 0 and 1a. Right image: stage 1b - 3.





Thickness top flange [mm]:
```
> t1:=15:
```
Thickness bottom flange [mm]:
```
> t2:=15:
```
Width left web [mm]:
```
> t4:=15:
```
Width right web [mm]:
```
> t5:=15:
```
Width left stiffener [mm]:
```
> t3:=10:
```
Width right stiffener [mm]:
```
> t6:=10:
```
Web height [mm]:
```
> h_w:=500:
```
Thickness of the concrete slab [mm]:
```
> h_c:=140:
```
Thickness view of steel decking (profile height) [mm]:
```
> h_p:=80:
```
Distance between left stiffener and left web [mm]:
```
> w1:=200:
```
Distance between both webs [mm]:
```
> w2:=150:
```

Distance between right web and right stiffener [mm]:
```
> w3:=200:
```
Effective width of the concrete slab on top of the profile (for hogging bending moment resistance) [mm]:
```
> b_eff:=3250:
```
Amount of reinforcement to resist sagging bending moment in concrete slab [mm2]:
```
> A_s:=2000:
```
Distance from top of slab to centre of reinforment to resist sagging bending moments [mm]:
```
> c_s:=25:
```
Width between two points in which bending moment is 0 [m]:
```
> L_e:=3.46:
```
Length of the span of the bridge [m]:
```
> L:=110:
```

Properties of the shear studs

Partial safety factor of a stud [-]:
```
> gam_v:=1.25:
```
Yield strength of a stud [MPa]:
```
> f_u:=450:
```
Diameter of the stud [mm]:
```
> d:=25:
```
Height of the stud [mm]:
```
> h:=120:
```
Number of studs in a rib [-]:
```
> n_r:=2:
```
Number of applied shear studs in a half span (between 2 hangers) in a single row [-]:
```
> N_red:=6000/300:
```

Properties of the steel decking

Distance b_0 [mm]:
```
> b_0:=135:
```

Material properties

Yield stress steel:
```
> f_y:=355:
```
Concrete strength (based on C30/37):
```
> f_ck:=30: gam_c:=1.5: f_cd:=f_ck/gam_c:
```
Yield strength reinforcement steel (B500B):
```
> f_yds:=500/1.15:
```
Youngs modulus of the reinforcement [MPa]:
```
> E_s:=200000:
```
Secand modulusof the concrete [MPa]:
```
> E_cm:=32800:
```
Assumed cracked E-modulus for the concrete (conservative):
```
> E_crack:=0:
```
Youngs modulus of the steel profile [MPa]:
```
> E_a:=210000:
```

Chosen reinforcement configuration

Diameter reinforcement to resist hogging bending - transversal [mm]:
```
> diam_trans:=16:
```
Diameter reinforcement to resist hogging bending - longitudinal [mm]:
```
> diam_long:=12:
```
Amount of reinforcement required to resist the large axial force introduced in the concrete deck, reinforcement and steel profile (number of reinforcement in the effective width) [mm2]:
```
> A_s_axial:=1500:
```

Forces

Maximum moment stage 0 [Nmm]:
```
> M_max_0:=1176*10^6:
```
Maximum horizontal force in the deck (occurs when there is maximal normal force in the arch) [N]:
```
> H:=5242*10^3:
```

Output - STAGE 0 - Transporation and lifting

Centre of gravity:
-Part 1: complete bottom flange
-Part 2: complete web
-Part 3: complete top flange

Profile dimensions [mm]:
```
> b_a:=t3+w1+t4+w2+t5+w3+t6: h_a:=t1+t2+h_w:
```
First step: output the static moments [mm3]:
```
> S1:=b_a*t2*t2/2: S2:=h_w*(t3+t4+t5+t6)*(t2+h_w/2): S3:=b_a*t1*(t2+h_w+t1/2): S_a:=S1+S2+S3:
```
Area of different profile parts [mm2]:
```
> A1:=b_a*t2: A2:=h_w*(t3+t4+t5+t6): A3:=b_a*t1: A_a:=A1+A2+A3:
```
Distance of NC to bottom of bottom flange [mm]:
```
> z_nc_bot:=evalf(S_a/A_a):
```
Distance of NC to top of top flange [mm]:
```
> z_nc_top:=t1+t2+h_w-z_nc_bot:
```
Internal arms, needed for calculating 2nd moment of intertia [mm]:

```
> z1:=z_nc_bot-t2/2: z2:=h_w/2 + t2 - z_nc_bot: z3:=h_w + t1/2 + t2 - z_nc_bot:
```
2nd moment of intertia (I_zz in TU-Delft convention) [mm4]:
```
> I_zz_a:=(1/12)*b_a*t2^3 + (t2*b_a*z1^2) + (1/12)*(t3+t4+t5+t6)*h_w^3 + (t3+t4+t5+t6)*h_w*z2^2 +
  (1/12)*b_a*t1^3 + (t1*b_a*z3^2);
```
$$I\_zz\_a := 1.714683333\ 10^{9} \quad (1)$$

Checks for stresses top and bottom flange (based on an elastic calculation)

Stress bot:
```
> stress_bot:=(M_max_0*z_nc_bot)/I_zz_a;
```
$$stress\_bot := 181.7478446 \quad (2)$$

Stress top:
```
> stress_top:=(M_max_0*z_nc_top)/I_zz_a;
```
$$stress\_top := 181.7478446 \quad (3)$$

Output - STAGE 1a - Installation of the hangers, concrete slab not poured yet

* This stage is not considered.

Output - STAGE 1b - Installation of the hangers, concrete slab poured but not hardened

* No composite action.

Output - STAGE 2 - Concrete slab hardened, maintenance phase

* Composite action need to be considered!
* This stage is not considered.

Information about the steel profile

Determination of line of half area (assumption: lay in the web):
```
> z_pl:=t2+(((A_a/2) - (b_a*t2))/(t3+t4+t5+t6)): evalf(z_pl):
```
The internal lever arms for the plastic force distribution:
```
> zpl1:=z_pl-t2/2: zpl2:=(z_pl-t2)/2: zpl3:=(h_w+t1+t2-z_pl-t1)/2: zpl4:=h_w+t2+t1/2-z_pl:
```
This leads to the plastic resisting moment:
```
> A1:=b_a*t2: A2:=(z_pl-t2)*(t3+t4+t5+t6): A3:=(h_w+t1+t2-z_pl-t1)*(t3+t4+t5+t6): A4:=b_a*t1:
> W_pl:=(zpl1*A1 + zpl2*A2 + zpl3*A3 + zpl4*A4):
> M_rd_no_slab:=W_pl*f_y;
```
$$M\_rd\_no\_slab := 2754800000 \quad (4)$$

Cases for the resistance for the sagging bending moments

-Case 1: the PNA is in the concrete slab
-Case 2: the PNA is in the steel top flange (not considered due to complex expressions)
-Case 3: the PNA is in the steel web

```
> F_cd:=h_c*b_eff*0.85*f_cd: a:=(A_a*f_y - F_cd)/(2*b_a*f_y): s:=F_cd/((t3+t4+t5+t6)*f_y):
> t_w:=t3+t4+t5+t6:
> a:=(A_a*f_y - F_cd)/(2*b_a*f_y):

> M_rd1_sag:=A_a*f_y*((1/2)*h_a + h_c - (1/2)*(A_a*f_y)/(b_eff*0.85*f_cd)):
> M_rd2_sag:=F_cd*((1/2)*h_a + (1/2)*h_c) + ((A_a*f_y - F_cd)/2)*(h_a-a):
> M_rd3_sag:=F_cd*((1/2)*h_a + (1/2)*h_c) + W_pl*f_y - (1/4)*(t3+t4+t5+t6)*s^2 * f_y:

> M_rd_sag:=piecewise(A_a*f_y < h_c*b_eff*0.85*f_cd,M_rd1_sag,A_a*f_y > h_c*b_eff*0.85*f_cd and
  h_c*b_eff*0.85*f_cd > h_w*t_w*f_y,M_rd2_sag,h_c*b_eff*0.85*f_cd < h_w*t_w*f_y,M_rd3_sag);
```
$$M\_rd\_sag := 4.503345774\ 10^{9} \quad (5)$$

Hogging bending moment resistance becomes

-Case 1: PNA in top flange of the steel section
-Case 2: PNA in the web of the steel section
-Case 3: PNA in concrete slab - - > **not considered**.

```
> h_s:=h_c+h_p-c_s:
> F_a:=f_y*A_a:
> N_ard:=A_s*f_yds:
> z_f:=(F_a-N_ard)/(2*b_a*f_y):
> z_w:=N_ard/(2*(t3+t4+t5+t6)*f_y):

> M_rd1_hog:=F_a*(0.5*h_a + h_s) - (F_a-N_ard)*(0.5*z_f+h_s):
> M_rd2_hog:=W_pl*f_y + N_ard*(0.5*h_a + 0.5*h_c + h_p) - 0.5*N_ard*z_w:

> M_rd_hog:=piecewise(F_a>N_ard and F_a-N_ard < 2*b_a*t1*f_y,M_rd1_hog,F_a>N_ard and F_a-N_ard > 2*
  b_a*t1*f_y,M_rd2_hog);
```
$$M\_rd\_hog := 3.105019654\ 10^{9} \quad (6)$$

Shear resistance of the studs (assume a fully shear connection)

-Case 1: failure of stud due to shear strength
-Case 2: failure due to crushing of the concrete
-For the sake of simplicity a fully shear connection is assumed.

```
> P_rd1:=evalf(((Pi*d^2)/4)*(0.8*f_u)/gam_v):
> P_rd2:=evalf(piecewise(h/d > 4,0.29*1*d^2 * (sqrt(f_ck * E_cm))/(gam_v), h/d = 3,0.29*0.8*d^2 *
```

```
(sqrt(f_ck * E_cm))/(gam_v))):
```

So the resistance of the shear connection equals [N]:

```
> P_rd:=min(P_rd1,P_rd2);
```

$$P\_rd := 141371.6694 \quad (7)$$

How many shear studs to apply?

-Assumption: based on fully shear connection
-Case 1: number of shear resistance based on PNA in concrete
-Case 2: number of shear resistance based on PNA in steel

-Sagging bending moment

```
> n_1_sag:=ceil(A_a*f_y/P_rd):
> n_2_sag:=ceil(h_c*b_eff*0.85*f_cd/P_rd):
```

-Hogging bending moment

```
> n_1_hog:=ceil((A_a*f_y + A_s*f_yds)/P_rd):
> n_2_hog:=ceil((h_c*b_eff*0.85*f_cd + A_s*f_yds)/P_rd):
```

Below a case selector for the position of the PNA:

-Case 1: the PNA is in the concrete slab
-Case 2: the PNA is in the steel top flange (not considered due to complex expressions)
-Case 3: the PNA is in the steel web

p=1: PNA in concrete slab. p=2: PNA in steel top flange. p=3: PNA in steel web.

```
> p:=piecewise(M_rd_sag=M_rd1_sag,1,M_rd_sag=M_rd2_sag,2,M_rd_sag=M_rd3_sag,3):
> n_sag:=piecewise(p=1,n_1_sag,p=2,n_2_sag,p=3,n_2_sag):
> n_hog:=piecewise(n_sag=n_2_sag,n_2_hog,n_sag=n_1_sag,n_1_hog):
```

Number of required shear studs in a longitudinal row (*2 because of double shear force sign and / 2 because two stud rows for each beam are considered.) to obtain a fully shear connection:

```
> n_row:=max(n_sag,n_hog)*2/2;
```

$$n\_row := 61 \quad (8)$$

Ductility check:

Applied number of shear connectors (in a row):
* Centre - to centre distance between two ribs: 300mm, hence maximum applied stud in a rib:

```
> n:=N_red:
> eta:=evalf(n/n_row):
```

Ductility check for eta:

```
> ductcheck:=max(1-(355/f_y) * (0.75-0.03*L_e),0.4):
```

Minimal amount of required shear connectors in a single row (too guarantee ductility):

```
> n_req:=ceil(n_row*ductcheck);
```

$$n\_req := 25 \quad (9)$$

This cannot fit if in each rib 2 shear connectors are placed. Therefore, at some places 3 shear connectors in a single rib need to be placed.

Adjusted shear connection

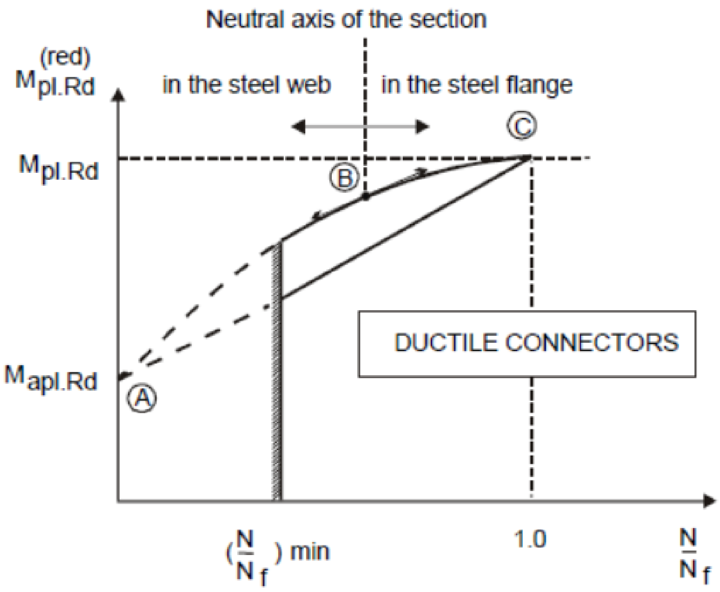
Reduction is calculated based on linear interpolation.

```
> M_pl_red_sag:=M_rd_no_slab + ductcheck*(n_req/n_row)*(M_rd_sag-M_rd_no_slab);
```

$$M\_pl\_red\_sag := 3.041446848\ 10^{9} \quad (10)$$

```
> M_pl_red_hog:=M_rd_no_slab + ductcheck*(n_req/n_row)*(M_rd_hog-M_rd_no_slab);
```

$$M\_pl\_red\_hog := 2.812213058\ 10^{9} \quad (11)$$



Calculations of the reinforcement to resist the hogging benidng moment resistance:
Amount of hogging reinforcement in longitudinal direction [mm2/m1] (direction is the thickness):

```
> A_s_m:=evalf(A_s/(b_eff/1000));
```

$A\_s\_m := 615.3846154$ **(12)**

Number of applied reinforcement bars to resist the hogging bending moments [-]:

```
> n_long:=ceil(A_s_m/(0.25*Pi*diam_long^2));
```

$n\_long := 6$ **(13)**

Calculations of the reinforcement to resist the horizontal forces in the bridge deck:
From the calculations as described in the file "Load distribution" a large axial force in the bridge deck is introduced.
-The axial force need to be resisted by the reinforcement and steel profile.
-Concrete does not resist the tensile force since this is an ULS calculation (concrete is cracked).
-Assumed that steel decking does not contribute in the longitudinal axial stiffness.
-No slip between the different elements considered (full shear connection), just as a first indication.
-Extra build-in safety for axial force and capacity.

```
> eq100:=H=dL*(E_crack*b_eff*h_c)/(L*1000) + dL*(E_s*A_s_axial)/(L*1000) + dL*(E_a*A_a)/(L*1000):
```

So the elongation of the deck becomes [mm]:

```
> dL:=evalf(solve(eq100,dL)):
```

And the strain [-]:

```
> eps:=dL/(1000*L):
```

Output of the forces:
Normal force in concrete [N]:

```
> N_c:=E_crack*b_eff*h_c*eps:
```

Normal force in reinforement [N]:

```
> N_s:=A_s_axial*E_s*eps:
```

Normal force in steel profile [N]:

```
> N_a:=A_a*E_a*eps:
```

Equilibrium check:

```
> res1:=piecewise(abs(H-(N_c+N_s+N_a))<tol,"OK");
```

$res1 :=$ "OK" **(14)**

Capacity of the reinforcement [N]:

```
> N_s_Rd:=A_s_axial*f_yds;
```

$N\_s\_Rd := 652173.9130$ **(15)**

Is the applied reinforcement sufficient?

```
> res2:=piecewise(N_s_Rd>N_s,"Sufficient",N_s_Rd<N_2,"Insufficient");
```

$res2 :=$ "Sufficient" **(16)**

Additional axial stress in the main beams [N/mm2]:

```
> sig_add:=N_a/A_a;
```

$sig\_add := 117.9871383$ **(17)**

Determination of the axial wapening configuration:
Number of bars /m1

```
> n_axial:=ceil((A_s_axial/(b_eff/1000))/(0.25*diam_long^2*Pi));
```

$n\_axial := 5$ **(18)**

```
> n_hogging:=ceil((A_s/(b_eff/1000))/(0.25*diam_long^2*Pi));
```

(19)

$$n\_hogging := 6 \quad (19)$$

Total applied longitudinal bars in the deck:

```
> n_apply:=n_axial + n_hogging;
```

$$n\_apply := 11 \quad (20)$$

Total stress in the profile [MPa]:

```
> sig_tot:=sig_add+stress_bot;
```

$$sig\_tot := 299.7349829 \quad (21)$$

G.6. Longitudinal and transversal beam calculations

Calculations transverse beams

```
> restart; with(ListTools): with(plots):
```

General info

I.A. van der Esch
d.d. 2019-03-18

Assumptions

-The highest load on the secondary longitudinal beams will occur if the maintenance vehicle is lifting and being positioned above these beams.
-Load transfer path: from slab to secondary longitudinal beams, from longitudinal beams to transversal beams, from transversal beams to main beams.
-Own weight of the steel beams is neglected.
-No momentary factors are used since only 1 variable load is present.
-Secondary girder is simply supported - - > bolted connections.

Geometry

Secondary longitudinal girder
Assumed longitudinal profile: HEA240, below the properties:

Length of longitudinal girder [m]:
```
> L_2nd_girder:=3:
```
Youngs modulus [N/mm2]:
```
> E:=210000:
```
Second moment of inertia [mm4]:
```
> I_z:=7763*10^4:
```
Plastic section modulus [mm3]:
```
> W_z_pl:=744.6*10^3:
```
Yield stress [N/mm2]:
```
> f_y:=355:
```
Bending stiffness [Nmm2]:
```
> EI_2nd_long:=E*I_z/(10^9):
```
Profile width [mm]:
```
> b_long:=240:
```
Area of the profile [mm2]:
```
> A_long:=7680:
```
Thickness of the flange [mm]:
```
> t_f_long:=12:
```
Thickness of the web [mm]:
```
> t_w_long:=7.5:
```
Radius of the profile [mm]:
```
> r_long:=21:
```

Span of the deck [m]:
```
> L:=3.5:
```
Distances [m]:
```
> a:=1.365: b:=2.135:
```

Assumed transversal profile: HEA300, below the properties:

Length of longitudinal girder [m]:
```
> L_trans:=2*L:
```
Second moment of inertia [mm4]:
```
> I_z_trans:=18260*10^4:
```
Plastic section modulus [mm3]:
```
> W_z_pl_trans:=1383*10^3:
```
Bending stiffness [Nmm2]:
```
> EI_trans:=E*I_z_trans/(10^9):
```
Profile width [mm]:
```
> b_trans:=300:
```
Area of the profile [mm2]:
```
> A_trans:=11250:
```
Thickness of the flange [mm]:
```
> t_f_trans:=14:
```
Thickness of the web [mm]:
```
> t_w_trans:=8.5:
```
Radius of the profile [mm]:
```
> r_trans:=27:
```

Build-in error to deal with Heaviside functions and Dirac functions:
```
> err:=0.001:
```

Loads

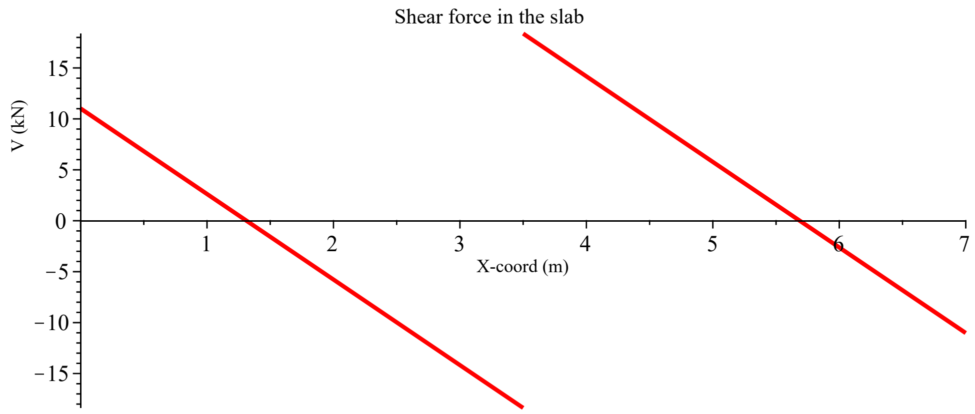
Own weight deck [kN/m2]:
```
> q_deck_k:=6:
```
UDL [kN/m2]
```
> UDL_lower:=3.20:
```

Wind load [kN/m2]
```
> q_wind_ver:=21.25/7.5:
```
Service vehicle [kN]
```
> q_serv:=50: q_install:=135:
```
Momentary factors[-]
```
> psi1:=0.4: psi2:=0.8:
```
Safety factors[-]
```
> saf1:=1.5: saf2:=1.65: saf3:=1.4: saf4:=0.9: saf5:=1:
```
Design loads:
```
> q_deck_d:=q_deck_k*saf3:
> q_install_d:=q_install*saf1;
```
$q\_install\_d := 202.5$ **(1)**

Calculations of secondary longitudinal girders

Support reaction due to q-load:

Support reaction q-load slab onto secondary longitudinal girder [kN/m1]:
```
> DV1:=EI*diff(w1(x),x$4)=q_deck_d: DV2:=EI*diff(w2(x),x$4)=q_deck_d:
> sol1:=dsolve({DV1,DV2},{w1(x),w2(x)}): assign(sol1): w1:=w1(x): w2:=w2(x):
> phi1:=-diff(w1,x): kappa1:=diff(phi1,x): M1:=EI*kappa1: V1:=diff(M1,x):
> phi2:=-diff(w2,x): kappa2:=diff(phi2,x): M2:=EI*kappa2: V2:=diff(M2,x):
> x:=0: eq1:=M1=0: eq2:=w1=0:
> x:=L: eq3:=M1=M2: eq4:=phi1=phi2: eq5:=w1=0: eq6:=w2=0:
> x:=2*L: eq7:=M2=0: eq8:=w2=0:
> x:='x':
> sol2:=solve({eq1,eq2,eq3,eq4,eq5,eq6,eq7,eq8},{_C1,_C2,_C3,_C4,_C5,_C6,_C7,_C8}): assign(sol2):
> AA:=plot(V1,x=0..L,thickness=3,color=red,title="Shear force in the slab",titlefont = ["ARIAL",
  12],labels = ["X-coord (m)", "V (kN)"],labeldirections=["horizontal","vertical"],labelfont=
  ["ARIAL",10],size=[1400,300]):
> BB:=plot(V2,x=L..2*L,thickness=3,color=red,title="Shear force in the slab due to the q-load",
  titlefont = ["ARIAL", 12],labels = ["X-coord (m)", "V (kN)"],labeldirections=["horizontal",
  "vertical"],labelfont=["ARIAL",10],size=[1400,300]):
> display(AA,BB);
```



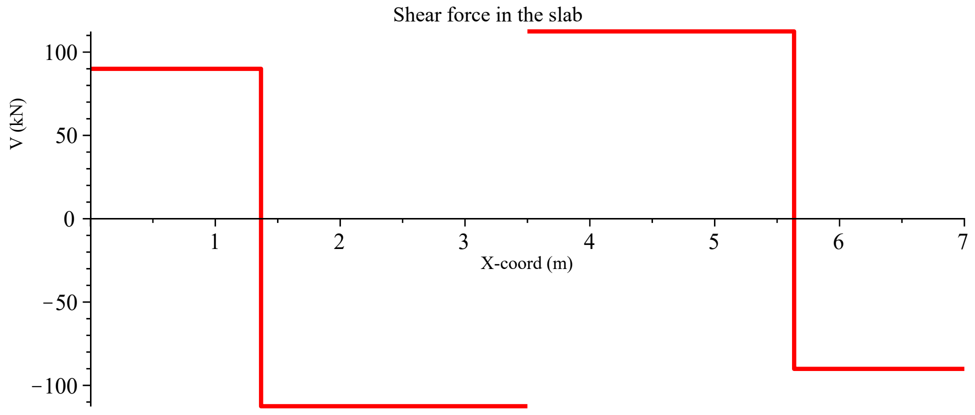
The distributed load onto the secondary longitudinal girder then becomes [kN/m1]:
```
> q_dist_2nd_long:=abs(subs(x=L,V2)) + abs(subs(x=L,V1));
```
$q\_dist\_2nd\_long := 36.75000002$ **(2)**

Support reaction due to F-load:

Support reaction F-load slab onto secondary longitudinal girder [kN]:

```
> DV3:=EI*diff(w3(x),x$4)=q_install_d*Dirac(x-a-err): DV4:=EI*diff(w4(x),x$4)=q_install_d*Dirac(x-
  b-L-err):
> sol3:=dsolve({DV3,DV4},{w3(x),w4(x)}): assign(sol3): w3:=w3(x): w4:=w4(x):
> phi3:=-diff(w3,x): kappa3:=diff(phi3,x): M3:=EI*kappa3: V3:=diff(M3,x):
> phi4:=-diff(w4,x): kappa4:=diff(phi4,x): M4:=EI*kappa4: V4:=diff(M4,x):
> x:=0: eq9:=M3=0: eq10:=w3=0:
> x:=L: eq11:=phi3=phi4: eq12:=w3=0: eq13:=w4=0: eq14:=M3=M4:
> x:=2*L: eq15:=M4=0: eq16:=w4=0:
> sol4:=solve({eq9,eq10,eq11,eq12,eq13,eq14,eq15,eq16},{_C9,_C10,_C11,_C12,_C13,_C14,_C15,_C16}):
  assign(sol4):
> x:='x':
> CC:=plot(V3,x=0..L,thickness=3,color=red,title="Shear force in the slab",titlefont = ["ARIAL",
  12],labels = ["X-coord (m)", "V (kN)"],labeldirections=["horizontal","vertical"],labelfont=
  ["ARIAL",10],size=[1400,300]):
> DD:=plot(V4,x=L..2*L,thickness=3,color=red,title="Shear force in the slab due to the q-load",
  titlefont = ["ARIAL", 12],labels = ["X-coord (m)", "V (kN)"],labeldirections=["horizontal",
```

```
"vertical"],labelfont=["ARIAL",10],size=[1400,300]):
> display(CC,DD);
```



The concentrated load onto the secondary longitudinal girder then becomes [kN]:

```
> evalf(subs(x=0,V3));
```

$$89.98570114 \quad \textbf{(3)}$$

```
> F_2nd_long:=abs(evalf(subs(x=L-err,V3))) + abs(evalf(subs(x=L+err,V4)));
```

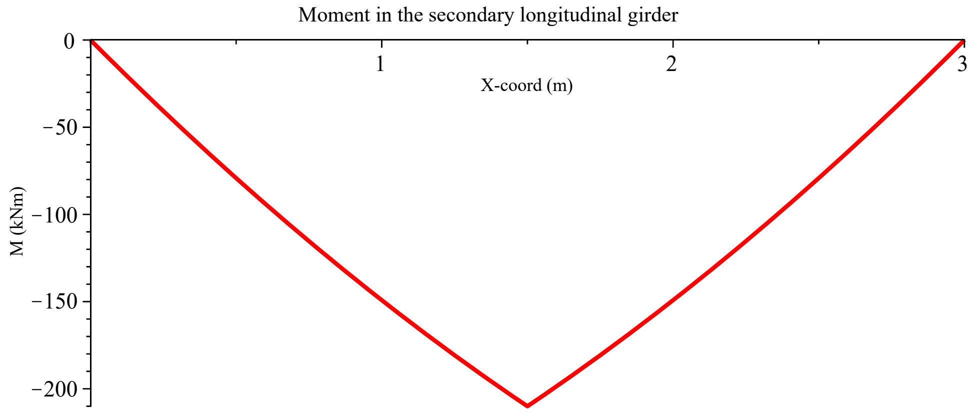
$$F\_2nd\_long := 224.9128835 \quad \textbf{(4)}$$

Forces in the secondary longitudinal girder:

```
> DV5:=EI_2nd_long*diff(w5(x),x$4)=q_dist_2nd_long + F_2nd_long*Dirac(x-0.5*L_2nd_girder):
> sol5:=dsolve(DV5,w5(x)): assign(sol5): w5:=w5(x):
> phi5:=-diff(w5,x): kappa5:=diff(phi5,x): M5:=EI_2nd_long*kappa5: V5:=diff(M5,x):
> x:=0: eq17:=w5=0: eq18:=M5=0:
> x:=L_2nd_girder: eq19:=w5=0: eq20:=M5=0:
> sol6:=solve({eq17,eq18,eq19,eq20},{_C17,_C18,_C19,_C20}): assign(sol6):
> x:='x':
```

Plot of the M-line in the secondary longtiudinal girder:

```
> plot(-M5,x=0..L_2nd_girder,thickness=3,color=red,title="Moment in the secondary longitudinal
  girder",titlefont = ["ARIAL", 12],labels = ["X-coord (m)", "M (kNm)"],labeldirections=
  ["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```

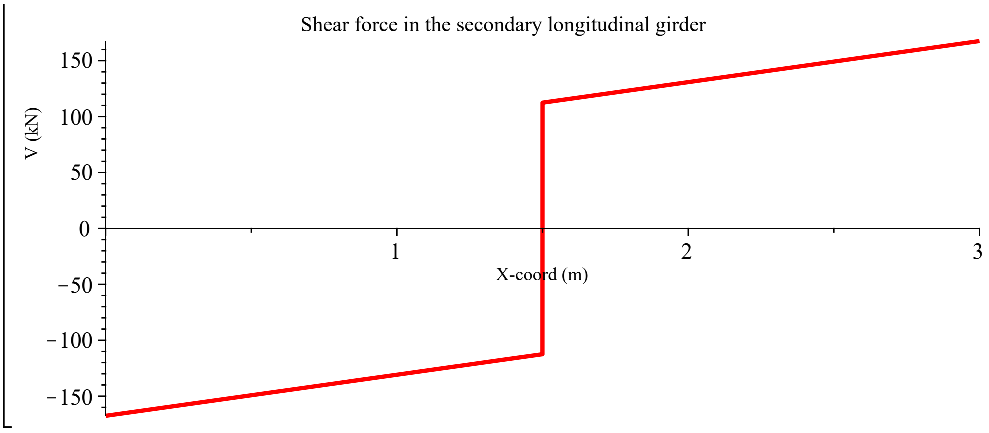



```
> M_max_long:=evalf(subs(x=0.5*L_2nd_girder-err,M5));
```

$$M\_max\_long := 209.9159378 \quad \textbf{(5)}$$

Plot of the V-line in the secondary longtiudinal girder:

```
> plot(-V5,x=0..L_2nd_girder,thickness=3,color=red,title="Shear force in the secondary longitudinal
  girder",titlefont = ["ARIAL", 12],labels = ["X-coord (m)", "V (kN)"],labeldirections=
  ["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```




```
> V_opleg:=evalf(subs(x=0-err,V5));
```

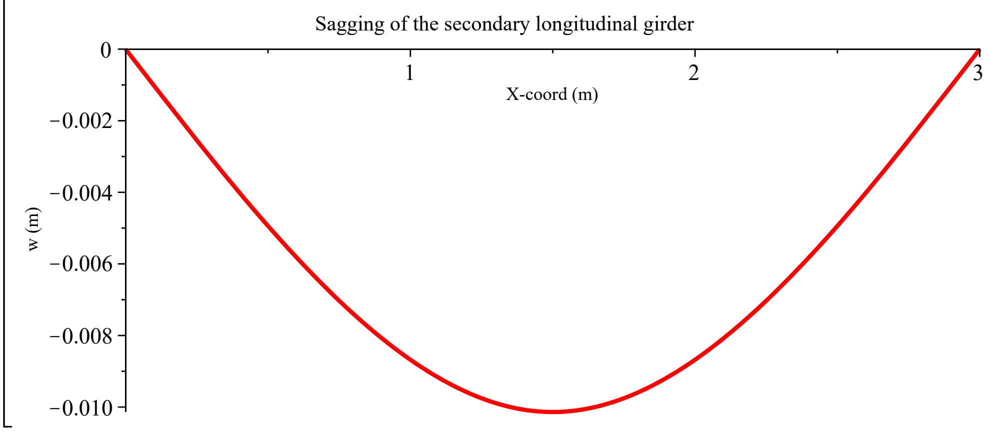
$V\_opleg := 167.6181918$ **(6)**

```
> V_max_long:=evalf(subs(x=0.5*L_2nd_girder-err,V5));
```

$V\_max\_long := 112.4931918$ **(7)**

Plot of the sagging line:

```
> plot(-w5,x=0..L_2nd_girder,thickness=3,color=red,title="Sagging of the secondary longitudinal
girder",titlefont = ["ARIAL", 12],labels = ["X-coord (m)", "w (m)"],labeldirections=
["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



Design checks

Sagging:

```
> w_max:=evalf(maximize(w5,x=0..L_2nd_girder))*1000;
```

$w\_max := 10.13803344$ **(8)**

The last check take into account the interaction between bending moments and shear forces. Since the profile class is 1, a plastic calculation is allowed. There is no need to reduce the plastic moment resistance due to shear forces if the design shear force is smaller than the half of the plastic shear force resistance.

Shear force area [mm2]:

```
> A_v_long:=A_long-2*b_long*t_f_long + (t_w_long + 2*r_long)*t_f_long;
```

$A\_v\_long := 2514.0$ **(9)**

Plastic shear force resistance [N]:

```
> V_pl_rd_long:=A_v_long*0.58*f_y;
```

$V\_pl\_rd\_long := 517632.600$ **(10)**

Check if one need to calculate with a reduced moment resistance:

```
> res11:=piecewise(V_max_long<0.5*V_pl_rd_long,"No reduction required",V_max_long>0.5*V_pl_rd_long,
"Reduction required");
```

res11 := "No reduction required" **(11)**

Therefore the following stress check can be performed:

Stress [N/mm2]:

```
> sig:=(evalf(subs(x=0.5*L_2nd_girder-err,M5))*10^6)/W_z_pl;
```
sig := 281.9177247 **(12)**

Stress check:

```
> res1:=piecewise(abs(sig)<f_y,"Sufficient",abs(sig)>f_y,"Insufficient");
```
res1 := "Sufficient" **(13)**

Calculations of transverse girders

The distributed load of [kN/m1] :

```
> q_dist_2nd_long;
```
36.75000002 **(14)**

Acts on the secondary longitudinal beam. This results in a support reaction of this beam onto the transversal girder. Since at each transversal beam there are 2 secondary longitudinal beams, the total support reaction from the longitudinal beams then equals [kN]:

```
> F_sup_long:=(1/2)*q_dist_2nd_long*L_2nd_girder*2;
```
F_sup_long := 110.2500001 **(15)**

Besides, the maximum force on the transversal beam is when a gantry is lifting directly above the transversal girder. This delives a force of 2 times [kN]:

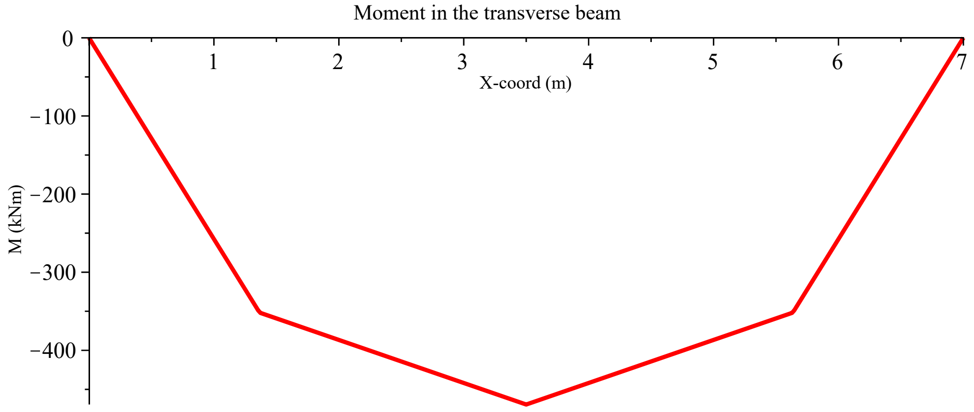
```
> F_sup_install:=q_install_d;
```
F_sup_install := 202.5 **(16)**

Forces in the transversal girder:

```
> DV6:=EI_trans*diff(w6(x),x$4)=F_sup_long*Dirac(x-0.5*L_trans) + F_sup_install*Dirac(x-a) +
  F_sup_install*Dirac(x-0.5*L_trans-b):
> sol7:=dsolve(DV6,w6(x)): assign(sol7): w6:=w6(x):
> phi6:=-diff(w6,x): kappa6:=diff(phi6,x): M6:=EI_trans*kappa6: V6:=diff(M6,x):
> x:=0: eq21:=w6=0: eq22:=M6=0:
> x:=L_trans: eq23:=w6=0: eq24:=M6=0:
> sol8:=solve({eq21,eq22,eq23,eq24},{_C21,_C22,_C23,_C24}): assign(sol8):
> x:='x':
```

Plot of the M-line in the transverse beam:

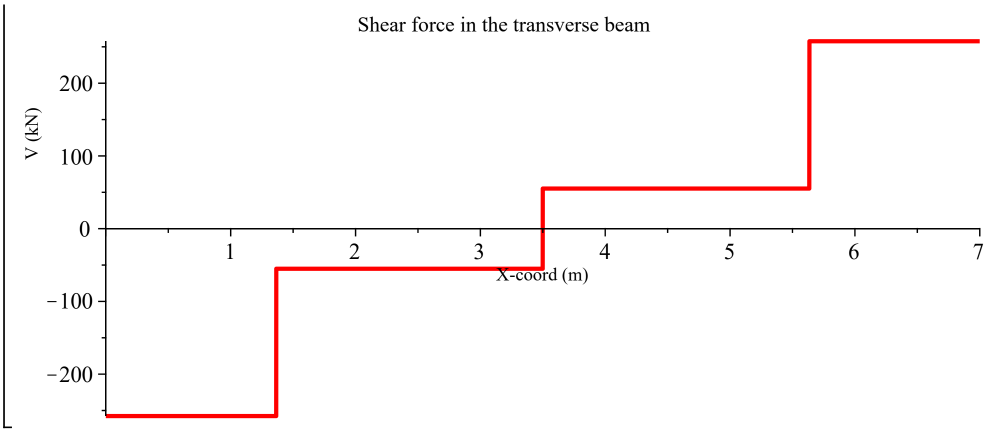
```
> plot(-M6,x=0..L_trans,thickness=3,color=red,title="Moment in the transverse beam",titlefont =
  ["ARIAL", 12],labels = ["X-coord (m)", "M (kNm)"],labeldirections=["horizontal","vertical"],
  labelfont=["ARIAL",10],size=[1400,300]);
```




```
> M_max_trans:=evalf(subs(x=0.5*L_trans-err,M6));
```
M_max_trans := 469.2948753 **(17)**

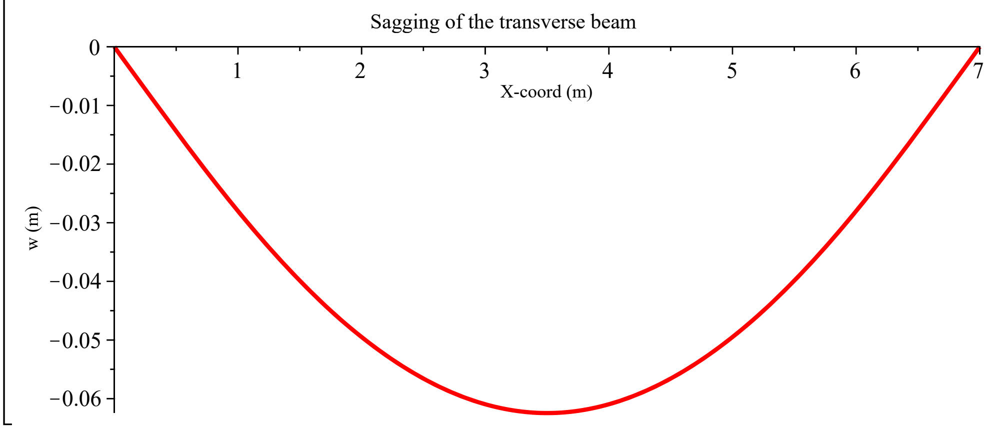
Plot of the V-line in the transverse beam:

```
> plot(-V6,x=0..L_trans,thickness=3,color=red,title="Shear force in the transverse beam",titlefont
  = ["ARIAL", 12],labels = ["X-coord (m)", "V (kN)"],labeldirections=["horizontal","vertical"],
  labelfont=["ARIAL",10],size=[1400,300]);
```




```
> V_max_trans:=evalf(subs(x=0.5*L_trans-err,V6));
```
V_max_trans := 55.1250001 **(18)**

Plot of the sagging line:
```
> plot(-w6,x=0..L_trans,thickness=3,color=red,title="Sagging of the transverse beam",titlefont = ["ARIAL", 12],labels = ["X-coord (m)", "w (m)"],labeldirections=["horizontal","vertical"], labelfont=["ARIAL",10],size=[1400,300]);
```



Design checks

Sagging [mm]:
```
> w_max_trans:=evalf(maximize(w6,x=0..L_trans))*1000;
```
w_max_trans := 62.45809857 **(19)**
```
> L_trans*1000/w_max_trans;
```
112.0751377 **(20)**

The last check take into account the interaction between bending moments and shear forces. Since the profile class is 1, a plastic calculation is allowed. There is no need to reduce the plastic moment resistance due to shear forces if the design shear force is smaller than the half of the plastic shear force resistance.

Shear force area [mm2]:
```
> A_v_trans:=A_trans-2*b_trans*t_f_trans + (t_w_trans + 2*r_trans)*t_f_trans;
```
A_v_trans := 3725.0 **(21)**

Plastic shear force resistance [N]:
```
> V_pl_rd_trans:=A_v_trans*0.58*f_y;
```
V_pl_rd_trans := 766977.500 **(22)**

Check if one need to calculate with a reduced moment resistance:
```
> res22:=piecewise(V_max_trans<0.5*V_pl_rd_trans,"No reduction required",V_max_trans>0.5*V_pl_rd_trans,"Reduction required");
```
res22 := "No reduction required" **(23)**

Stress [N/mm2]:
```
> sig_trans:=(evalf(subs(x=0.5*L_trans-err,M6))*10^6)/W_z_pl_trans;
```

$$sig\_trans := 339.3310740 \quad \textbf{(24)}$$

Stress check:

```
> res2:=piecewise(abs(sig_trans)<f_y,"Sufficient",abs(sig_trans)>f_y,"Insufficient");
```

$res2$:= "Sufficient" **(25)**

G.7. Arch calculation

Calculations steel arch

```
> restart; with(plots): with(plottools):
> err:=0.01:
```

General info

I.A. van der Esch
d.d. 2019-03-29

Loads

Value of the distributed load along the arch (based on combination ULS-1.03) [kN/m1]:

```
> q_0:=63.11:
```

Value of the concentrated load of the service vehicle [kN]:

```
> q_serv_d:=30:
```

Materials

Youngs modulus of the hanger [N/mm2]:

```
> E_hanger:=138000:
```

Area of an equivalent hanger (included 2 single hangers) [mm2]:

```
> A_hanger:=793:
```

Number of hangers in a single arch [-]:

```
> n_hanger:=19:
```

Cross sectional properties of the arch

Shape of arch: circular hollow section
Thickness of the arch wall [m]:

```
> t:=0.025:
```

Outer diameter [m]:

```
> D_outer:=1.3:
```

Second moment of intertia Izz [m4] of a single arch [m4]:

```
> I_zz:=(1/64)*Pi*(D_outer^4 - (D_outer-2*t)^4):
```

$$I\_zz := 0.02035623186 \quad (1)$$

E-modulus [kN/m2]:

```
> E:=210*10^6:
```

Bending stiffness of a single arch [kNm2]:

```
> EI:=E*I_zz;
```

$$EI := 4.274808691\ 10^{6} \quad (2)$$

Area of a single arch:

```
> A:=(1/4)*Pi*(D_outer^2 - (D_outer-2*t)^2):
```

$$A := 0.1001382658 \quad (3)$$

Axial stiffness [kN]:

```
> EA:=E*A;
```

$$EA := 2.102903582\ 10^{7} \quad (4)$$

Geometry of the arch

Ratio span / arch height [-]:

```
> r3:=6:
```

Length [m]:

```
> L:=110:
> Margin:=0:
```

Crest height [m]:

```
> f:=18.333
```

$$f := 18.333 \quad (5)$$

Point coordinates (Bottom Left (x-coord), Bottom Right (x-coord), Top (y-coord))
Coordinate convention: origin is at midspan deck, positive z-axis is downwards, negative upwards.

```
> P1:=-L/2: P2:=L/2: P3:=-L/r3:
```

With three points and three unknows the shape of the parabola can be determined uniquely.

```
> eq0:=a*x^2 + b*x + c:
> eq1:=subs(x=P1,eq0)=0:
> eq2:=subs(x=P2,eq0)=0:
> eq3:=subs(x=0,eq0)=P3:
> sol1:=solve({eq1,eq2,eq3},{a,b,c}): assign(sol1):
> z:=eq0;
```

$$z := \frac{x^2}{165} - \frac{55}{3} \quad (6)$$

Starting angle in radians (definition stated in Handbook of structural stability):

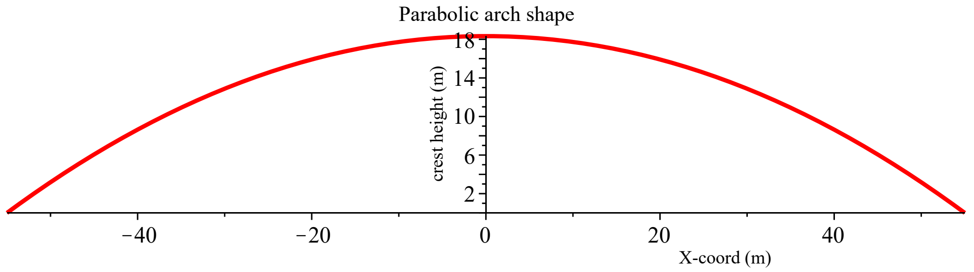
```
> alpha:=abs(evalf(arctan(subs(x=P1,diff(z,x)))));
```

$$\alpha := 0.5880026036 \quad (7)$$

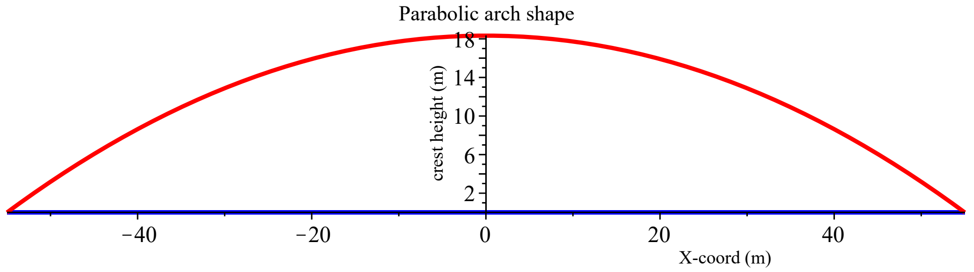
Plot of the arch

The parabola of the arch now yields:

```
> AA:=line([P1,0], [P2,0], color=blue,thickness=3):
> BB:=plot(-z,x=P1-Margin..P2+Margin,thickness=3,color=red,title="Parabolic arch shape",titlefont =
  ["ARIAL", 12],labels = ["X-coord (m)","crest height (m)"],labeldirections=["horizontal",
  "vertical"],labelfont=["ARIAL",10],size=[1400,200]):
```




```
> display(AA,BB);
```



Stress checks:

Stress check based on combination ULS1.02:

Accompanying forces (moments [kNm] and normal forces [kN]):

```
> M_ULS102:=2940: N_ULS102:=5699:
```

Maximal stress in outer fiber [N/mm2]:

```
> sigma_max:=(M_ULS102*10^6 * (D_outer/2)*10^3)/(I_zz*10^12) + (N_ULS102*10^3)/(A*10^6);
```

$$sigma\_max := 150.7891964 \quad (8)$$

Stress check based on combination ULS1.03:

Accompanying forces (moments [kNm] and normal forces [kN]):

```
> M_ULS103:=180.47: N_ULS103:=6295:
```

Maximal stress in outer fiber [N/mm2]:

```
> sigma_max:=(M_ULS103*10^6 * (D_outer/2)*10^3)/(I_zz*10^12) + (N_ULS103*10^3)/(A*10^6);
```

$$sigma\_max := 68.62571518 \quad (9)$$

Buckling check, in plane - According to handbook of structural stability:

-Approach according to "Handbook of Structural Stability"

Radius, based on the curvature (just defined as the 2nd derivatie of the shape of the arch) [m]:

```
> R:=evalf(1/diff(z,x$2));
```

$$R := 82.50000000 \quad (10)$$

Critical load [kN/m1]:

```
> q_cr1:=(EI/R^3)*((Pi^2/alpha^2)-1);
```

$$q\_cr1 := 209.7052104 \quad (11)$$

Then the critical buckling force becomes [kN]:

```
> N_cr1:=R*q_cr1;
```

$$N\_cr1 := 17300.67986 \quad (12)$$

Capacity check according to handbook of structural stability:

```
> check1:=piecewise(N_cr1>max(N_ULS102,N_ULS103),"Sufficient",N_cr1<max(N_ULS102,N_ULS103),
  "Insufficient");
```

$$check1 := \text{"Sufficient"} \quad (13)$$

Buckling check, in plane - According to EC3:

Factor according to table D.4.

```
> beta:=0.95:
```

The length of the half of the arch is calculated by using the arc length formula [m]:

```
> s:=evalf(int(sqrt(1+diff(z,x)^2),x=P1..0));
```

$$s := 58.83812278 \quad (14)$$

Then the critical buckling force becomes [kN]:

```
> N_cr2:=(Pi/(beta*s))^2 * EI;
```

$$N\_cr2 := 13503.66335 \quad (15)$$

Capacity check according to handbook of structural stability:

```
> check2:=piecewise(N_cr2>max(N_ULS102,N_ULS103),"Sufficient",N_cr2<max(N_ULS102,N_ULS103),
  "Insufficient");
```

check2 := "Sufficient" **(16)**

Buckling check, in plane - According to handbook of structural stability:

Ratio crest height / span [-]:

```
> f/L;
```

0.1666636364 **(17)**

Factor according to figure 18.28, line 2 (book: Steel Bridges) [-]:

```
> C:=30;
```

$$C := 30 \quad (18)$$

Critical normal force, neglecting the stabilizing forces of the hangers, according to figure 18.28, line 2, [kN]:

```
> N_cr:=C*EI/L^2;
```

$$N\_cr := 10598.69923 \quad (19)$$

Critical normal force, including the stabilizing forces of the hangers, according to figure 18.29, line 1, [kN]:

```
> delta:=0.11:
> N_cr_sus:=(1+delta)*N_cr;
```

$$N\_cr\_sus := 11764.55615 \quad (20)$$

G.8. Pier calculation

Calculations piers

```
> restart; with(ListTools): with(plots):
```

General info

I.A. van der Esch
d.d. 2019-03-20

Assumptions

-The highest load on the piers occur if the deck is fully loaded and a service vehicle is positioned above a pier.
-Besides a collision force need to be taken into account.
-This load distribution is taken into account in combination ULS-1.07.
-The loads are obtained from Scia Engineer.
-All the reinforcement yields.

Geometry

Top chord height [mm]:
```
> t1:=900:
```
Column cross section height [mm]:
```
> t2:=900:
```
Column cross section width [mm]:
```
> b:=600:
```
Distance reinforcement - outer cross sec [mm]:
```
> a:=50:
```
Assumed area of reinforcement in a single row [mm2] - for bending around strong axis:
```
> A_sy:=1206:
```
Useful height [mm]:
```
> d:=t2-a:
```
Assumed area of reinforcement in a single row [mm2] - for bending around weak axis:
```
> A_sx:=1206:
```

Material properties

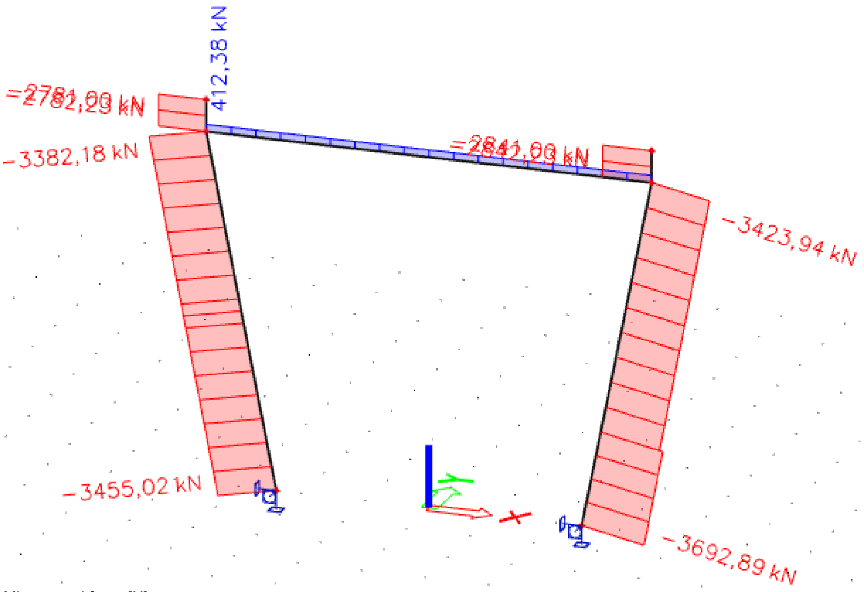
Yield stress [N/mm2]:
```
> f_y:=500:
```
Safety factor for reinforcement [-]:
```
> gamma_s:=1.15:
```
Characteristic concrete compression stress [N/mm2]:
```
> f_ck:=30:
```
Safety factor for concrete [-]:
```
> gamma_c:=1.5:
```
Yield strain concrete [-]:
```
> eps_c:=0.0035:
```
E-modulus reinforcement [N/mm2]:
```
> E_s:=200000:
```
Angle truss analogy [deg]:
```
> theta:=21.8:
```

Forces

*For the forces see the figures below.

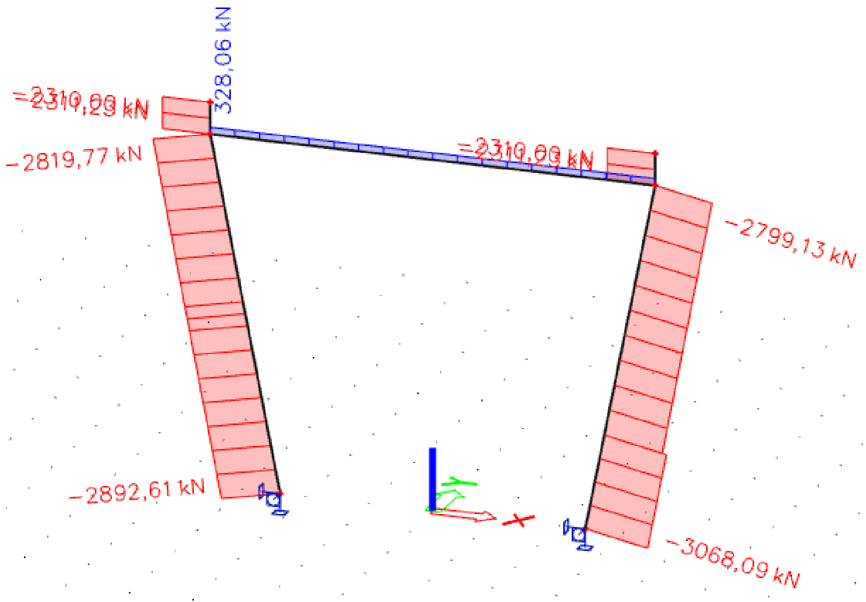
Due to bending around y-axis (strong axis):

Max. normal force [N]:
```
> N_max_y:=3693*10^3:
```



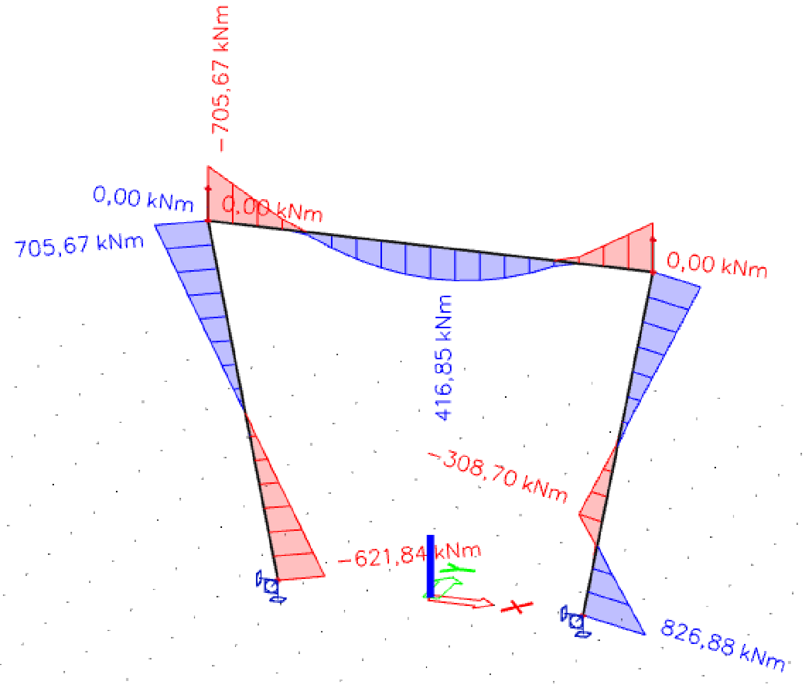
Min. normal force [N]:

```
> N_min_y:=3068*10^3:
```



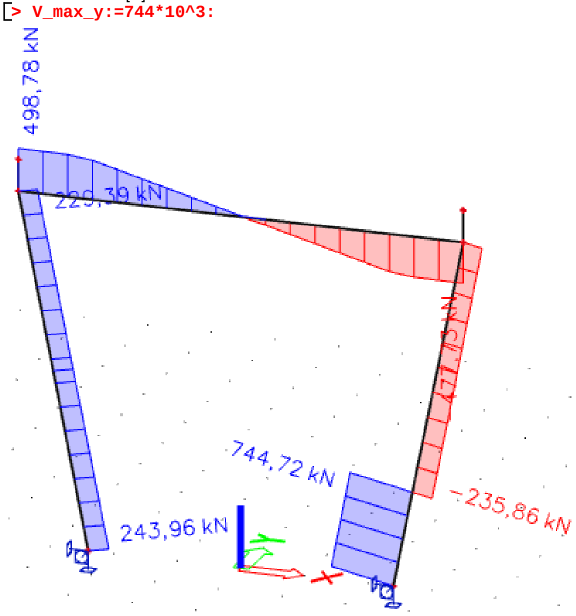
Max. moment [Nmm]:

```
> M_max_y:=827*10^6:
```



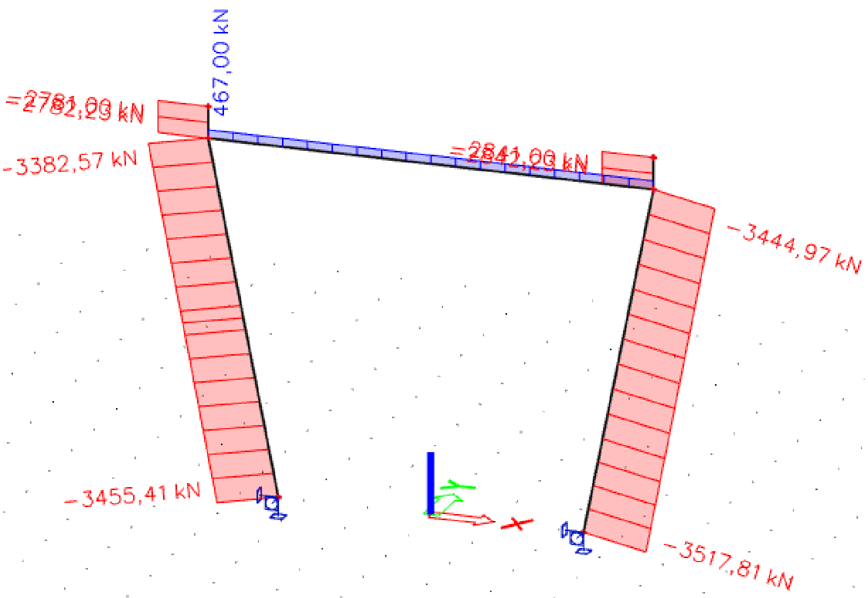
Max. shear force [N]:

```
> V_max_y:=744*10^3:
```



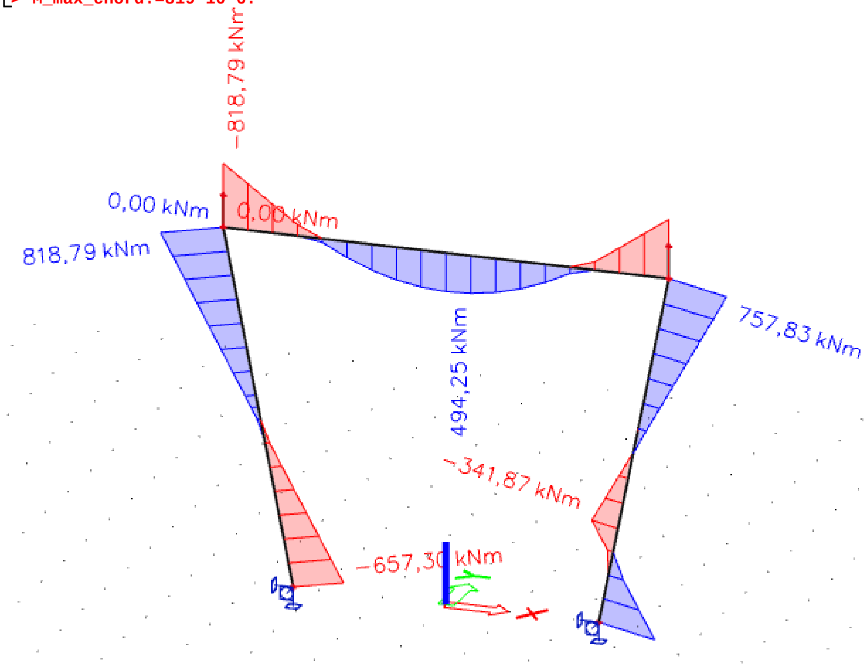
Maximum normal force in top chord [N]:

```
> N_top_chord_y:=467*10^3:
```



Maximum bending moment top chord (strong axis) [kNm]:

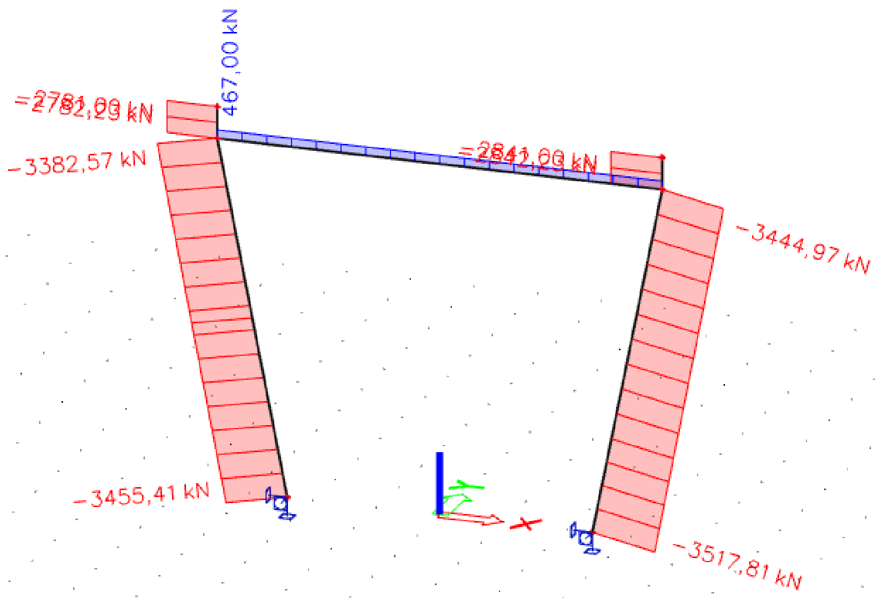
```
> M_max_chord:=819*10^6:
```



Due to bending around x-axis (weak axis):

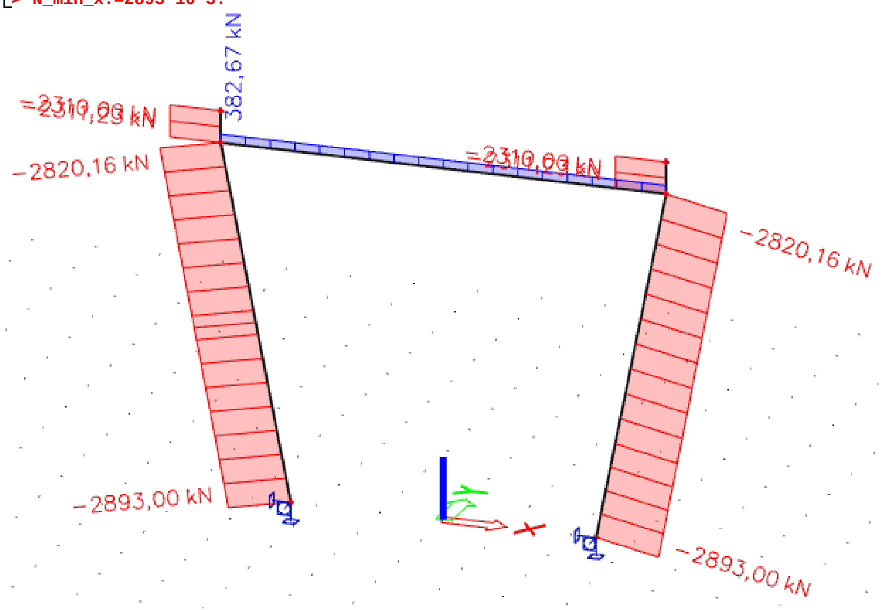
Max. normal force [N]:

```
> N_max_x:=3518*10^3:
```



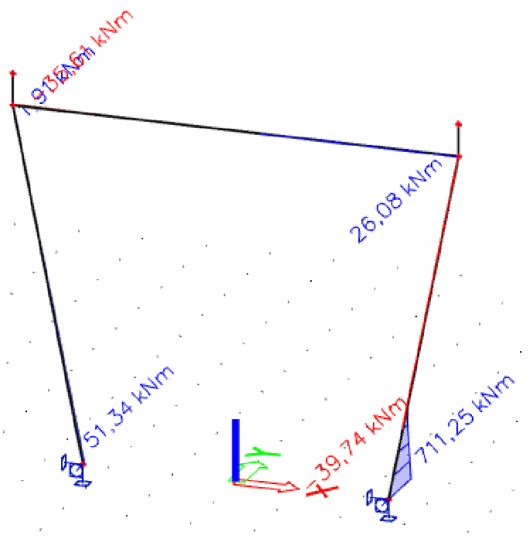
Min. normal force [N]:

```
> N_min_x:=2893*10^3:
```



Max. moment [Nmm]:

```
> M_max_x:=711*10^6:
```



Temp output

Design yield stress of reinforcement [N/mm2]:
```
> f_yd:=f_y/gamma_s:
```
Design yield strain reinforcement [-]:
```
> eps_s:=f_yd/E_s:
```
Design concrete compressive strength [N/mm2]:
```
> f_cd:=f_ck/gamma_c:
```

Bending moment resistance check - based on max. N-force - Bending around strong axis

Excentricity [m]:
```
> e1y:=evalf(M_max_y/1000/N_max_y):
```
Vertical equilibrium (assumption: all the reinforcement is yielding) [N]:
```
> eq11y:=A_sy*f_yd - A_sy*f_yd + N_max_y - N_c1y=0:
> N_c1y:=solve(eq11y,N_c1y):
```
Height of the concrete compressive strength [mm]:
```
> x_c1y:=N_c1y/(0.75*b*f_cd):
```
Distance right reinforcement row and N.A. [mm]:
```
> d_r1y:=x_c1y-a:
```
Distance left reinforcement row and N.A. [mm]:
```
> d_L1y:=t2-x_c1y-a:
```
Distance right reinforcement row and NC [mm]:
```
> d_11y:=t2/2 - a:
```
Distance left reinforcement row and NC [mm]:
```
> d_21y:=t2/2 - a:
```
Distance NC and concrete compression zone [mm]:
```
> d_31y:=t2/2 - (7/18)*x_c1y:
```
Bending moment resistance (maximum normal force) [Nmm]:
```
> M_Rd_N_max_y:=d_11y*A_sy*f_yd + d_21y*A_sy*f_yd + d_31y*N_max_y;
```
$$M\_Rd\_N\_max\_y := 1.492021206\ 10^{9} \quad (1)$$

Checks - - > result is only valid if both reinforcement rows are yielding:

Does right reinforcement row yield?
```
> res11y:=piecewise((d_r1y/x_c1y)*eps_c>eps_s,"Right row reinforcement yields",(d_r1y/x_c1y)*
  eps_c<eps_s,"Right row reinforcement does not yield");
```
res11y := "Right row reinforcement yields" (2)

Does left reinforcement row yield?
```
> res21y:=piecewise((d_L1y/x_c1y)*eps_c>eps_s,"Left row reinforcement yields",(d_L1y/x_c1y)*
  eps_c<eps_s,"Left row reinforcement does not yield");
```
res21y := "Left row reinforcement yields" (3)

Is bending moment resistance sufficient for max N-force?
```
> res31y:=piecewise(M_Rd_N_max_y>M_max_y,"Bending moment resistance sufficient",
  M_Rd_N_max_y<M_max_y,"Bending moment resistance not sufficient");
```
res31y := "Bending moment resistance sufficient" (4)

Excentricity: e/h > 0.1?
```
> res41y:=piecewise(e1y/(t2/1000)>0.1,"No reduced yielding required",e1y/(t2/1000)<0.1,"Reduced
  yielding required");
```
res41y := "No reduced yielding required" (5)

Bending moment resistance check - based on min. N-force - Bending around strong axis

Excentricity [m]:
```
> e2y:=evalf(M_max_y/1000/N_min_y):
```
Vertical equilibrium (assumption: all the reinforcement is yielding) [N]:
```
> eq12y:=A_sy*f_yd - A_sy*f_yd + N_min_y - N_c2y=0:
> N_c2y:=solve(eq12y,N_c2y):
```
Height of the concrete compressive strength:
```
> x_c2y:=N_c2y/(0.75*b*f_cd):
```

Distance right reinforcement row and N.A.:
```
> d_r2y:=x_c2y-a:
```
Distance left reinforcement row and N.A.:
```
> d_L2y:=t2-x_c2y-a:
```
Distance right reinforcement row and NC:
```
> d_12y:=t2/2 - a:
```
Distance left reinforcement row and NC:
```
> d_22y:=t2/2 - a:
```
Distance NC and concrete compression zone:
```
> d_32y:=t2/2 - (7/18)*x_c2y:
```
Bending moment resistance (minimum normal force):
```
> M_Rd_N_min_y:=d_12y*A_sy*f_yd + d_22y*A_sy*f_yd + d_32y*N_min_y;
```
$$M\_Rd\_N\_min\_y := 1.393359940\ 10^{9} \quad (6)$$

Checks:
Does right reinforcement row yield?
```
> res12y:=piecewise((d_r2y/x_c2y)*eps_c>eps_s,"Right row reinforcement yields",(d_r2y/x_c2y)*
  eps_c<eps_s,"Right row reinforcement does not yield");
```
res12y := "Right row reinforcement yields" **(7)**

Does left reinforcement row yield?
```
> res22y:=piecewise((d_L2y/x_c2y)*eps_c>eps_s,"Left row reinforcement yields",(d_L2y/x_c2y)*
  eps_c<eps_s,"Left row reinforcement does not yield");
```
res22y := "Left row reinforcement yields" **(8)**

Is bending moment resistance sufficient for max N-force?
```
> res32y:=piecewise(M_Rd_N_min_y>M_max_y,"Bending moment resistance sufficient",
  M_Rd_N_min_y<M_max_y,"Bending moment resistance not sufficient");
```
res32y := "Bending moment resistance sufficient" **(9)**

Excentricity: e/h > 0.1?
```
> res42y:=piecewise(e2y/(t2/1000)>0.1,"No reduced yielding required",e2y/(t2/1000)<0.1,"Reduced
  yielding required");
```
res42y := "No reduced yielding required" **(10)**

Shear force reinforcement calculation in the columns - Due to bending around strong axis

Calculation of the shear reinforcement

Design shear [N/mm2]:
```
> nu_Edy:=evalf(V_max_y/(b*d)):
```
Shape factor [-]:
```
> ky:=1+sqrt(200/d):
```
Shear resistance - lower bound [N/mm2]:
```
> nu_Rdcy:=evalf(0.035*(ky^1.5)*sqrt(f_ck)):
```
Is shear reinforcement required?
```
> res5:=piecewise(nu_Edy<nu_Rdcy,"Shear reinforcement not required",nu_Edy>nu_Rdcy,"Shear
  reinforcement required");
```
res5 := "Shear reinforcement required" **(11)**

Amount of required shear reinforcement [mm2/m1]:
```
> A_swy:=evalf((nu_Edy*b)/(0.9*f_yd*cot((theta/180)*Pi)))*1000:
```

Check of compression diagonal

Factor for the reduced resistance due to cracked concrete:
```
> v_1y:=0.6*(1-f_ck/250):
> nu_rdmaxy:=(0.9*v_1y*f_cd)/(cot((theta/180)*Pi) + tan((theta/180)*Pi)):
```
Check if the compression diagonal is sufficient:
```
> res6:=piecewise(nu_Edy<nu_rdmaxy,"Resistance of compression diagonal is OK",nu_Edy>nu_rdmaxy,
  "Resistance of compression diagonal not OK");
```
res6 := "Resistance of compression diagonal is OK" **(12)**

Longitudinal reinforcement in top chord of the pier

The required reinforcement in the top chord is determined by using the interaction diagrams from GTB-2010. The longitudinal reinforment in each row (top/bottom)equals [mm2]:
```
> A_s_top_chordy:=2160:
```
For the determination of this value, see the last page of this appendix.

Value y-axis:
```
> val_y_axis:=evalf(N_top_chord_y/(f_cd*t1*b)):
```
Value x-axis:
```
> e:=evalf((M_max_chord/(10^6)))/(N_top_chord_y/(10^3)):
> val_x_axis:=(N_top_chord_y/(f_cd*t1*b))*(e/(t1/1000)):
```

Bending moment resistance check - based on max. N-force - Bending around weak axis

Excentricity [m]:
```
> e1x:=evalf(M_max_x/1000/N_max_x):
```
Vertical equilibrium (assumption: all the reinforcement is yielding) [N]:
```
> eq11x:=A_sx*f_yd - A_sx*f_yd + N_max_x - N_c1x=0:
> N_c1x:=solve(eq11x,N_c1x):
```
Height of the concrete compressive strength [mm]:
```
> x_c1x:=N_c1x/(0.75*t2*f_cd):
```

Distance right reinforcement row and N.A. [mm]:
```
> d_r1x:=x_c1x-a:
```
Distance left reinforcement row and N.A. [mm]:
```
> d_L1x:=b-x_c1x-a:
```
Distance right reinforcement row and NC [mm]:
```
> d_11x:=b/2 - a:
```
Distance left reinforcement row and NC [mm]:
```
> d_21x:=b/2 - a:
```
Distance NC and concrete compression zone [mm]:
```
> d_31x:=b/2 - (7/18)*x_c1x:
```
Bending moment resistance (maximum normal force) [Nmm]:
```
> M_Rd_N_max_x:=d_11x*A_sx*f_yd + d_21x*A_sx*f_yd + d_31x*N_max_x;
```
$$M\_Rd\_N\_max\_x := 9.610542917\ 10^{8} \quad (13)$$

Checks - - > result is only valid if both reinforcement rows are yielding:
Does right reinforcement row yield?
```
> res11x:=piecewise((d_r1x/x_c1x)*eps_c>eps_s,"Right row reinforcement yields",(d_r1x/x_c1x)*
  eps_c<eps_s,"Right row reinforcement does not yield");
```
res11x := "Right row reinforcement yields" **(14)**

Does left reinforcement row yield?
```
> res21x:=piecewise((d_L1x/x_c1x)*eps_c>eps_s,"Left row reinforcement yields",(d_L1x/x_c1x)*
  eps_c<eps_s,"Left row reinforcement does not yield");
```
res21x := "Left row reinforcement yields" **(15)**

Is bending moment resistance sufficient for max N-force?
```
> res31x:=piecewise(M_Rd_N_max_x>M_max_x,"Bending moment resistance sufficient",
  M_Rd_N_max_x<M_max_x,"Bending moment resistance not sufficient");
```
res31x := "Bending moment resistance sufficient" **(16)**

Excentricity: e/h > 0.1?
```
> res41x:=piecewise(e1x/(t2/1000)>0.1,"No reduced yielding required",e1x/(t2/1000)<0.1,"Reduced
  yielding required");
```
res41x := "No reduced yielding required" **(17)**

Bending moment resistance check - based on min. N-force - Bending around weak axis

Excentricity [m]:
```
> e2x:=evalf(M_max_x/1000/N_min_x):
```

Vertical equilibrium (assumption: all the reinforcement is yielding) [N]:
```
> eq12x:=A_sx*f_yd - A_sx*f_yd + N_min_x - N_c2x=0:
> N_c2x:=solve(eq12x,N_c2x):
```
Height of the concrete compressive strength [mm]:
```
> x_c2x:=N_c2x/(0.75*t2*f_cd):
```
Distance right reinforcement row and N.A. [mm]:
```
> d_r2x:=x_c2x-a:
```
Distance left reinforcement row and N.A. [mm]:
```
> d_L2x:=b-x_c2x-a:
```
Distance right reinforcement row and NC [mm]:
```
> d_12x:=b/2 - a:
```
Distance left reinforcement row and NC [mm]:
```
> d_22x:=b/2 - a:
```
Distance NC and concrete compression zone [mm]:
```
> d_32x:=b/2 - (7/18)*x_c2x:
```
Bending moment resistance (maximum normal force):
```
> M_Rd_N_min_x:=d_12x*A_sx*f_yd + d_22x*A_sx*f_yd + d_32x*N_min_x;
```
$$M\_Rd\_N\_min\_x := 8.889786746\ 10^{8} \quad (18)$$

Checks - - > result is only valid if both reinforcement rows are yielding:
Does right reinforcement row yield?
```
> res12x:=piecewise((d_r2x/x_c2x)*eps_c>eps_s,"Right row reinforcement yields",(d_r2x/x_c2x)*
  eps_c<eps_s,"Right row reinforcement does not yield");
```
res12x := "Right row reinforcement yields" **(19)**

Does left reinforcement row yield?
```
> res22x:=piecewise((d_L2x/x_c2x)*eps_c>eps_s,"Left row reinforcement yields",(d_L2x/x_c2x)*
  eps_c<eps_s,"Left row reinforcement does not yield");
```
res22x := "Left row reinforcement yields" **(20)**

Is bending moment resistance sufficient for max N-force?
```
> res32x:=piecewise(M_Rd_N_min_x>M_max_x,"Bending moment resistance sufficient",
  M_Rd_N_min_x<M_max_x,"Bending moment resistance not sufficient");
```
res32x := "Bending moment resistance sufficient" **(21)**

Excentricity: e/h > 0.1?
```
> res42x:=piecewise(e2x/(t2/1000)>0.1,"No reduced yielding required",e2x/(t2/1000)<0.1,"Reduced
```

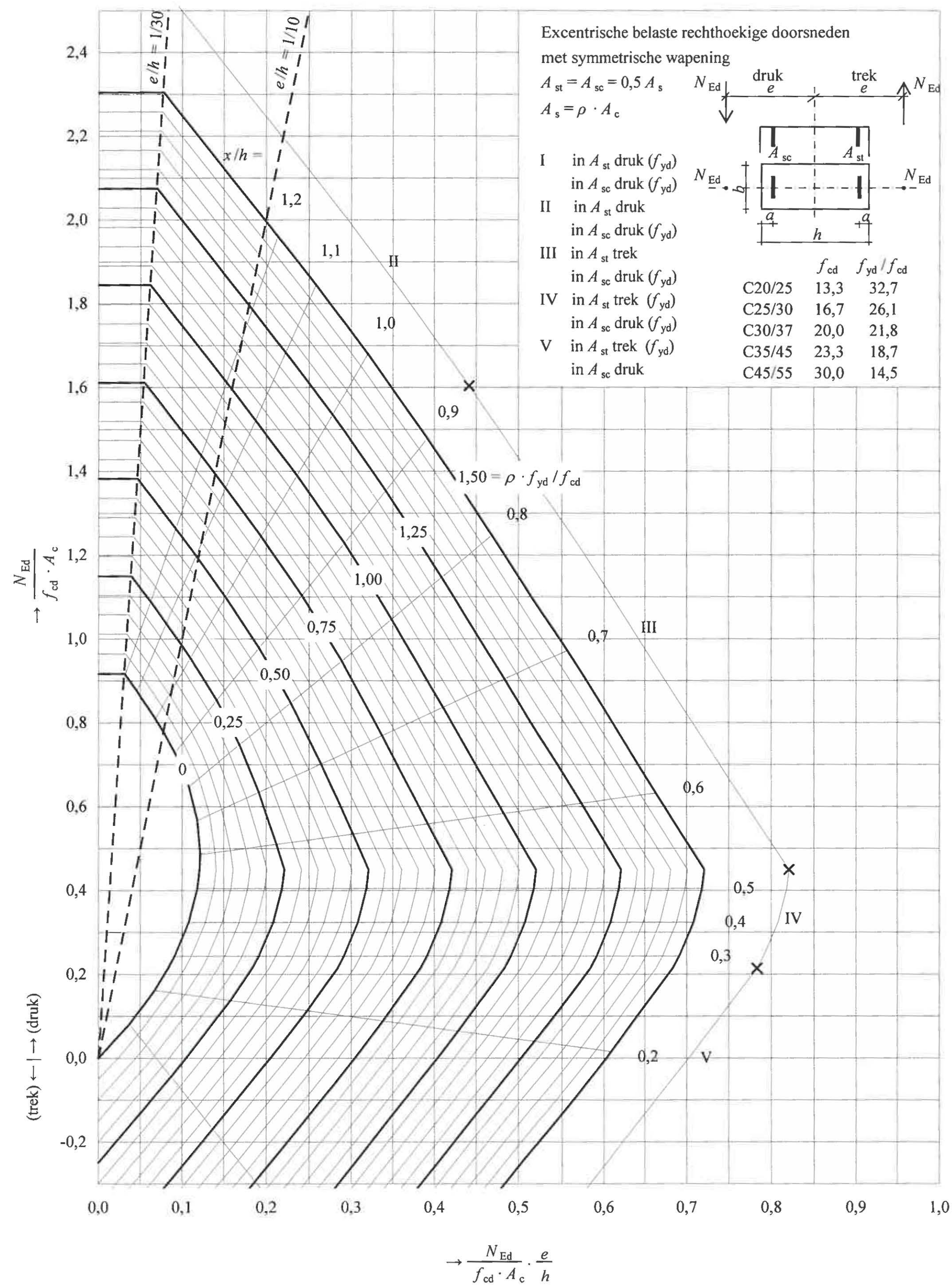
```
yielding required");
```

$res42x := $ "No reduced yielding required" **(22)**

GTB 2010 - 10.2.a

buiging en normaalkracht

C20/25 - C45/55 B500 0,10



G.9. Calculation of the expansion joints

Expansion joints

```
> restart; with(ListTools): with(plots):
```

General info

I.A. van der Esch
d.d. 2019-03-23

Assumptions

-Expansion occurs due to:
-1) Differences in temperature
-2) Axial deformation of the deck due to the increased normal force in the deck
-Additonal deformation due to braking- and acceleration forces is neglected.
-Axial resistance of the concrete deck neglected.

Geometry

Length of the bridge deck [m]:

```
> L:=110:
```

Cross sectional area of the profile [mm2]:

```
> A_a:=43000:
```

Centre - to - centre distance between the main beams [m]:

```
> hoh_main_beam_cross:=7:
```

Chrest height of the arch [m]:

```
> f:=18.3333:
```

Material properties

Youngs modulus [N/mm2]:

```
> E:=210000:
```

Loads

Temperature difference according to the temperature difference [C]:

```
> d_T:=15:
```

Linear expansion coefficient of steel [-]:

```
> alpha:=12*10^(-6):
```

Characteristic load arch [kN/m1]:

```
> q_arch_k:=8:
```

Characteristic load deck [kN/m1]:

```
> q_deck_k:=2:
```

Characteristic load hangers [kN/m1]:

```
> q_hangers_k:=1:
```

Safety factors [-]:

```
> saf1:=1.5: saf2:=1.65: saf3:=1.4:
```

Design load on a the arch [kN/m1]:

```
> q_char_d:=saf3*(hoh_main_beam_cross/2)*q_deck_k + q_hangers_k*saf3 + q_arch_k*saf3;
```

$$q\_char\_d := 22.40000000 \quad (1)$$

Maximum axial force [kN] (see combination ULS-1.03, file load distribution):

```
> H_max:=5242:
```

Minimum axial force [kN]:

```
> H_min:=(q_char_d*L^2)/(8*f);
```

$$H\_min := 1848.003360 \quad (2)$$

Output

Elongation due to temperature [mm]:

```
> d_L_t:=evalf(d_T*alpha*L*1000);
```

$$d\_L\_t := 19.80000000 \quad (3)$$

Elongation due to difference in normal force [mm]:

```
> d_L_F:=((H_max - H_min)*L*1000/(A_a*E))*1000;
```

$$d\_L\_F := 41.34436660 \quad (4)$$

So the total elongation becomes [mm] (2* d_L_t due to cooling down and warming up):

```
> d_L_tot:=2*d_L_t + d_L_F;
```

$$d\_L\_tot := 80.94436660 \quad (5)$$

G.10. Calculation of the transversal end beams

Calculations end beams

```
> restart; with(plots): with(plottools):
```

General info

I.A. van der Esch
d.d. 2019-03-25

Assumptions

-Rectangular profile assumed.
-Profile class: 1, plastic calculation allowed.
-Calculation phases:
  -Phase 1: usage phase (max. bending moment when gantry is located on top of the transversal girder).
  -Phase 2: jacking up of the deck for the replacement of bearings. Deck is jacked up when there is no variable load on the deck.

```
> err:=0.001:
```

Geometry

Height of the web [mm]:
```
> h_web:=500:
```
Width of the top and bottom flange [mm]:
```
> b_flange:=400:
```
Top and bottom flange thickness [mm]:
```
> tf:=10:
```
Web thickness [mm]:
```
> tw:=15:
```
Thickness of the profile [mm]:
```
> t:=tf:
```
Deck width [m]:
```
> deck_width:=7:
```
Span of the transversal beams [m]:
```
> L:=3.5:
```
Length of the longitudinal beam [m]:
```
> L_trans:=3:
```
Length of the end beam [m]:
```
> L_end:=deck_width:
```
Span of the bridge [m]:
```
> L_span:=110:
```
Jacking excentricity [m]:
```
> e_jacking:=0.5:
```

Material properties

Yield stress steel [N/mm2]:
```
> f_y:=355:
```
Youngs modulus of the steel profile [N/mm2]:
```
> E_a:=210000:
```
Partial material factor steel [-]:
```
> y_m0:=1.0:
```

Forces and loads

Maximum normal force in end beam - phase 1 - usage phase [N]:
```
> N_max:=663*10^3:
```
Own weight deck - total [kN/m2]:
```
> q_deck_k:=6: q_hanger_k:=1: q_arch_k:=8:
```
Force of gantry outrigger, including lifting weight [kN]:
```
> q_install:=125:
```
Position of the gantry (left support - left gantry outrigger) [m]:
```
> a:=1.365:
```
Safety factors [-]:
```
> saf1:=1.5: saf2:=1.65: saf3:=1.4: saf4:=0.9: saf5:=1:
```

Output

Profile height [mm]:
```
> h_tot:=h_web+2*tf:
```
Moment of inertia (only valid for rectangular profile) [mm4]:
```
> I_zz:=evalf((1/12)*b_flange*h_tot^3 - (1/12)*(b_flange-(2*tw))*(h_tot-(2*tf))^3):
```
Plastic moment resistance [Nmm]:
```
> z1:=h_web/4: z2:=h_web/2 + tf/2: z3:=h_web/4: z4:=h_web/2 + tf/2:
> A1:=(2*h_web/2)*tw: A2:=(b_flange*tf): A3:=(2*h_web/2)*tw: A4:=(b_flange*tf):
> W_pl_y:=z1*A1 + z2*A2 + z3*A3 + z4*A4:
> M_pl_y_Rd:=W_pl_y*f_y:
```
Area of the profile [mm2]:
```
> A:=2*b_flange*tf + 2*h_web*tw:
```

Design loads

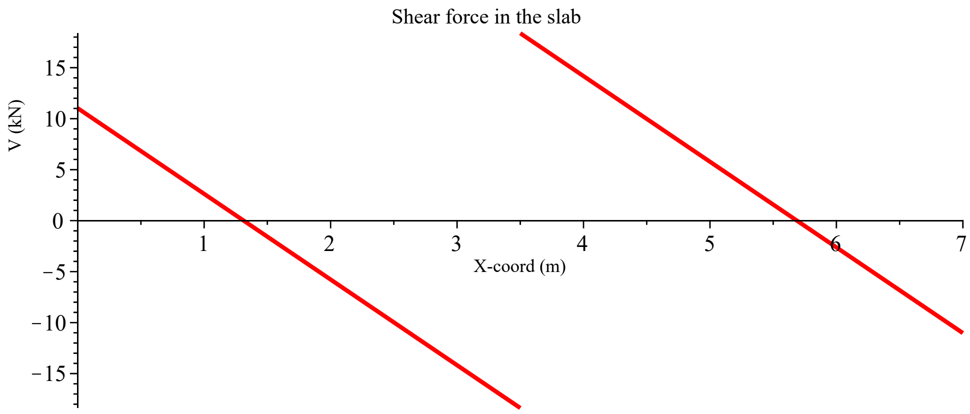
Safety factors [-]:

```
> saf3:=1.4:
```
Design load deck [kN/m2]:
```
> q_deck_d:=q_deck_k*saf3:
```
Design load gantry [kN]:
```
> q_install_d:=q_install*saf1;
```
$$q\_install\_d := 187.5 \quad (1)$$

Calculation of end beam - Situation 1: usage phase

Support reaction due to q-load:

Support reaction q-load slab onto secondary longitudinal girder [kN/m1]:
```
> DV1:=EI*diff(w1(x),x$4)=q_deck_d: DV2:=EI*diff(w2(x),x$4)=q_deck_d:
> sol1:=dsolve({DV1,DV2},{w1(x),w2(x)}): assign(sol1): w1:=w1(x): w2:=w2(x):
> phi1:=-diff(w1,x): kappa1:=diff(phi1,x): M1:=EI*kappa1: V1:=diff(M1,x):
> phi2:=-diff(w2,x): kappa2:=diff(phi2,x): M2:=EI*kappa2: V2:=diff(M2,x):
> x:=0: eq1:=M1=0: eq2:=w1=0:
> x:=L: eq3:=M1=M2: eq4:=phi1=phi2: eq5:=w1=0: eq6:=w2=0:
> x:=2*L: eq7:=M2=0: eq8:=w2=0:
> x:='x':
> sol2:=solve({eq1,eq2,eq3,eq4,eq5,eq6,eq7,eq8},{_C1,_C2,_C3,_C4,_C5,_C6,_C7,_C8}): assign(sol2):
> AA:=plot(V1,x=0..L,thickness=3,color=red,title="Shear force in the slab",titlefont = ["ARIAL",
  12],labels = ["X-coord (m)", "V (kN)"],labeldirections=["horizontal","vertical"],labelfont=
  ["ARIAL",10],size=[1400,300]):
> BB:=plot(V2,x=L..2*L,thickness=3,color=red,title="Shear force in the slab due to the q-load",
  titlefont = ["ARIAL", 12],labels = ["X-coord (m)", "V (kN)"],labeldirections=["horizontal",
  "vertical"],labelfont=["ARIAL",10],size=[1400,300]):
> display(AA,BB);
```

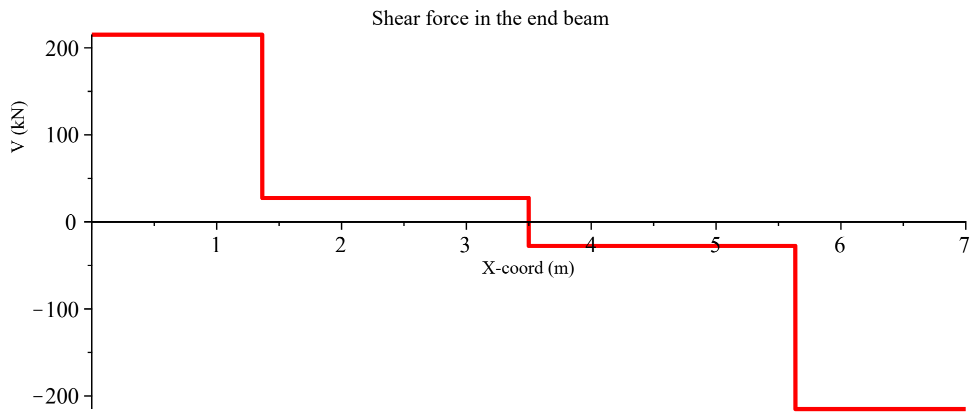



```
> q_dist_2nd_long:=abs(subs(x=L,V2)) + abs(subs(x=L,V1));
```
$$q\_dist\_2nd\_long := 36.75000002 \quad (2)$$

Thus the support reaction of the longitudinal girder on the end beam equals [kN]:
```
> F_load:=(1/2)*L_trans*q_dist_2nd_long;
```
$$F\_load := 55.12500005 \quad (3)$$

Force distribution in the end girders:
```
> q_end:=q_install_d*Dirac(x-a) + q_install_d*Dirac(x-(L_end-a)) + F_load*Dirac(x-L_end/2):
> DV3:=EI*diff(w3(x),x$4)=q_end:
> sol3:=dsolve(DV3,w3(x)): assign(sol3): w3:=w3(x):
> phi3:=-diff(w3,x): kappa3:=diff(phi3,x): M3:=EI*kappa3: V3:=diff(M3,x):
> x:=0: eq9:=M3=0: eq10:=w3=0:
> x:=L_end: eq11:=M3=0: eq12:=w3=0:
> x:='x':
> sol4:=solve({eq9,eq10,eq11,eq12},{_C9,_C10,_C11,_C12}): assign(sol4):
```

Shear force in end beam
```
> plot(V3,x=0..L_end,thickness=3,color=red,title="Shear force in the end beam",titlefont =
  ["ARIAL", 12],labels = ["X-coord (m)", "V (kN)"],labeldirections=["horizontal","vertical"],
  labelfont=["ARIAL",10],size=[1400,300]);
```




```
> evalf(subs(x=0,V3));
```

215.0625000 **(4)**

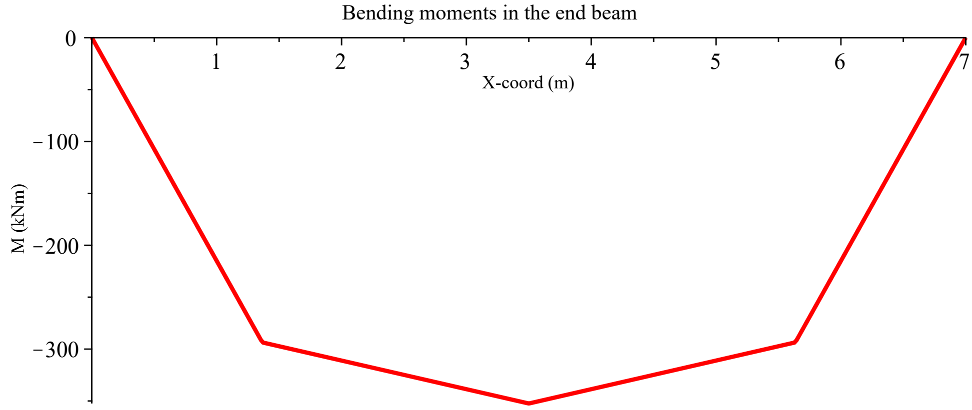
Shear force in the end beam [N]:

```
> V_z_Ed1:=evalf(subs(x=L_end/2 - err,V3))*10^3;
```

$V\_z\_Ed1 := 27562.50000$ **(5)**

Bending moments in end beam

```
> plot(-M3,x=0..L_end,thickness=3,color=red,title="Bending moments in the end beam",titlefont =
  ["ARIAL", 12],labels = ["X-coord (m)", "M (kNm)"],labeldirections=["horizontal","vertical"],
  labelfont=["ARIAL",10],size=[1400,300]);
```



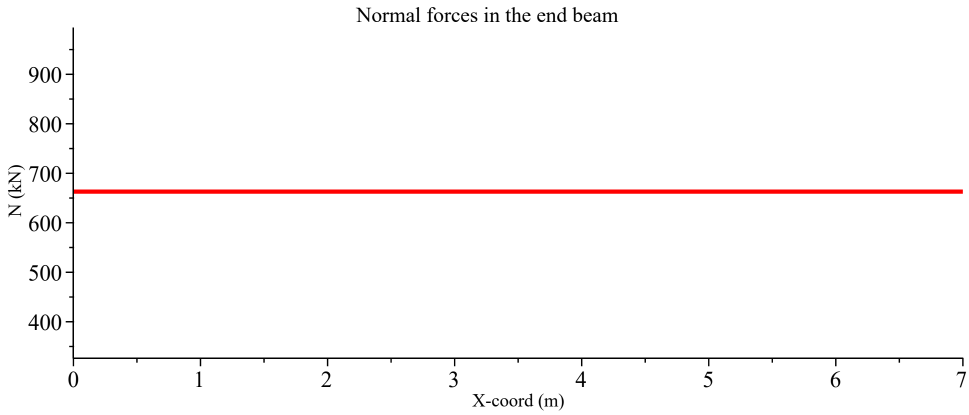
Design bending moment in end beam [Nmm]:

```
> M_y_Ed1:=evalf(subs(x=L_end/2,M3))*10^6;
```

$M\_y\_Ed1 := 3.524062501\ 10^8$ **(6)**

Normal forces in end beam

```
> plot(N_max/1000,x=0..L_end,thickness=3,color=red,title="Normal forces in the end beam",titlefont
  = ["ARIAL", 12],labels = ["X-coord (m)", "N (kN)"],labeldirections=["horizontal","vertical"],
  labelfont=["ARIAL",10],size=[1400,300]);
```



Design normal force in end beam [N]:

```
> N_Ed1:=N_max;
```

$$N\_Ed1 := 663000 \quad (7)$$

Profile check

-Assumed plastic profile resistance.
-Profile check based on art. 6.2.10 (interaction of bending moments, shear forces and normal forces) according to NEN-EN 1993-1-1-C2 and NEN-EN 1993-1-1-C2/NB.

Shear force area [mm2]:

```
> A_v:=h_tot/(b_flange+h_tot)*A:
```

Plastic shear force resistance [N]:

```
> V_pl_z_Rd:=A_v*f_y/(sqrt(3)*y_m0):
```

Equivalent distributed force [N/mm]:

```
> q_z1:=1.03*sqrt(1-(V_z_Ed1/V_pl_z_Rd)^2):
```

Reduced plastic bending moment resistance [Nmm]:

```
> M_y_vRd:=(M_pl_y_Rd-((1-q_z1)*((t*h_tot^2*f_y)/2)))/y_m0:
```

Plastic normal force resistance [N]:

```
> N_pl_Rd:=A*f_y/y_m0:
```

Plastic normal force resistance reduced due to shear force [N]:

```
> N_v_z_Rd:=(N_pl_Rd-(2*(1-q_z1)*t*h_tot*f_y))/y_m0:
```

Ratio of area of web and bruto area [-]:

```
> a_3:=min((A-(2*b_flange*t))/A,0.5):
```

[N/mm]:

```
> a4_z1:=q_z1*a_3:
```

Resistance check - situation 1:

Ratio:

```
> M_y_Ed1/M_y_vRd + ((N_Ed1/N_v_z_Rd)-(a4_z1/2))/(1-a4_z1/2);
```

$$0.0120875740 \quad (8)$$

```
> res:=piecewise(M_y_Ed1/M_y_vRd + ((N_Ed1/N_v_z_Rd)-(a4_z1/2))/(1-a4_z1/2)<1,"Sufficient",
  M_y_Ed1/M_y_vRd + ((N_Ed1/N_v_z_Rd)-(a4_z1/2))/(1-a4_z1/2)>1,"Insufficient");
```

$$res := \text{"Sufficient"} \quad (9)$$

Calculation of end beam - Situation 2: jacking the deck

Design normal force in end beam [N]:

```
> N_Ed2:=N_max:
```

Maximum jacking force: when the deck only has its own weight [kN/m1].

```
> q_own_weight_d:=saf3*q_deck_k*deck_width/2 + saf3*q_hanger_k + saf3*q_arch_k:
```

Max. force on bridge bearing, is equal to maximum shear force [N]:

```
> V_z_Ed2:=(q_own_weight_d*L_span*0.5)*10^3:
```

Maximum bending moment [Nmm]:

```
> M_y_Ed2:=V_z_Ed2*e_jacking*1000:
```

Shear force area [mm2]:

```
> A_v:=h_tot/(b_flange+h_tot)*A:
```

Plastic shear force resistance [N]:

```
> V_pl_z_Rd:=A_v*f_y/(sqrt(3)*y_m0):
```

Equivalent distributed force [N/mm]:

```
> q_z2:=1.03*sqrt(1-(V_z_Ed2/V_pl_z_Rd)^2):
```

Reduced plastic bending moment resistance [Nmm]:

```
> M_y_vRd:=(M_pl_y_Rd-((1-q_z2)*((t*h_tot^2*f_y)/2)))/y_m0:
```

Plastic normal force resistance [N]:

```
> N_pl_Rd:=A*f_y/y_m0:
```

Plastic normal force resistance reduced due to shear force [N]:

```
> N_v_z_Rd:=(N_pl_Rd-(2*(1-q_z2)*t*h_tot*f_y))/y_m0:
```

[N/mm]:

```
> a4_z2:=q_z2*a_3:
```

Resistance check - situation 2:

Ratio:

```
> M_y_Ed2/M_y_vRd + ((N_Ed2/N_v_z_Rd)-(a4_z2/2))/(1-a4_z2/2);
```

$$0.9711431893 \tag{10}$$

```
> res:=piecewise(M_y_Ed2/M_y_vRd + ((N_Ed2/N_v_z_Rd)-(a4_z2/2))/(1-a4_z2/2)<1,"Sufficient",
  M_y_Ed2/M_y_vRd + ((N_Ed2/N_v_z_Rd)-(a4_z2/2))/(1-a4_z2/2)>1,"Insufficient");
```

$$res := \text{"Sufficient"} \tag{11}$$

G.11. Continuously elastic support

Calculations steel arch

```
> restart; with(plots): with(plottools):
> err:=0.01:
```

Materials

Youngs modulus of the hanger [N/mm2]:

```
> E_hanger:=138000:
```

Area of an equivalent hanger (included 2 single hangers) [mm2]:

```
> A_hanger:=793:
```

Number of hangers in a single arch [-]:

```
> n_hanger:=18:
```

Cross sectional properties

Bending stiffness of the composite main beam [kNm2]:

```
> EI_main_beam:=919524:
```

Bending stiffness of the arch [kNm2]:

```
> EI_arch:=4.2748*10^6:
```

Axial stiffness of the arch [kN]:

```
> EA_arch:=2.1029*10^7:
```

Geometry of the arch

Ratio span / arch height:

```
> r3:=6:
```

Length:

```
> L:=110:
> Margin:=0:
```

Crest height:

```
> f:=18.333
```

$$f := 18.333 \quad (1)$$

Point coordinates (Bottom Left (x-coord), Bottom Right (x-coord), Top (y-coord))
Coordinate convention: origin is at midspan deck, positive z-axis is downwards, negative upwards.

```
> P1:=-L/2: P2:=L/2: P3:=-L/r3:
```

With three points and three unknows the shape of the parabola can be determined uniquely.

```
> eq0:=a*x^2 + b*x + c:
> eq1:=subs(x=P1,eq0)=0:
> eq2:=subs(x=P2,eq0)=0:
> eq3:=subs(x=0,eq0)=P3:
> sol1:=solve({eq1,eq2,eq3},{a,b,c}): assign(sol1):
> z:=eq0;
```

$$z := \frac{x^2}{165} - \frac{55}{3} \quad (2)$$

Starting angle in radians (definition stated in Handbook of structural stability):

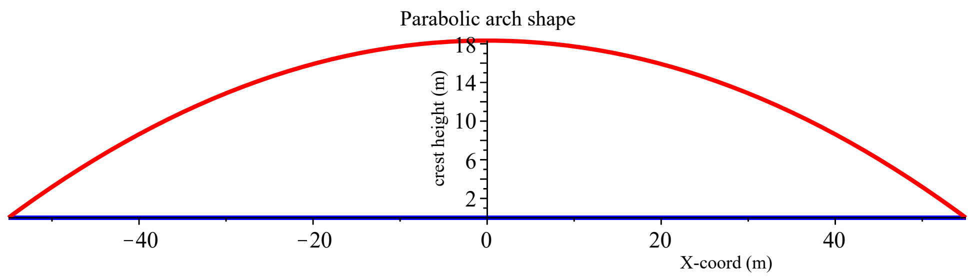
```
> alpha:=abs(evalf(arctan(subs(x=P1,diff(z,x)))));
```

$$\alpha := 0.5880026036 \quad (3)$$

Plot of the arch

The parabola of the arch now yields:

```
> AA:=line([P1,0], [P2,0], color=blue,thickness=3):
> BB:=plot(-z,x=P1-Margin..P2+Margin,thickness=3,color=red,title="Parabolic arch shape",titlefont =
  ["ARIAL", 12],labels = ["X-coord (m)","crest height (m)"],labeldirections=["horizontal",
  "vertical"],labelfont=["ARIAL",10],size=[1400,200]):
> display(AA,BB);
```



Loads

Value of the distributed load along the arch (based on combination ULS-1.03) [kN/m1]:

```
> q_serv_d:=20:
> q_d_SLS_left:=34.61:
> q_d_SLS_right:=25.25:
```

Computing the distributed spring stiffness along the girder:

Axial stiffness of a hanger [N]:

```
> EA_hanger:=E_hanger*A_hanger;
```

$$EA\_hanger := 109434000 \quad \textbf{(4)}$$

Create a loop to extract the axial stiffness for each equivalent hanger:

```
> K_hanger:=Array(0..(n_hanger-1)):
> X_coord:=Array(0..(n_hanger-1)):
> for i from 1 to (n_hanger-1) do:
  #x=evalf(i*(L/n_hanger));
  L_hanger:=abs(evalf(eval(z,x=i*(L/n_hanger)+P1)))*1000;
  K_hanger[i]:=round(EA_hanger/(abs(evalf(eval(z,x=i*(L/n_hanger)+P1)))*1000)):
  X_coord[i]:=evalf(i*(L/n_hanger)):
  end do:
> K_hanger_list:=convert(K_hanger,list):
> nonZeroIndices := [seq(`if`(K_hanger_list[i]=0,NULL,i), i=1..nops(K_hanger_list))]:
> K_new_list:=K_hanger_list[nonZeroIndices];
```

$$K\_new\_list := [28441, 15109, 10744, 8634, 7438, 6715, 6279, 6044, 5969, 6044, 6279, 6715, 7438, 8634, 10744, 15109, 28441] \quad \textbf{(5)}$$

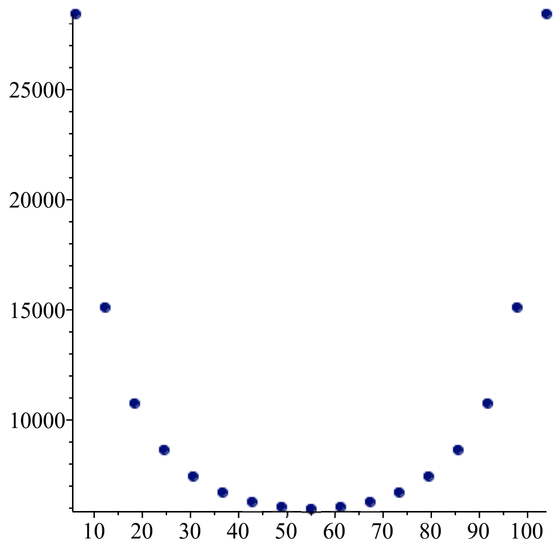
```
> X_coord_list:=convert(X_coord,list):
> nonZeroIndices := [seq(`if`(X_coord_list[i]=0,NULL,i), i=1..nops(X_coord_list))]:
> X_coord_new_list:=X_coord_list[nonZeroIndices];
```

$$X\_coord\_new\_list := [6.111111111, 12.22222222, 18.33333333, 24.44444444, 30.55555556, 36.66666667, 42.77777778, 48.88888889, 55., 61.11111111, 67.22222222, 73.33333333, 79.44444444, 85.55555556, 91.66666667, 97.77777778, 103.8888889] \quad \textbf{(6)}$$

Plot of the discrete spring stiffness for each hanger

Coordinate: left origin is at x=0. Below the stiffness of the hangers at each point [kN/m/6m]:

```
> dataplot(X_coord_new_list, K_new_list,style=point);
```



Trend line of the distributed stiffness [kN/m]:

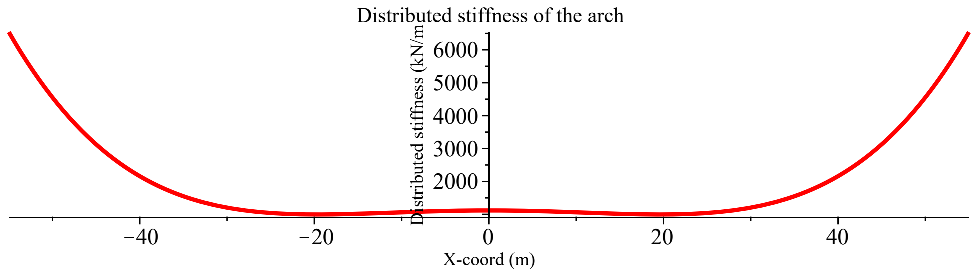
To overcome the problem of too much coupled ODE's, one choose to 'spread' the stiffness over the length of the bridge. In that case the force distribution can be calculated with a single ODE.

```
> stiff_trend:=0.0008*x^4 - 0.6279*x^2 + 1118.7;
```

$$stiff\_trend := 0.0008\,x^4 - 0.6279\,x^2 + 1118.7 \quad \textbf{(7)}$$

Plot the trend

```
> plot(stiff_trend,x=P1..P2,color=red,thickness=3,title="Distributed stiffness of the arch",
  titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Distributed stiffness (kN/m)"],
  labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,200]);
```



Check of the displacements using the continuously elastic supported approach for a beam

Now determine the force distribution in the main beam of the deck

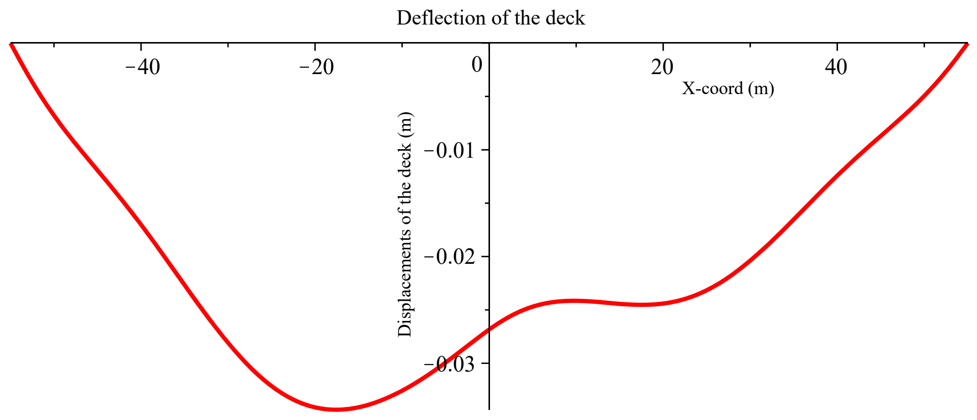
Check this result by subtracting the total deformation of the deck minus deformation of the arch!

SLS2.03

-Displacements of the deck

-Effect of deflection of arch is neglected.

```
> q_203:=Heaviside(x-P1)*q_d_SLS_left - Heaviside(x+err)*q_d_SLS_left + Heaviside(x-err)*
  q_d_SLS_right - Heaviside(x-P2)*q_d_SLS_right + Dirac(x-(P1/2))*q_serv_d:
> DV0:=EI_main_beam*diff(w0(x),x$4) = q_203 - stiff_trend*w0(x):
> BC0:=w0(P1)=0,-1*EI_main_beam*(D@@2)(w0)(P1)=0,-1*EI_main_beam*(D@@2)(w0)(P2)=0,w0(P2)=0:
> sol2:=dsolve({DV0,BC0},{w0(x)},maxmesh=20000,abserr=0.0005,type=numeric):
> plots[odeplot](sol2, [[x,-w0(x),color=red, thickness=3]],P1..P2,numpoints=500,title="Deflection
  of the deck",titlefont = ["ARIAL", 12],labels = ["X-coord (m)","Displacements of the deck (m)"],
  labeldirections=["horizontal","vertical"],labelfont=["ARIAL",10],size=[1400,300]);
```



G.12. Bolted connection longitudinal - transverse beam

Calculation bolted connection longitudinal beam - transverse beam

```
> restart;
```

General info

I.A. van der Esch
d.d. 2019-04-16

Assumptions

* Type of connection: single fin plate, welded to column and beam
* Ultimate strength of S355: fu=490 MPa, source: https://www.eurocodeapplied.com/design/en1993/steel-design-properties
* Assumed that required gap is available in joint design

Geometry

Beam (HEA240):

```
> h_b:=230: b_f_b:=240: t_f_b:=12: t_w_b:=7.5: r_b:=21: A_b:=7680: f_y_b:=355: f_u_b:=490: A_b:=
  7680:
```

Fin plate:

```
> h_p:=210: b_p:=100: t_p:=18: f_y_p:=355: f_u_p:=490:
```

Bolts M24, grade 8.8:

```
> d:=20: d_0:=22: A_s:=245: fyb:=640: fub:=800: n_1:=3: n_2:=1:
```

Edge distances:

```
> e_1_p:=40: e_2_p:=40: e_1_b:=79: e_2_b:=40: p_1:=65: e:=55:
> a_w:=10: l_w:=h_p:
```

Number of shear faces:

```
> m:=1:
```

Partial safety factors:

```
> gam0:=1: gam2:=1.25:
```

Forces

Design shear force in the connection [N]:

```
> V_Ed:=168000:
```

Output

Total number of bolts:

```
> n:=n_1*n_2;
```

$$n := 3 \tag{1}$$

Failure mechanism 1 - Failure of bolts in shear

```
> a_v:=0.6:
> F_1_v_Rd:=m*a_v*fub*A_s/gam2:
> V_Rd_1:=evalf(n*F_1_v_Rd/(sqrt(1+((6*e)/((n+1)*p_1))^2)));
```

$$V\_Rd\_1 := 174670.4972 \tag{2}$$

Failure mechanism 2 - Resistance of fin plate in bearing fails

Bearing resistance of one bolt within the group in the vertical direction

```
> e_2:=e_2_p: e_1:=e_1_p:
> k_1:=min(2.8*e_2/d_0 - 1.7,2.5):
> a_b:=evalf(min(fub/f_u_b,1,p_1/(3*d_0) - 0.25,e_1/(3*d_0))):
> F_b_ver_Rd:=k_1*a_b*f_u_b*d*t_p / gam2:
```

Bearing resistance of one bolt within the group in the horizontal direction

```
> e_2:=e_1_p: e_1:=e_2_p: p_2:=p_1:
> k_1:=min(2.8*e_2/d_0 - 1.7, 1.4*p_2/d_0 - 1.7, 2.5):
> a_b:=evalf(min(fub/f_u_b,1,e_1/(3*d_0))):
> F_b_hor_Rd:=k_1*a_b*f_u_p*d*t_p/gam2:
```

Bearing resistance of the bolt group at the fin plate

```
> beta:=evalf((6*e)/(p_1*n*(n+1))): alpha:=0:
```

So the bearing resistance of the bolt group at the fin plate then becomes:

```
> V_Rd_2:=n/(sqrt(((1+n*alpha)/(F_b_ver_Rd))^2 + ((n*beta)/(F_b_hor_Rd))^2));
```

$$V\_Rd\_2 := 390651.8260 \tag{3}$$

Failure mechanism 3 - Resistance of fin plate in shear (gross cross-section) fails

```
> V_Rd_3:=evalf((h_p*t_p*f_y_p/(sqrt(3)))/(1.27*gam0));
                              V_Rd_3 := 610036.4775                    (4)
```

Failure mechanism 4 - Resistance of fin plate in shear (net cross-section) fails

```
> V_Rd_4:=evalf(((h_p - n_1*d_0)*t_p*f_u_p/(sqrt(3)))/gam2);
                              V_Rd_4 := 586624.8241                    (5)
```

Failure mechanism 5 - Shear block failure of fin plate

```
> A_nt:=t_p*(e_2_p-d_0/2):
> A_nv:=t_p*(h_p-e_1_p-(n_1-0.5)*d_0):
> F_eff_Rd:=evalf(0.5*f_u_p*A_nt/gam2 + f_y_p*A_nv/(sqrt(3)*gam0)):
> V_Rd_5:=F_eff_Rd;
                              V_Rd_5 := 526577.8454                    (6)
```

Failure mechanism 6 - Resistance failure of the fin plate in bending

Is the resistance of the fin plate in bending governing?

```
> res6:=piecewise(h_p>2.73*e,"Not governing",h_p<2.73*e,"Governing");
                              res6 := "Not governing"                  (7)
```

The resistance is then:

```
> V_Rd_6:=piecewise(h_p>2.73*e,1000000,h_p<2.73*e,evalf((((t_p*h_p^2)/6)/e)*(f_y_p/gam0)));
                              V_Rd_6 := 1000000                        (8)
```

Failure mechanism 7 - Buckling failure of the fin plate

```
> res7:=piecewise(e/t_p < 9*sqrt(235/f_y_p),"No risk for plate instability",e/t_p > 9*sqrt
  (235/f_y_p),"Risk for plate instability");
                              res7 := "No risk for plate instability"  (9)
> evalf(e/t_p); evalf(9*sqrt(235/f_y_p));
                              3.055555556
                              7.322548623                              (10)
```

Failure mechanism 8 - Resistance failure of the beam web in bending

Bearing resistance of one bolt within the group in the vertical direction

```
> e_2:=e_2_b:
> k_1:=min(2.8*(e_2/d_0) - 1.7,2.5);
                              k_1 := 2.5                               (11)
> a_b:=min((fub/f_u_b),1,(p_1/(3*d_0))-0.25);
                              a_b := 0.7348484848                      (12)
> F_b_ver_Rd:=k_1*a_b*f_u_p*d*t_w_b/gam2:
```

Bearing resistance of one bolt within the group in the horizontal direction

```
> e_1:=e_2_b:
> k_1:=min(1.4*(p_1/d_0)-1.7,2.5):
> a_b:=min((fub/f_u_b),1,e_1/(3*d_0)):
> F_b_hor_Rd:=k_1*a_b*f_u_p*d*t_w_b/gam2:
```

So the bearing resistance of the bolt group at the beam web plate then becomes:

```
> V_Rd_8:=n/(sqrt(((1+n*alpha)/(F_b_ver_Rd))^2 + ((n*beta)/(F_b_hor_Rd))^2));
                              V_Rd_8 := 173378.3708                    (13)
```

Failure mechanism 9 - Resistance failure of the beam web in shear (gross cross-section)

```
> A_v_b:=A_b - 2*b_f_b*t_f_b + (t_w_b + 2 * r_b)*t_f_b:
> V_Rd_9:=evalf(A_v_b*f_y_b/(sqrt(3)*gam0));
                              V_Rd_9 := 515267.7949                    (14)
```

Failure mechanism 10 - Resistance failure of beam web in shear (net cross-section)

```
> A_v_b_net:=A_v_b-n_1*d_0*t_w_b:
> V_Rd_10:=evalf(A_v_b_net*f_u_b/(sqrt(3)*gam2));
                              V_Rd_10 := 456942.7160                   (15)
```

Failure mechanism 11 - Shear block failure of the beam web

```
> A_nt:=t_w_b*(e_2_p-d_0/2):
> A_nv:=t_w_b*(e_1_b+(n_1-1)*p_1 - (n_1-0.5)*d_0):
> F_eff_Rd:=evalf(0.5*f_u_b*A_nt/gam2 + f_y_b*A_nv/(sqrt(3)*gam0)):
> V_Rd_11:=F_eff_Rd;
                              V_Rd_11 := 279358.0442                   (16)
```

Failure mechanism 12 - Resistance of the welds

* The thickness of the welds is sufficient to have the same resistance as fin plate that is connected.

```
> beta_w:=0.8:
> evalf(((beta_w/(sqrt(2))) * (f_y_p/f_u_p) * (gam2/gam0) * t_p));
                                9.221249655                                  (17)
> res12:=piecewise(evalf(((beta_w/(sqrt(2))) * (f_y_p/f_u_p) * (gam2/gam0) * t_p))>a_w,
  "Insufficient",evalf(((beta_w/(sqrt(2))) * (f_y_p/f_u_p) * (gam2/gam0) * t_p))<a_w,"Sufficient");
                             res12 := "Sufficient"                           (18)
```

Capacity of the welded connection:

```
> V_Rd:=min(V_Rd_1,V_Rd_2,V_Rd_3,V_Rd_4,V_Rd_5,V_Rd_6,V_Rd_8,V_Rd_9,V_Rd_10,V_Rd_11);
                             V_Rd := 173378.3708                             (19)
```

Unity check

```
> finalres:=piecewise(V_Rd>V_Ed,"Sufficient",V_Rd<V_Ed,"Insufficient");
                           finalres := "Sufficient"                          (20)
```

H

Comparison bicycle paths São Paulo-Amsterdam

Bicycle lanes and bridges for motorised traffic

Figures H.1a and H.1b visualises the comparison of bicycle bridges in São Paulo and Amsterdam. There is almost no room for cyclists to ride on the bicycle path on Ponte Jaguare and not possible to take over. On the other hand, there is enough space for cyclists to take over at the Berlagebrug.

(a) Ponte Jaguare

(b) Berlagebrug

Dutch bicycle bridges

There are almost no bicycle and pedestrian bridges in São Paulo. For future bicycle lane expansion projects the Tietê and Pinheiros rivers need to be crossed and therefore in chapter 5 a parametric design of a bicycle and pedestrian bridge is performed. Some examples of bicycle and pedestrian bridges in The Netherlands are presented in figure H.2a and H.2b.

Traffic lights for cyclists

At many intersections in São Paulo there are no traffic lights for cyclists to indicated whether it is possible to cross the street. They need to anticipate on the traffic lights for regular traffic. An example is the intersection between Avenida Queiroz Filho and Avenida Prof. Fonseca Rodrigues (see figure H.3a). This could lead to dangerous situations. A counterexample is given in figure H.3b, where traffic lights are available for the cycling traffic.

(a) Dutch bicycle bridge - Nesciobrug

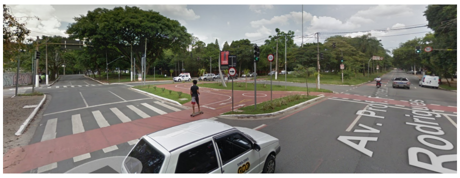
(b) Dutch bicycle bridge - Daphne Schippersbrug

(a) Intersection Queiroz Fonsesca

(b) Intersection Vrijheidslaan - Amsteldijk

Position of the bicycle lanes

Many bicycle lanes along major roads are situated in the middle of the two carriageways. Therefore these streets need to be crossed by cyclists. An example is the bicycle lane located at Avenida Prof. Fonseca Rodrigues and praça Beethoven. In The Netherlands the bicycle lanes are located at the sides of the roads, causing less crossing traffic (see figure H.4b).



(a) Intersection Fonsesca - Praça Beethoven, bicycle paths in middle of intersection

(b) Intersection Vrijheidslaan - Amsteldijk, bicycle paths next to the roads

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