Prefab vs. In-Situ Concrete Viaducts

Master Thesis Research Study

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PREFACE

This document presents the results of a Research Study for my Master Thesis: Prefab vs. In-Situ concrete viaducts. The Master Thesis project is performed to complete the master's degree in Civil Engineering at Delft University of Technology. The project is carried out at BAM Infraconsult in cooperation with the Faculty of Civil Engineering and Geosciences, department Structural and Building Engineering.

The Master Thesis investigates the design process of viaducts. Which criteria are important in the selection of an alternative in Prefab or In-Situ concrete. Different aspects are elaborated and eventually an assessment is made to obtain the most economically design.

I would like to thank the employees of BAM Infraconsult and employees of BAM Civiel for the provided help during the Master Thesis. Furthermore, I would like to thank the assessment committee for their support, advice and personal guidance during the Master Thesis.

Gouda, December 2014

Michel Bakker

SUMMARY

Introduction

The Netherlands is a small country, with a large network of roads, rail tracks and waterways. One type of structure that is often used for the crossings in the network of infrastructure is a concrete viaduct. A distinction can be made between Prefab and In-Situ concrete viaducts. In practice in The Netherlands it seems that more often a solution of Prefab concrete is chosen. In response of this development a question arose from the section of Concrete Structure from Delft University of Technology. It was wondered if a solution of In-Situ concrete still has an opportunity (economical interesting solution) in the construction of concrete viaducts. Hence, a subject for the Master Thesis is established: Prefab vs. In-Situ concrete viaducts.

Figure I Left: In-Situ concrete deck with false and formwork, right: installation of Prefab box beams

Literature Study

To investigate the question from Delft University of Technology first a Literature Study is made. Due to investigation into Selection Directories for tenders and reference projects of Royal BAM Group, it can be seen which aspects in the design process are of importance to win a tender. Aspects like functional requirements, boundary conditions, structural design, cost estimation, time schedule, execution method, impact on traffic, impact on environment, durability and sustainability can be part of a design process. All these aspects can have an influence in the selection of an alternative.

The result of the Literature Study is a problem definition for the research study of the Master Thesis. Some governing aspects from the Literature Study are highlighted to answer this problem definition. The problem definition for the main part of the Master Thesis is formulated as follows:

"Which alternative in Prefab or In-Situ concrete viaducts is considered the most economically attractive when combining different governing aspects?"

In relation to this question, the following criteria will be used to evaluate the alternative:

- Performance: structural design, building time-schedule, impact on traffic/environment;
- Quality: sustainability, risk management;
- Price: cost estimation.

Research Study

To answer the problem definition a fictitious case is developed with starting points and boundary conditions which can occur in The Netherlands (during the whole research the scope is restricted to The Netherlands). Six different alternatives in In-Situ and Prefab concrete are described to elaborate aspects which are related to the criteria of the problem definition. The following alternatives are elaborated:

- In-Situ I – conventional execution method with false and formwork;
- In-Situ II – a deck is built on a higher level and lowered down;
- In-Situ III – a deck is built next to the highway and driven into location;
- In-Situ IV – a deck is built in longitudinal direction and launched into location;
- Prefab I – inverted T-beams with a structural topping;
- Prefab II – box beams.

The aspects that are elaborated for each of the alternatives are the following: Boundary conditions and requirements, Preliminary design, Execution method (alternatives above), Time schedule, Impact on traffic, Cost estimation, Sustainability and Risk management.

After the elaboration of these aspects, one can obtain the better solution of an alternative for these aspects. It seems that the different aspects have each their own better alternative, displayed in table I.

Table I Better alternative per aspect

Aspect	“better alternative”
Structure depth deck	In-Situ I
Time schedule	Prefab beams (alternative I as well as alternative II)
Impact on traffic	Prefab beams (alternative I as well as alternative II)
Direct costs	In-Situ I
CO_2 emission	Prefab II
Risk Analysis	Prefab I

However, the problem definition of the Master Thesis is to search for an alternative which is considered the most economically attractive. Therefore the aspects that are elaborated during the Master Thesis have to be combined to compare the different alternatives. An assessment is done for the alternatives, the assessment is based on the method of a fictitious discount. If an alternative is beneficial for a certain aspect, a high fictitious discount is obtained. The alternative which has the lowest fictitious description price (direct costs – fictitious discount + costs Risks), is considered the most economically attractive alternative.

Conclusion

During the Master Thesis various aspects are elaborated for different alternatives in Prefab and In-Situ concrete. With this elaboration of aspects an answer can be given on the problem definition. In the Literature Study some governing aspects are established. According to these governing aspects, an alternative in Prefab beam elements is considered the most economically attractive.

However, besides this conclusion, an In-Situ alternative still has an opportunity in certain specific cases. The Research Study includes assessments where different combinations of the aspects are presented. Also recommendations for further research are given.

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1. INTRODUCTION

1.1. Introduction

The Netherlands is a small country, with a large network of roads, rail tracks and waterways. The infrastructure of The Netherlands contains bridges, tunnels, aqueducts and viaducts to take care of the crossings in the network of roads, rail tracks and waterways. During the realization of new infrastructure, different new structures are required to make sure the total network of infrastructure is accessible for a long period of time.

In a design process of infrastructure many different choices have to be made. Several disciplines in Civil Engineering work together to design and construct successful infrastructure. The main subject of this Master Thesis in Civil Engineering is concrete viaducts. Different aspects of the design process of a viaduct will be emphasized during the research of the Master Thesis.

Figure 1-1 Prins Clausplein, Enneus Heermabrug Amsterdam, Waterwolftunnel N201

1.2. Problem description

Structures in The Netherlands are constructed in different materials. Steel and concrete are materials that often are used. In The Netherlands, the realization of a viaduct is often a selection between an alternative in Prefab and In-Situ concrete. But how is this decision made? Which alternative is better and which criteria have an influence on the final design? In practice it seems that more often a solution of Prefab concrete is chosen. In response to this development in practice a question arose from the section Concrete Structures from Delft University of Technology. It was wondered if a solution of In-Situ concrete still has an opportunity (economical interesting solution) in the construction of concrete viaducts.

A Master Thesis subject was born: Prefab vs. In-Situ concrete viaducts. In the design of a concrete viaduct, several aspects of design and execution have to be combined. These different aspects lead to an optimal design for a viaduct, on a specific location. For the realization of a concrete viaduct, a distinction can be made between Prefab concrete elements, or In-Situ concrete. Both methods have their advantages and disadvantages.

Factors which can be relevant to the design process and selection of an alternative in prefab and In-Situ concrete are the following:

- Client (type of contract, MEAT criteria (EMVI);
- Functional requirements;
- Boundary conditions;
- Execution methods;
- Structural design;
- Cost estimation;
- Construction time;
- Risk management;
- Environmental impact;
- Impact on traffic;
- Life cycle management;
- Material;
- Durability/sustainability/CO_2 emission;
- Maintenance.

The research of the Master Thesis will discuss the differences between Prefab and In-Situ concrete viaducts. Further several aspects described above will be investigated to answer the question from Delft University of Technology. A Literature Study is performed to investigate which aspects are of most importance in the design process of a project. In the conclusion of the Literature study a research question is developed. The following paragraph describes the problem definition for the Master Thesis.

1.3. Problem definition

The problem definition for the research of the Master Thesis is defined as follows:

"Which alternative in Prefab or In-Situ concrete viaducts is considered the most economically attractive when combining different governing aspects?"

The governing aspects in the design process are established by means of the investigation in the Selection Directories (Literature Study). In relation to the problem definition, the following criteria will be used to evaluate the alternatives:

- Performance: structural design, building time-schedule, impact on traffic/environment;
- Quality: sustainability, risk management;
- Price: cost estimation.

1.4. Work approach

The Master Thesis is split up into two parts:

I. Literature Study;
II. Research Study;

The Literature Study has discussed a lay out and possibilities of a viaduct, also several criteria which can be used to select an alternative are described. Several reference projects of Royal BAM Group are used as a source to obtain the decisions made during a design process of a viaduct. The desires of a client are clarified due to an investigation of the selection directories of several projects.

The Literature Study has discussed several aspects that can be of importance in the selection of an alternative in In-Situ or Prefab concrete. The Research Study will contain an elaboration of the following aspects:

- Boundary conditions and requirements;
- Preliminary design;
- Execution method;
- Time schedule;
- Impact on traffic;
- Cost estimation;
- Sustainability;
- Risk management.

The last part of the Master Thesis will contain an assessment of the aspects listed above. A conclusion will be given to answer the problem definition. Furthermore, recommendations for further research are presented. The research study will focus on viaducts in The Netherlands which crosses a 2x3 traffic lanes national highway.

1.5. Objective

The objective of the Master Thesis is to investigate which criteria play a role in the selection procedure of alternatives in Prefab and In-Situ concrete viaducts. What is the motivation behind the design process to choose a certain alternative? In this process, the solution in Prefab and In-Situ will be elaborated equivalently to make sure, that in the end of the Master Thesis an integral comparison can be made. The aim is to clarify which aspects will be governing in each situation.

Each part as explained in paragraph 1.4 has an objective itself. The objective of the conclusion of the Master Thesis is the objective described above.

I. The objective of the literature study is to discuss several criteria which are considered in the design of a viaduct. An investigation into the requirements and desires of a client will lead to an overview of the important aspects for design. The important aspects for design will be elaborated in the Preliminary Study and Research Study.

II. The Preliminary Study will embrace a Preliminary Design of an In-Situ Prestressed and a Prefab concrete viaduct. This design can be used as a case for the investigation of the other criteria for evaluation. The objective is also to elaborate certain aspects which can be used in the integral comparison in the conclusion of the Master Thesis. The Literature Study made clear which criteria are important for the client, in The Netherlands at this moment in time. The information obtained from criteria which are worked out in the Preliminary Study is used to analyse the alternatives.

1.6. Reading guide

Chapter 2 contains a Preliminary design to evaluate the problem definition. The execution methods for different alternatives in Prefab or In-Situ are elaborated in chapter 3. The time-schedule per alternative is discussed in chapter 4 and chapter 5 will discuss the impact on traffic according to the execution methods and time-schedules. Chapter 6 is dedicated to the cost estimation of different alternatives. The sustainability aspect of the different alternatives is discussed in chapter 7. Risks per alternative are discussed in chapter 8. In chapter 9 an assessment of the alternatives on governing aspects will be elaborated. An analysis and interpretation of the results of the Research Study will be given in chapter 10. Chapter 11 will conclude the Master Thesis and recommendations will be given.

2. PRELIMINARY DESIGN

2.1. Introduction

As been discussed in the introduction, the subject of this Master Thesis is prefab vs In-Situ concrete viaducts. An assessment will be elaborated to answer the problem definition. The governing aspects in the design process are established by means of the investigation in the Selection Directories (Literature Study). The following aspects are worked out during the Research Study:

- Boundary conditions and requirements;
- Preliminary design;
- Execution method;
- Time schedule;
- Impact on traffic;
- Cost estimation;
- Sustainability;
- Risk management.

To elaborate the criteria above and to make the assessment, a fictitious case is used. This case is developed by starting points from Delft University of Technology and other boundary conditions derived from reference projects found in the Literature Study. During the Literature Study several interesting alternatives in Prefab and In-Situ concrete are noticed. During the research of the Master Thesis four different In-Situ alternatives and two Prefab alternatives will be developed and elaborated. With these six alternatives the assessment is done to answer the problem definition. The following alternatives will be elaborated:

- In-Situ I – conventional execution method with false and formwork (two phases, traffic redirected on one carriageway);
- In-Situ II – a deck is built on a higher level and lowered down, traffic continues during construction at higher level;
- In-Situ III – a deck is built next to the highway and is driven into location;
- In-Situ IV – a deck is built in longitudinal direction and is launched into location;
- Prefab I – inverted T-beams with a structural topping;
- Prefab II – box beams.

In this chapter the preliminary design of the fictitious case is determined. The first step will be drafting requirements and boundary conditions. The Master Thesis is not worked out for a specific project. The research is in general meant for all viaducts, with the properties that are described. Therefore the requirements and boundary conditions are drafted with help of norms and directives that are described by Rijkswaterstaat (Dutch Ministry of Infrastructure and the Environment). For a real project that will be executed, some requirements, assumptions or boundary conditions can change and therefore the preliminary design can differ.

The second step in this chapter is the preliminary design with global dimensions. The preliminary design will be performed by some hand calculations and will be based on experience and rules of thumb. The global dimensions of the following parts of the viaduct will be determined.

- In-Situ prestressed deck (execution method: constructing in two phases);
- Prefab concrete deck (Inverted T-Beam or Box girder);
- Bank seat;
- Intermediate pier.

2.2. Starting points and boundary conditions

For design of the viaduct a number of requirements and boundary conditions must be taken into account. Viaducts commissioned by client Rijkswaterstaat, must be designed by the ROK (Richtlijnen Ontwerpen Kunstwerken) [11]. Further requirements and norms included in the preliminary design are presented in Appendix A1.

The following boundary conditions are taken into account during the design of the viaduct:

- The location of the viaduct will be in a crowded area of infrastructure;
- The viaduct will realized next to an existing viaduct;
- The viaduct crosses a national highway of 2x3 traffic lanes + emergency lane (elaboration in Appendix A3);
- Founded by two bank seat and one intermediate support;
- A central verge is present;
- Foundation on piles;
- Slope of embankment is 2:3;
- Free space under viaduct has a minimum of 4.6 m;
- Max slope of approach ramp of the viaduct is 4%;
- Crossing angle of the viaduct is between $90 \leq \alpha \leq 100$;
- Architectural ambition is not considered during design of the viaduct.

Length and width viaduct

In Appendix A2, the geometrical assumptions of the viaduct are elaborated. For an easy calculation, the span of the viaduct will be set on 30m and the total length of the viaduct will be set on 61,5m. The width of the viaduct is built up out of two traffic lanes, an emergency lane and safety guards. This division can differ. It is also possible to divide the viaduct into two traffic lanes and two bicycle paths. The hard strip and emergency lane are not included in that configuration. Figure 2-1 shows a sketch of the length and cross-section of the viaduct.

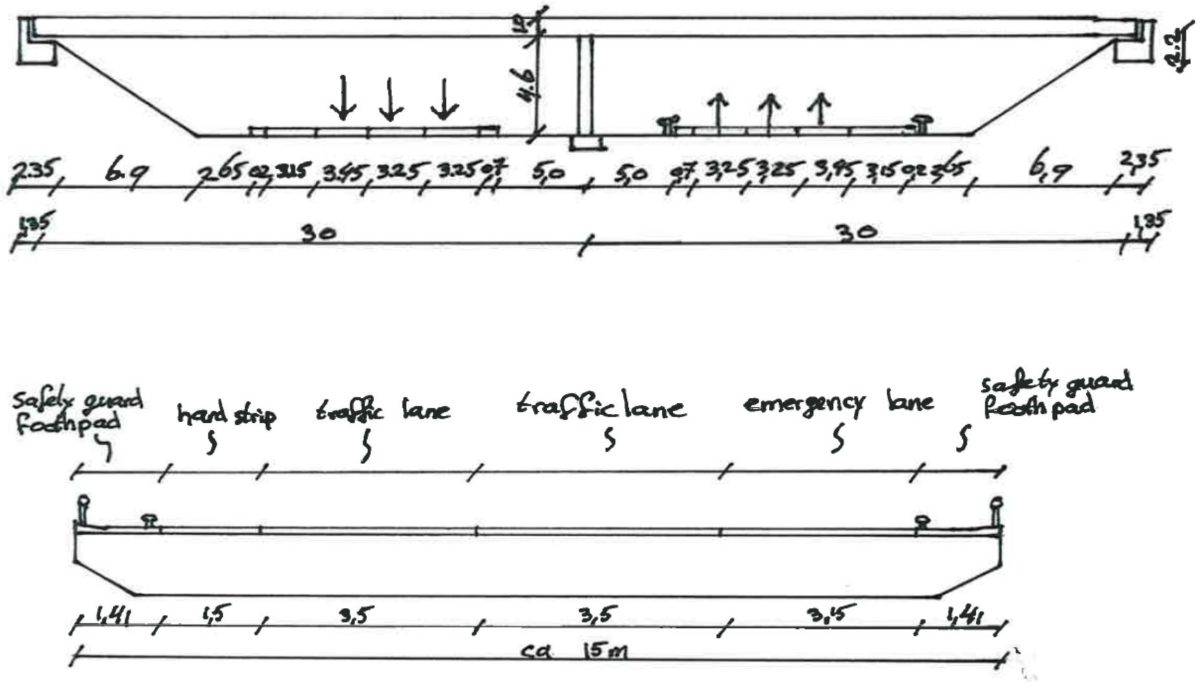


Figure 2-1 Longitudinal cross section and cross section Viaduct

Load cases

For material properties of the concrete and reinforcement steel is referred to Appendix A3. For the preliminary design the following load cases (Appendix A4) are considered:

- Self-weight;
- Variable traffic loading;
- Thermal loading.

Because of the preliminary design, not all load cases are considered. The following load cases are not included in the design and have to be included if a final design is elaborated of the viaduct:

- Shrinkage and relaxation;
- Wind loading;
- Calamity (collision of truck against deck or intermediate pier).

2.3. In-Situ prestressed viaduct

The deck for the alternatives in In-Situ concrete is elaborated in prestressed concrete. The structure depth depends on execution stages as well as the final stage. The four different alternatives in In-Situ concrete can therefore differ in structure depth. In the Master Thesis the first alternative in In-Situ will be elaborated and the other three alternatives are based on the calculation of the first alternative and rule of thumbs.

2.3.1. In-Situ I

The deck has a cross-section of a massive plate (figure 2-2). The following assumptions hold for calculation of the deck:

- The deck can be built on falsework and formwork and can be constructed as one deck;
- Statically undetermined structure;
- Continuous beam on three supports;
- Two theoretical spans of 30 m;
- Width of the deck is 15 m;
- Slenderness ratio of l/h=30;
- Calculation is made for a strip of 1m width.

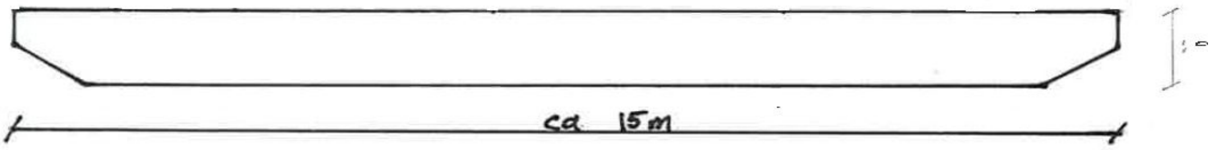


Figure 2-2 Cross-section massive plate

The design of the In-Situ prestressed deck is elaborated in Appendix B1. The following steps are taken in the preliminary design:

- Determination of tendon profile;
- Load cases and moment distribution;
- Determination of prestressing force;
- Determination of amount of reinforcement;
- Verifying bending moment resistance;
- Verifying shear force.

After these steps the cross section is checked and prestress and reinforcement steel is calculated for the In-Situ concrete deck per strip of 1 m in width. The cross section is provided with prestress and reinforcement steel:

- Structure depth = 1 m;
- 2 tendons with each 22 strands (6600 mm²);
- ϕ20 – 100 in the first layer in transversal direction;
- ϕ20 – 150 in the second layer in longitudinal direction;
- Reinforcement is at the top and bottom of the cross-section.

2.3.2. Structure depth other In-Situ alternatives

The preliminary design of the other In-Situ alternatives is based on the elaboration of the first In-Situ alternative. The structure depth of the second and third alternative differs, because it is not possible in the execution method to design the structure as a statically undetermined structure. Therefore the structures are considered as a statically determined beam on two supports. In table 2-1, the structure depths are presented. The amount of prestressing steel and reinforcement is based on the amount of steel in the first alternative. The quantities are further elaborated in chapter 6 for the cost estimation.

Table 2-1 Structure depth

	In-Situ II	In-Situ III	In-Situ IV
Structure depth [m]	1.3	1.3	1.0

2.4. Prefab viaduct

During the Literature Study, three different types of Prefab beam elements are discussed. The solid deck slabs are rejected in this Master Thesis because the method is not applicable for spans of 30m. Spanbeton [i1] has developed certain design graphs, such that for the first global dimensioning of a viaduct a prefab beam can be chosen. These graphs are very conservative. Spanbeton has developed the design graphs following the Load Model in NEN-EN 1992-2. In Appendix B2 and B3 the design graphs are used to select a type of the prefab beams.

In tables 2-2 and 2-3 the dimensions are presented of the chosen profiles.

Table 2-2 Cross sectional properties ZIPXL1100

Properties		
h_t	1,350	mm
I	221,140*10^{6}	mm^{4}
z_b	675	mm
W	325*10^{6}	mm^{3}
q_G	23.4	kN/m^{2}

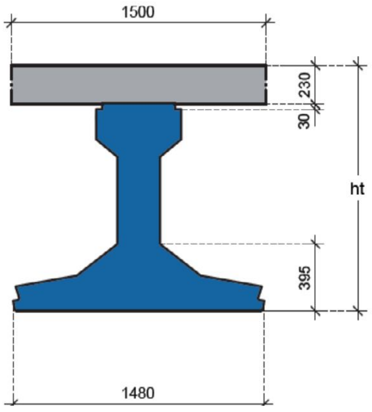
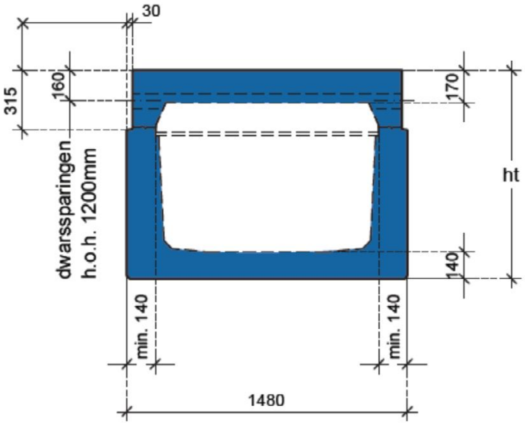


Table 2-3 Cross sectional properties SKK1000

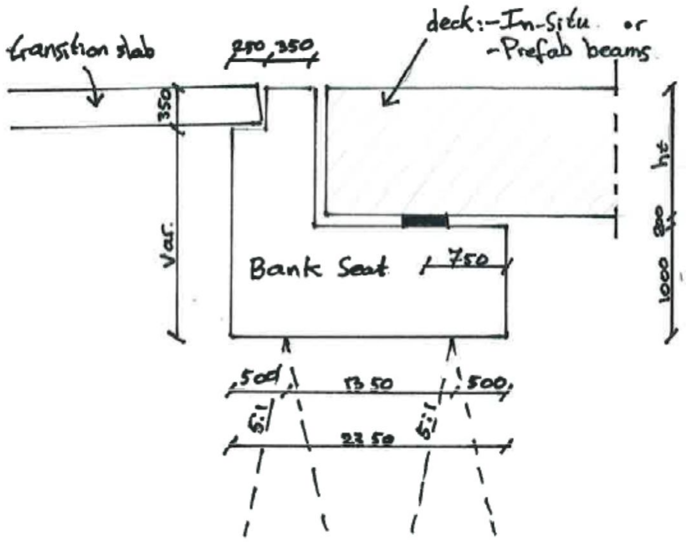
Properties		
h_t	1,000	mm
I	315*10^{9}	mm^{4}
z_b	830	mm
W	385*10^{6}	mm^{3}
$q_{G,massive}$	36.5	kN/m^{2}
$q_{G,hollow}$	17.6	kN/m^{2}



2.5. Bank seat

The basic dimensions for the bank seat are equally designed for the In-Situ and Prefab viaducts (elaboration in Appendix B4). The bank seat consists of the following parts:

- Pad;
- Front wall (depending on height of the deck);
- Transition slab;
- Pile foundation (depending on the load model, number of piles presented in Appendix B).



	h_t [m]
In-situ	1.0
ZIPXL1100	1.35
SKK1000	1.0

Figure 2-3 Cross section bank seat

2.6. Intermediate pier

An architect can influence the design of the intermediate pier. Architectural ambition is not considered during design of the viaduct. In this concept, the choice has been made for round columns of 1 m in diameter. The intermediate pier is equally designed for the In-Situ as for the Prefab beams viaducts (elaboration in Appendix B5). The intermediate pier consists out of:

- Pad;
- Column;
- Capping beam (in case of prefab);
- Pile foundation (depending on the load model, number of piles based on piles bank seat).

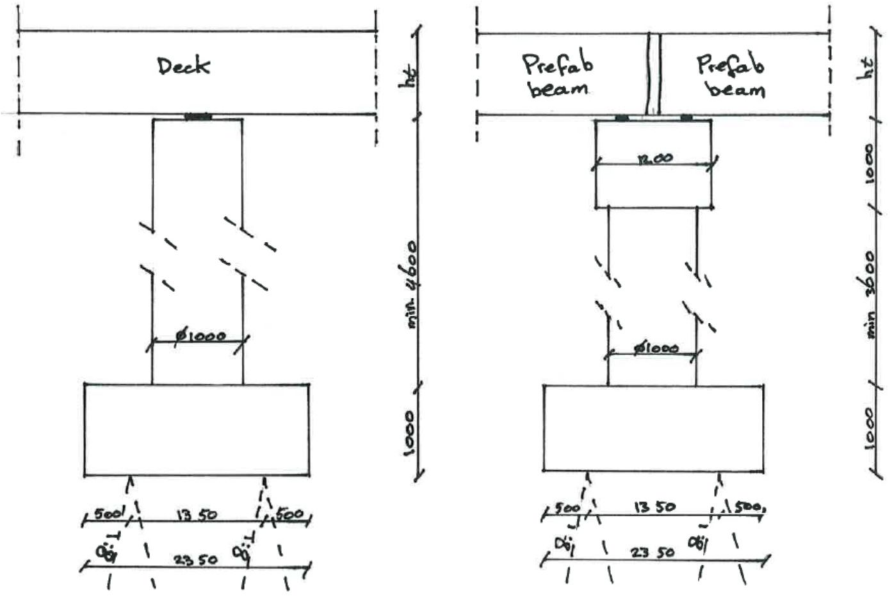


Figure 2-4 Cross section intermediate pier. Left: In-Situ, right: Prefab

3. EXECUTION METHOD

3.1. Introduction

The selection of an alternative in In-Situ or Prefab concrete can depend on the boundary conditions at the location of the project. For a comparison between Prefab and In-Situ concrete viaducts, there will be several execution methods discussed. After the completion of the method statement, a time schedule can be made. In developing the execution method, it will become visual where impact on traffic exists. Lost vehicle hours can be calculated according to the time schedule. The execution method for the six different alternatives will be discussed in this chapter.

3.2. In-Situ concrete viaduct

In-Situ concrete viaducts can be constructed in several ways. The basic method and the most convenient one, is if a viaduct can be built in a free field. Falsework and formwork can be constructed in a simple manner. The disadvantage of this method is that it is not possible for traffic to pass under the viaduct. In the master thesis a boundary condition is that the viaduct is to be realized in a crowded area of infrastructure, therefore it is not possible to obstruct the road for a long time. Other solutions must be considered. The following execution methods are considered:

I. Constructing the viaduct in two phases, with temporary closing of a carriageway and redirect traffic to one carriageway;
II. Constructing the viaduct on a higher platform and lower the viaduct;
III. Constructing the viaduct next to the road and drive the viaduct into place;
IV. Constructing the viaduct in the longitudinal direction of the viaduct.

3.2.1. In-Situ I: Constructing deck in two phases

This alternative of execution method consists of constructing the deck in two phases. In each phase one carriageway will be closed, such that a temporary construction can be installed for constructing the deck. Several sub phases are necessary before the final construction of the viaduct is complete.

Start situation

In this phase the construction site will be prepared for execution. The site will be prepared with a site-office and storage for material and equipment. A temporary road is necessary for construction traffic and transport of materials. The viaduct will be realized on a certain height (depending on the free space required). The approach ramp will be placed in most cases on soil body. The soil body will be executed some time before the start of the realization of the substructure, such that settlements can occur without any consequences for the structure. In this Master Thesis it is assumed that the soil body is already situated.

Figure 3-1 Start situation: 2x3 traffic lanes with emergency lane

Groundwork

Groundwork is here defined as the excavation of ground with the purpose of constructing the bank seats and intermediate support. In this phase a temporary exit will be created in the central verge, with an extra safety barrier if needed (to protect temporary constructions). The exit is needed for transport of material and equipment needed for construction of the intermediate pier.

Substructure

For the substructure the following basic activities are required:

- Drive foundation piles for bank seat and intermediate pier;
- Construction of foundation slabs;
- Construction of front walls for the bank seat;
- Construction of columns for the intermediate pier;
- Installing of bearings.

Figure 3-2 Bank seat and intermediate pier ready

Superstructure

The construction of the deck is split up into two sub phases:

Phase 1

- Redirect traffic on one carriage way. The driving speed is decreased and the traffic lanes are smaller than normal. The temporary road is a 4x0 system instead of 2x3 (figure 3-3);
- Construct the false work and subsequently the formwork of one span of the viaduct (figure 3-4);
- Install reinforcement and the ducts for prestress cables;
- Cast the concrete;
- After the hardening of concrete, prestressing can be applied;
- Removing of form- and falsework.

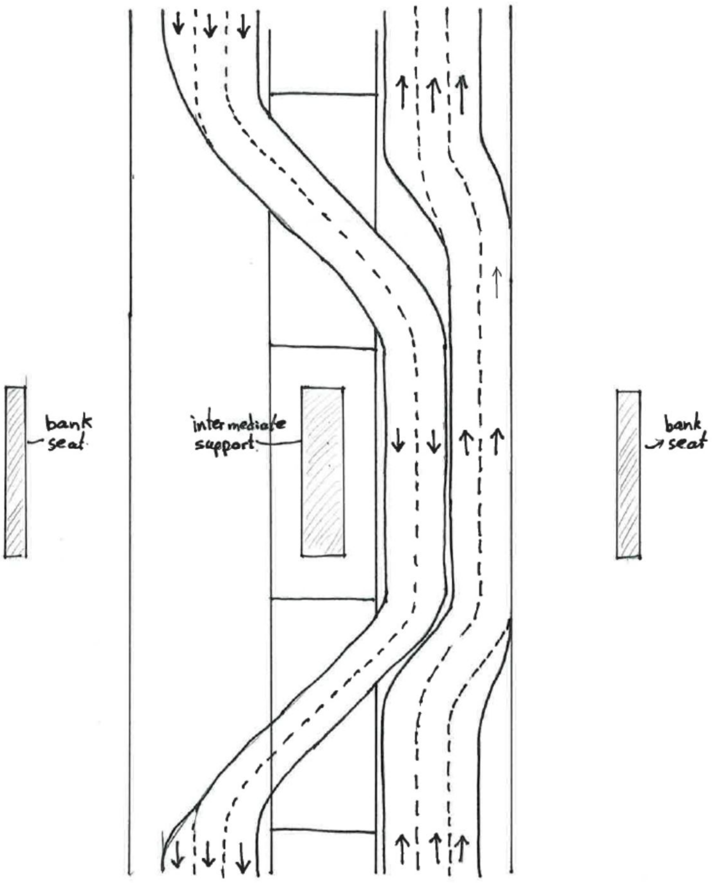


Figure 3-3 Redirection of traffic on one carriage way

Figure 3-4 Form- and falsework on the carriageway

Phase 2

- Redirect traffic under the finished side of the viaduct, same configuration (mirrored) as at phase 1;
- Construct the false work and subsequently the formwork of one span of the viaduct (figure 3-5);
- Install reinforcement and the ducts for prestress cables;
- Cast the concrete;
- After the hardening of concrete, prestressing can be applied;
- Removing of form- and falsework;
- Redirect traffic in the normal new situation.

Figure 3-5 One span finished, form- and falsework for phase 2

Finishing works

The following activities can take place after the deck is finished:

- Applying expansion joints;
- Casting asphalt;
- Installing transition slabs;
- Finishing works of embankments;
- Installing safety guards and parapets.

Figure 3-6 Finished viaduct

Points of attention

The preliminary design from the latter chapter is based on this specific execution method. A point of attention during design for the execution method is the coupling of prestressing cables at intermediate support. To prestress the cables, a platform is needed at the intermediate support.

Further points of attention are:

- The subsoil must have enough load carrying capacity for the transfer of loads through the falsework;
- Design of temporary situation of the redirection of the highway. Additional costs for temporary roads in the central verge.

3.2.2. In-Situ II: Constructing deck on a higher level

The second execution method considered for In-situ viaducts is building the viaduct on a higher platform and lowering the viaduct. The start situation and the groundwork for the viaduct are the same as described in In-situ I. This also applies for the substructure of the viaduct.

Superstructure

Again, the superstructure of this alternative is executed in two phases.

Phase 1

- Temporary supporting system is built up and the formwork for the deck is placed. The free space required (4.6 m) need to be taken into account during construction. Special safety measures are needed against dropping material from the viaduct on the road;
- The road is temporary closed during the night to build up the supporting system;
- The possibility is to build one span at a time, or both spans at the same time.

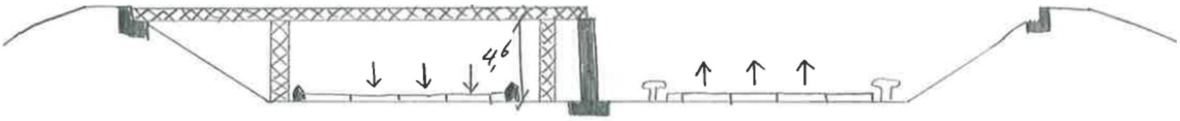


Figure 3-7 Constructing deck on higher level

Phase 2

- Install reinforcement and the ducts for prestress cables;
- Cast the concrete;
- After hardening of the concrete, prestressing can be applied;
- Remove formwork deck;
- Striking of the deck. During striking of the deck, the road is temporary closed;
- Remove the supporting system.

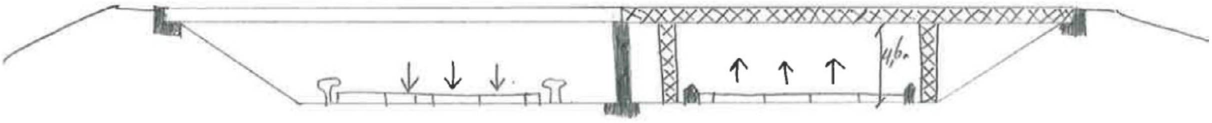


Figure 3-8 Constructing deck on higher level

Finishing works

The following activities can take place after the deck is finished:

- Applying expansion joints;
- Casting asphalt;
- Installing transition slabs;
- Finishing works of embankments;
- Installing safety guards and parapets.

Points of attention

- Traffic measures are needed for construction of the intermediate support;
- The viaduct must be designed for lowering the deck. The height of the deck can differ in comparison with the In-Situ deck at execution method 1;
- During constructing of the temporary supporting system, the national highway shall be temporary closed for installation of longitudinal beams. The traffic lanes are temporary smaller and a speed reduction is necessary for a temporary safety guard against collision of the temporary supporting system;
- Extra safety measures are needed for working on height.

3.2.3. In-Situ III: Construct deck next to road and drive into place

The third execution method considered for In-situ viaducts is building the deck next to the final location of the viaduct. When the deck is finished, the deck will be driven into the final location with help of a SPMT (Self Propelled Modular Transporter). The start situation and the groundwork for the viaduct are the same as described with the first In-Situ method. This also applies for the substructure and finishing works of the viaduct.

Superstructure

The superstructure is constructed in a competitive manner as with In-Situ I. The difference is that the falsework and formwork are constructed next to the final location of the viaduct.

The following steps are needed:

- Constructing the supporting frame for driving;
- Construct formwork deck;
- Installing of reinforcement and ducts for prestress cables;
- Casting of concrete;
- After hardening of concrete, prestressing can be applied;
- The deck is lifted by SPMT;
- SPMT drives to the final location of the viaduct;
- The deck will be lifted on the bank seat and intermediate pier;
- These steps are also applicable for deck 2.

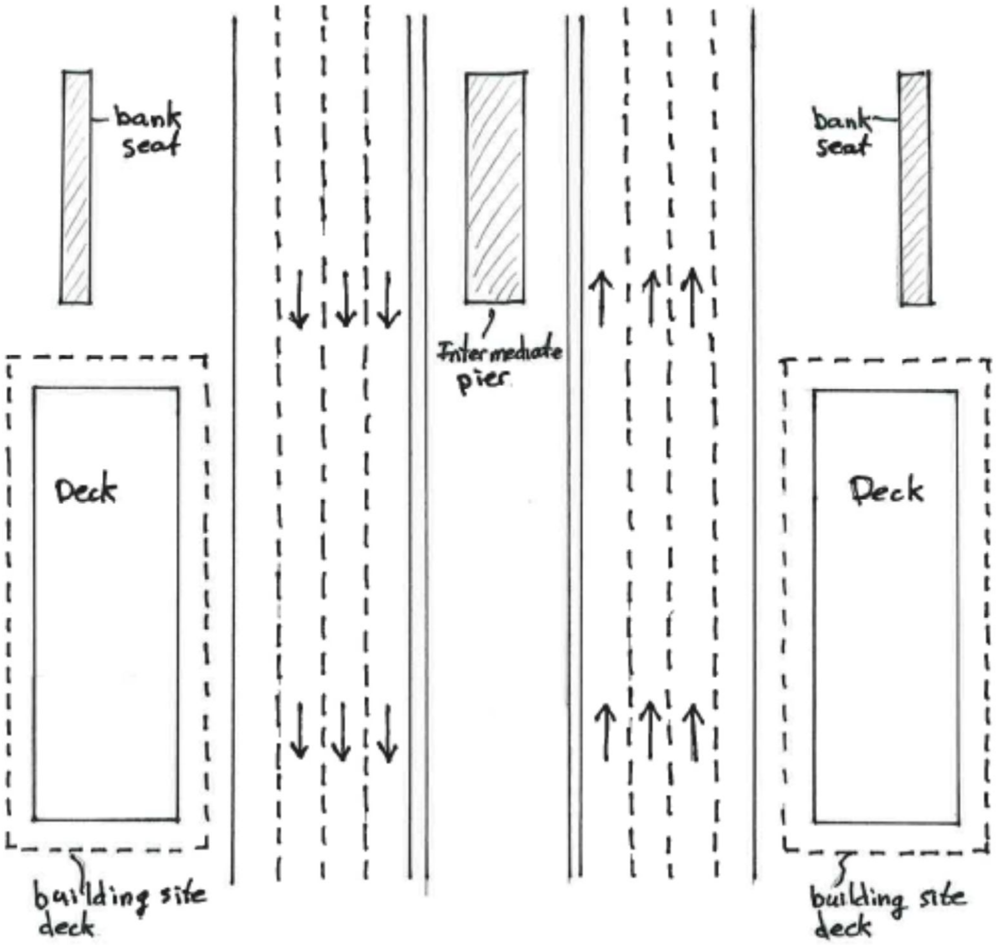


Figure 3-9 Building deck next to national highway

Figure 3-10 Driving a viaduct into place. Courtesy, nufoto.nl

Points of attention

- The viaduct must be designed for driving the deck, the height of the deck differs in comparison with the In-Situ deck at execution method 1. In case of driving the deck, the structure changes into a statically indeterminate structure. The two spans of the viaduct are built separately and will be driven into place. It is not possible afterwards to couple the prestress cables. The structure will be more like a Prefab element viaduct. With the slenderness ratio of a massive plate on two supports, the height of the deck is estimated:
    - l/h=23, the height is thus 1.3 m.
- Traffic measures are needed for construction of the intermediate support, the transport of material and equipment is during the night. One traffic lane needs to be closed, and a speed reduction is necessary;
- During driving the deck into final location, the national highway needs to be closed down, this is done in one weekend. During this weekend different preparing activities take place. Removing the safety barriers of the highway, temporary steel sheets for driving. Measurements for driving and installing the deck.

3.2.4. In-Situ IV: Construct deck behind bank seat and launch into position

Another possibility is to construct the deck next to the final location and launch the deck into place. The start situation and the groundwork for the viaduct are the same as described with the first In-Situ method. This also applies for the substructure and finishing works of the viaduct.

Superstructure

The deck is constructed in longitudinal direction of the viaduct.

- A sliding frame is constructed above the road and behind the bank seat;
- The formwork needed is installed;
- Installing of reinforcement and ducts for prestress cables;
- Casting of concrete;
- After hardening of concrete, prestressing can be applied;
- Remove the formwork;
- The deck will be launched into position;
- Remove temporary sliding frame.

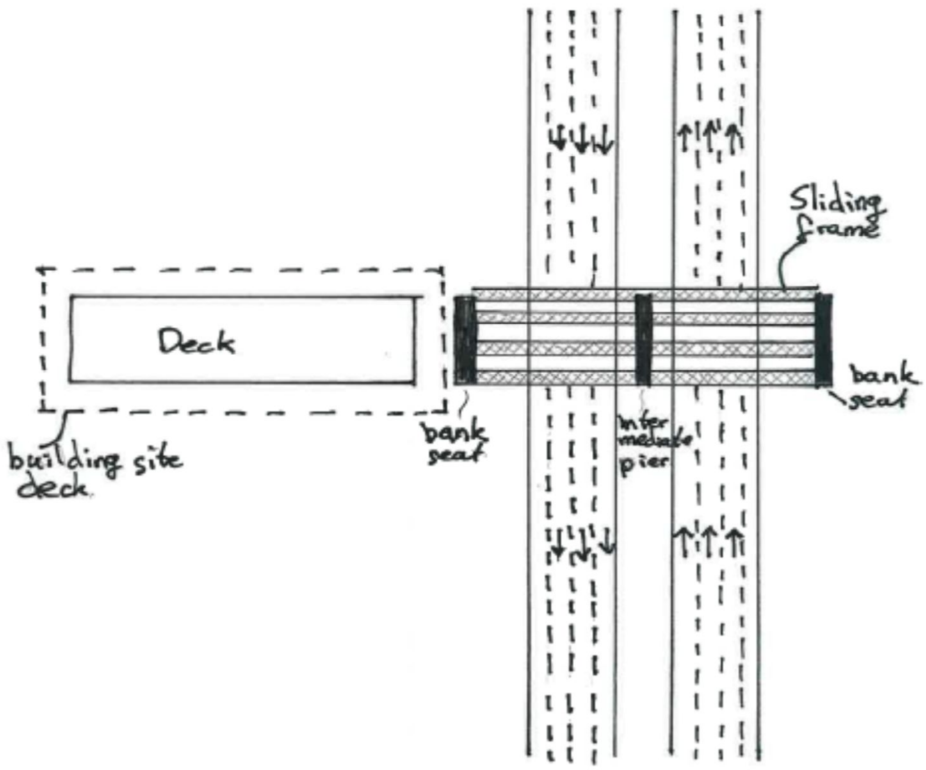


Figure 3-11 Constructing deck in longitudinal direction and sliding frame over bank seats and intermediate pier

Points of attention

- In case of launching the deck into place, a steel framework needs to be constructed over de road to be crossed. The viaduct can be launched over this framework into place. During design of the deck, the execution phases must be considered;
- Traffic measures are needed for construction of the intermediate support, the transport of material and equipment is during the night. One traffic lane needs to be closed, and a speed reduction is necessary;
- The sliding frame is installed during the night and needs therefore traffic stops;
- During sliding of the deck, continuation of traffic is possible. When the deck is in position, the framework is removed during the night and the deck installed on final location.

3.3. Prefab concrete viaduct (ZIPXL as well as SKK)

The main phases of execution method for a Prefab viaduct are already described in the Literature Study. The following alternatives of prefab beams are considered in the preliminary design:

I. Prefab inverted T-beam (ZIPXL);
II. Prefab box girders (SKK);

The execution method for these two alternatives is practically the same. The differences appear in the finishing works of the prefab beams.

Start situation

In this phase the construction site will be prepared for execution. The site will be prepared with a site-office and storage for material and equipment. A temporary road is necessary for construction traffic and transport of materials. The viaduct will be realized on a certain height (depending on the free space required). The approach ramp will be placed in most cases on a soil body. The soil body will be executed some time before the start of the realization of the substructure. Such that settlements can occur without any consequences for the structure. In this master thesis it is assumed that the soil body is already situated.

Groundwork

Groundwork is defined here as an excavation of ground for the purpose of constructing the bank seats and intermediate support.

Substructure

For the substructure the following basic activities are needed:

- Drive foundation piles for bank seat and intermediate pier;
- Constructing foundation slabs;
- Construction of front walls for the bank seat;
- Construction of columns for the intermediate pier;
- Construction of the capping beam.
- Installing of bearings.

Superstructure

In this phase the Prefab beams will be transported to the construction site and installed on the bearings. For the installation of the prefab beams the road must be closed down temporarily.

Figure 3-12 Installation of prefab beams, viaduct Lage Weide A2

After installation of the prefab beams, the following activities take place to finish the deck:

- Cast structural topping in can of inverted T-beam;
- Transversal prestressing in case of Box girders;
- Cast longitudinal joints in case of Box girders.

Finishing works

After the deck is finished, the following activities take place:

- Apply expansion joints;
- Cast asphalt;
- Install transition slabs;
- Finishing works of embankments;
- Installing safety guards and parapets.

4. TIME SCHEDULE

4.1. Introduction

The preliminary design and the execution methods are described in the last two chapters. These two items can be used to schedule the execution methods over time. The global dimensions are known, such that for each part of the viaduct the quantity can be calculated. The quantities of the viaduct are used as a basis for the time schedule. After completing the time schedules for the executions methods, the total construction time is known. The indirect costs can be calculated according to the total construction time. The time schedules can be used to obtain the days or weeks of impact on traffic due to construction activities.

Based on experience of BAM Civiel the time schedules are worked out. Several activities are displayed in the time schedule. However, the time schedule cannot be used for execution of a viaduct in practice. Some activities are not described extensive enough, such that the time schedule can be used for real execution.

Assumptions

The following assumptions hold for the alternatives:

- The soil body for the approach ramp is present and the settlements already occurred;
- For each variant the preparation activities like arranging the construction site and groundwork are identical;
- The construction of the bank seat is equal for each alternative, the height of the front wall can differ (depending on the construction height of the deck);
- The intermediate pier is partially the same for each alternative, difference is the capping beam for the alternatives of prefab concrete elements;
- The activities for the finishing works are the same for each variant;
- The asphalt layer is not taken into account in the time-schedule, it is assumed that this is done during the construction of the road over the viaduct.

4.2. Basic activities

For each alternative the execution method is already described in chapter 3. The following basic activities from the execution methods are scheduled:

- Preparation activities: arranging building site and groundwork;
- Installing the pile foundation;
- Concrete works of the bank seat, intermediate pier and deck.
  Activities of concrete works include: installing falsework, formwork, reinforcement, prestressing duct, casting the concrete, removal of form- and falsework;
- Finishing activities like: installing the transition slab, expansion joints, side elements, side edges, parapets and constructing the embankment;

Appendix C contains the time-schedules for the six execution methods. In table 4-1 a summary of the construction time per subpart and a total construction time is given. Some subparts partly overlap to shorten the total construction time. As can been seen in table 4-1 the prefab beams have the shortest time in execution. However, the prefab beams must be ordered in advance prior to the start of construction. The production capacity of the prefab beams is one beam each day. In the time schedule this is included.

The engineering and drafting activities for each alternative is not included in the time-schedule.

Table 4-1 Duration of activities in days

	In-Situ I	In-Situ II	In-Situ III	In-Situ IV	Prefab I	Prefab II
Substructure	62	62	62	62	62	62
Superstructure	90	96	92	100	12	5
Finishing works	50	50	50	50	50	50
Total	190	190	187	195	117	117

5. IMPACT ON TRAFFIC

5.1. Impact on traffic

Each execution method has a certain impact on the traffic. For each execution method the activities that need a (partly) closure of the national highway are described. In tables 5-1 up to 5-6, the activities are described where impact on traffic exists. For reference of the activity, the ID number of the activity according to the time schedules is added.

The impact on traffic exists out of two parts:

- A 'hard' part that is the lost vehicle hours (LVH);
- A 'soft' part that is the experience from the road user on impact on traffic.

The definition of a lost vehicle hour (LVH) is as follows: One lost vehicle hour means that one vehicle has one hour of delay on a specific trajectory, or more likely, 60 vehicles with one minute of delay on a specific trajectory. The lost vehicle hours can be calculated with certain programs. The experience is a more difficult to measure. It is about the thought of people on the delay that is caused by the traffic measures. This can differ per measure and per person. The experience on impact on traffic is therefore neglected in this Master Thesis.

The construction of the bank seats and the intermediate pier is equal for each alternative. Starting point is: it is not necessary to reduce the width of the carriage way to construct the bank seats and the intermediate pier. A safety barrier is placed, for protection due to collision of traffic. Further, each execution methods have some measures needed for the execution, which are described in the tables. A solution for minimizing the impact on traffic due to transportation of materials in equipment, is to transport during the night.

During the night, closure of 1 or 2 traffic lanes is allowable on the most highways and does not have a big consequence for impact on traffic. Also a request for a traffic stop is possible with the authorities. An authorized vehicle will stop the traffic on the highway, such that the contractor has 15 minutes to perform activities over the road. After this traffic stop, the possible traffic jam, must be resolved, before a new traffic stop can be initiated.

Table 5-1 Traffic measures In-Situ I

In-Situ I: Construct deck in two phases			
ID	Traffic impact	Activity	Measure
9	5 nights	- Creating temporary exit central verge; - Safety barrier.	During night, closure of most left traffic lane. Speed reduction to 70 km/h.
10	10 nights	- Temporary road in central verge; - Redirect traffic to one carriage way.	From 2x3 to 4x0 traffic lanes with a reduction of speed to 90 km/h.
48-56	45 days	Construction of deck phase 1	From 2x3 to 4x0 traffic lanes with a reduction of speed to 90 km/h.
11	10 nights	Redirect traffic from carriage way of the national highway	From 2x3 to 4x0 traffic lanes with a reduction of speed to 70 km/h.
58-66	45 days	Construction of deck phase 2	From 2x3 to 4x0 traffic lanes with a reduction of speed
12	5 nights	Redirect traffic into new final situation	From 4x0 to 2x3 new situation

Table 5-2 Traffic measures In-Situ II

In-Situ II: Construct deck on a higher level			
ID	Traffic impact	Activity	Measure
9	5 nights	- Creating temporary exit central verge; - Safety barrier.	During night, closure of most left traffic lane. Speed reduction to 70 km/h.
10	2 nights	Removing traffic measures of the road (ID 9)	Temporary 1 lane closed
11,51	2 nights	Installing falsework beams above road, deck phase 1	Police stops of 15 min. to install beams. 20 stops needed
52	5 days	Constructing formwork deck phase 1	During traffic stops
57	5 days	Removing formwork deck phase 1	During traffic stops
12, 63	2 nights	Installing falsework beams above road, deck phase 2	Police stops of 15 min. to install beams. 20 stops needed
64	5 days	Constructing formwork deck phase 2	During traffic stops
69	5 days	Removing formwork deck phase 2	During traffic stops

Table 5-3 Traffic measures In-Situ III

In-Situ III: Construct deck next to road and drive into place			
ID	Traffic impact	Activity	Measure
9	5 nights	- Creating temporary exit central verge; - Safety barrier.	During night, closure of most left traffic lane. Speed reduction to 70 km/h.
10	2 nights	Removing traffic measures of ID 9	During the night, closure of left traffic lane, speed reduction
11,57	1 day	Driving deck 1 into place	Closure of one carriage way, during a weekend
12,68	1 day	Driving deck 2 into place	Closure of one carriage way, during a weekend

Table 5-4 Traffic measures In-Situ IV

In-Situ IV: Construct deck behind bank seat and launch into position			
ID	Traffic impact	Activity	Measure
9	5 nights	- Creating temporary exit central verge; - Safety barrier.	During night, closure of most left traffic lane. Speed reduction to 70 km/h.
10	2 nights	Removing traffic measures of ID9	During the night, closure of left traffic lane, speed reduction.
11,49	10 nights	Constructing falsework above road	Traffic stops to install beams
58	2x a weekend	Launching of the deck	Weekend closure
12, 59	8 nights	Removing falsework above road	Traffic stops during the night

Table 5-5 Traffic measures Prefab I

Prefab I – ZIPXL1100			
ID	Traffic impact	Activity	Measure
9	5 nights	- Creating temporary exit central verge; - Safety barrier.	During night, closure of most left traffic lane. Speed reduction to 70 km/h.
10	2 nights	Removing traffic measures of ID9	During the night, closure of left traffic lane, speed reduction
11, 48	1 night	Installing beams deck 1	Traffic stops to install beams (10 beams)
11, 48	1 night	Installing beams deck 2	Traffic stops to install beams (10 beams)

Table 5-6 Traffic measures Prefab II

Prefab II – SKK1000			
ID	Traffic impact	Activity	Measure
9	5 nights	- Creating temporary exit central verge; - Safety barrier.	During night, closure of most left traffic lane. Speed reduction to 70 km/h.
10	2 nights	Removing traffic measures of ID9	During the night, closure of left traffic lane, speed reduction
11, 48	1 night	Installing beams deck 1	Traffic stops to install beams (10 beams)
11, 48	1 night	Installing beams deck 2	Traffic stops to install beams (10 beams)

5.2. Lost vehicle hours

The execution methods are causing an impact on traffic. In The Netherlands the impact on traffic is measured by ‘lost vehicle hours’. The definition is explained earlier. For the comparison of the different execution methods, it is interesting to calculate the lost vehicle hours per method. The total lost vehicle hours depends on the location of the road and the current capacity of that road. It is more likely that a dense area of roads has more lost vehicle hours that a road in the polder. To calculate the lost vehicle hours for each execution method described in chapter 3, a location is chosen which is nearly similar to the boundary conditions described in chapter 3.

The following assumptions are made for the calculation:

- Location: A9 Holendrecht – Badhoevedorp (figures 5-1 and 5-2);
- At HMP 25.9 at Amstelveen, intensity information at HMP 26.0;
- Lost vehicle hours are calculated with program ‘Wegwerkplanner van Transpute’;
- Capacity of the different alternatives are determined by ‘Capaciteitscalculator van Transpute’ (The program assumes ROA instead of NOA, capacity according to CROW publication 96a);
- The calculation of lost vehicle hours is based on a static calculation method and is used as indication. This is a limited method for the calculation. A more accurate calculation can made with a dynamic model (not done in Master Thesis);
- The capaciteitcalculator used data from two sources: Nationale Databank Weggegevens and Verkeerscentrum Nederland. The data from these two sources are combined to formulate a reliable result;
- The data used is from the period July - December 2013. The data can be used for comparison purposes, however this is not applicable for the future years.

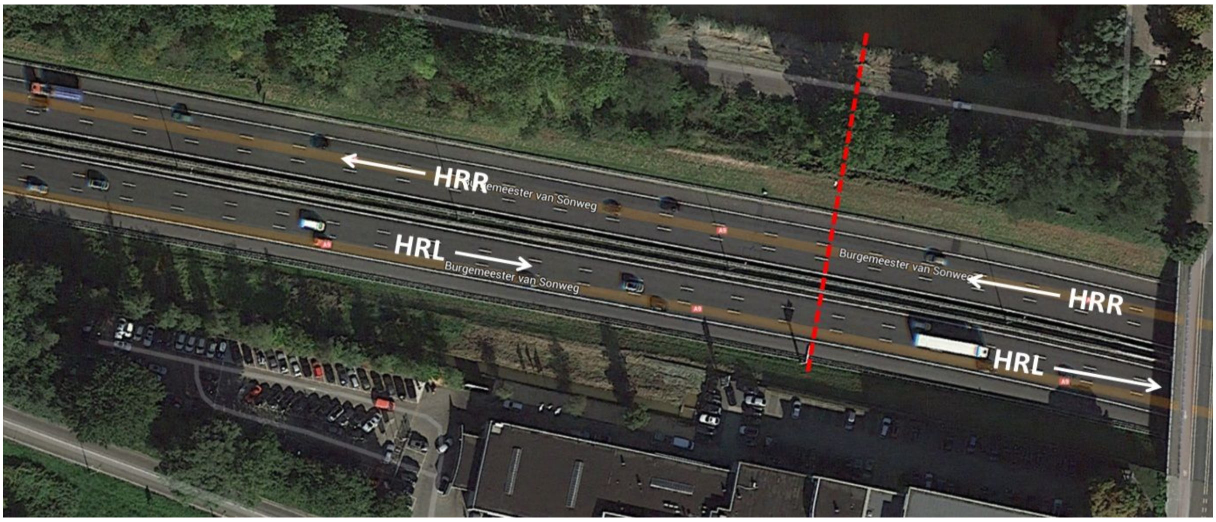


Figure 5-1 Location A9 Holendrecht – Badhoevedorp

Figure 5-2 Above: HRL, under: HRR

For each execution method a traffic measure is required. The following three traffic systems are considered, which are applicable for the execution methods:

- The normal start situation 2x3 traffic lanes with v=100 km/h (figure 5-3);
- A 4x0 traffic lanes system, where one carriageway is closed and the traffic is on the other carriageway (figure 5-4);
- A 2x3 traffic lanes system with reduced traffic lanes. A speed reduction is necessary of v=90 km/h (figure 5-5).

Per traffic measure the amount of lost vehicle hours is different. In table 5-7 the different systems are depicted. A distinction is made between the lost vehicle hours daily, on Saturday, on Sunday, during a traffic stop (only allowed at night) and a weekend closure of the road. Due to the regular traffic congestion, the road has already a certain amount of lost vehicle hours. The lost vehicle hours during a traffic stop or a weekend closure is the same for each system, the chosen system will not express in a variation of amount of lost vehicle hours.

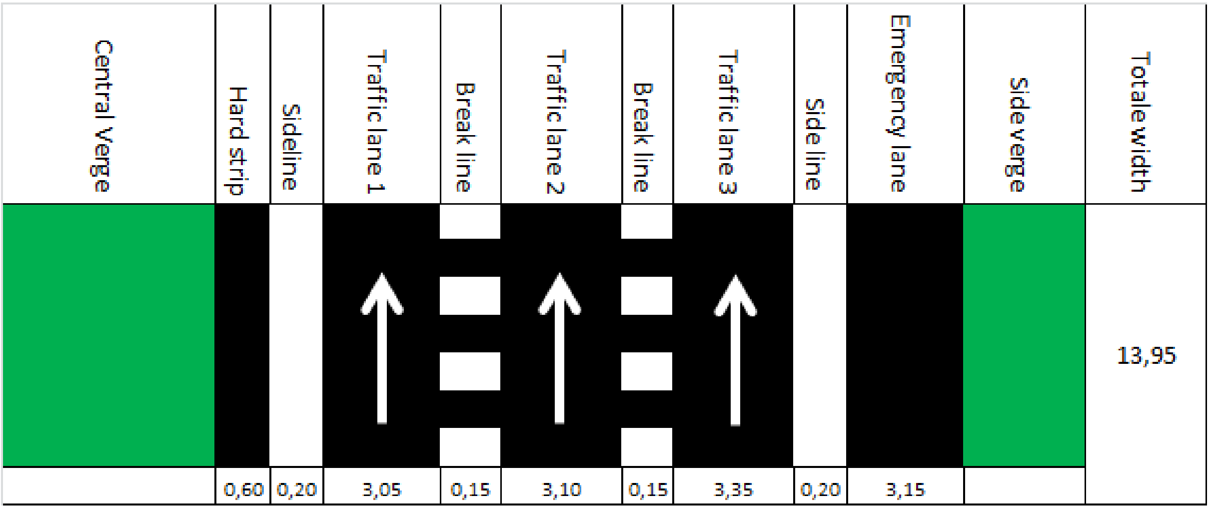


Figure 5-3 Start situation v=100km/h

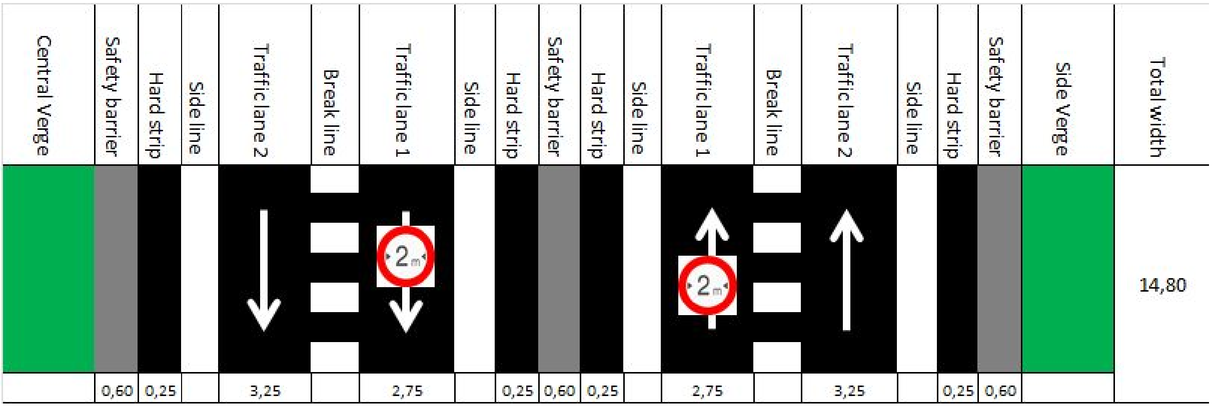


Figure 5-4 4x0 traffic lanes v=90 km/h

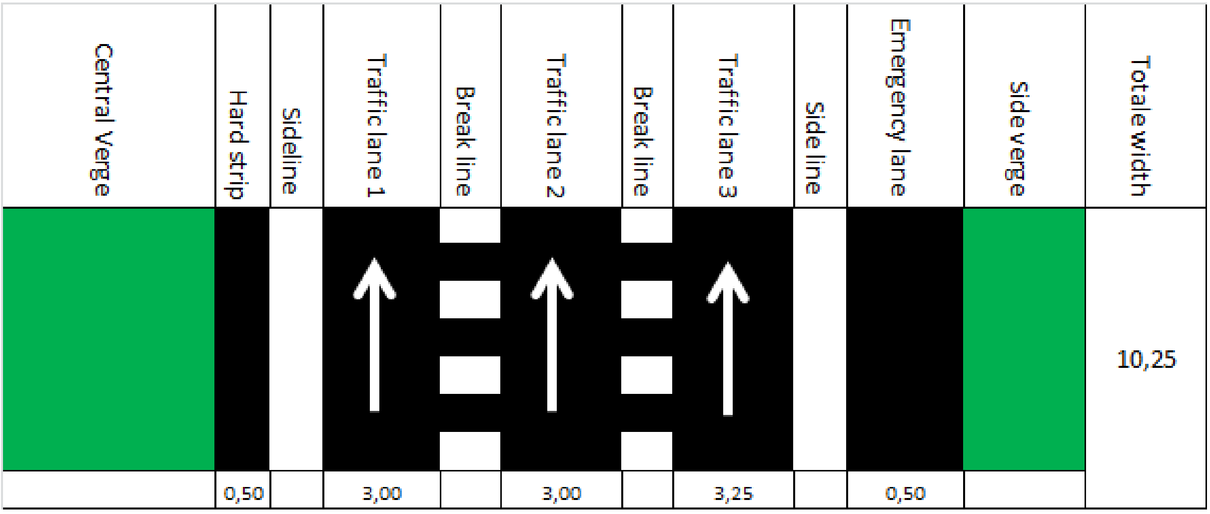


Figure 5-5 2x3 traffic lanes v=90 km/h

Table 5-7 Amount of LVH per traffic system

		LVH daily	LVH Saturday	LVH Sunday	LVH Traffic stop	Weekend closure Fr 22:00 - Mo 05:00
Start situation	HRL	5,094	0	0	13	1,209,788
	HRR	1,848	0	0	10	1,215,319
2x3 v=90 km/h	HRL	6,248	0	0	13	1,209,788
	HRR	2,504	0	0	10	1,215,319
4x0 v=90 km/h	HRL	174,452	9,476	10,257	13	1,209,788
	HRR	137,369	4,309	7,970	10	1,215,319

Depending on the space required for realization different systems can be worked out to temporary reduce the carriageway. An assumption for the Master Thesis is that the substructure is equal for all alternatives in In-Situ and Prefab. Also the space required for the construction of the bank seats and intermediate pier is enough. The difference is in the construction method of the deck. As been described at the execution methods, the following traffic measures are required:

- In-Situ I: all traffic on one carriageway, this is a 4x0 traffic lanes system. A speed reduction is necessary for safety of the road users (figure 5-4);
- In-Situ II: the carriageway is reduced for the space required of the temporary construction (figure 5-5). Traffic stops are required for construction of the temporary structure and striking the deck;
- In-Situ III: a weekend closure of the road is necessary to drive the deck into location;
- In-Situ IV: temporary traffic stops to construct and remove the sliding frame;
- Prefab I and II: temporary traffic stops for installing the prefab beams.

The total lost vehicle hour for each alternative can be calculated according to the information described above. In table 5-1 until 5-6, the activities are depicted where impact on traffic can exist. Together with table 5-7, the total lost vehicle hours per alternative can be calculated. As can been seen in table 5-8, the execution method In-Situ I is causing the most lost vehicle hours and a weekend closure is also very unfavourable for the lost vehicle hours.

Table 5-8 Amount of LVH per alternative

	In-Situ I	In-Situ II	In-Situ III	In-Situ IV	Prefab I	Prefab II
System	4x0	2x3 v=90km/h	Start situation	Start situation	Start situation	Start situation
Daily	50x174,452 50x137,369	50x6,248 50x2,504	-	-	-	-
Saturday	10x9,476 10x2,504	10x0 10x0	-	-	-	-
Sunday	10x10,257 10x7,970	10x0 10x0	-	-	-	-
Weekend closure	-	-	1x1,209,788 1x1,215,319		-	-
Traffic stop	-	20x13 20x10	-	20x13 20x10	10x13 10x10	10x13 10x10
Total (LVH)	15,893,120	438,060	2,425,107	460	230	230

5.3. Impact due to transportation

Impact on traffic and environment is not only caused by lost vehicle hours due to traffic measures. The transportation of material and equipment during the execution is also causing impact on traffic. Sometimes heavy transportation is needed and extra traffic measures are involved. The transportation of materials and equipment can also cause a negative experience on impact on traffic. To measure the impact on traffic caused by transportation, the quantities of the alternatives is calculated. Further the following assumptions are made:

- 25 m³ formwork by one trailer;
- The transportation for falsework is difficult to estimate. In the different In-Situ alternatives, different falsework is needed. In strength and stiffness. The weight of the parts for falsework can differ (difference in amount of transportation). Therefore the number of transportation for falsework is set on 20 (delivery and pick up);
- 12 m³ concrete can be transported by one concrete mixer;
- 25 ton reinforcement by one trailer;
- Prestress supplies, is transported in two transport trucks;
- Pile foundation: 2 concrete piles per transportation;
- Transportation activities for finishing not taken into account (equal for each alternative).

The transport is divided per subpart of the viaduct. Per alternative is the amount of transport specified in Appendix E. In table 5-9 an overview is given per alternative. The bank seat and intermediate pier is nearly the same for each alternative, the amount of transport is therefore the same. The transportation for the deck and the total transportation are depicted in table 5-9. For the In-Situ alternatives the amount of transportation is high, because of the amount of concrete. The Prefab alternatives are beneficial because the transport is only required for the beams. In this overview of amount of transportation, only full trucks are included. However, the empty trucks and concrete mixers have also an impact on traffic and environment. The amount of transportation in table 5-9 need actually be doubled.

Table 5-9 Amount of transportation (in nr of trucks)

	In-Situ I	In-Situ II	In-Situ III	In-Situ IV	Prefab I	Prefab II
Deck	103	103	128	108	46	20
Total	144	143	168	148	86	56

6. COST ESTIMATION

6.1. Cost estimation

To estimate the costs of the different alternatives and execution methods, a quantity list is made with help of the global dimensions of the viaducts. Together with cost planners of BAM Civiel, the cost estimation is composed. In Appendix D the cost estimation of the alternatives are worked out.

The following boundary conditions and assumptions are composed to draft the cost estimation:

- The cost estimation is based on direct costs only;
- Soil condition are good enough for a stable falsework construction;
- Not taken into account:
    - Costs for impact on traffic;
    - Any possible costs for safety measures;
    - General overhead costs;
    - Approach ramp.

In table 6-1 an overview is given of the direct costs for the different alternatives. In Appendix D the complete cost estimation is given. Also a square meter price is given for the viaduct. As can been seen, the first alternative of In-Situ has the lowest square meter price.

Table 6-1 Overview direct costs per alternative

	In-Situ I [x €1,000]	In-Situ II [x €1,000]	In-Situ III [x €1,000]	In-Situ IV [x €1,000]	Prefab I [x €1,000]	Prefab II [x €1,000]
Substructure	104	104	107	104	116	111
Pile foundation	65	65	65	65	56	48
Deck	438	532	577	803	456	530
Other	197	197	197	197	203	203
Total	804	898	946	1,169	831	892
Total per m² [in €]	871	973	1,025	1,267	901	968

The largest difference between the alternatives is in the direct costs of the deck structure. In the In-Situ alternatives this is mainly due to costs of temporary constructions.

I. False- and formwork: €139,860.00
II. False-, formwork and striking deck: €234,047.50
III. False-, formwork and driving deck: €189,770.50
IV. False-, formwork and launching deck: €505,172.50

The costs of the deck for the prefab alternatives include:

- Constructing beams in concrete factory;
- Transport to construction site;
- Installing beams on construction site;
- Finishing works of deck included (structural topping, transversal prestressing, and bearings).

6.2. Indirect and General overhead costs

Besides the direct costs like material and equipment, other costs like indirect and general overhead costs are taken into account in a cost estimation. Indirect costs include, for example, the following:

- Site office, including man-hours for management and supporting staff;
- Site facilities for storage, repair and maintenance;
- Site preparation: levelling, roads and fences;
- Auxiliaries: oil, gas, water and electrical supply;
- Small tools: positioning/ survey tools (total stations), compressor, compactors.

The indirect costs are set on a percentage of the direct costs. In consultation with cost planners of BAM Civiel, the indirect costs for In-Situ alternatives are 20% and for Prefab 18% of the direct costs. These percentages are based on experience of BAM Civiel. General overhead costs are normally a percentage of the direct and indirect costs of a project. Due to market situation and commercial interests, this can differ. For the cost estimation the percentage will be set on 15%.

In table 6-2 an overview is provided for indirect and general overhead costs per alternative.

Table 6-2 Direct, Indirect and general overhead costs

	In-Situ I [x €1,000]	In-Situ II [x €1,000]	In-Situ III [x €1,000]	In-Situ IV [x €1,000]	Prefab I [x €1,000]	Prefab II [x €1,000]
Direct costs	804	898	946	1,169	831	893
Indirect costs (In-Situ 20%, prefab 18%)	161	180	189	234	150	161
General overhead 15% of DC+IC	145	162	170	210	147	158
Total	1,109	1,239	1,305	1,613	1,128	1,212
Total per m² [in €]	1,202	1,343	1,414	1,749	1,223	1,313

7. SUSTAINABILITY

7.1. Introduction

As been discussed in the Literature Study, the term sustainability can affect many environmental impact categories. Durability focusses on the life time of a construction. Sustainability focusses on maintaining the living conditions on earth for future generations. Durability and sustainability can be taken into account on various manners in a project. The measures that need to be taken are different for durability and sustainability. In the Literature Study it was concluded that the durability of structures in Prefab or In-Situ concrete, does not make a big difference. In the Selection Directories it also was not a leading aspect for the fictitious discount. Durability as a criterion for evaluation is therefore neglected in this Master Thesis research. The term Sustainability is in this Master Thesis discussed in the form of CO_2 emission. The environmental impact category global warming is causing 80% of the CO_2 emission [8]. For an impression of the impact on environment is therefore a calculation in CO_2 emission made and not in the other environmental impact categories with a factor in CO_2 equivalent. In this chapter the different alternatives in In-Situ and in Prefab concrete will be elaborated in a CO_2 emission.

7.2. Life cycle

According to the report "Sustainable constructing with materials" [9] the CO_2 emission is calculated for a Prefab and an In-Situ concrete deck. The focus is in the report on the materials concrete and steel. In a viaduct these are also the main materials, and the production of cement and CO_2 includes 80% of the total emission of materials [7,8]. In the Preliminary Design it is noticed, that the substructure for Prefab and In-Situ concrete viaducts are the same.

To compare the In-Situ and Prefab concrete, only the deck is investigated. In the following paragraphs first the CO_2 emission for the concrete mixtures and transport and installation is calculated for one cubic meter of concrete. After the CO_2 emission is known, these numbers will be used to discuss the CO_2 emission of the alternatives in In-situ and Prefab. To calculate the CO_2 emission a life cycle must be known. For the Master Thesis the same live cycle (cradle-to-site) is used as in the report "Sustainable constructing with materials". This life cycle is depicted in table 7-1.

Table 7-1 Cradle-to-site life cycle

	In-Situ	Prefab
1	Mining raw materials	Mining raw materials
2	Transport of raw materials to concrete mixing plant	Transport of raw materials to prefab factory
3	Mixing raw material into concrete mortar	Mixing raw material into concrete mortar
4	Transport mortar to site	Casting concrete
5	Casting concrete	Demoulding formwork
6	Curing concrete	Transport elements to site
7	Demoulding formwork	Transport an installation of elements on site

7.3. Concrete mix

In the Literature Study and preliminary design an assumption is formulated for the concrete strength class. The strength class is needed to perform design calculations. The assumptions for strength class are as follows:

- C35/45 for In-Situ concrete;
- C55/67 for Prefab concrete beams.

In case of inverted T-beams a structural topping is required, for the diaphragm action of the deck. Spanbeton [i1] requires a minimum strength class of C28/35 for In-Situ structural toppings. In this Master Thesis the structural topping will be calculated also with a concrete strength class of C35/45.

The strength classes required can be reach with different concrete mixtures. The basis of concrete mixtures consists of cement, sand, gravel and water. To begin the research study a common concrete mixture is composed, which is usable for the required strength classes. In cooperation with concrete technologists of BAM Infraconsult, the mixture depicted in table 7-2 is composed.

Table 7-2 In-Situ and Prefab concrete mixtures

In Situ C35/45	kg/m³
CEM III/B 42,5N LHHS	310
CEM I 52,5R	75
Sand 0-4 mm	750
Gravel 4-16mm	500
Gravel 4-32mm	500
Water	165
Total	2,300

Prefab C55/67	kg/m³
CEM III/A 52,5N (50% slag)	400
Limestone powder	120
Sand 0-4 mm	750
Gravel 2-8mm	200
Gravel 8-12mm	650
Water	170
Total	2,290

7.4. CO_2 emission concrete mixture

First step in the life cycle is the mining of raw materials. During the mining of these raw materials, certain CO_2 emissions are obtained. The concrete mixture consists out of different particles, as have been discussed in paragraph 7.3. Mining of raw materials sand and gravel is mostly done in Belgium/The Netherlands. The following CO_2 emissions can be obtained [9]:

- Sand: 3.4 kg CO_2/ton sand, with a density of 1,350kg/m³ the CO_2 emission becomes 4.6 kg CO_2/m³ sand;
- Gravel: 2.7 kg CO_2/ton gravel, with a density of 1,600 kg/m³ the CO_2 emission becomes 4.3 kg CO_2/m³ gravel;
- Water: 0.3 kg CO_2/ton water, with a density of 1,000 kg/m³ the CO_2 emission becomes 0.3 CO_2/m³ water;
- Limestone powder: 32 kg CO_2/ton limestone powder, with a density of 1,120 kg/m³ the CO_2 emission becomes 35.8 kg CO_2/m³ limestone powder;
- CEM I: 788 kg CO_2/ton cement, with a density of 1,050 kg/m³ the CO_2 emission becomes 827 kg CO_2/m³;
- CEM III/B: 291 kg CO_2/ton cement, with a density of 1,100 kg/m³ the CO_2 emission becomes 320 kg CO_2/m³;
- CEM III/A: 384 kg CO_2/ton cement, with a density of 1,000 kg/m³ the CO_2 emission becomes 384 kg CO_2/m³.

Table 7-3 CO_2 emission C35/45

C35/45	kg	m³	kg/m³	kg CO_2 /m³	CO_2 emission concrete mortar
CEM III/B 42,5N LHHS	310	0.282	1,100	320	90.2
CEM I 52,5R	75	0.071	1,050	827	58.7
Sand 0-4 mm	750	0.5556	1,350	4.6	2.6
Gravel 4-16mm	500	0.3125	1,600	4.3	1.3
Gravel 4-32mm	500	0.3125	1,600	4.3	1.3
Water	165	0.165	1,000	0.3	0.05
Total	2,300	1.000			154.2

Table 7-4 CO_2 emission C55/67

C55/67	kg	m³	kg/m³	kg CO_2 /m³	CO_2 emission concrete mortar
CEM III/A 52,5N (50% slag)	400	0.400	1,000	384	153.6
Limestone powder	120	0.107	1,120	32	3.42
Sand 0-4 mm	750	0.556	1,350	4.6	2.56
Gravel 2-8mm	200	0.125	1,600	4.3	0.54
Gravel 8-12mm	650	0.406	1,600	4.3	1.75
Water	170	0.170	1,000	0.3	0.05
Total	2,290	1.000			161.9

Reinforcement steel

The concrete is provided with reinforcement and prestressing steel, for convenience the CO_2 emission for reinforcement and prestressing steel is kept the same and is 1,640 kg CO_2/ton steel. This value holds for the production of steel. The emission for transport of the steel to the prefab factory or building site needs to be added. The CO_2 emission for a truck which transports more than 20 ton non bulk goods is 0.13 kg CO_2/ton/km. For an average transport of 75 km, the CO_2 emission is 9.75 kg CO_2/ton steel. The total emission per ton steel is then 1,649.75 kg CO_2.

7.5. Transport and installation

Besides the CO_2 emission for production, one has to take into account the emission for transport and installation in the different stages of the life cycle. For In-Situ and Prefab there are a few differences.

In-Situ

In case of In-Situ concrete, the transport of raw materials to the concrete factory and the transport of the concrete mortar to the building site are taken into account. The following assumptions are made for transport and installation:

- Transport cement is approximately 100 km;
- Transport sand/gravel is approximately 50 km;
- The transportation of raw materials to the concrete factory gives in total an emission of 17 kg CO_2/m³ concrete;
- Transport concrete mortar to site is approximately 75km and gives an emission of 23 kg CO_2/m³ concrete;
- Production on building site included installing and removing of formwork 20 kg CO_2/m³.

The total CO_2 emission for the production of cement and the transportation and installation is then: 154.2+17+23+20=214.2 kg CO_2/m³.

Prefab

In case of Prefab concrete, the transport of raw materials to the prefab factory, production of concrete mortar in the prefab factory, and the transportation and installation of the prefab elements on the building site is taken into account.

- Transport cement is approximately 100 km;
- Transport sand/gravel is approximately 50 km;
- The transportation of raw materials to the concrete factory gives in total an emission of 17 kg CO_2/m³ concrete;
- Production of concrete mortar in the prefab factory gives an emission of 18 kg CO_2/m³;
- Transport of prefab elements to the building site is approximately 75 km. Together with the installation of the prefab elements this gives an emission of 33 kg CO_2/m³ concrete.

The total CO_2 emission for the production of a prefab element and the transportation and installation is then: 161.9+17+18+33=229.9 kg CO_2/m³.

7.6. CO_2 emission deck

The substructure for an In-Situ and Prefab concrete viaduct is practically the same. A small difference in the intermediate pier, however this difference in emission for CO_2 is negligible. A comparison of emission is done for the deck of the viaducts. For In-Situ concrete two different alternatives are compared. A deck height of 1.0 m and 1.3 m is considered. The Prefab alternatives of inverted T-beams and box beams are both considered.

The CO_2 emission of the In-Situ alternatives are the highest, as can been seen in table 7-5. Despite the fact that the concrete mixture for prefab elements is emitting more CO_2 per m³ concrete, the prefab elements still have a lower CO_2 emission in total for the deck.

Table 7-5 CO_2 emission

	Concrete			Steel			Total
	m³	kg CO_2/m³	subtotal	kg	kg CO_2/ton	subtotal	kg CO_2
In-Situ d=1.0m	922.50	214.2	197,600	121,696	1,649.75	200,768	398,368
In-Situ d=1.3m	1,199.25	214.2	256,879	158,205	1,649.75	260,999	517,878
Prefab I Topping	272.18	214.2	58,301	40,827	1,649.75	67,354	125,656
Beams	389.30	229.9	89,500	48,662	1,649.75	80,280	169,780
Prefab II	535.67	229.9	123,151	66,959	1,649.75	110,466	233,617

7.7. Environmental Costs

The environmental costs can be calculated for each alternative. An unit price of €0.05 is used for the emission of 1 kg CO_2 [9]. In table 7-6 the total environmental costs for CO_2 is depicted. An In-Situ deck of 1.3m has the highest emission and environmental impact of CO_2. This means that the alternatives of In-Situ building on a higher level and driving the deck into place have the highest costs of environmental impact. Prefab concrete Box-beams are the most beneficial in CO_2 emission.

Table 7-6 Environmental costs

	kg CO_2	Costs [€]
In-Situ d=1.0 m	398,368	19,918.40
In-Situ d=1.3 m	517,878	25,892.90
Prefab I	295,436	14,771.80
Prefab II	233,617	11,680.85

7.8. Verification

During the calculation of the CO_2 emission some assumptions are made. To make sure the method used in the Master Thesis is reliable enough and the results can be used for the assessment of the different alternatives, a verification is made. The verification of this calculation is done with help of Fase B of [8]. In this report cases of viaducts are worked out to calculate the emission of CO_2. The objective of this report is to assess the possibilities and give recommendations for the reducing of environmental impact with an emphasis on CO_2 emission. During the research certain adjustments are made to the viaduct, to notice the difference in CO_2. The following adjustments were done:

- Extend the life time of a structure (50 vs. 100 year), 100 year is the reference design;
- Secondary aggregates instead of primary aggregates;
- Prefab vs. In-Situ Viaducts.

From these three adjustments, the reference design and the Prefab solution ins inverted T-beams and box beams are used for verification of the results of the Master Thesis.

The starting points and boundary conditions are different in the Master Thesis and in the report [8]. For example the dimension in length and width of the viaduct are different. For the verification the unit numbers of the Master Thesis alternatives and the report alternatives are calculated (table 7-7). The research of Stufib/Stutech makes use of CO_2 equivalent. In the Literature Study it is explained that CO_2 is for 80% responsible for the environmental impact. In this verification the total amount of CO_2 of Stufib/Stutech is therefore multiplied by a factor of 0.8. The amount of CO_2 in the calculation of the Master Thesis can then be compared to the amount of CO_2 in the report of Stufib/Stutech.

Table 7-7 Amount of kg CO_2/m^3

	Master Thesis (l x b = 61.5 x 15 m)			Stufib/Stutech (l x b = 54 x 13.8 m)			
	CO_2 [kg]	Concrete [m^3]	kg CO_2 /m^3	CO_2 [kg]	Concrete [m^3]	Kg CO_2 /m^3 (equivalent)	Kg CO_2 /m^3
In-Situ	398,368	922.5	431.83	242,354	569	425,93	340.74
Prefab Inverted T-beam	295,436	272.18 389.30	446.62	167,954	178 268	361,98	289.58
Prefab Box beam	233,617	535.67	436.12	144,406	315	458,43	366.74

As can been seen in table 7-7 the amount of CO_2 of the Master Thesis differs according to the results of the report in Stufib/Stutech. The amount of CO_2 (variation of approximately 20%) calculated in the Master Thesis is higher than the results in [8]. These differences can be explained due to a few reasons.

Differences for In-Situ alternatives

- Concrete mixture: different amounts of cement, sand, gravel and water. The concrete mixture in the Stufib/Stutech report has a less amount of CEM I and CEM III, which gives a lower amount of CO_2 emission;
- Amount of reinforcement/prestress differs for the alternatives:
  - Stutech: reinforcement 78kg/m^3 and prestress 33 kg/m^3;
  - Master Thesis: reinforcement 80 kg/m^3 and prestress 52 kg/m^3;

  A higher amount of steel gives automatically a higher amount of CO_2 emission.

Differences for Prefab alternatives

- Concrete mixture: different amounts of cement, sand, gravel and water. The concrete mixture in the Stufib/Stutech report has a combination of CEM I and CEM III and limestone powder, while in the Master Thesis a concrete mixture of CEM III and limestone powder is used; which gives a lower amount of CO_2 emission;
- Amount of reinforcement/prestress differs for the alternatives:
  - Stutech: prefab beams 185 kg/m^3 and structural topping 35 kg/m^3;
  - Master Thesis: prefab beams 125 kg/m^3 and structural topping 150 kg/m^3;
- Amount of reinforcement/prestress differs for the alternatives:
  - Stutech: reinforcement 95kg/m^3 prestress 100 kg/m^3;
  - Master Thesis: reinforcement 125 kg/m^3;

  A higher amount of steel gives automatically a higher amount of CO_2 emission.

Impact of parameters

The amount of CO_2 (Stufib/Stutech vs. Master Thesis) differs approximately 20%, in this case it is an acceptable difference. Due to reasons explained earlier, the results can get closer to each other if certain parameters are changed. Some parameters are also project specific, like requirements on the concrete mixture or the transport distance. To sum up, the following parameters can have an influence on the total CO_2 emission, between brackets the percentage of the total CO_2 emission calculated for the Master Thesis):

- In-Situ:
  - Transport of raw materials to a concrete mixing plant (4% of total);
  - Amount of raw materials in the concrete mixture (36% of total);
  - Transport of concrete mortar to site (5% of total);
  - Installing and removing of formwork (4.7% of total);
  - Transport steel (0.3% of total);
  - Amount of steel (50% of total);
- Prefab:
  - Transport of raw materials to a concrete prefab factory (4% of total);
  - Amount of raw materials in the concrete mixture (37% of total);
  - Production of concrete mortar in prefab factory (4% of total);
  - Installing and removing of prefab beams (7.7% of total);
  - Transport steel (0.3% of total);
  - Amount of steel (47% of total);

8. RISK MANAGEMENT

8.1. Introduction

During the Literature Study a study is done in the Selection Directories of recent projects from different clients. In most of the projects discussed, a Risk analysis is requested. The Risk analysis can differ from Risks that a client can take or the Risk that a contractor can have on the project. In the Literature Study it seems that risks can have different angles, from legal permits until risks of impact on traffic and the possible accidents involved. This Master Thesis does not have a client, nonetheless a Risk Analysis can be made for the different alternatives in Prefab and In-Situ concrete.

For each alternative a Risk Analysis is elaborated. The RISMAN Method is used for a risk analysis. In this method risks are viewed from different angles. The following angles are defined for the risk analysis:

- Legal;
- Organization;
- Technical;
- Realization;
- Spatial/Geographical;
- Financial/Economical;
- Social;
- Politics.

Various aspects can be described for the different angles. The Risk Analysis per alternative is inserted in Appendix F. The Risk Analysis gives a description of the risk, the cause of the risk, the consequence of the risk, the consequence rating, a control measure and at last a consequence rating after the control measure is taken into account.

The following paragraphs discuss the most important risks per angle/aspect for each alternative. The last paragraph of this chapter will focus on the quantification of the risks. This quantification of risks can be used for the assessment of the Prefab and In-Situ Alternatives. After the quantification of the risks, if possible, control measures can be conceived for the risks to lower the chance of the risk or to lower the consequences of the risk. The risk analysis is made in a stage where all different aspects in the design process are elaborated on a global level. For a good system of Risk management, the risk analysis has to be redone in certain moments:

- With modification in the boundary conditions or starting points of the project;
- At the start of each new phase in a project;
- During the project phases as a review to check if control measures are taken and to evaluate these control measures;
- The Risk analysis has to be up to date after previous points.

8.2. Legal

The aspects described for the angle Legal have mainly to do with permits which are obtained from the authorities. This aspect can differ per project, because the risk depends on project locations and on project authorities. Appendix F includes the Legal Risks, which are described and quantified. It seems that for each alternative in In-Situ and Prefab the risks are the same. The following risks can be obtained:

- The risk that a building permit is not granted. Cause can be that the contractor does not have a sufficient document planning, such that the permit is incomplete. Or that an objection procedure is started against the building permit. The consequence is the same: the design process is delayed and the realization begins later than planned. In the Prefab alternative, the risk can occur by a difficult communication of the contractor and the supplier of the Prefab beams;

- The risk that parcels on the project location is not available for construction. Cause can be a delay of acquisition by the client. This is a risk that not applies for each situation, because it is depended on the location. Consequence is a delay of the start of execution;
- The risk that additional requirements are received from the permits. Cause is that authorities, who granted the permits, are giving new requirements for the project. Consequence is a possible adjustment in the design of the viaduct.

8.3. Organization

The organization of a project is very important for the success of a project. Aspects like communication and realization in a design process can influence the outcome and can form a risk during the project. For a total overview of risks reference is made to Appendix F. A few risks are presented here. A similar risk for In-Situ and Prefab is:

- The risk that the start of the realization is delayed, because the existing infrastructure on location is wrongly interpreted for the design. The consequence is a delay in time schedule because of reconsideration of execution plans.

In-Situ

A delay in the design process can exist because of a under estimation of the design process of In-Situ parts of the viaduct. A cause can also be an insufficient internal decision making process. In both cases a delay in time schedule is the consequence and if the design documents are not ready in time, an application for the building permit can also be delayed.

Prefab

The prefab beams are normally designed by a supplier and not by the main contractor. Therefore the risk exist that due to communication issues between contractor and subcontractor the design of a Prefab beam is not ready in time, with a consequence in the time schedule. The different interfaces between a prefab beam and bank seat have to be adapted on each other.

8.4. Technical

Technical risks can occur if a certain design solution is chosen. For In-Situ and Prefab viaduct the same substructure is designed. Therefor the risk that a modification in the boundary conditions of the subsoil can occur for both alternatives. Consequences are a delay in the time schedule and a possible adjustment in the substructure (e.g. foundation piles).

In-Situ

The prestressed In-Situ deck is designed as a statically undetermined structure. Therefore a coupling is required between the prestress cables above the intermediate pier. If the coupling is not provided, the structure can fail because the load bearing capacity is not sufficient enough.

Prefab

For Prefab structures the risk can occur that a selected design solution is impossible to materialize. A modification in the design solution is needed, to create a structure that will satisfy the requirements.

8.5. Realization

Certain risks in realization are the same for a solution in In-Situ or Prefab concrete. Risks with aspects of the realization of the intermediate pier and risks that can occur due to existing structures can occur to all alternatives. For an explanation of these risks is referred to Appendix F.

In-Situ

The four In-Situ alternatives each have their own risks that can occur due to the realization of the structure. Some of the risks for the alternatives are the following:

- The lifetime of a structure cannot be guaranteed because of the weather influences during casting of the concrete. The consequence can be a demolition of parts of the structure when the quality cannot be guaranteed;
- For driving the deck the risk is that the deck is not driven into place. Different causes can be held responsible for this risk. Due to unexpected circumstances during driving the deck, or during constructing the deck next to the road can have a consequence that activities are not ready during the weekend closure. Or that the requested weekend closure is not achieved;
- The risk that settlements of the soil body of the approach ramp are bigger than estimated during design. Consequence is sagging of falsework of the deck, which can result in settlements of the structure. Also, it can give problems during launching the deck into place.

Prefab

For Prefab beams exists the risk that during installing of prefab beams something happens, such that the requested traffic stop is exceeded or that due to collapsing of the prefab beam during installing, the highway cannot reopen and a traffic jam exist. For both of the prefab alternatives this can be the case and has consequences in the time schedule.

8.6. Spatial / Geographical

Risks that can occur in geographically angle are depending on the location of the project. Because the Master Thesis is not elaborated in a certain area, these risks are difficult to describe. However, in parts of the Netherland risks can occur due to protected Flora and Fauna, Archaeology founding's and explosive coming from the second world war. For In-Situ and Prefab alternatives are three risks described with the same causes and consequences. Consequences are a delay in activities (time schedule) and a possible adjustment in the execution method. In Appendix F these risks are further elaborated.

8.7. Financial / Economical

The risk that the design budget of a project exceeds can occur to each alternative. Problems with the method statement or no information in time, or the fluctuation in the market for procurement costs can be the cause of this risk. The consequence is exceeding in time and money.

8.8. Social

Impact on traffic and impact on the environment is an occurrence that happens for each alternative and execution method (as has been discussed in chapter 5). In the case of the In-Situ alternatives the causes are: temporary adjustment of traffic lanes, frequent transport of concrete mixers and a long duration of activities. In case of the Prefab alternatives the causes are the transport of the prefab beams and the temporary traffic stop to install the prefab beams. In all cases the consequences are the same: an irritation of traffic users expressed in complaints or an object procedure during the application of building permits. However, the difference is made due to a different quantification of the impact on traffic and environment. The alternatives have a different duration of the impact on traffic.

8.9. Politics

Risks according to politics can arise if some authorities cannot agree on terms for the project. In each alternative the design process is delayed and the realization cannot start. This topic is further disregarded during the Master Thesis.

8.10. Quantification

The risks that are described in the previous paragraphs have a certain value in time and money. A quantification can be given to the risks, before as well as after the control measure. The risks have a chance of occurrence and a value of the consequences. The total score of risk is defined as follows: Score = chance x sum of consequences. The consequences are expressed in: money, time, quality, safety and environment. Table 8-1 presents the possible scores of the risk.

Table 8-1 Legend of Quantification

	Chance	Money [euro]	Time [weeks]	Quality	Safety	Environment
0	0	0	0	Requirement is met	-	-
1	<1% (rarely)	<10,000	0 - 2	Not conform norm	First aid	Hardly nuisance
2	1-5% (unlikely)	10,000 - 20,000	2 - 4	Not conform norm, but functional	Incident with injury <1 day absent	Some nuisance
3	5-10% (chance exist, not great)	20,000 - 100,000	4 - 12	Function loss of not important part	Incident with injury > 1 day absent	Moderate nuisance
4	10-25% (real chance)	100,000 - 1,000,000	12 - 24	Repairable essential functional loss	Serious injury	Big hindrance
5	25-100% (major chance)	1,000,000 - 2,000,000	24 - 52	Irreparable essential functional loss	Fatal injury	Major hindrance

8.11. Results of quantification

Each risk of the alternatives is quantified in Appendix F. The quantification in time and money have an average value, this is also presented in Appendix F. In table 8-2 the total average in money and time is presented for each alternative. The result is given before as well as after the control measure. Control measures have also some costs, these costs have to be added up to the costs after control measures. In the Master Thesis the costs for control measures are neglected, because of the difficulty to quantify the costs of the control measures.

Table 8-2 Results of quantification

	Before control measure		After control measure	
	Costs [€]	Time [weeks]	Costs [€]	Time [weeks]
In-Situ I	367,125	20.7	38,350	6.4
In-Situ II	367,125	21.7	37,150	6.9
In-Situ III	420,850	17.1	35,975	6.5
In-Situ IV	403,875	18.8	38,100	4.5
Prefab I	277,125	17.9	34,025	5.1
Prefab II	277,125	17.9	34,025	5.1

8.11.1. Prioritization of most important risk per alternative

Per alternative some of the risks still have a high score after the control measure. The cause of this high score can differ per risk. In this subparagraph the priority risks are described. An ID number is given for the reference to the Risk Analysis in Appendix F.

In-Situ I

- ID 31, Impact on traffic has a score after the control measure of 32. The risk involves nuisance for environment and stakeholders due to the execution method. The high score is the result of a very high chance and a high consequence rating. The risk has a major chance of happening, because the traffic measures are necessary for the execution method. Some understanding with stakeholders will occur due to the control measure, such that the consequence for environment is a bit decreased.
- ID 32, Impact on environment has also a score of 32 after the control measure. The risks involves nuisance for environment and stakeholders due to the execution method. The period of time that the national highway is redirected and that hindrance exists due to frequently transport is very long.

In-Situ II

The alternative where the deck is built on a higher level and is lowered down has the same risks high on the priority list after the control measures as In-Situ I. However, the scores of both risks are 21 instead of 32. This is due to the a lower chance of happening and the consequence of hindrance is less than with In-Situ I. Traffic measures are needed for In-Situ II, but the effect on the traffic is less than with In-Situ I. This is also explained in chapter 5 with lost vehicle hours.

In-Situ III

Risks ID 32 and ID 33 have again a high score after the control measure. For both of the risks the score after control measure is 16. Due to a high chance, the risk score after the control measure is still high. The control measure will bring some understanding to the stakeholders, such that the consequence for environment is decreased.

In-Situ IV

For alternative In-Situ IV the same high risk profile exist as with In-Situ II.

Prefab I and Prefab II

The risks for the Prefab alternatives are on each aspect the same. The structural design of these two alternatives differ, however, there are no risks worth mentioning. Important risks are if due to the transport of the heavy beams (ID 19), existing structures are damaged. The consequences of this risk are depending on the surroundings and existing structures of the project location.

9. ASSESSMENT ALTERNATIVES

9.1. Introduction

In chapter 1 the problem description of the Master Thesis is formulated as:
“Which alternative in Prefab and In-Situ concrete viaducts is considered the most economically attractive when combining different governing aspects?”

The Literature Study and the Research Study have provided information that can be used to make an assessment involving this question. Nowadays in practice the assessment for a winning tender is done with EMVI. In chapter 4 of the Literature Study several selection directories of projects that are tendered in 2013 and 2014 are discussed. This investigation shows the current requirements and needs of the clients.

Based on these practical reference projects, it can be seen that a Risk management plan and a Plan for the organization is of high priority for the client. However, a plan for the organization is difficult to assess for this Master Thesis. In the reference projects, not only one viaduct is designed, but other structures and roads belong to the scope of the projects.

However, for the Master Thesis the following aspects can be assessed (elaborated per alternative in the previous chapters):

- Direct and indirect costs;
- Time schedule;
- Impact on traffic;
- Impact on environment;
- CO_2 emission;
- Risk Analysis.

In this chapter, first an assessment is done for each aspect itself. Subsequently an assessment is made based on EMVI fictitious discount. In practice an assessment committee will evaluate the documents given at the tender submission. There is no assessment committee in the Master Thesis, which can be used for the evaluation of the Alternatives. Therefore a simple and clear method is developed specifically for this Master Thesis, which can be used for the assessment of the alternatives.

9.2. Best alternative per aspect

In the previous chapters, alternatives are elaborated on different aspects, concerning the time-schedule, direct costs, impact on traffic and the CO_2 emission. Each stand-alone aspect has a “better” alternative. The alternatives are put in a sequence per aspect (table 9-1). In this table it is become visible that the alternatives in Prefab concrete are more attractive. Only in the direct costs, the In-Situ alternative is better.

Table 9-1 List of better alternatives per aspect

	Direct costs	Impact on traffic	Impact on environment	Time schedule	CO_2 emission	Risk Analysis
1	In-Situ I	Prefab I / II	Prefab II	Prefab I / II	Prefab II	Prefab I / II
2	Prefab I		Prefab I		Prefab I	
3	Prefab II	In-Situ IV	In-Situ II	In-Situ III	In-Situ I	In-Situ III
4	In-Situ II	In-Situ II	In-Situ I	In-Situ I / II	In-Situ II / III / IV	In-Situ II
5	In-Situ III	In-Situ III	In-Situ IV			In-Situ IV
6	In-Situ IV	In-Situ I	In-Situ III	In-Situ IV		In-Situ I

9.3. Assessment method fictitious discount

To consider the most economically attractive alternative, the alternatives are assessed based on a method with fictitious discount. The assessment method for the Master Thesis will be based on reference projects discussed in the Literature Study. For each aspect a percentage for the fictitious discount is calculated. These percentages are based on the percentages found in the investigation in selection directories (discussed in the Literature Study). The percentages are based on a maximum subscription price. In the Master Thesis this subscription price is set on €2,000,000. In table 9-2 an overview is given of the maximum fictitious discount per aspect. The aspect of Risk Analysis is not taken into account in this table. For this aspect the cost value of the risks after the control measure is added to the direct costs.

Table 9-2 Fictitious discount

	Percentage of subscription price	Fictitious discount [x €1,000]
Impact on traffic	20%	400
Impact on environment	10%	200
Time schedule	10%	200
CO_2 reduction	5%	100
Total	45%	900

The assessment in the reference projects is done in a few methods:

- The fictitious discount is calculated according to a grade, which is assigned by an assessment committee;
- The fictitious discount is calculated based on the 'facts' which come forward from a calculation for each aspect.

In the Master Thesis, an assessment committee is not possible to assess the different alternatives. Therefore the following method is developed for the assessment:

- The best alternative gets the highest fictitious discount;
- The worst alternative gets none of the fictitious discount;
- In between, the alternative gets a fictitious discount proportional to the maximum of the fictitious discount.

  $$\frac{X-Y}{X-Z}\cdot €_{max}$$

  Where:
  X= worst alternative;
  Y= alternative being assessed;
  Z= best alternative
  $€_{max}$ = maximum fictitious discount
- There is a deviation in the given discount for the impact on traffic. Based on reference project [S4] the following is used for the fictitious discount:
  - Full fictitious discount if Lost Vehicle Hours (LVH) ≤ 100,000;
  - No fictitious discount if LVH ≥ 1,133,333;
  - If 100,000 ≤ LVH ≤ 1,133,333, the fictitious discount is calculated as:

    $$\frac{1{,}133{,}333 - LVH_{alternative}}{1{,}033{,}333}\cdot €_{max}$$

The alternative considered the most attractive, is the alternative with the lowest fictitious subscription price. The lowest fictitious subscription price is calculated as follows:
Fictitious subscription price = direct costs – total fictitious discount + costs of the Risks.

9.4. Assessment alternatives different aspects combined

According to the method described in paragraph 9.3, an assessment is made for the different alternatives. In Appendix G1, an EMVI table is elaborated, with the different alternatives, aspects, and fictitious discount. In the assessment different combinations are made with the aspects, to obtain which alternative is the most economical in certain situations. In the assessments first of all the Direct and Indirect costs are compared. After this, for each new assessment an extra aspect is added to the assessment for comparing the alternatives. In tables 9-3 unto 9-9 the assessments are summarized. The alternatives are ranked from lowest to highest fictitious subscription price. The difference between the alternatives is also presented in percentage of the best solution. During the assessments Impact on traffic and Impact on environment are always considered together, because in both cases, the underlying information has an impact on traffic and environment.

Table 9-3 Assessment variant I

Direct + indirect costs	Fictitious subscription price [x €1,000]	Percentage
In-Situ I	1,109	100.0%
Prefab I	1,128	101.7%
Prefab II	1,212	109.2%
In-Situ II	1,239	111.7%
In-Situ III	1,305	117.6%
In-Situ IV	1,613	145.5%

Table 9-4 Assessment variant II

Direct + indirect costs, Time Schedule	Fictitious subscription price [x €1,000]	Percentage
Prefab I	928	100.0%
Prefab II	1,012	109.0%
In-Situ I	1,096	118.1%
In-Situ II	1,226	132.1%
In-Situ III	1,284	138.4%
In-Situ IV	1,613	173.8%

Table 9-5 Assessment variant III

Direct + indirect costs, Impact on traffic, Impact on environment	Fictitious subscription price [x €1,000]	Percentage
Prefab I	582	100.0%
Prefab II	612	105.2%
In-Situ II	925	159.1%
In-Situ I	1,066	183.3%
In-Situ IV	1,178	202.5%
In-Situ III	1,305	224.3%

Table 9-6 Assessment variant IV

Direct + indirect costs, CO_2 emission	Fictitious subscription price [x €1,000]	Percentage
Prefab I	1,050	100.0%
In-Situ I	1,067	101.7%
Prefab II	1,112	105.9%
In-Situ II	1,239	118.0%
In-Situ I	1,305	124.3%
In-Situ IV	1,613	153.7%

Table 9-7 Assessment variant V

Direct + indirect costs, Risk Analysis	Fictitious subscription price [x €1,000]	Percentage
In-Situ I	1,148	100.0%
Prefab I	1,162	101.3%
Prefab II	1,246	108.5%
In-Situ II	1,276	111.2%
In-Situ III	1,341	116.8%
In-Situ IV	1,651	143.9%

Table 9-8 Assessment variant VI

Direct + indirect costs, Time schedule, Impact on traffic, Impact on environment	Fictitious subscription price [x €1,000]	Percentage
Prefab I	382	100.0%
Prefab II	412	107.9%
In-Situ II	913	239.1%
In-Situ I	1,054	276.1%
In-Situ IV	1,178	308.6%
In-Situ III	1,284	336.5%

Table 9-9 Assessment variant VII

Direct + indirect costs, Time schedule, Impact on traffic, Impact on environment, CO_2 emission	Fictitious subscription price [x €1,000]	Percentage
Prefab I	304	100.0%
Prefab II	312	102.7%
In-Situ II	913	300.8%
In-Situ I	1,012	333.4%
In-Situ IV	1,178	388.2%
In-Situ III	1,284	423.3%

The result of the assessment with all aspects combined is summarized in table 9-10. The Prefab alternative with inverted T-beams is the most economically attractive alternative according to this assessment. It is interesting that the alternative with the highest fictitious discount has ended in second place. This alternative has a higher direct cost price, such that the difference cannot be forced by the highest fictitious discount. The best alternative in In-Situ concrete is to build a concrete deck on a higher platform above the road and lower the deck when finished.

Table 9-10 Assessment variant VIII

Alternative	Direct costs [x €1,000]	Total fictitious discount [x €1,000]	Risk Analysis [x €1,000]	Fictitious subscription price [x €1,000]	Percentage
Prefab I	1,128	825	34	337	100.0%
Prefab II	1,212	900	34	346	102.4%
In-Situ II	1,239	327	37	950	281.5%
In-Situ I	1,109	98	38	1,050	311.2%
In-Situ IV	1,613	436	38	1,216	360.3%
In-Situ III	1,305	21	36	1,320	391.3%

9.5. Assessment alternatives different aspects combined, without costs

It is also interesting which alternative is economical the most attractive if Direct and Indirect costs do not influence the selection of an alternative. This situation can occur, if a client requires the best solution, no matter the costs. In this paragraph different combinations are made with the fictitious discount of the governing aspects. In Appendix G2 the assessments are presented.

Table 9-11 Assessment variant IX

Time Schedule	Fictitious discount [x €1,000]	Percentage
Prefab I	200	100.0%
Prefab II	200	100.0%
In-Situ III	21	10.3%
In-Situ I	13	6.4%
In-Situ II	13	6.4%
In-Situ IV	0	0%

Table 9-12 Assessment variant X

Impact on traffic, Impact on environment	Fictitious discount [x €1,000]	Percentage
Prefab II	600	100.0%
Prefab I	546	91.1%
In-Situ IV	436	72.6%
In-Situ II	314	52.3%
In-Situ I	43	7.15
In-Situ III	0	0%

Table 9-13 Assessment variant XI

CO_2 emission	Fictitious discount [x €1,000]	Percentage
Prefab II	100	100.0%
Prefab I	78	78.3%
In-Situ I	42	42.0%
In-Situ II	0	0%
In-Situ II	0	0%
In-Situ III	0	0%

Table 9-14 Assessment variant XII

Time Schedule, Impact on traffic, Impact on environment	Fictitious discount [x €1,000]	Percentage
Prefab II	800	100.0%
Prefab I	746	93.3%
In-Situ IV	436	54.5%
In-Situ II	327	40.8%
In-Situ I	56	7.0%
In-Situ III	21	2.6%

Table 9-15 Assessment variant XIII

Time Schedule, Impact on traffic, Impact on environment, CO_2 emission	Fictitious discount [x €1,000]	Percentage
Prefab II	900	100.0%
Prefab I	825	91.6%
In-Situ IV	436	48.4%
In-Situ II	327	36.3%
In-Situ I	98	10.9%
In-Situ III	21	2.3%

Table 9-16 Assessment variant XIV

Time Schedule, Impact on traffic, Impact on environment, CO_2 emission, Risk Analysis	Fictitious discount [x €1,000]	Percentage
Prefab II	866	100.0%
Prefab I	791	91.3%
In-Situ IV	398	45.9%
In-Situ II	289	33.4%
In-Situ I	59	6.9%
In-Situ III	15	-1.8%

9.6. Scatter of assessment

To interpret the results of the assessment a scatter is calculated of the aspects. In Appendix G1, the total result of scatter is presented. In table 9-17 the results are summarized of a scatter of the fictitious discount. The scatter is calculated relative to the lowest direct costs. The other aspects are calculated relative to the highest fictitious discount. In the scatter it can be seen that some values are close to each other.

Table 9-17 Scatter fictitious discount

	Direct costs	Time schedule	Impact on traffic	Impact on environment	CO_2	Total
In-Situ I	100%	6.4%	0%	21.4%	42.0%	10.9%
In-Situ II	111.7%	6.4%	67.3%	22.3%	0%	49.6%
In-Situ III	117.6%	10.3%	0%	0%	0%	39.9%
In-Situ IV	145.5%	0%	100%	17.9%	0%	48.4%
Prefab I	101.7%	100%	100%	73.2%	78.3%	91.6%
Prefab II	109.2%	100%	100%	100%	100%	100%

Coherence

After this assessment it can be noticed that a choice in a certain design aspect, will directly influence other aspects of the design. It must be said, that the result of an assessment will depend on the criteria of a client, the priority of this criteria and the starting points and boundary conditions of a project. If a different fictitious discount is given to the aspects, another rating can be obtained.

If the aspects are evaluated separate from each other, then each aspect has a different better alternative. None of the alternatives is unambiguously the “best” on all the aspects. In the next chapter an analysis and interpretation of the results is done.

10. ANALYSIS AND INTERPRETATION OF RESULTS

10.1. Introduction

During the Research Study several aspects are worked out for Prefab and In-Situ alternatives. These aspects are assessed in a fictitious discount model. By means of this assessment an economic most attractive alternative can be indicated. However, in the Master Thesis some starting points and boundary conditions are drafted to elaborate the alternatives. In this chapter an analysis will be done on the results of the Master Thesis. What happens with the results if a starting point or boundary condition will change. Also, the potential of the different alternatives will be looked at.

10.2. Project location dependent

A factor which can influence the design of a viaduct is the location of the viaduct. A lot of starting points and boundary conditions depends on this factor. The Netherlands is a country with a lot of variation in the environment. This variation can be in the surroundings:

- Crowded infrastructure because of a main capital;
- Industrial area;
- A not crowded area like a polder.

There are situations where the preference goes to a Prefab viaduct, this is not specially depending on the project location. In the next paragraphs this will be further discussed. If a viaduct needs to be realized in an area like a polder, with no limitation of space and execution time, the preference goes to an In-Situ viaduct. It was also found that the direct costs are the lowest of this alternative. However, for execution of an In-Situ alternative the subsoil must have a good load carrying capacity. A good load carrying capacity is necessary for the stabilization of false and formwork.

The subsoil in The Netherlands is rather variable. So along with the project location, the boundary conditions can have also a variation in the subsoil condition. The Netherlands has six main landscapes [i8] which can influence the substructure of a viaduct or the type of temporary construction:

- Clay (River), near areas of the Rivers: Rijn, Maas, Waal en IJssel;
- Clay (Sea), in the coastal areas of The Netherlands;
- Lösssoil, hills in the south of The Netherlands (Limburg);
- Peat, areas in North and South Holland (e.g. Amsterdam);
- Dune landscape, in the dunes of coastal area;
- Sand landscape, large areas of the North, Mid and South of The Netherlands.

As been said, the subsoil is of importance for the foundation and the substructure. If the subsoil has a bad load carrying capacity (like a peat underground), the foundation needs extra foundations piles or has a need of foundation piles for the falsework to make sure that no calamities occur. In the Master Thesis an assumption is made, that the substructure for Prefab and In-Situ viaducts are equal. So a variation in the subsoil will not express in a difference in the alternatives.

10.3. Preliminary design

Global dimensions are calculated for the In-Situ and Prefab alternatives in the preliminary design. Dimensions of the deck, bank seat, intermediate pier and foundation piles are determined. The substructure of both type of viaducts are almost equal. The difference is in the number of foundation piles. The number of piles for the In-Situ alternatives of building on a higher level, driving and launching the deck into place, is not specified in the preliminary design. Therefore the estimation of number of piles is omitted.

Table 10-1 Structure depth per alternative

	In-Situ I	In-Situ II	In-Situ III	In-Situ IV	Prefab I	Prefab II
Deck height [m]	1.00	1.30	1.30	1.00	1.35	1.00
Number of piles	46	-	-	-	40	34

The depth of the deck for the different structures is estimated with rule of thumbs and design graphs of Spanbeton. The calculations made for the In-Situ deck are very conservative and a number of load cases are not taken into account. In experience of BAM Infraconsult, it seems that for a span of 2x30 m, the construction height of a prestressed In-Situ deck can be optimized until 900 mm.

The design graphs of Spanbeton are developed according to NEN-EN 1992-2. This means that the same load model as described in the boundary conditions is applicable. The design graphs are a good estimation for the construction height of a prefab concrete viaduct. However, when adjusting the concrete strength class, or spans with different type of beams, the structure depth can also be optimized until a certain point.

For an extensive comparison between the structural design of an In-Situ and a prefab concrete viaduct, the following steps have to be taken:

1. Model the In-Situ deck as a massive plate. Model the Prefab beam elements as an Orthotropic plate;
2. Import these models in a finite element program;
3. Take all possible load cases and load combinations into account in the finite element program. Schematize the supports as springs;
4. From this calculation, the maximum force distribution is obtained. Both in the longitudinal and in the transversal direction;
5. With these values, the prestressing cables and reinforcement is calculated.

Without this extensive calculation, it can be concluded that the construction height of a prestressed In-Situ concrete deck will be lower than the construction height of a prefab beam. For a span of 30 m it is not possible to realize a construction height of 900 mm for prefab beams that can carry all the load cases.

An adjustment can be made in the design by reducing the span of the viaduct by means of adding one or two extra intermediate piers. Another option can be to construct an abutment instead of a bank-seat. The result of reducing the span is a reduction in amount of concrete and reinforcement steel. Direct costs will be decreased and the reduction of the span will also be beneficial for the time schedule and for sustainability. The disadvantage of an abutment is less sight for the traffic user behind the viaduct. Example and description are given in the Literature Study (paragraph 2.2.3). This can cause a decrease of safety of the national highway. The control measure can be a speed reduction over a certain length of the national highway.

The change in dimensions of the viaduct gives also a change in the following aspects. In case of In-Situ alternatives this will be the most beneficial:

- Time schedule, subsequently the impact on traffic (in case of In-Situ I and II);
- Cost estimation;
- Durability (amount of CO_2 emission).

10.4. Execution method and execution time

The following execution methods are discussed during the preliminary study:

- In-Situ I, deck constructed in two phases;
- In-Situ II, deck constructed on a higher level;
- In-Situ III, deck driven into place;
- In-Situ IV, deck launched into place;
- Prefab I, inverted T-beams;
- Prefab II, box-girders.

The execution method for the substructure of a viaduct will be the same in case of either an In-Situ or a Prefab concrete viaduct. The differences are obtained in the superstructure of the viaduct. Generally, the deck construction can differ. For an In-situ deck structure relatively many man hours are needed on the building site, and a construction time of nearly 90 days is required. The prefab beams can be installed in one weekend. However, the preparation time of prefab beams must be included. The beams need to be produced in a factory and transported to location of the project. The concrete factory can produce one beam each day, for the total viaduct the production for beams is completed in 20 days. The execution time of the alternatives is displayed in table 10-2.

Table 10-2 Execution time alternatives

	In-Situ I	In-Situ II	In-Situ III	In-Situ IV	Prefab I	Prefab II
Substructure	62	62	62	62	62	62
Superstructure	90	96	92	100	12	5
Finishing works	50	50	50	50	50	50
Total days	190	190	187	195	117	117

Based on the total construction time of the alternatives, the Prefab viaducts is the better choice. The In-Situ alternatives require approximately 65% more time to complete the viaduct. This is mainly caused by the large amount of time required to build a falsework, to install the reinforcement and cast the concrete. In case of safety, the Prefab beams are preferred. On the construction site itself, less activities are needed. The fewer activities on site will also increase the safety during construction of the viaduct. Especially with In-Situ alternatives II and IV, because the alternatives are built above a national highway that is still in use.

When a project contains more viaducts, an In-Situ viaduct becomes beneficial because of the repetition of the false and formwork. The costs of the false and formwork can be spread over the project. Also, a repetition factor is beneficial for execution time (because of experience).

If speed in the execution method is a boundary condition, the obvious choice is a Prefab beam viaduct. However, in combination with other boundary conditions the choice is not necessary a Prefab construction. For prefab beam elements there must be enough space to manoeuvre and install the beams. So, if at a location the range is small, such that a Prefab beam of 25 – 30 m cannot be installed, the alternative is not automatically the best choice.

Another point of attention is the weight of the cargo for Prefab or In-Situ alternatives. A Prefab box beam (SKK1100) of 30 m has a weight of approximately 50 tonnes (only the beam, not the weight of the truck). The infrastructure must be able to bear this load. When infrastructure is damaged, the damage has to be repaired by the contractor. To compare: an In-Situ truck mixer of 12 m³ has a weight of approximately 29 tonnes.

The change in an execution method gives also a direct change in the following aspects:

- Structural design;
- Time schedule, subsequently the impact on traffic;
- Cost estimation.

10.5. Impact on traffic

Impact on traffic exists of the lost vehicle hours and the experience of road users on the impact on traffic. The lost vehicle hours is calculated for each alternative in Prefab and In-Situ concrete. This is elaborated by the traffic measures needed to construct the viaduct. It has been found that the construction of the intermediate pier and the bank seats is executed on the same manner for each alternative. The difference is obtained in the required traffic measures to construct the deck.

When the impact on traffic is of high priority to clients, certain alternatives are beneficial. Less impact on traffic will cause less traffic jams and also the sympathy of the road user for construction activities will enlarge. It follows from table 10-3 that the Prefab beams are causing the least impact on traffic (due to traffic stops in the night). It seems that launching the deck is also a favourable solution for a small impact on traffic. However, other aspects like a long total execution time can work as a disadvantage. The first three alternatives in In-Situ concrete are having a large amount of lost vehicle hours. This is caused due to the measures needed for execution (explained in chapter 5):

- 4x0 system;
- 2x3 system with speed reduction;
- Weekend closure.

Table 10-3 Lost vehicle hours

	In-Situ I	In-Situ II	In-Situ III	In-Situ IV	Prefab I	Prefab II
System	4x0	2x3 v=90km/h	Start situation	Start situation	Start situation	Start situation
Total (LVH)	15,893,120	438,060	2,425,107	460	230	230

The impact on the environment is measured by means of the amount of transportation needed. Again, the Prefab alternatives are more beneficial than the In-Situ alternatives. Because the In-Situ alternatives are casted on site, there is a large amount of concrete trucks required. The Prefab inverted T-beams have 50% more impact on the environment then Prefab box beams. This is caused because of the required In-Situ structural topping.

If impact on traffic is a leading requirement, the choice is again Prefab beams. Impact on traffic and Impact on environment combined, gives Prefab box beams as best alternative (table 9-14). Combined with the Direct and Indirect costs, the inverted T-beams is most beneficial.

10.6. Cost estimation

The cost estimation contains three parts: direct, indirect, general overhead. Direct costs are based on the structure itself (the materials and equipment), indirect costs are based on time depending costs. General overhead is a percentage from the direct and indirect costs, and is depending on market situation (risks and profit). In table 10-4 it can be seen that the direct costs of an In-Situ concrete viaduct build in two phases is the lowest. To build a deck next to the location and launch into place, is the worst scenario in the direct costs with an additional cost of 45% relative to In-Situ I. This is mainly caused by the large one time execution costs which are estimated on €250,000. The other alternatives are closer together with difference of approximately 2%-18%. This means in principle, that the direct costs cannot be a leading requirement in the selection of an alternative.

Table 10-4 Cost estimation (in thousands of euros)

	In-Situ I [x €1,000]	In-Situ II [x €1,000]	In-Situ III [x €1,000]	In-Situ IV [x €1,000]	Prefab I [x €1,000]	Prefab II [x €1,000]
Direct costs	804	898	945	1,169	831	893
Indirect costs	161	180	189	234	150	161
General overhead	145	162	170	210	147	158
Total	1,109	1,239	1,305	1,613	1,128	1,212

The costs of traffic measures and safety measures are not taken into account in the cost estimation. This can make a difference in the cost estimation. Especially for In-Situ I (lowest direct costs), because this alternative has the largest amount of traffic measures (redirection of the carriage way).

The market fluctuation can be of influence on the direct costs. The alternatives have a large amount of concrete and reinforcement. The In-Situ alternatives require a large amount of steel for the temporary structures. If steel has a high price, the In-Situ alternatives become more expensive. The market fluctuation can also have an influence during the project. If a tender is done with a certain price, this can differ during the project by the market fluctuation.

It is interesting what happens if the suppliers of each alternative are involved in the very beginning of a project. If steel suppliers or Prefab suppliers are involved in the beginning of a project, the solution can be optimized in an early stage of the project. It is possible that the direct costs of the six different alternatives are approaching each other, such that all alternatives are within the 5% difference. The Master Thesis has not discussed the procurement phase during the project. This matter can be of value for the Royal BAM Group, however it is not of value for this Master Thesis (as stated by the assessment committee).

10.7. Durability

During the Literature Study it was found that In-Situ concrete is more advantageous then Prefab in emission of CO_2. This is caused by the difference in the type of cement. In chapter 7 of the Master Thesis the CO_2 emission was calculated for each of the alternatives in In-Situ and Prefab. After this calculation it was found that the amount of CO_2 emission of an In-Situ alternative was larger than prefab. As can be seen in table 7-6, the CO_2 emission of an In-Situ alternative can be as twice as much relatively to the Prefab. The reason for this is the amount of concrete required for the construction. The In-Situ decks have a solid cross section over the total length of the viaduct. The Prefab decks have in contrast a non-solid cross section. In paragraph 7-8 the impact of the parameters is discussed. It seems that concrete has a contribution of 40% and steel has a contribution 50% of the total CO_2 emission. To bring the Prefab and In-Situ alternatives closer to each other, one has to look into the structural design of the viaduct. If an In-Situ alternative can be optimized in dimension, the CO_2 emission will decrease.

Other aspects which have an influence on the CO_2 emission are the following:

- Location of the project: transport distances;
- Structural design: concrete mixture, amount of concrete and steel;
- Execution method: Prefab or In-Situ.

10.8. Risk Analysis

According to the RISMAN method, a risk analysis is made for the alternatives. As can been seen in table 10-5, the Prefab alternatives are advantageous in costs over the In-Situ alternatives. The difference in the costs after the control measures has a maximum of 12%. This can be explained by a high risk profile. If boundary conditions and starting points change because of a different project location in the Netherlands, the risk profile can change. The consequences at a different location can be lower or higher. During the risk analysis some aspect are discussed. However, safety risks for each execution method are a little bit underexposed during the Master Thesis. For example, what are the consequences for employees working with heavy equipment and large Prefab elements.

Table 10-5 Result of quantification of alternatives

	Before control measure		After control measure	
	Costs [€]	Time [weeks]	Costs [€]	Time [weeks]
In-Situ I	367,125	20.8	38,350	6.5
In-Situ II	367,125	21.7	37,150	6.9
In-Situ III	420,850	17.1	35,975	6.6
In-Situ IV	403,875	18.9	38,100	4.5
Prefab I	277,125	18.9	34,025	5.1
Prefab II	277,125	17.9	34,025	5.1

The control measures have some costs, these costs have to be added up to the costs after control measures. In the Master Thesis the costs for control measures are neglected, because of the difficulty to quantify the costs of the control measures. This means, that the rating in table 10-5, is not the actual rating. It can be possible that control measures for the Prefab elements are more expensive than the In-Situ alternatives.

10.9. Assessment of alternatives

During the assessments of the different alternatives in chapter 9 and Appendices G1 and G2, several configurations of the aspects are presented. It can be seen in the results that if more aspects are combined, the Prefab and In-Situ alternatives are diverging in the fictitious subscription price. A doubling in the fictitious discount is no exception in combining more aspects. The two Prefab alternatives are always close to each other, a difference of 5-10%.

The following combinations are close to each other considering In-Situ and Prefab:

- Direct and Indirect costs, Time schedule: 18% difference in favour of Prefab;
- Direct and Indirect costs, Impact on traffic, Impact on environment: 59% in favour of Prefab;
- Direct and Indirect costs, CO_2 emission: 1.7% in favour of Prefab;
- Direct and Indirect costs, Risk Analysis: 1.3% in favour of Prefab.

If combinations are made with the different aspects, but without the influence of Direct and Indirect costs, the conclusion is that an alternative of Prefab Box beams is receiving the most fictitious discount. The difference between the Prefab and In-Situ alternatives is approximately 30% in case of Impact on traffic and Impact on environment. The difference is more than 50% in all the other configurations of aspects.

The difference between the two Prefab alternatives is 20% in case of CO_2 emission and approximately 10% in all the other configurations of aspects. These assessments are in favour of the Prefab box beam.

11. CONCLUSIONS AND RECOMMENDATIONS

11.1. Conclusions

The answer on the problem definition of the Master Thesis is as follows:

> *"According to the governing aspects: time schedule, impact on traffic/environment, sustainability, risk analysis and cost estimation, which are established during the Literature Study, the alternative of Prefab inverted T-beams with a structural topping is considered the most economically attractive."*

A side note has to be made to this conclusion: the elaborated aspects are depending on the boundary conditions which are formulated for the Master Thesis. In a real project the location of the viaduct has to be considered. When the surroundings at the location and the subsoil conditions differ from the boundary conditions stated in the Master Thesis, the choice in structural design and execution method can change. Consequently the answer has to be reconsidered.

Impact on traffic has a large influence in consideration of the most economically attractive alternative. At other locations in The Netherlands, the impact on traffic can be less than in the case of the situation described in the Master Thesis. Also, when impact on traffic has no priority for the client, the impact on traffic is not taken into account in the assessment and the alternatives in Prefab and In-Situ are becoming more equal.

The following conclusions can be drawn, if different combinations (presented in Appendix G1) are made with the governing aspects:

- Purely based on Direct and Indirect costs, alternative In-Situ I is the best alternative;
- Combining Direct and Indirect costs with the fictitious discount of the Time schedule, alternative Prefab I (inverted T-beams) is the best alternative;
- The fictitious subscription price of alternative Prefab I is the lowest, when combining Direct and Indirect costs, Impact on traffic and Impact on environment;
- Aspect of CO_2 emission combined with Direct and Indirect costs, gives Prefab I as the best alternative;
- Direct costs and Indirect costs with the additional costs of possible risks results in the best alternative of In-Situ I;
- Alternative Prefab I is the best alternative if the following aspects are combined: Direct and Indirect costs, Time schedule, Impact on traffic, Impact on environment;
- Alternative Prefab I is the best alternative if the following aspects are combined: Direct and Indirect costs, Time schedule, Impact on traffic, Impact on environment, CO_2 emission;
- If combinations are made from the different aspects, but without the influence of Direct and Indirect costs, the conclusion is that an alternative with Prefab Box beams is the most economically attractive. The combinations are presented in Appendix G2.

11.2. Recommendations

During the Research Study some interesting points came forward. Because of the scope of the Master Thesis and the limited time to elaborate the Master Thesis, these interesting points are not further elaborated. In this paragraph some recommendations for future research and development in the selection in a Prefab or In-Situ concrete alternative are suggested.

Structural design

The structural design of the viaducts can change by the adjustment of the boundary conditions. This gives uncertainties in amount of concrete and steel, which in their turn influence the cost estimation, time schedule (impact on traffic) and CO_2 emission. This has the largest influence with In-Situ alternatives. Per new project the consideration of Prefab and In-Situ have to be reviewed. At the start of a tender, all possible solutions for the project location have to be taken into account. A multidisciplinary project team with a blank sheet as a start up for a project is a good start.

Possible questions for structural design can be:

- Is an In-Situ alternative becoming more equal to the Prefab solution if a voided concrete slab is used? (Perhaps in combination with a reduction in span).
- If concrete mixture or concrete strength is adjusted for the In-Situ alternative, is there a consequence in structural design and CO_2 emission?

Change of location viaduct

Crossing a 2x3 national highway is one of the boundary conditions in the Master Thesis. Based on that, a design of a viaduct is elaborated and execution methods are described. It is worth investigating whether the conclusion of the Master Thesis is also true for other national highways instead of 2x3 traffic lanes.

A 2x2 national highway is also a common road in The Netherlands. The width of a carriageway is smaller than the carriageway of a 2x3 national highway. A change in structural design can be obtained (smaller span) and subsequently a change in cost estimation and CO_2 emission due to the variation in quantity. Impact on traffic is also one of the aspects that will be influenced due to this new boundary condition. The Lost Vehicle Hours (LVH) in case of the Prefab alternatives will not change. The prefab beams are still transported and installed during the night. Though, the impact on traffic for In-Situ alternatives can change.

If the carriageway of the national highway is approximately 13m in width, a 4x0 traffic lanes system is possible. In this case, alternative In-Situ I does not have a large influence on Impact on traffic. The reduction in capacity of the road is not that large. The traffic lanes will be temporary reduced with a speed reduction, however there will be still two traffic lanes available for each direction of the road. Hence, the influence of the traffic measures will not cause a large impact on traffic. Also the LVH will be rated in a different way in areas with a less density in traffic and environment.

In a new assessment with governing aspects of Time schedule, Impact on environment and CO_2 reduction, a Prefab alternative will probably still have the preference. However, the result of the assessment will be closer to each other. So, if direct costs are an important factor and not the aspects of the assessment model, an In-Situ alternative can be beneficial instead of the Prefab alternatives.

Maintenance

During the Master Thesis the maintenance of a viaduct is not taken into account. The need of repairing the viaduct after completion of the viaduct can be of interest during a design process. Which alternative is more sensitive for maintenance? If maintenance is required upon the viaduct, there can be again Impact on traffic. Also, the materials required for maintenance have a certain CO_2 emission. These two aspects can be taken into account during the design process and assessment of an alternative.

However, the design of an In-Situ as well as a Prefab viaduct must meet the requirements from the different norms (Eurocode or ROK). When a lifetime of 100 years is required, both alternatives must be designed in such a way, that this requirement is met. There will be no large difference in the concrete quality of In-Situ and Prefab concrete if the four critical C's: "Concrete mix, Cover to reinforcement, Compaction and Curing of concrete" [2] are taken into account in a proper way during design and execution.

A factor during casting of In-Situ concrete can be the weather. If weather conditions change in such a way that it can influence the quality of the concrete, this can be anticipated by adjusting the concrete mix, proper curing or maybe a temporary tent construction over the viaduct. The maintenance activities of the asphalt, furniture on the viaduct or the bearings of the viaduct are equal for both alternatives and do not make a difference in the selection of an alternative.

Due to the consideration above can be said that maintenance does not have a large influence on the assessment of the alternatives.

Safety

During the execution of a viaduct, the safety of traffic users and of employees of the contractor is of importance. Which execution method has more influence on safety? At first it seems that an execution method with prefab elements is safer because of less activities than associated with an In-Situ execution method. However, these large elements have to be produced in a factory and have to be transported. During these phases also a lot of safety measures need to be taken into account. In a future research it can be interesting to investigate and compare different execution methods and assess these on working conditions of employees, safety for traffic users and safety for public.

Prefab vs. In-Situ in other structures then viaducts

Will there be a different answer on the problem definition if other structures then viaducts are considered? For example the use of Prefab and In-Situ concrete in tunnels? It is an interesting question, because different execution methods can be used for constructing a tunnel. E.g. bored tunnels, immersed tunnels, cut and cover, or constructing a tunnel in an open building pit.

Another possible structure is a bridge. Which alternative in Prefab or In-Situ concrete is more economical in the balanced cantilever method of a bridge with a span of 200 m or larger? By constructing a bridge in this manner the question is interesting because other aspects as impact on shipping traffic becomes interesting. Impact on traffic will also change, because there is no road to cross.

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