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Harmonised traffic load model between Eurocode 1 - part 2 (EN 1991-2) and TRV specifications:

A pilot study on reinforced concrete portal frame bridges

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Harmonised traffic load model between Eurocode 1 - part 2 (EN 1991-2) and TRV specifications:

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Abstract

The advancement of society has led to an increase in demand for infrastructure, particularly bridges, which are designed in accordance with different design codes. In Sweden, bridge design adheres to the Eurocode and national code (TRV specifications), with the most adverse scenario of the two codes determining the basis for bridge design. The process of designing a bridge according to both codes and subsequently comparing them necessitates a prolonged design duration, resulting in an increase in project costs.

This thesis explores the possibility of determining multiplication factors α_M and α_V for the bending moment and shear force respectively, which would enable the direct transition from the most unfavourable load case in the Eurocode to the worst one in the TRV specifications. Thus, the bridge can be modelled based on the most conservative of the two.

The study concentrates on portal frame bridges ranging in length from 6 to 25 m, with a 1 m step between each case study and expanding from 1 to 4 traffic lanes. The FEM software "Brigade/Plus" was used to analyse the portal frame bridges, with the key internal forces being the longitudinal bending moments and shear forces in the deck slab.

The analysis of the different models showed that bridges with four lanes had α_M increasing according to a quadratic relation while α_V increased linearly. In the case of three-lane bridges, only one value of α_M was greater than one. In conclusion, the analysis indicated that the Eurocode is more conservative for short-span bridges of up to three lanes and less conservative for four lanes above a span length of 16 m.

Keywords: Live load, Bridge design, Portal frame bridge, Concrete bridge, Eurocode, Swedish annexe, Brigade/Plus, Finite Element Analysis.

Sammanfattning

Samhällets utveckling har lett till en ökad efterfrågan på infrastruktur, särskilt broar, som är utformade enligt olika designkoder. I Sverige följer brodesignen eurokoderna och nationella krav (TRV:s krav), där det mest ogynnsamma scenariot av de två regelverken utgör grunden för dimensionering av en bro. Processen att designa en bro enligt båda regelverken och därefter jämföra dem kräver en förlängd prjekteringstid, vilket resulterar i en ökning av projektkostnaderna.

Denna studie undersöker möjligheten att bestämma multiplikationsfaktorerna α_M och α_V för böjmoment respektive skjuvkrafter, vilket skulle möjliggöra en direkt övergång från det mest ogynnsamma belastningsfallet i Eurokoden till det motsvarande i TRV:s krav. Därmed kan bron kontrolleras utifrån den mest konservativa av de två.

Studien koncentrerar sig på plattrambroar med en längd från 6 till 25 m, med ett steg på 1 m mellan varje fallstudie och en bredd från 1 till 4 körfält. FEM-mjukvaran "Brigade/Plus" användes för att analysera plattramsbroarna, där de inre snittkrafterna var de längsgående böjmomenten och skjuvkrafterna i farbaneplattan.

Analysen av olika modeller indikerade att broar med fyra körfält hade ett α_M som ökade med ett kvadratiskt samband, medan α_V ökade linjärt. I fallet med broar med tre körfält var endast ett värde på α_M större än ett. Sammanfattningsvis visade analysen att Eurokoden var mer konservativ för broar med korta spann på upp till tre filer och mindre konservativ för fyra filer med en spännvidd över 16 m.

Nyckelord: Trafiklast, Brodesign, Plattrambro, Betongbro, Eurokoder, Brigad/Plus, Finita elementmetoden

Preface

This master thesis is the final task of the master’s programme civil and architectural engineering at the Royal Institute of Technology (KTH). The study took place during the spring of 2023 and accounted for 30 credits, furthermore the project was made in collaboration with AECOM Nordic in Stockholm.

We would like to thank all the people who helped us during our thesis, mainly we want to give a special thanks to our supervisors John Leander, associate professor at KTH and Dr. Filippo Sangiorgio, Project manager Civil infrastructures at AECOM Nordics. We would also like to thank all the staff at AECOM for the warm welcoming to the office and the support during our time there. We also want to thank the provider of the FEM tool Brigade/Plus “Scanscot” who helped us tremendously with providing the student licences.

Last but not least, we want to thank our parents and siblings for all their support up until now. This would not be possible without them and we want them to know that we are truly grateful for your presence in our lives and will never forget all the sacrifices you have made to make this possible.

Abbreviations

EC	Eurocode
EEC	European Economic Community
FE	Finite element
FEA	Finite Element Analysis
FEM	Finite Element Method
LM 1	Eurocode Load Model 1
LM 2	Eurocode Load Model 2
TRV	Swedish Transport Administration (in Swedish: Trafikverket)
TS	Tandem System
TSFS	Swedish Transport Agency Regulations "Transportstyrelsens författningssamling"
UDL	Uniform Distributed Load
ULS	Ultimate Limit State
WIM	Weigh In Motion

Symbols

α_M	Bending Moment Load Multiplication Factor
α_q	Load model 1 vehicle load coefficient
α_Q	Load model 1 UDL coefficient
α_V	Shear force Load Multiplication Factor
ε	Dynamic factor
d	Thickness of the deck
E	Young elasticity modulus
E_d	Design value of the effect of actions
L	Total length of the bridge
l_{bd}	Anchorage length
M	Bending Moment
P	Point load
q_k	Load model 1 characteristic UDL
Q_k	Load model 1 characteristic vehicle load
R_d	Design value of corresponding resistance
V	Shear Force
v	Poisson's ratio
2D	Two dimensions
3D	Three dimensions

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1. Introduction

Society is constantly evolving and demand for new infrastructures is increasing to both expand and increase the efficiency of the transportation network in Sweden. One of these infrastructures is portal frame bridges which are widely used in both roads and railways. When designing these bridges certain standards are necessary to take into account, such as the Eurocode and Swedish Codes (TRV specifications)(Ellingwood et al., 2013). Standards in general are set to maintain a structural behaviour that will carry the expected load within the region of the standards (American Concrete Institute [ACI], 2015).

The main objective of the thesis is to find the relation between Eurocode 1 part 2 (EN 1991-2) and TRV specifications, which is one part of the Swedish annexe. This relation will be in the form of a multiplication factor both for the bending moment and also for the shear forces in the deck slab.

These multiplication factors (α_M and α_v) will not only give a better understanding of the standards that are considered, but they are also calculated for the following reasons:

- Faster design process, in regards to computational time when designing in FEM tools.
- Minimize the design cost and increase the design efficiency.

Portal frame bridges are constructed in a diverse range of sizes. In order to make the study both more comprehensive in regards to the multiplication factors and to cover as many sizes of portal frame bridges as possible, a total of 80 different case studies have been studied where each study consists of a bridge with a specific number of lanes and lengths. The selection of 80 bridges was made with two primary objectives in mind, to ensure the study could be completed within a reasonable timeframe while also providing sufficient data to confidently answer the research questions.

1.1 Background

For a long period of time, standards have served as a cornerstone of human civilization. As far back as 1772 BC during the Babylonian Empire, the concept of building a standard emerged. King Hammurabi established a performance-based code that prescribed strict consequences for projects not including the use of these standards, thereby cementing the importance of normalising established standards (National Council of Governments on Building Codes and Standards, 2016).

While the primary aim of standards remains the preservation of health and safety, their scope has expanded considerably over time. Modern standards also include a wealth of information, such as environmental precautions aimed at minimising damage to nature. These regulations also do serve as a vital means of facilitating communication within the industry, with regulatory authorities defining the requirements that engineers must follow (European Commission, 2023.).

In the early 1990s, the European Union introduced the Eurocode, intending to introduce a unified set of standards that could be implemented across all member states. One of the aims was to promote greater collaboration among member states and establish consistent safety parameters throughout the Union (European Commission, 2023.). At present, the TRV specifications have incorporated the Eurocode as the basis for its applications, which have been adapted to conform to both the climatic conditions in Sweden and the regulatory framework established by the government (Transportstyrelsen, 2018).

In the TRV specifications, there are 14 different traffic load models that should be tested on a bridge, depending on its specifications. While certain load models exhibit greater weight than others, all must undergo testing to ascertain the most adverse load model (Transportstyrelsen, 2018). The establishment of a pre-validated factor would serve to abbreviate this process, thereby conserving both time and financial resources which could then be allocated to other pertinent aspects of the project.

1.2 Aim and Scope

The aim of this study is to analyse both the Eurocode and the TRV specifications´ loads on portal frame bridges to find a multiplication factor α_M and α_V that will make it possible to directly go from the worst load case in the Eurocode to the worst one in the TRV specifications and therefore model the bridge after the most adverse of these. This study was carried out on portal frame bridges with lengths varying between 6 and 25 m, with a 1 m step in between each case study, the bridges had the widths from 1 to 4 traffic lanes. The portal frame bridges were analysed with the FEM software "Brigade/Plus". The internal forces that are set to be considered are both longitudinal bending moments and shear forces in the deck slab.

The research questions that are of interest for this thesis are:

- Is it possible to define a load multiplication factor for the Eurocode that will be able to give the results of TRV specifications?
- What load case will give the most conservative section forces and moments?
- When will the factor switch from EC being more conservative to TRV being more conservative?
- Will the factor be constant?

1.3 Limitations

For this thesis study, there were some limitations implemented in order to make the study more comprehensive and not too broad. Linear elastic calculations were performed and without considering reinforcement in the FE analyses. This was done in order to make the model simple. Only the responses of the deck were of importance, therefore the wing walls were not included in the study which gave the legs more flexibility. Only the positive bending moment in the deck was studied while the hogging moment at the supports were not studied. The study could consider the negative bending moment as well but this would not provide important information and was therefore neglected. All case studies were only subjected to traffic load models and no earth action loads or traffic surcharge loads were added to the model as the focus was on the deck slab.

2. Literature Review

2.1 Introduction

Different loads are considered when designing a bridge. These loads can be categorised as permanent and variable loads, such as wind, temperature and traffic loads. Live load models are mathematical representations of loads that are necessary for the structure to be able to carry, such as lorries or trains. These models are created to ensure a certain level of safety when designing a bridge.

Traffic loads tend to increase over time, in order to minimise the risk of exceeding the bearing capacity of the bridge components, the creation of the load models involves specifying a return period where load models are not expected to differ from real loads during a given period. The return periods vary significantly between different regions, with a range of 75 years in the United States and up to 1000 years in Europe (O'Brien, Nowak, & Caprani, 2022).

2.2 A Historical Overview

2.2.1 Bridge Design History: Sweden

By definition a bridge is a structure that transfers a path over a free opening with at least 2 m span in any direction. These structures have been built for a long time and are necessary to our infrastructure. Throughout the years the loads that bridges have to carry have increased which have made several bridges less robust. This is a natural progression since previously bridges were often made out of timber and needed to carry horses while nowadays concrete bridges are more frequently built and have to be able to carry heavy vehicles such as big trucks. This has led to the use of materials for bridges to vary throughout the years as seen in Figure 1, which only shows the change in material between 1950 and 1990 and the curves still vary a lot. This data is available since the road authority in Sweden was nationalised in 1944 (Von Olnhausen, 1991). The idea of making the road authority nationalised started in 1941 when the communication department sent a principle report that stated that it should be questioned whether or not the authority of roads should become nationalised. This report was sent due to the high costs and the incompetence of the board that addressed questions about roads at that time (Dahlin, 1941). When the Swedish road authority was made there were a lot of changes and rules that were made. Now it was required to document, inspect and have road requirements, This is also where the Swedish load cases started to develop more frequently (Von Olnhausen, 1991).

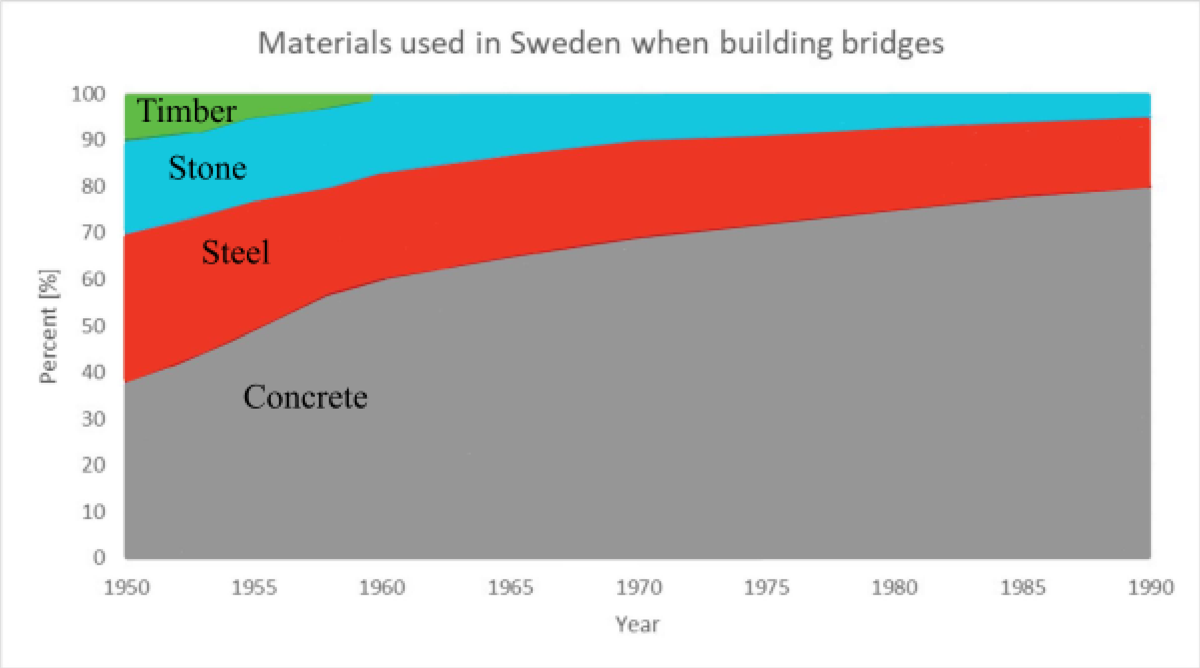


Figure 1: Type of material used for Swedish bridges in percent (Von Olnhausen, 1991).

2.2.1.1 Load models: 1840-1930

Although The Swedish road authority was nationalised in 1944 there are building codes that are older and were used before the nationalisation. Already in 1841 the board of road and water structures (Konliga styrelsen för allmänna väg- och vattenbyggnader) was created. This board aimed to assist the road construction. In 1883 the name was changed to “Kungliga väg- och vattenbyggnadsverket" and in 1886 the first standard was provided. It was required to design the superstructure of a highway bridge with a traffic load that consisted of 480 kg/m^2. The axle load was still not implemented in the load model but was introduced around 1901 when the distributed load was increased to 500 kg/m^2 but the structure could also be designed for one or two vehicles. The vehicles had a maximum distance of 4 m between the axles and an axle load of 1.5/3 tons. The highest total load would be 9 tons with two vehicles combined (Ronnebrantt, 2023).

In 1931 new demands were set for load cases on bridges. Two new alternatives were created as load models:

- $P = 2 - 0,01 \cdot L$ where P is the point load and L the length of the bridge, but the lowest possible used weight would be at least 1.2 kg/m with a traffic lane of 2.5 m width.
- One or two lanes that includes two vehicles with a weight of 12 tons and with an axle width of 4 m. The axle lead is set to 3/9 tons with a dynamic factor of 20%.

These two alternatives were set (Ronnebrant, 2023).

2.2.1.2 Load models: 1930-1990

Another department that made standards shortly after was the communication department which released “Statens Offentliga Utredningar" in 1938, which consisted of load cases that were used for iron structures. It included calculations for both house structures, bridge structures and encounters for loads such as wind loads, temperature changes and self-weight. For instance, one traffic load that was used for a road bridge is one or several triaxial motor vehicles that weigh 15 tons, this may or may not be combined with a biaxial trailer that weighs 10 tons as seen in Figure 2. (Kommunikationsdepartementet, 1938)

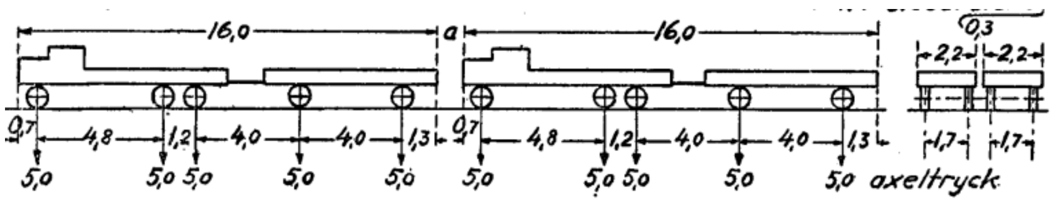


Figure 2: Loadcase for road bridges in 1938, communication department.

When the Swedish road authority was nationalised in 1944, all bridges were assessed in order to be classified. New internal rules were set that needed to be followed. The two load models for designing bridges A/B where A is the axle load and B is the bogie load which are both a part of the variable load and were set to 8/10 tons. This was later on changed two times, in the 1960s it was changed to 8/12 tons and in 1974 to 10/16 tons. Vehicles with a double bogie were introduced in 1985 as seen in Figure 3 and the older vehicles were now calculated with A/B = 12/18 tons (Ronnebrant, 2023).

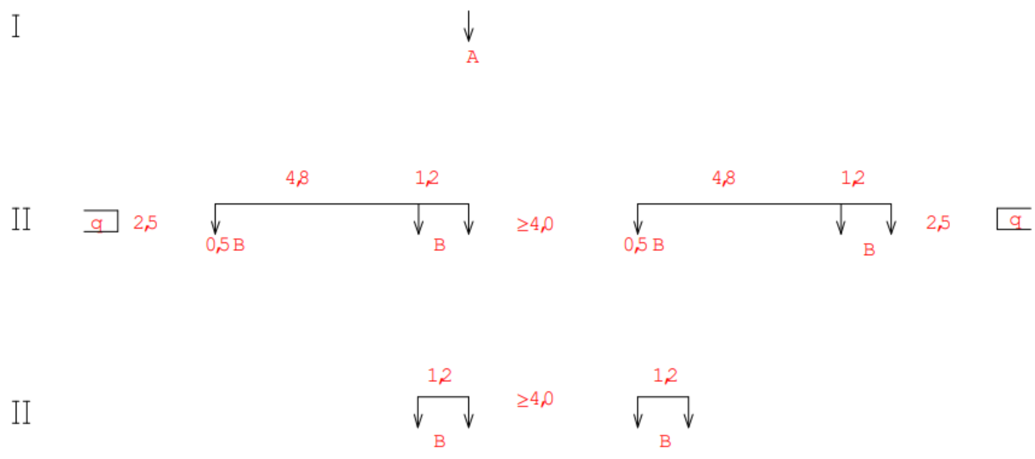


Figure 3: Load models for road bridges in 1985

2.2.1.3 Load models: 1990s

As seen in the previous sections the traffic loads from 1938 and the traffic loads from 2018 (see section 2.5.2) are in many ways different but at the same time similar. This similarity is something that we keep seeing throughout the evolution of traffic loads in Europe and Sweden. "BRO94" which is a document provided by "Vägverket" (now Trafikverket) in 1994, which includes a traffic load shown in Figure 4, where A is 250 kN for the first lane and 170 kN for the second lane, the distributed load is set to 12 and 9 kN/m for the first and second lanes in each direction and 4 or 2 kN/m for all the other lanes (3 and 4). This load model is similar to the EC LM 1. This could be observed in Figure 5, where the width of the lane is the same as in BRO94. Furthermore, both codes include vehicle loads as well as distributed loads and a gradually decrease for each extra lane (Sundquist, 1998.).

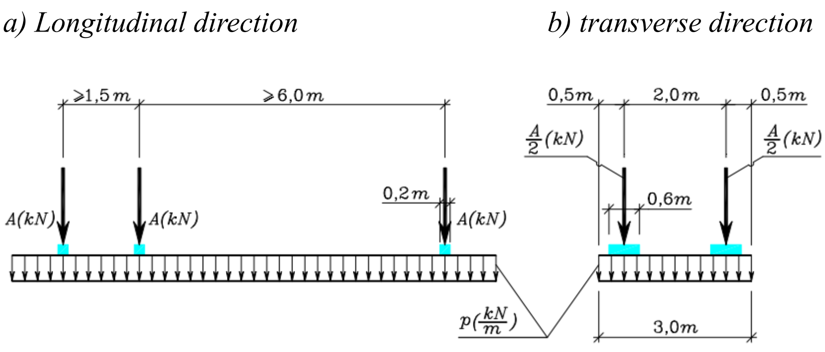


Figure 4: Traffic load model in BRO94.

a) Longitudinal direction *b) transverse direction*

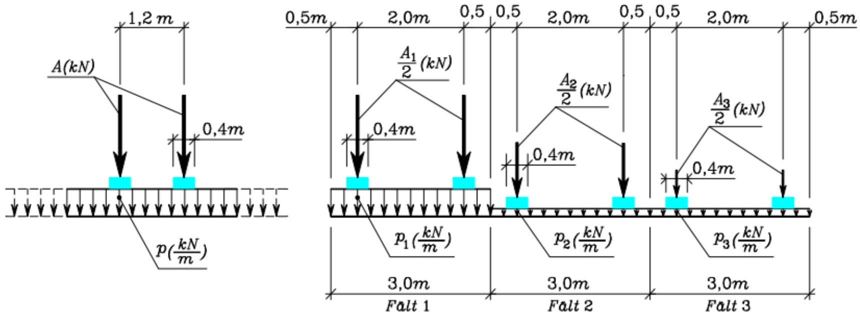


Figure 5: Eurocode traffic load model 1.

2.2.2 Bridge Design History: Europe

The first copy of the Eurocode was published in 1993 (CEN, ENV 1991–3). During the 1960s and before publishing the EC traffic load models were created through empirical methods. Load models were limited to local vehicles. Short to medium-span bridges were designed after the most common vehicle moving along each bridge with some safety margins added.

Bridge spans, transportation distances and vehicle loads increased over time. These factors made the traffic load models a national issue and new design codes were created. During the 1980's united efforts were made to create a model that could be applied in Europe by collecting vehicle data in Auxerre, France (O'Brien, Nowak, & Caprani, 2022).

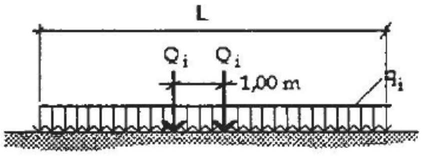
2.2.3 Background of EC Traffic Loads on Bridges

The work of creating a standard model that can be used in Europe when designing bridges in the ULS started in 1987, at a request of the European Economic Community, EEC. The EC is applied in the Euro Region so the background of it was based on the data from the four countries Germany, Italy, Spain and France (Bruls et al., 1996). The method used when collecting the data is known as Weigh In Motion (WIM) (O'Connor et al., 2001). The method is based on collecting data of the vehicles passing on specific roads, data collected was the length, width and weight of the vehicles passing through a specified distance in a given time.

The target model aimed for was based on several factors: traffic samples, traffic situations, influence surfaces and the probability considered that the model created will differ during 50 years was less than 5% (mean return period of 1000 years), (Bruls et a.l, 1996).

The calibration of the LM 1 aimed to combine dynamic effects, concentrated loads and distributed loads. The model was studied starting with loads on one lane up to loads on four lanes. The first draft of EC LM 1 is illustrated in Table 1 below (Bruls et al., 1996):

Table 1: Load Model 1 characteristic values after the first calibration.

	Load Lanes(s)	Q_k [kN]	q_k [kN/m]
	1	$Q_1 = 185$	$q_1 = 29.3 + 375.6/L$
	2	$Q_2 = 100$	$q_2 = 0.487 \cdot q_1$
	3+4	$Q_3 + Q_4 = 150$	$q_3 + q_4 = 0.56 \cdot q_1$

The model was then modified to have constant values for simplicity rather than variable distributed loads as described in Section 2.5.1 later.

Load Model 2 completes Load Model 1. The main difference is that LM 2 takes into account local verification, especially in orthotropic decks and it considers larger contact surfaces of wheels. LM 3 and LM 4 represent other types of loads, abnormal vehicles and crowds on a bridge respectively, (Bruls et al., 1996).

2.3 Studies Performed on EC Load Models

Vehicles' weight had developed rapidly during the last years, while the base data collected for the EC was during the 1980s (Bruls et al., 1996; O'Connor et al., 2011). Several studies were made to ensure the quality and adequacy of EC LM1 to predict future loads on bridges. A study published in 2011 aimed to compare the LM1 created using the data from the 1980s and modern WIM data from 1997. The study was based on reproducing the original model using the old data and replicating the same procedure but using modern data such as updated influence surfaces and vehicle data. The study showed that a significant difference is observed between the two models based on different data but EC LM1 is sufficient and can be still used in the design of new bridges, this could be due to the fact that the main model aimed for a mean return period of 1000 years (O'Connor et al., 2011).

Another study published in 2019 aimed to study new load patterning approaches of real vehicles on long bridges. The study showed that the EC LM1 is too conservative as it targets the worst case scenario by combining the worst case loading topology and the worst loading values. The study showed that by using different modelling approaches such as microsimulations and changing the load value-topology combinations the traffic loading demand may be reduced up to 45% (Guo & Caprani, 2019).

2.4 Design in ULS

When designing a new bridge, different verifications must be made to ensure that the bridge will not collapse. One of the verification methods used in Europe is designing at the ultimate limit state (ULS). The ULS according to EN 1990-2, is a limit concerning the total failure or the collapse of the structure (Gulvanessian, 2009).

The general limit state function according to EN 1990-2 is represented below:

$$E_d \leq R_d \tag{1}$$

Where E_d is the design value of an effect of actions and R_d is the design value of the corresponding resistance (not taken into consideration in this study).

The main parts of a portal frame bridge such as the deck and the legs are mainly constructed of reinforced concrete. These parts are designed by considering different key internal forces as bending moments and shear forces. The different design loads needed when designing different types of bridges are provided by EN 1991-2. While guidelines for how the concrete structures should be analysed are provided by EN 1992-1-1.

2.5 Design Codes

2.5.1 Load models in EN-1991-2 section 4

Eurocode 1 part 2 concerning traffic loads on bridges was established in September 2003. The code provides different traffic load models that should be considered when designing a bridge at the ULS. EN-1991-2 section 4 focuses on road bridges and provides four different traffic load models that should be considered.

The loads in the models are vertical loads modified and calibrated to represent the loads in the European countries year 2000. In the scope of this thesis, only load models 1 and 2 were considered since the other loads represent abnormal loads (EN 1991-2, 2003).

Load model 1 (LM 1): This model aims to capture the main effects of the vehicles on the road such as lorries and cars. The model is made up of two loads, a concentrated load consisting of double axle loads called tandem system (TS) and a uniformly distributed load (UDL). The loads of the TS and UDL are represented with the following equations:

$$\alpha_Q Q_k \tag{2}$$

$$\alpha_q q_k \tag{3}$$

Where the partial factor α_Q should be ≥ 0.8 and decided by the national annexe, see table 4 below. While α_q should be ≥ 1 when two or more lanes are considered.

Different characteristic values should be used depending on the number of bridge lanes according to Table 2 below. A dynamic magnification factor of the loads is included in the characteristic values.

Table 2: Load Model 1 characteristic values.

Location	Tandem System, TS	UDL System
	Axle Loads Q_k [kN]	q_k [kN/m^2]
Lane Number 1	300	9
Lane Number 2	200	2.5
Lane Number 3	100	2.5
Other Lanes	0	2.5
Remaining Area q_k	0	2.5

The TS model has an axle width of 2 m, axle distance of 1.2 m and a contact area equal to 0.40 x 0.40 m^2, see Figure 6, a) below. When considering the UDL, it should be placed in the area where the most adverse effect can be obtained in combination with TS according to the influence surfaces.

Load model 2 (LM 2): This model aims to capture the dynamic effects of traffic loads on short structural members, leading to a higher effect compared with load model 1 for bridges with lengths 3 to 7 m. The load model consists of a single axle load of 400 kN including the dynamic magnification factor.

The single axle load has an axle width of 2 m and a contact area equal to 0.60 x 0.35 m^2, see Figure 6, b) below.

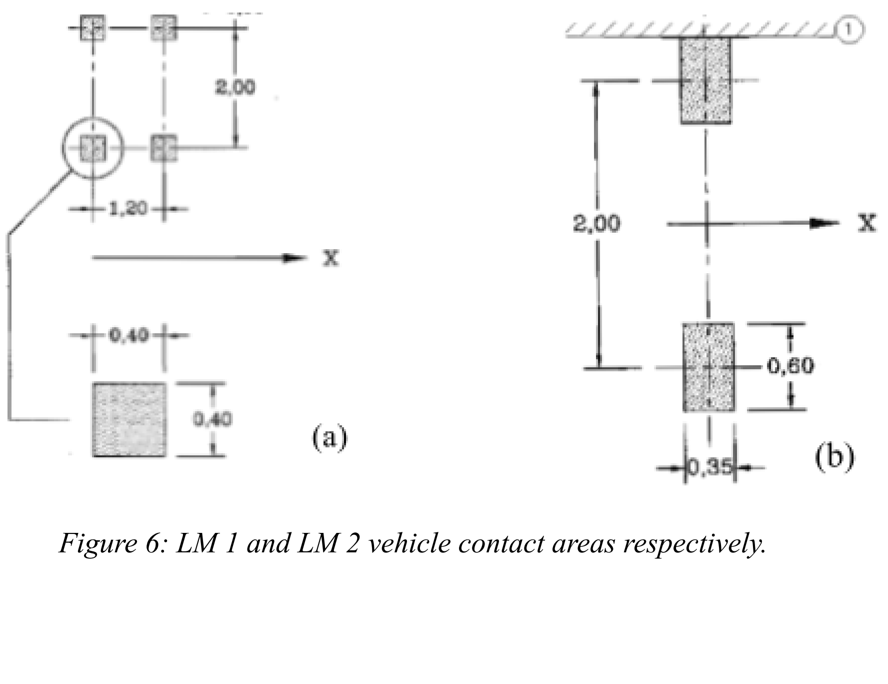


Figure 6: LM 1 and LM 2 vehicle contact areas respectively.

2.5.2 Swedish Design Codes

In Sweden there are two authorities that provide regulations for how to design bridges. These authorities together make the Swedish annexe which are The Swedish Transport Administration and Swedish Transport Agency, “Trafikverket” and “Transportstyrelsen” respectively and also the Swedish national board of housing “Boverket” (Boverket, n.d). These have similar obligations but also have different focuses in regards to how they work. Trafikverket focuses more on the long-term planning of all infrastructures, while Transportstyrelsen focuses more on keeping track of what has been done around the infrastructure and verifying it (Trafikverket, 2022). Although both authorities provide regulations they do not differ a lot, in fact they are very similar and both are made from the same principles which are the Eurocodes.

TRVFS 2011-12 is the design standard provided by Trafikverket which was replaced by TFSF 2018:57 which is the latest version of standards provided by Transportstyrelsen. These documents are very similar and provide the information needed for road and bridge construction. There are regulations for hazardous areas, different loads that should be used in bearing capacity calculations as well as guidelines for the design stages of structures.

The document includes guidelines on how to apply EC and provide safety classes for different construction works. The document also includes nationalised parameters that are applied when using EC traffic load models. These regulations are applied in regards to the stability, bearing capacity and durability of the structures. (Transportstyrelsen, 2018; Trafikverket, 2011).

In TSFS 2018:57, it is stated that permanent bridges should be dimensioned with a traffic load that follows EN 1991-2 but with the following changes: The loads seen in Figure 7 are added to the other load models according to EN 1991-2, where A is equal to 180 kN and B is equal to 300 kN. The distributed load q is set to either 0 kN/m^2 or 5 kN/m^2 inside the load model as there are also UDL that are separate and only added on lanes three and four which also are equal to either 0 kN/m^2 or 5 kN/m^2. The axles of the vehicle should be placed at the centre of the area that will be applied with the load. The pressure of the tires should be 0.3 m in the transverse direction and 0.2 m in the longitudinal direction (Transportstyrelsen, 2018). Furthermore, the axle width is set to be 2 m. There should be an additional dynamic factor "ε". This factor is added to the point loads and is set to at least 20% depending on the parameters of the structures, for instance, if the thickness of a deck is three metres then ε is equal to zero (Transportstyrelsen, 2018).

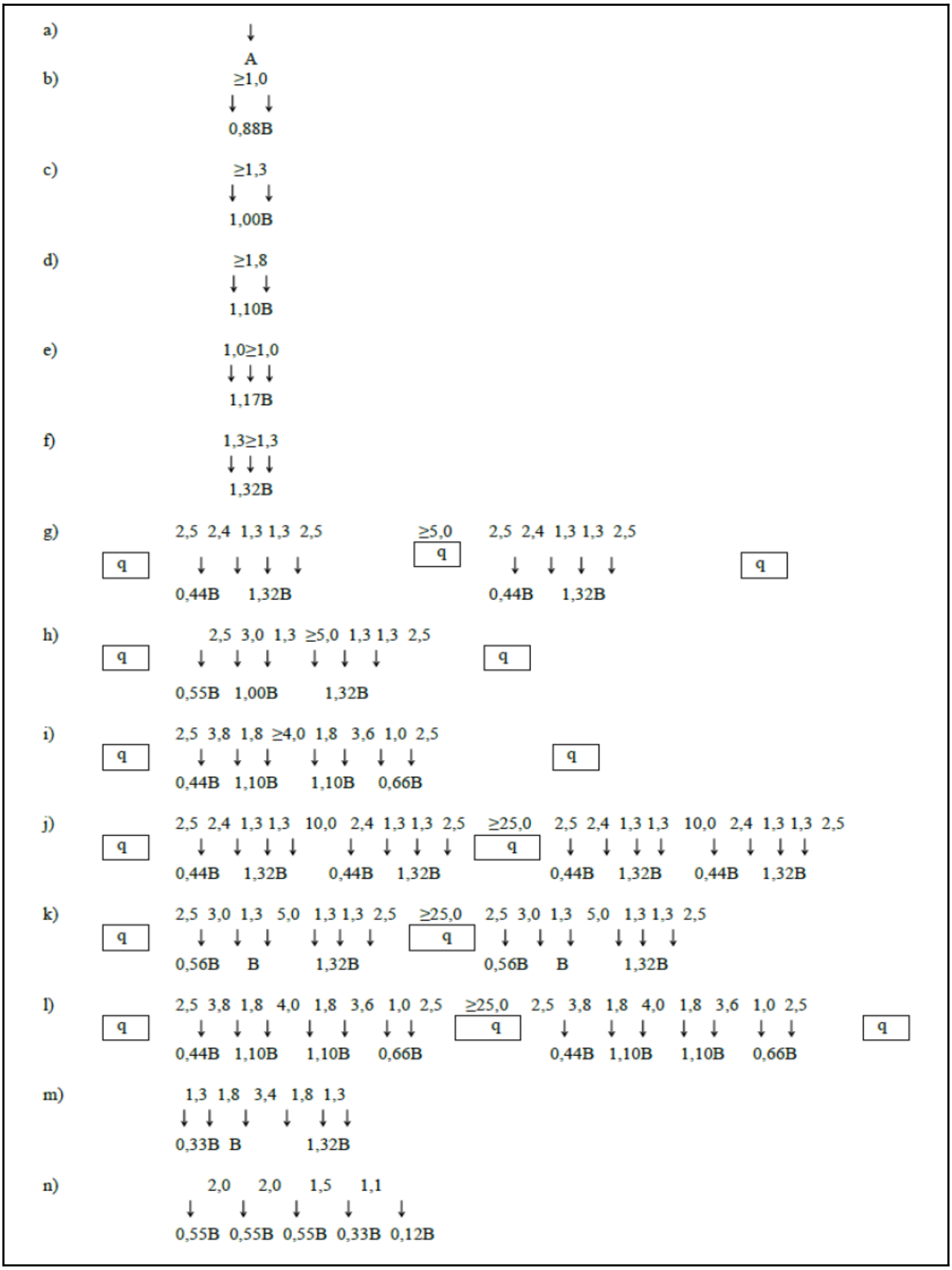


Figure 7: Classification vehicles in TFSF 2018:57 (Transportstyrelsen, 2018).

The maximum amount of traffic lanes is 2 and will have different load cases according to Table 3. If there are additional lanes, they will be loaded with a UDL that is either 0 kN/m^2 or 5 kN/m^2. The areas will be placed depending on the bridge and should bring the most conservative results (Transportstyrelsen, 2018).

Table 3: Swedish load´s lane factors and values.

Lanes	Load type	
	Load Model	Lane UDL [kN/m^2]
1	1 x Lorry	0
2	0.8 x Lorry	0
3	0	0 or 5
4	0	0 or 5

The partial coefficients of EC LM 1 are decided in the Swedish code. Both codes that were mentioned share the same coefficients except for lane 1 partial coefficient of the UDL where Transportstyrelsen gives a more conservative coefficient of 0.8 which could be seen in Table 4. (Transportstyrelsen, 2018)

Table 4: TSFS adjustment factors for EC LM 1.

Adaptation Factor	**Value: TRV**	**Value: TFSF**
α_{Q1}	0.9	0.9
α_{Q2}	0.9	0.9
α_{Q3}	0	0
α_{q1}	0.7	0.8
α_{q2}	1.0 for $i > 1$	1.0 for $i > 1$
α_{q3}	1.0	1.0

3. Research Method

This thesis aims to find a load multiplication factor connecting Eurocode to TRV specifications. In this chapter, the load multiplication factor definition and data treatment method are presented.

3.1 Load Multiplication Factor Definition

The main method chosen in this thesis was to compare the results obtained from both codes by the analysis of a FE programme. The key internal forces used in the comparison were the bending moment and shear force in the longitudinal and transverse longitudinal directions of the bridge respectively.

The load multiplication factors α_M and α_V were defined according to Eq. (4).

$$\alpha_{M,\,V} = \text{(Maximum TRV response)/(Maximum EC response)} \tag{4}$$

The maximum of each of the key internal forces obtained from the TRV specification was divided by the corresponding maximum key internal force from the EC. This definition was repeated for every length in every lane category. The multiplication factors were then plotted in separate graphs to obtain an equation that describes the change of α_M and α_V with the length of the bridge for α_M and α_V values greater than one.

3.2 Data Extraction

The data required was extracted along the deck´s length to obtain the distribution of the key internal-forces along the bridge. The bending moments were extracted between the deck´s edges connected with the legs. The shear forces were extracted from the same path but between the non-shear areas defined by EN-1992.

Shear area according to EC is defined in the following equation and presented in Figure 8 below:

$$\text{Shear area} \geq l_{bd} + d \quad (5)$$

Where d is the thickness of the deck and l_{bd} is the anchorage length.

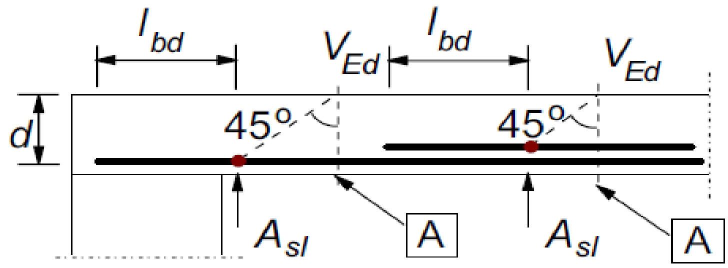


Figure 8: Definition of l_{bd}.

The analysis assumed an idealised portal frame bridge, the l_{bd} was calculated according to EN 1992-1-1, section 5.3, and was equal to a_i in Figure 9 below. The shear area was defined as:

$$a_i + d < \text{shear area} < L - a_i + d \quad (6)$$

Where L is the total length of the bridge.

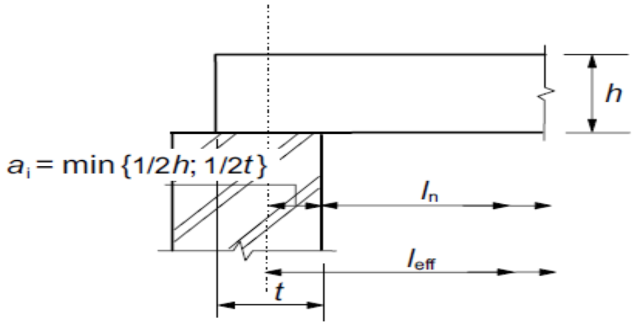


Figure 9: Non-continuous members.

3.3 Load Combination

After extracting the data, it was organised in groups to obtain the maximum envelopes of each code. Data combination could either be done in the FE programme or Excel. The latter was chosen in this report due to easier data treatment.

The results of the EC were combined in the following way: the results of LM 1_TS were added to LM 1_UDL. The results of LM 1 and LM 2 were compared and the most adverse effects were chosen to represent the maximum envelope of the EC.

The results of the Swedish National Annexe were combined in the following way: the results from all lorries were compared and the most adverse effects were chosen to represent the maximum envelope of the TRV specification.

The maximum envelopes were then compared with each other as described in the previous Section 3.1. Table 5 gives a summary of the research method followed:

Table 5: Summary of the research method.

Code:	EC		**Max E_d Envelopes ($Max_{Mx, Vx}$)**
Load models	LM 1 = LM 1_TS + LM 1_UDL	LM2	Max(LM 1, LM 2)
Code:	Swedish National Annexe		$Max(Lorries_{a-n})$
Load models	$Lorries_{a-n}$		
Load Factor	$\alpha_{M,V}$ =Max ($Lorries_{a-n}$) / Max (LM 1, LM 2)		

4. Calculation Method

The analysis in this report was carried out using the Finite Element Analysis (FEA) programme Brigade/Plus 2022. It was chosen as it allowed linear analysis, contained the traffic load models from both EC and TRV and gave the possibility to change the load coefficients of each load model. Brigade/Plus was also supplied with a Live Load module that allowed the inbuilt FEA solver to analyse the response of moving loads on the structure using the concept of influence surface.

In this chapter, the method and theory used in the FEA are presented in Section 4.1 and the modelling procedure is presented in Section 4.2.

4.1 FEA in Brigade/Plus

4.1.1 Linear Analysis

The linear-elastic material property was chosen to simulate the reinforced concrete in this thesis as the aim was to study an idealised portal frame bridge without being interested in the type of concrete or reinforcement used. The Young´s modulus used was E = 33 GPa, assuming an uncracked concrete section.

The FEA solver for the moving loads in Brigade/Plus starts by creating influence surfaces to identify the response at each point due to the moving loads. When the analysis was done Brigade/Plus created maximum and minimum envelopes of the required key internal forces for each load model.

4.1.2 Influence Line Method

One of the important steps when designing a structure is knowing the most sensitive points of the structure and knowing the highest possible load affecting that point. In bridge design the loads are in motion along the bridge without a constant position, this case causes different responses at the severe point depending on the load’s position.

During the 19th century, the concept of influence function was introduced in bridge design (Zheng et al., 2019). The influence function is defined as “a function that represents the load effect (force or displacement) at a point in the structure as a unit action moves along a path or over a surface” (Barker & Puckett, 2013). The influence line and influence surface are representations of the influence function in 1D and 2D respectively. Different responses can be studied from these functions such as bending moments, shear forces, displacements and so on.

4.1.2.1 Identification Methods: Muller-Breslau principle

Different methods can be followed when creating the influence lines. The two primary methods are the Muller-Breslau principle and the Statics-base method (Shen, 1992; Barker & Puckett, 2013).

The Muller-Breslau principle became the basis of several new methods (Shen, 1992; Jepsen & Damkilde, 2018), it was created by the German civil engineer Heinrich Muller. The Muller principle is applied based on Betti’s theorem (Barker & Puckett, 2013; Fiorillo & Ghosn, 2015). Betti’s theorem is an energy theorem that creates a relationship between the forces applied on the system and its deformation. Betti’s theorem assumes a linear elastic relationship (Barker & Puckett, 2013).

The Muller-Breslau principle states that the influence line of a beam is the deflection shape of that beam when a unit point load is applied on a specific point. The deflection shape at any point on the beam is calculated using the principle of superposition (Barker & Puckett, 2013; Williams, 2015). An example of Muller’s principle is presented in Figure 10 below, where load *I* will have the deflection shape (b) when acting on point *K* and the shear force influence line (c) is obtained for load *I* (Williams, 2015).

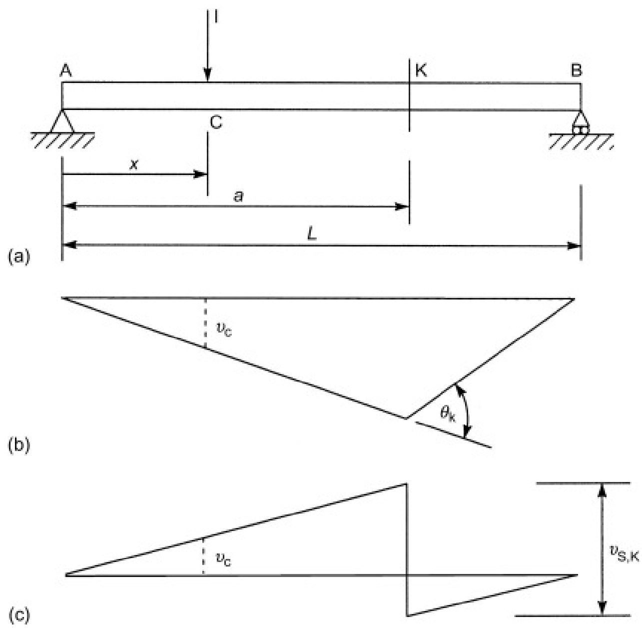


Figure 10: (a) Simple beam, (b) influence function for R_A, (c) influence function for V_B, (Barker & Puckett, 2013).

4.2 Portal Frame Bridge Model and Dimensions

A standardised model of the portal frame bridge in Figure 11 was created in Brigade/Plus. The lane width was considered 3 m as it is the minimum lane width according to EN 1991-2, when increasing the number of lanes the bridge´s width increased as a multiplier of 3. The thicknesses chosen were equal to 0.5 m and 0.8 m for the deck and the legs respectively with a leg height of 6 m. The model was created using the shell elements as the thicknesses are smaller than the other dimensions.

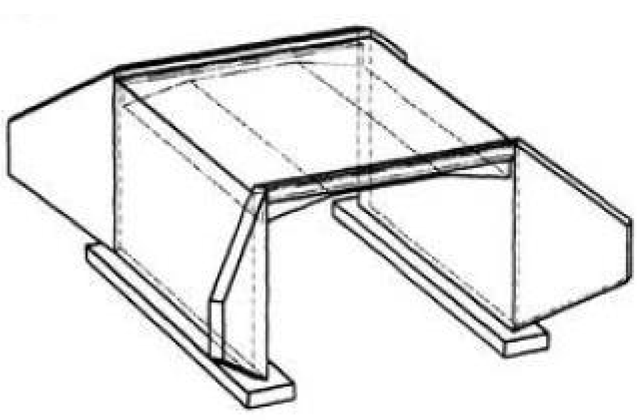


Figure 11: A sketch of a standard portal frame bridge.

4.2.1 Topology

The simplified portal frame bridge included the main parts (slab and legs) without including the wing walls to increase the efficiency of the model and decrease the analysis time. The model was created as one part to ensure the continuous behaviour between the different parts of the bridge and to avoid adding extra constraints between the bridge´s parts, see Figure 12. The model was created using shell elements as it allows extraction of section moments and forces along the bridge´s deck.

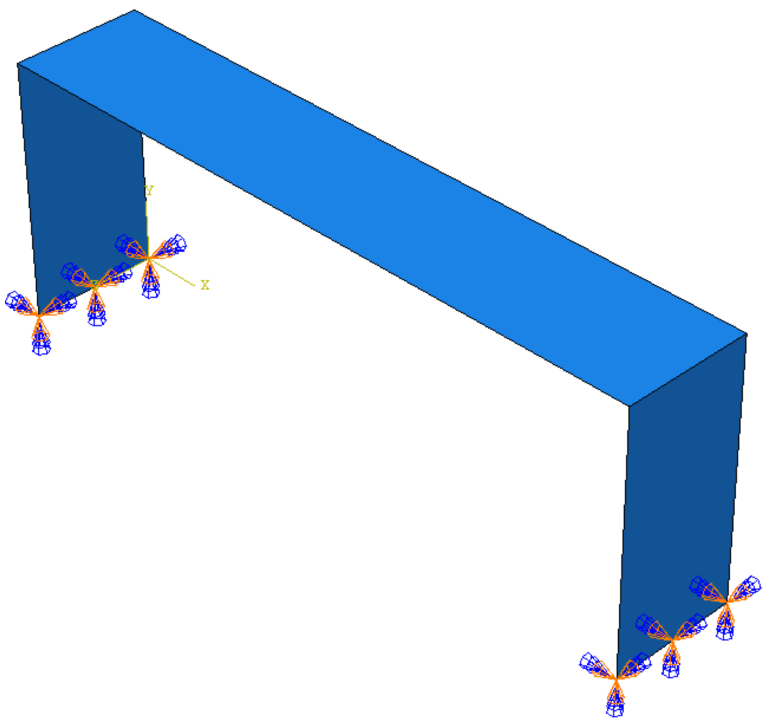


Figure 12: 3D model in Brigade/Plus including the coordinate system and boundary conditions.

The lanes were created as lines with a width property of 3 m. The lanes were centred in the middle of the desired lane according to Figure 13 and 14. All lanes created started and ended 5 m before and after the bridge´s deck.

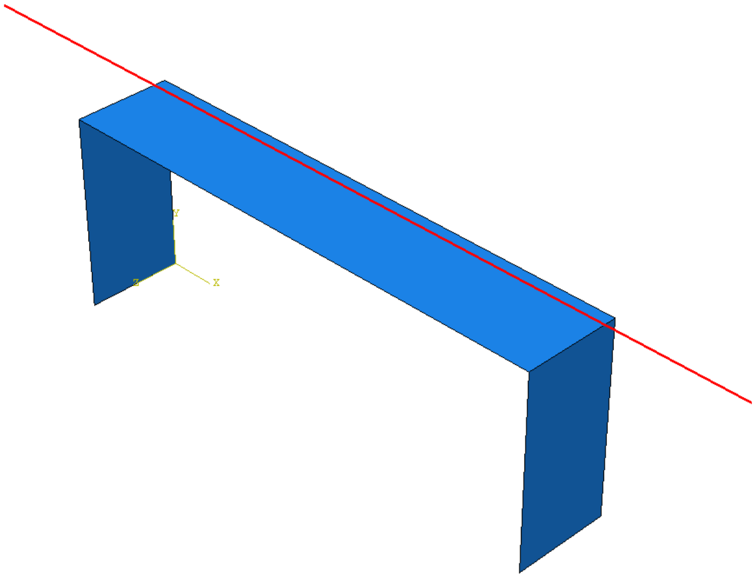


Figure 13: 3D model in Brigade/Plus with one lane.

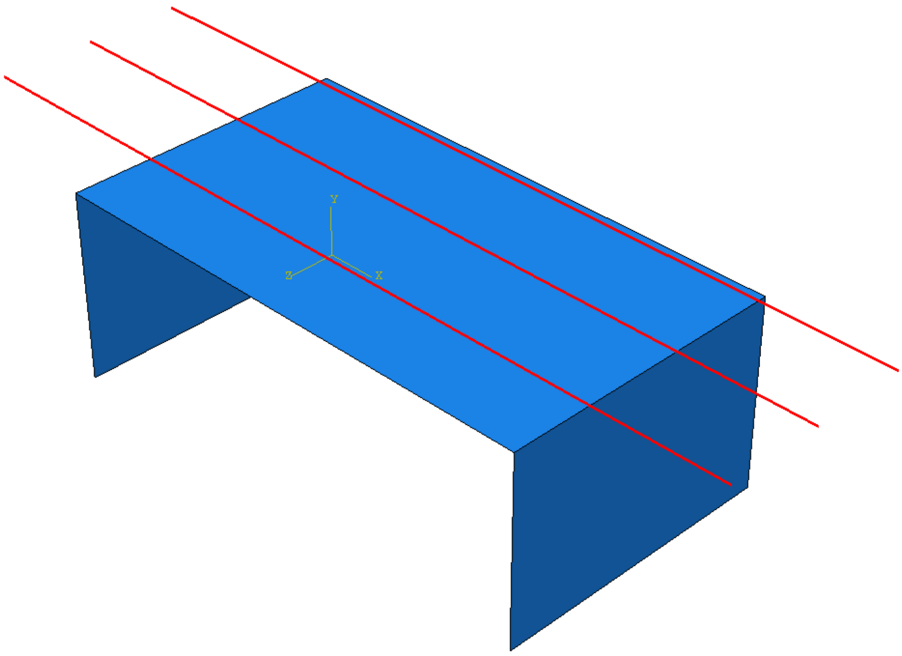


Figure 14: 3D model in Brigade/Plus with three lanes.

The boundary conditions were applied on the legs and assumed to be fixed see Figure 12 above. The model was created for different lengths starting with 6 m up to 25 m with a 1 m step between each bridge with different widths presented in Table 6 below

Table 6: Width of the bridges in relation to the number of lanes.

Number of lanes	Bridge´s width
1	3
2	6
3	9
4	12

4.2.2 Applied Loads

The loads were applied in the negative y-axis on the deck. Two types of loads were used: point loads and surface lane loads to represent the TS and UDL respectively. The loads were designed to move a step of 0.1 m to ensure that the worst case scenario is met. The load settings used in Brigade/Plus are presented in Appendix B.

4.2.2.1 EC: Live Loads

The loads applied from the EC were LM1 and LM2 using the partial coefficients described in the TSFS 2018:52, no dynamic factors were added since it was included in the loads. The loads applied on each lane and the coefficients used are presented in Tables 7 and 8 respectively below.

Table 7: LM 1 and LM 2 values used in the analysis for each lane.

Lanes	LM1		LM2
	Vehicle [kN]	UDL [kN/m^2]	Single axle [kN]
1	270	7.2	360
2	180	2.5	0
3	0	2.5	0
4	0	2.5	0

Table 8: LM 1 partial coefficients applied.

Vehicle coefficients	Value	UDL Coefficients	Value
α_{Q1}	0.9	α_{q1}	0.8
α_{Q2}	0.9	α_{q2}	1
$\alpha_{Q3,4}$	0	$\alpha_{q3,4}$	1

4.2.2.2 TSFS 2018: Live Loads

The loads applied from the TRV specifications were taken from the TSFS 2018:52. The load models were a, b, c, d, e, f, g, h, i, m and n. Load models j, k and l were omitted as the models consisted of two repeated parts. Loads j, h and i consist of TS and UDL, these loads were analysed twice since the value of the UDL inside the load model was analysed for $q = 0$ and 5 kN/m^2 respectively to ensure that the maximum effects were obtained. The load on lanes 3 and 4 was taken equal to 5 kN/m^2 to obtain the most adverse responses. The dynamic increament used was equal to 20% which is the minimum required factor for the design of new bridges.

The loads used for the point loads in the analysis were A = 180 kN and B = 300 kN. The loads applied on the lanes are presented in Table 9 below:

Table 9: Swedish load partial coefficients applied for each lane.

Lanes	Load type	
	Load Model	Lane UDL [kN/m^2]
1	1 x Lorry	0
2	0.8 x Lorry	0
3	0	5
4	0	5

4.2.3 Mesh Sensitivity Analysis

The size and shape of the element used in a FEA have a direct effect on the analysis. A coarse mesh will have a lower accuracy while a fine mesh will lead to a higher accuracy but may affect the efficiency of the analysis (Cook et al., 1995).

In order to define the proper element size and shape a convergence analysis was carried out. The analysis was done on a one lane bridge with a span length of 25 m. The analysis was performed with a live moving load instead of a concentrated load in a constant position which was chosen as it gave a better representation of the study.

The analysis was done in Brigade/Plus using quadrilateral elements using linear (S4R) and quadratic (S8R) elements. The tested combinations were 0.5 m S4R, 0.25 m S4R/S8R, 0.15 m S4R/S8R, 0.10 m S4R/S8R and 0.05 m S4R. The analysed data was only extracted from the deck for the moment distribution along the deck. The results of the moments distribution were compared to define the most proper choice.

4.2.4 Model Verification: Simply Supported Beam

In order to ensure both the accuracy and the quality of the model a verification analysis was done by comparing results from Brigade/Plus with results from analytical calculation.

A portal frame bridge is a simple structure compared to other bridges such as a cable-stayed bridge. Although it is a simple bridge an analytical solution for this bridge is still necessary in order to verify the quality of the FEM software "Brigade/Plus". Therefore a simplified model consisting of a simply supported beam was created in Brigade/Plus. The beam was subjected to an axle load corresponding to half of the load of LM 1 placed in the middle of the beam, see Figure 15 below. The beam had a length of 25 m resembling the longest portal frame bridge.

The results from both the FEA and the analytical solution were compared for the moment distribution along the beam to ensure the quality and accuracy of the model representation in Brigade/Plus.

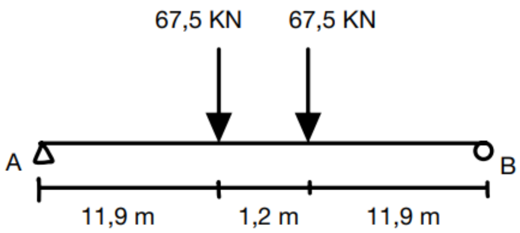


Figure 15: Simply supported beam that was analysed.

4.2.5 Method Validation

Validating the research method of obtaining the multiplication factors α_M and α_V was important to ensure the quality of the method and detect the percentage error between the real results and the expected results after using α_M and α_V.

The model validation was based on comparing the results of the maximum envelopes of the EC after implementing the α_M on the EC load models with the results of the maximum envelopes of the TRV specifications. The result comparison was done for the section moment extracted in the longitudinal direction of the bridge to detect the highest error, see Figure 16 below for the data path. The error was defined according to the following equation:

$$error = Max(\alpha_{M,V} \cdot EC)/Max(TRV) - 1 \quad (7)$$

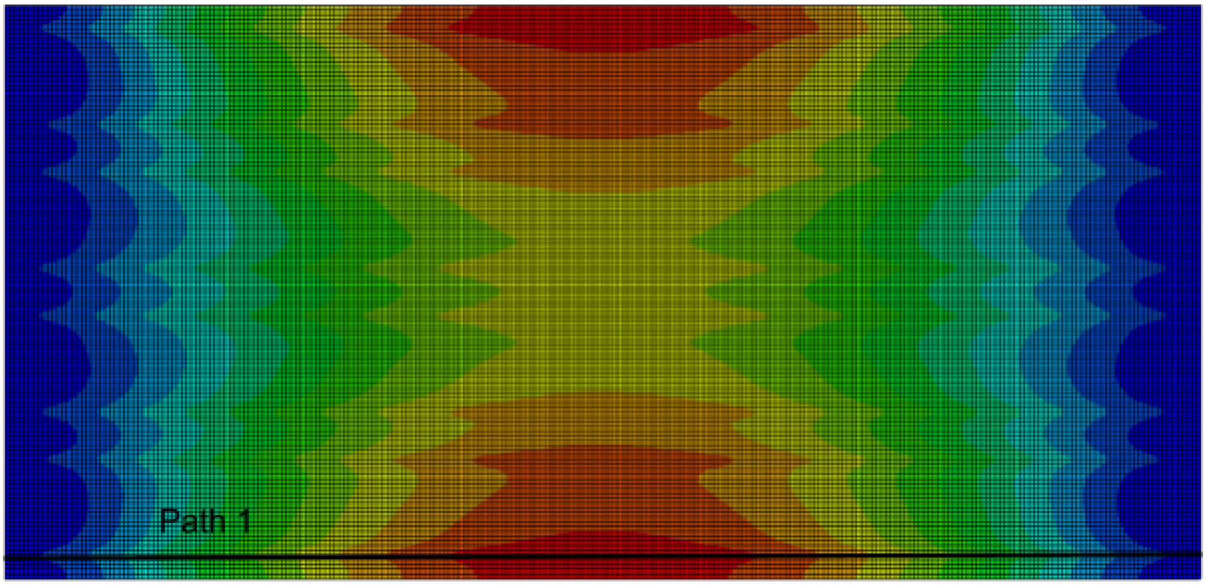


Figure 16: Example of the path used on a bridge with four lanes.

In order to minimise the scientific error when calculating the error of the analysis, the validation was done for two bridges one for each lane and a different length for each validation. The bridges chosen for the validation were the bridges that have α_M greater than 1. The bridges chosen are presented in the following table:

Table 10: Bridge samples used in model validation.

Lanes:	3	4
Length [m]:	25	20

4.2.6 Data Extraction Path

The data extracted for the bending moment and shear force was around the *z*-axis and in the negative *y*-axis respectively, along path 1 presented in Figure 16 above. The shear force data path was limited according to Chapter 3.2, after calculation the path is presented in the following interval:

$$0.75 \text{ m} < \text{Path 1} < (L - 0.75) \text{ m} \quad (8)$$

4.3 Example application

In order to validate if these factors are usable in modelling a real portal frame bridge, an example application of an already built bridge in Uppsala, Sweden was studied. This was made by modelling the bridge with its structural components in Brigade/Plus. The validation on the Uppsala bridge followed the steps described in Section 4.2.5.

The bridge seen in Figure 17 is called "bridge over the yellow path" as stated in the construction drawings. The bridge is about 5 m high, the deck is 16 m long with a width of 12 m. It consists of two driving lanes and one lane for both pedestrians and bikers. The bridge is located between Gottsunda and Ultuna in Uppsala and acts as a connection point between these suburbs.

Figure 17: Bridge over the yellow path

4.3.1 Topology of the Uppsala bridge

The Bridge was modelled with more details in comparison to the 80 studied cases. This model included the wingwalls, bottom plate as well as the deck and legs which also were included in the case studies. The wingwalls in the bridge consisted of two parts; this could be studied closer in Figure 18 where the separation is shown. The second part is designed as a retention wall with its own foundation to the soil and was constructed this way due to the bad soil condition. Furthermore the legs also needed extra support due to the soil and this was solved using piles that went deep into the soil for extra stability.

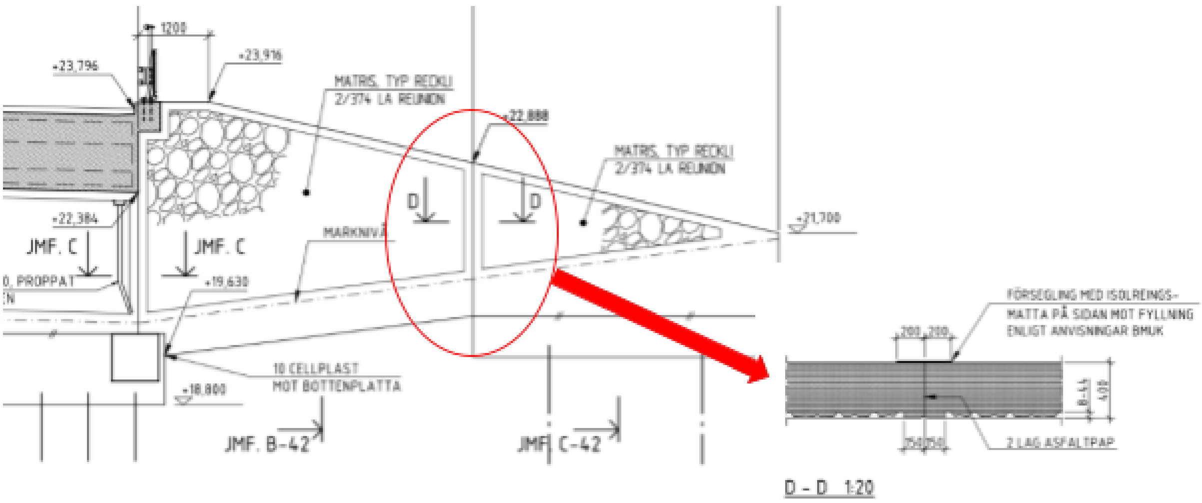


Figure 18: Wingwall separation

The created model followed the same procedure described in Section 4.2 regarding the analysis type, applied loads and lane position. However, the thicknesses of the bridge were changed and presented in Table 11 below:

Table 11: Bridge thicknesses.

Part	Thickness [m]
Deck	0.8
Legs	0.8
Bottom Plates	1.2
Wingwalls	0.4

The created model did not include the second part of the wingwall as well as the piles. This is due to the boundary conditions that were applied to the bottom plate which were fixed and therefore would give the required stability, see Figure 19.

The bridge is currently used as stated with only two driving lanes but since the objective is to study the maximum response with maximum use, the bridge was modelled with four driving lanes.

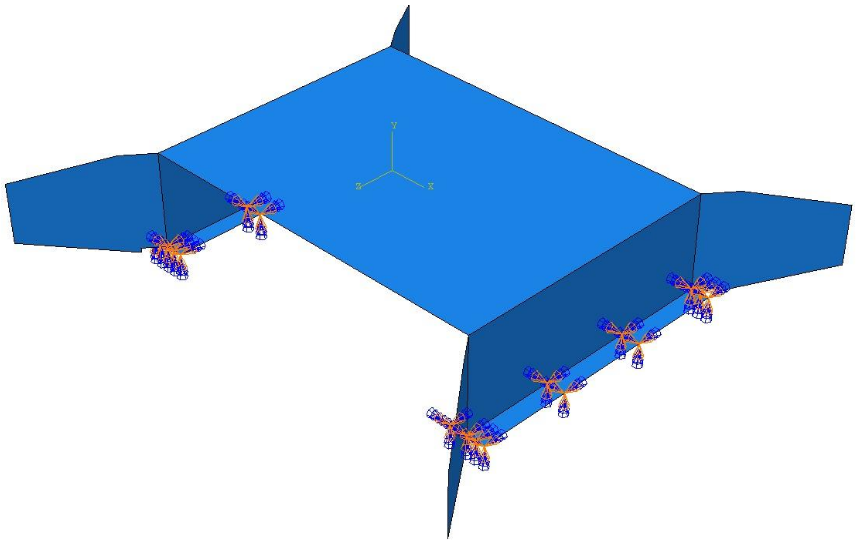


Figure 19: FEM-model of Uppsala bridge with its boundary conditions.

5. Results

5.1 Mesh Sensitivity Analysis

The results of the mesh analysis are presented in Figure 20 below. The results show an increase in convergence when decreasing the size of the element and using the quadratic shape function. The linear element with 0.1 m size was used for all parts in this model and for all different sizes of the bridge analysed.

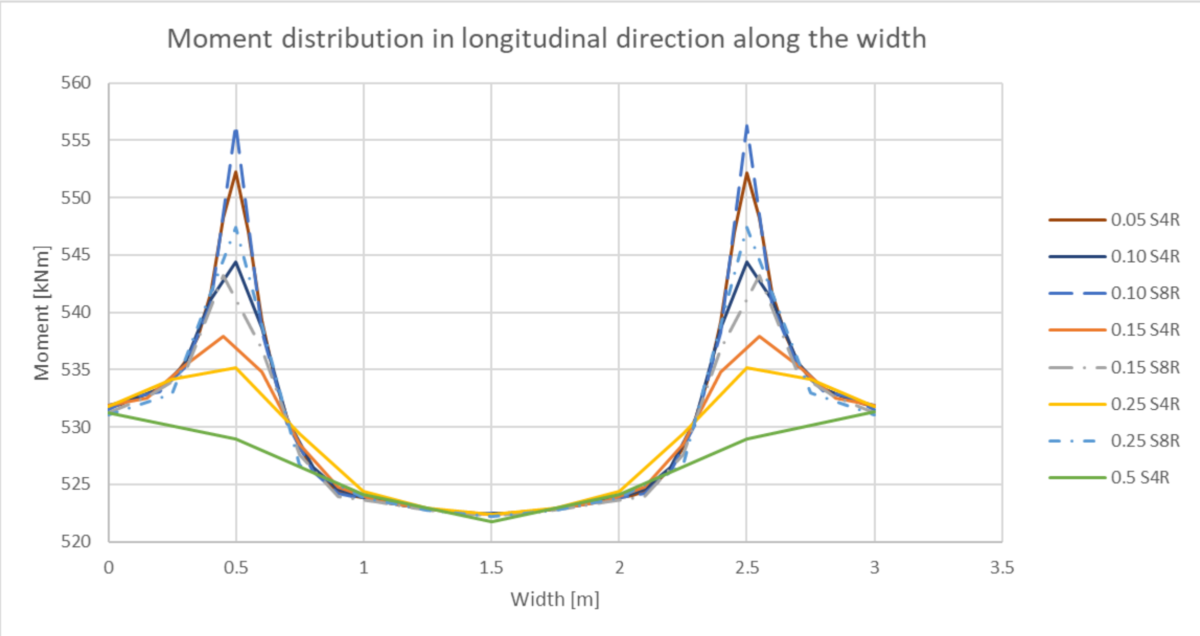


Figure 20: Mesh analysis results of different element sizes and deformation shapes.

5.2 Model Verification

The results of the model verification are presented in Figure 21, more information is provided in Appendix A. The figures showed that the maximum bending moment distribution from both the FE model and the analytical solution are equal in values and shape and thus the model was verified.

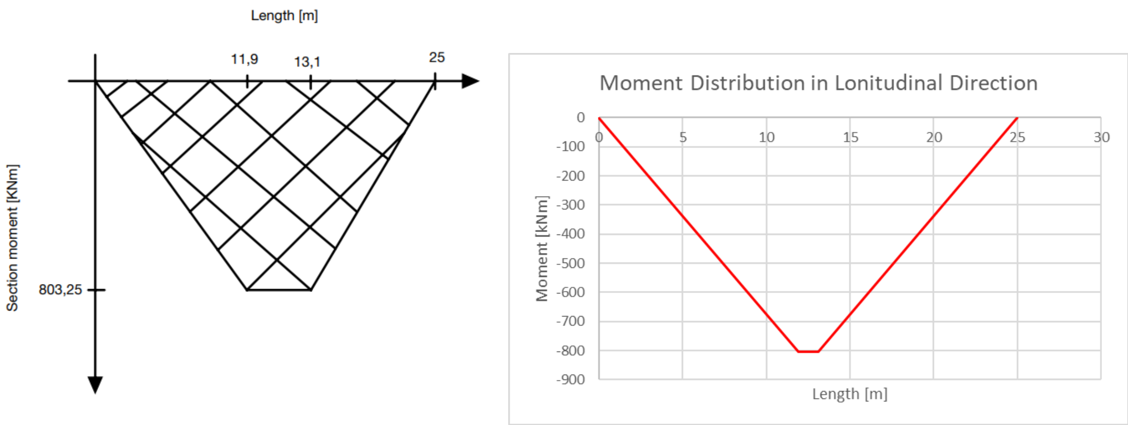


Figure 21: Hand calculated (left) and extracted moment distribution from Brigade/Plus (right) of the simply supported beam.

5.3 Load Multiplication Factor for Bending Moments α_M

The factors showing the relationship between the Eurocode and the TRV specifications regarding the bending moment according to equation (4) are presented in Table 12 and plotted in Figure 22 below. The data showed that only some bridges with 3 and 4 lanes had a factor over 1. This means that the TRV is more conservative only in wider and longer bridges while EC is more conservative in the other bridges.

The increase in α_M for lane 4 and lane 3 data above the value of 1 had quadratic and linear properties respectively, presented in Eqs. (9) and (10), and Figures 22 and 23 below.

$$y = -0.0005x^2 + 0.0292x + 0.6666,\ R^2 = 0.9997 \tag{9}$$

$$y = 0.0077x + 0.8153,\ R^2 = 1 \tag{10}$$

Table 12: Section moment factors for each bridge in each lane.

Factor SF4	1 Lane	2 Lanes	3 Lanes	4 Lanes
Bridge 6m	0.630	0.640	0.712	0.725
Bridge 7m	0.644	0.662	0.740	0.758
Bridge 8m	0.668	0.689	0.769	0.793
Bridge 9m	0.695	0.721	0.803	0.832
Bridge 10m	0.717	0.750	0.833	0.867
Bridge 11m	0.741	0.777	0.860	0.898
Bridge 12m	0.759	0.800	0.883	0.925
Bridge 13m	0.773	0.820	0.895	0.948
Bridge 14m	0.784	0.838	0.919	0.968
Bridge 15m	0.797	0.853	0.933	0.985
Bridge 16m	0.803	0.865	0.945	1.001
Bridge 17m	0.810	0.876	0.956	1.014
Bridge 18m	0.815	0.885	0.965	1.025
Bridge 19m	0.819	0.893	0.973	1.035
Bridge 20m	0.822	0.899	0.980	1.044
Bridge 21m	0.824	0.905	0.986	1.051
Bridge 22m	0.825	0.909	0.991	1.058
Bridge 23m	0.826	0.912	0.995	1.064
Bridge 24m	0.838	0.921	0.999	1.069
Bridge 25m	0.852	0.939	1.007	1.074

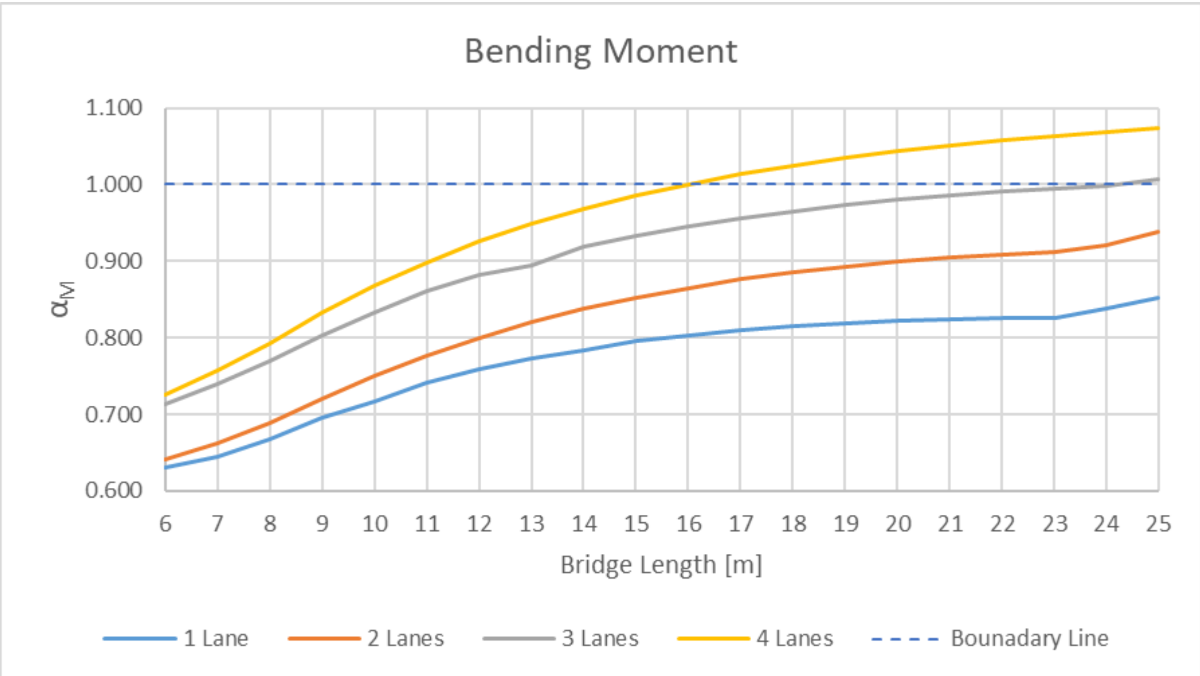


Figure 22: The factors for bending moment plotted on a graph.

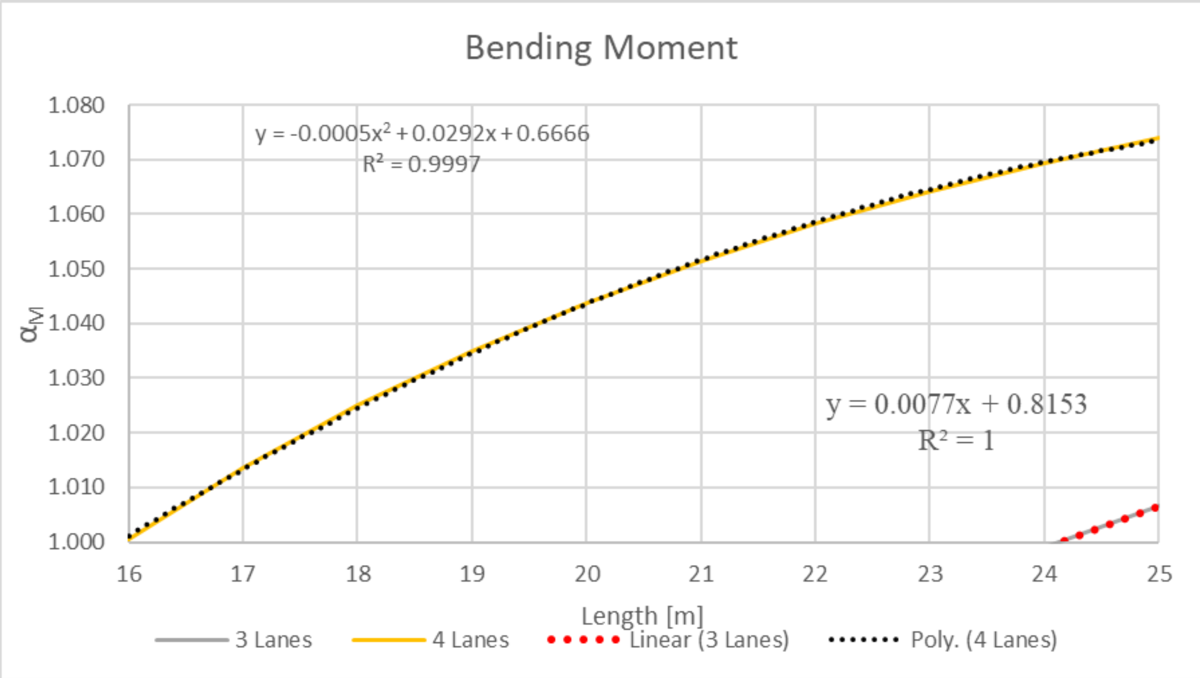


Figure 23: Bending moment factors greater than 1 plotted on a graph.

5.4 Load Multiplication Factor for Shear Force α_v

The factors showing the relationship between the Eurocode and the TRV specifications regarding the shear forces are presented in Table 13 and plotted in Figure 24 below. The data showed that only some bridges and 4 lanes had a factor of over 1. This meant that the TRV was more conservative only in wider and longer bridges while EC was more conservative in the other bridges.

The increase in α_v for lane 4 data above the value of 1 had a linear property presented in Eq. (11) and Figures 24 and 25.

$$y = 0.0091x + 0.7944, R^2 = 1 \tag{11}$$

Table 13: Section forces factors for each bridge in each lane.

Factor SF4	1 Lane	2 Lanes	3 Lanes	4 Lanes
Bridge 6m	0.654	0.657	0.689	0.696
Bridge 7m	0.687	0.690	0.730	0.733
Bridge 8m	0.718	0.722	0.771	0.775
Bridge 9m	0.748	0.751	0.808	0.814
Bridge 10m	0.769	0.771	0.832	0.839
Bridge 11m	0.790	0.787	0.850	0.859
Bridge 12m	0.801	0.794	0.862	0.874
Bridge 13m	0.807	0.799	0.873	0.887
Bridge 14m	0.811	0.803	0.882	0.898
Bridge 15m	0.814	0.805	0.889	0.907
Bridge 16m	0.821	0.806	0.896	0.915
Bridge 17m	0.833	0.814	0.907	0.928
Bridge 18m	0.843	0.822	0.921	0.944
Bridge 19m	0.853	0.828	0.933	0.958
Bridge 20m	0.861	0.834	0.943	0.971
Bridge 21m	0.858	0.839	0.953	0.982
Bridge 22m	0.875	0.844	0.961	0.993
Bridge 23m	0.880	0.847	0.969	1.003
Bridge 24m	0.885	0.851	0.976	1.012
Bridge 25m	0.890	0.853	0.982	1.020

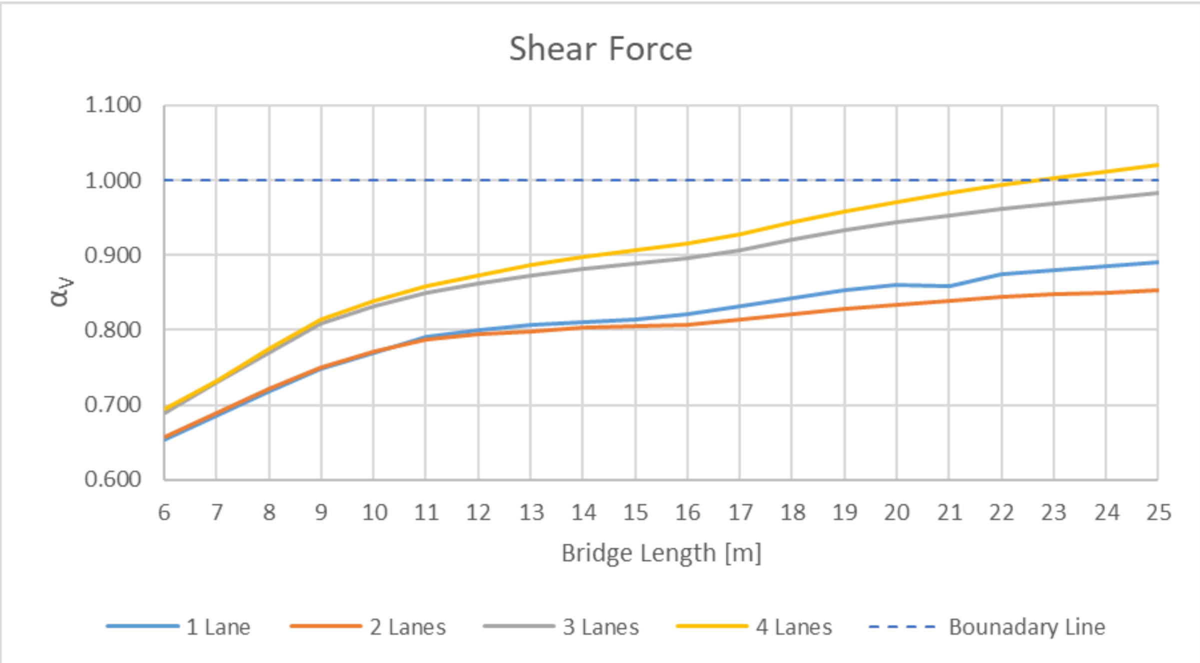


Figure 24: The factors for shear force plotted on a graph.

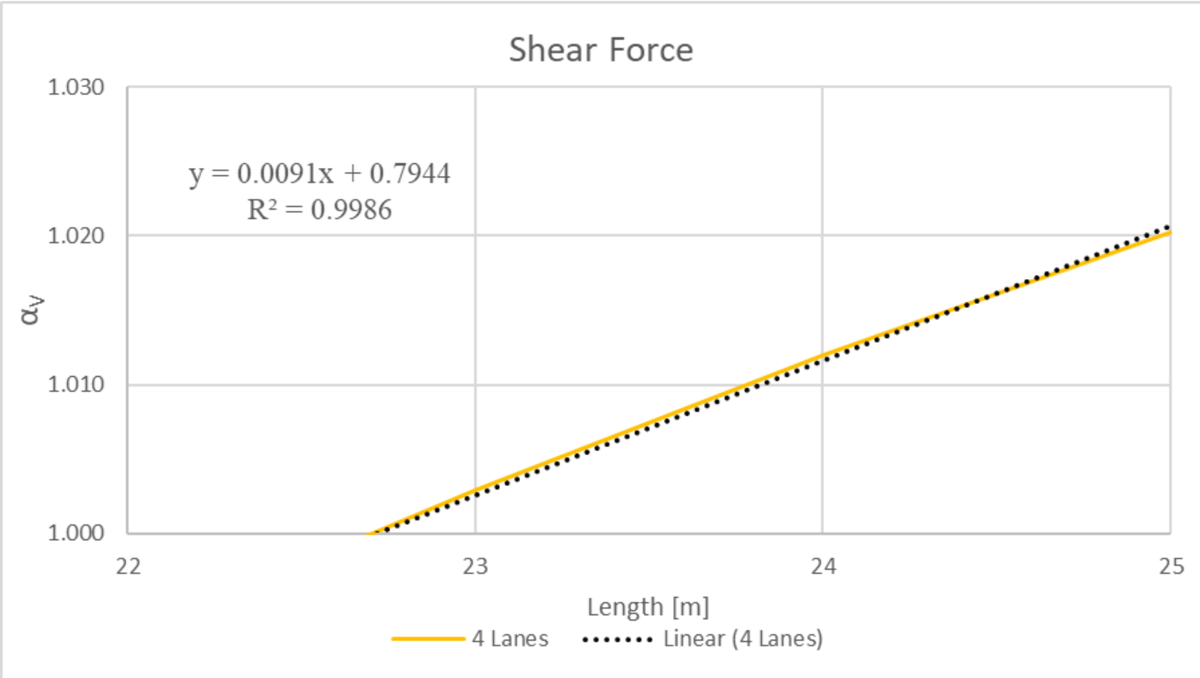


Figure 25: Shear force factors greater than 1 plotted on a graph.

5.5 Method Validation

The results of the validation are seen in Figures 26 and 27, and Table 14 below. The calculated errors showed that the research method was valid since the errors were almost equal to zero at the target values (maximum bending moments) of the bridge.

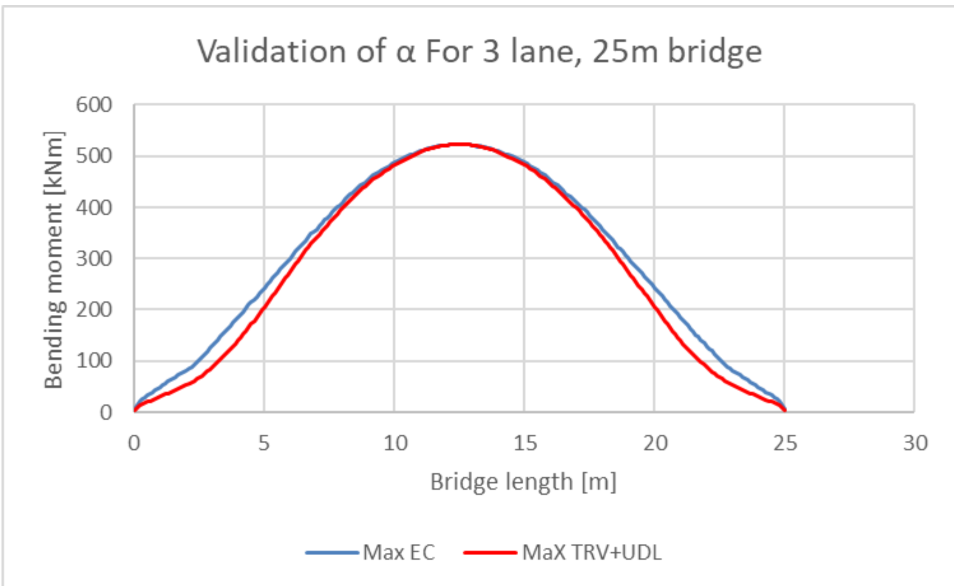


Figure 26: Comparison of Swedish annexe and EC multiplied by a factor α_M.

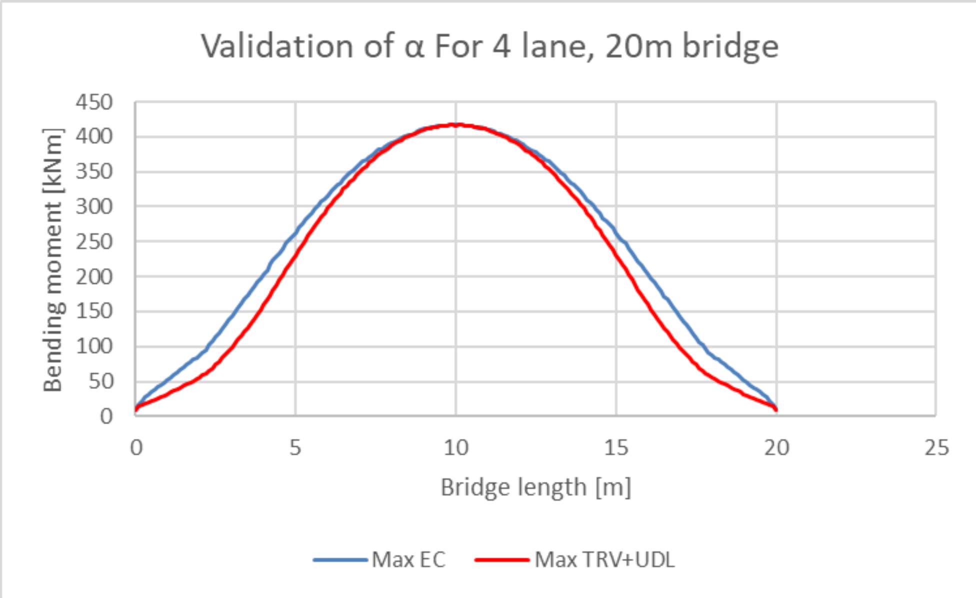


Figure 27: Comparison of Swedish annexe and EC multiplied by a factor α_M.

Table 14: Calculated errors for each of the validation bridges.

Lanes:	3	4
Length [m]:	25	20
Error	7,0e-04	7,0e-04

5.5.1 Example Application

The results of the validation for the bending moment are seen in Figure 28 below. The calculated error was equal to -1.4%. The negative error showed that TRV specification was more conservative even after applying α_M. The maximum bending moment was higher compared with the results from the idealised model. Figure 29 shows the results of the shear force validation using α_M. The EC is more conservative than the TRV load models when using α_M, so the factor may be used.

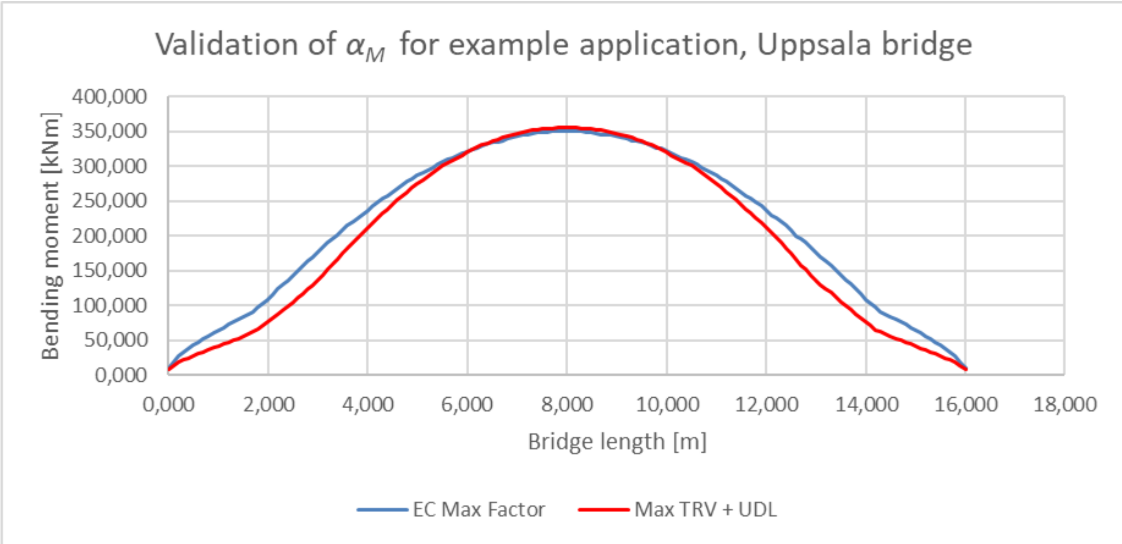


Figure 28: Comparison of Swedish annexe and EC multiplied by a factor α_M for Uppsala bridge.

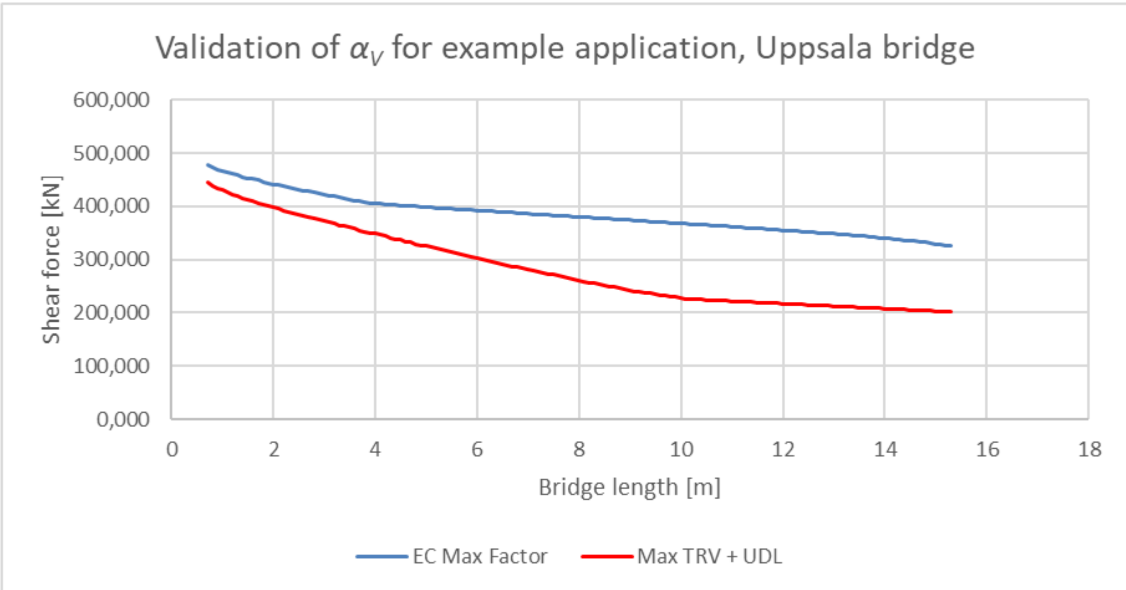


Figure 29: Comparison of Swedish annexe and EC multiplied by a factor α_V for Uppsala bridge.

6. Discussion

6.1 Modelling using FEM

The tool that was used frequently throughout the study was Brigade/Plus. The knowledge and understanding of such software and its background were crucial in order to both obtain a good and reliable model but also to be efficient in regards to time management. Simulating over 80 bridges with different load models is time consuming and doing this while creating a new model for each bridge would not be possible in the time frame intended for the study. This however was noticed early when analysing the different meshes that potentially would fit the model that was created. In order to try several meshes in a time efficient way several identical models were made which was the starting point for managing all 80 bridges in an efficient and sorted way.

The tested mesh sizes consisted of both coarse and fine mesh sizes in order to find how the model will converge and which mesh size would hold the quality to a high standard but also respect the time frame that was intended. It was noticed that coarse meshes didn't transition well in between the integration points. This was noticed since the visualisation of the force presentation showed a non-continuous colour gradation. The finer meshes showed a continuous colour gradation but could take up to 30 minutes to simulate one specified load model. The 0.10 m mesh size would give less accurate results compared to 0.05 m mesh size. However, when simulating both the Eurocode and the TRV specifications with the same mesh, the systematic error will be the same. These reasons lead to choosing 0.10 m S4R as the mesh throughout the whole study.

Furthermore, when verifying the abilities of the software a change of element type was implemented. The elements used for the bridge model were shell elements but when creating the simply supported beam, that was compared to an analytical calculation, the elements used were wire elements. The wire elements were more suitable because of its 1D property. This was also clear in the results since the two graphs that were compared in the verification analysis were identical. This could verify that the method of using FEM is suitable for such a study and also increases the credibility of the results. The choice of comparing a FEM programme to an analytical calculation was taken in order to minimise errors that may occur in the comparison. If an error would be made when creating the FE-model, it is likely that the same error would be made in a different FEM software. Comparing two different FEM softwares was therefore not an option.

The timeline for the study was respected but could be made shorter by implementing a python script to Brigade/Plus which would increase the time efficiency of the simulations. This would automate the whole "bridge-modelling process" simultaneously adding length and width to the bridge while simulating the load model. This would only require an initial model that would be made and python would do the rest of the work.

6.2 Multiplication Factors α_M and α_V

The load multiplication factors were calculated from the graphs presented in Appendix C. The factors were chosen to be calculated at the maximum response points of each bridge length because bridges should be designed for maximum loads according to the ULS principle. The factors were always calculated at mid points of the given lengths and not at the quarter distances because it was noticed that EC was always more conservative in the other areas along the bridge even when the validation was done. Even after applying the national parameters, the EC was still conservative for some bridges; this could be due to the high return period when designing the EC LM.

The results of both load multiplication factors α_M and α_V showed an increasing trend for each length step. However an upward shift was noticed for both factors between lanes 1, 2 and 3, 4, this shift could be due to the extra UDL added by the TRV specifications on lanes 3 and 4. The bending moment multiplication factor α_M showed an increase in value for bridges with four lanes and lengths longer than 16 m. The line of best fit was chosen to be a quadratic function as it gave a better representation of α_M compared with the linear function. The linear function had some values where α_M were lower than the calculated value and may risk the safety of the design, see Appendix C.6.

An extra validation was done on a portal frame bridge that includes all the structural parts to analyse the efficiency of the load multiplication factors calculated using the idealised bridge model. The result showed that TRV loads were more conservative regarding the bending moment even after applying the EC. It was also noticed that the responses in the example application had higher responses which could be due to the thicker deck or due to the upgraded geometry of the bridge. This may mean that TRV load responses increase faster than the responses of the EC when increasing the thickness of the slab and adding structural components, thus a safety factor should be added to the load multiplication factors calculated. When it comes to the shear force, the results followed the same path of the earlier results and EC was more conservative.

The study could be improved by extracting the data not only along the length of the bridge but also along its width crossing all lanes when calculating α_M and α_V. Both multiplication factors could be calculated at the centre of the deck and see how the two codes behave in less adverse positions. Understanding this behaviour may help when optimising the bridge design.

6.3 Conclusion

To conclude, the thesis showed the possibility to define a load multiplication factor that will transfer the maximum load responses from EC LMs to TRV LM responses. The EC was more conservative for short span bridges when considering both bending moments and shear forces. But it became less conservative regarding the bending moment for bridges with 4 lanes and longer than 16 m. The factors did not have a constant value but increased according to a quadratic and a linear function for both α_M and α_V respectively.

6.4 Future Studies

This thesis focused on an idealised portal frame bridge with lengths between 6 and 25 m up to 4 lanes for each length. This report did not consider any limitation for maximum vertical deformation in the deck slab. Considering these factors, different studies can be done in the future to develop the multiplication load factor concept between codes, such as:

- A study that takes into account the maximum allowed deformations when comparing two design codes.
- A study where that takes into account different types of bridges with even longer spans. This may lead to faster design stages and lower project costs in the future.

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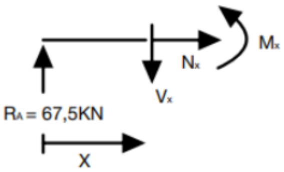
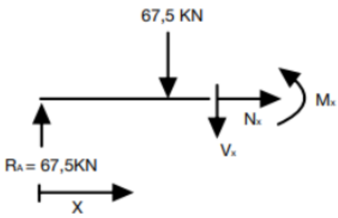
Appendix A: Verification Calculations

Calculations of simply supported beam for verification:



(1) $M_{X,1} - 67.5 \cdot X = 0$

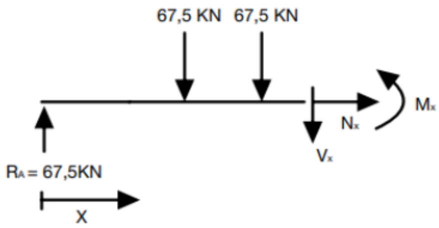
$\rightarrow M_{X,1} = 67.5 \cdot X$



(2) $M_{X,2} + 67.5 \cdot (X - 11.9) - 67.5X = 0$

$\rightarrow M_{X,2} = 67.5X - 67.5X + 67.5 \cdot 11.9$

$\rightarrow M_{X,2} = 803.25$ [KNm]



(3) $M_{X,3} + 67.5 \cdot (X - 13.1) + 67.5 \cdot (X - 11.9) - 67.5X = 0$

$\rightarrow M_{X,3} = 67.5X - 67.5 \cdot X + 67.5 \cdot 113.9 - 67.5 \cdot X + 67.5 \cdot 11.9$

$\rightarrow M_{X,3} = 1687.5 - 67.5 \cdot X$

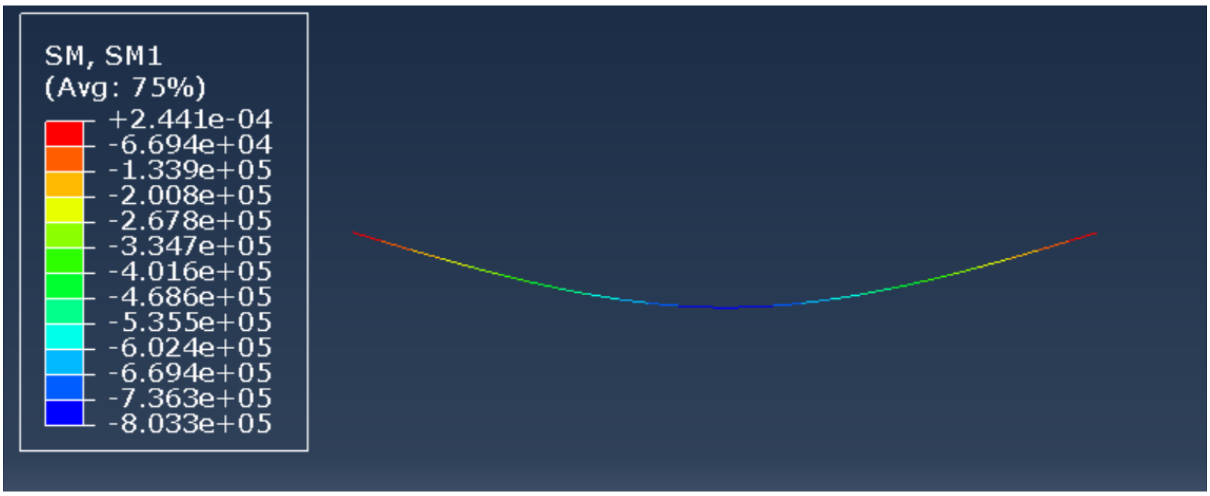


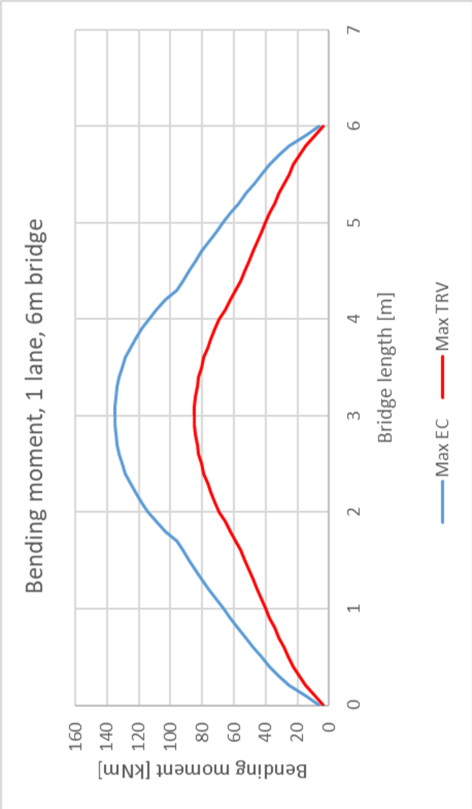
Figure A.1: Verification analysis of simply supported beams in Brigade/Plus.

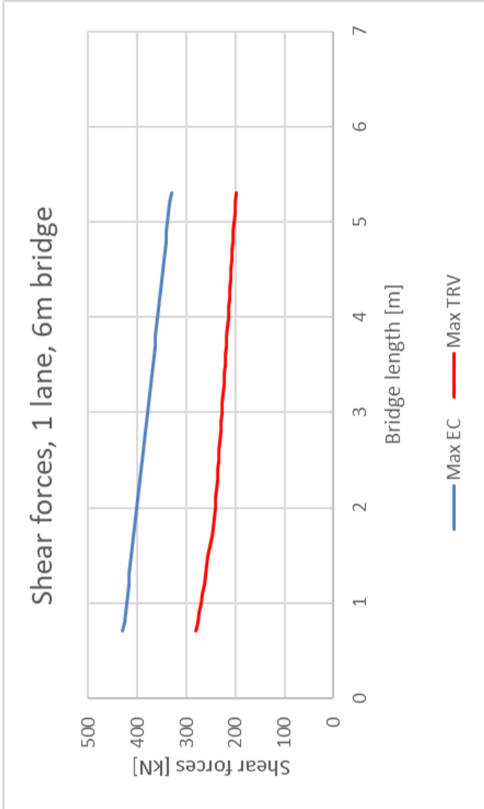
Appendix B: Brigade/Plus Load Settings

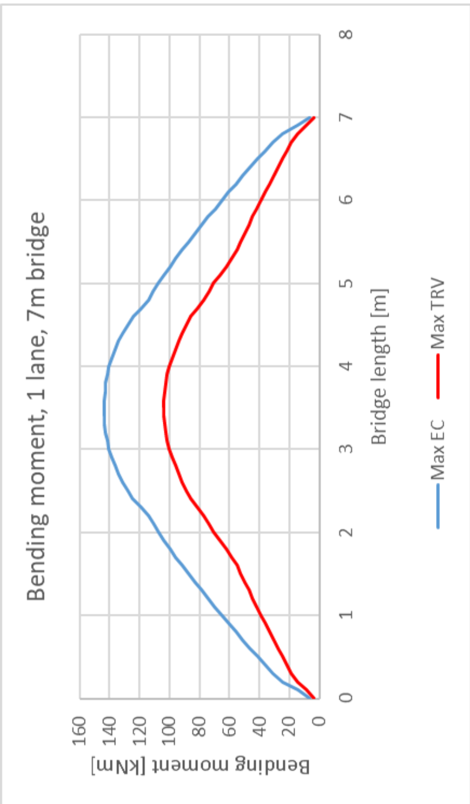
Load Model	Load Type	Load Intensity	Load/Axle Width	Dynamic Factor	Lane 1 Factor	Lane 2 Factor	Lane 3 Factor	Lane 4 Factor
		[kN], [kN/m^2]	[m]					
LM 1, TS	Vehicle	270	2	1	1	0.667	0	0
LM 1, UDL	Lane Surface	7.2	3	1	1	0.347	0.347	0.347
LM 2	Vehicle	360	2	1	1	0	0	0
Validation: LM 1, TS	Vehicle	α(moment) x 270	2	1	1	0.667	0	0
Validation: LM 1, UDL	Lane Surface	α(moment) x 7.2	3	1	1	0.347	0.347	0.347
Validation: LM 2	Vehicle	α(moment) x 360	2	1	1	0	0	0
Lorry a	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
Lorry b	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
Lorry c	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
Lorry d	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
Lorry e	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
Lorry f	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
Lorry g	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
Lorry k	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
Lorry l	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
Lorry m	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
Lorry n	Vehicle	combination according to the annex	2	1.2	1	0.8	0	0
TRV UDL, 3 Lanes	Lane Surface	5	3	1.2	1	0	0	0
TRV UDL, 4 Lanes	Lane Surface	5	3	1.2	1	1	0	0

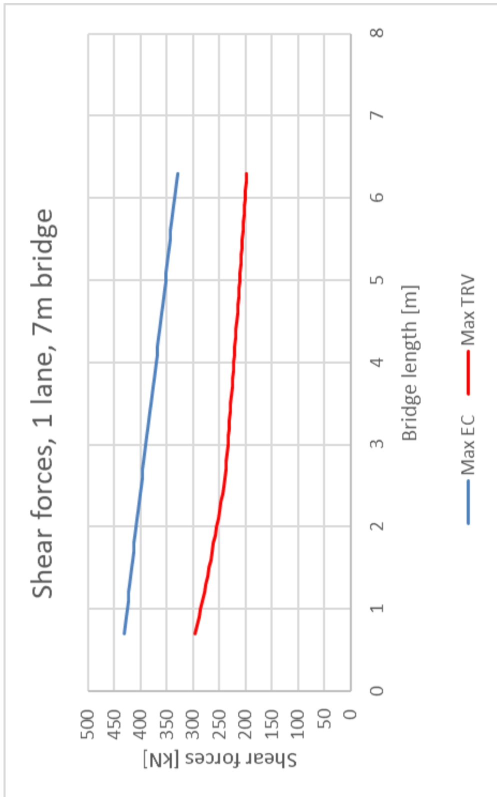
Appendix C: EC and TRV Result Comparison

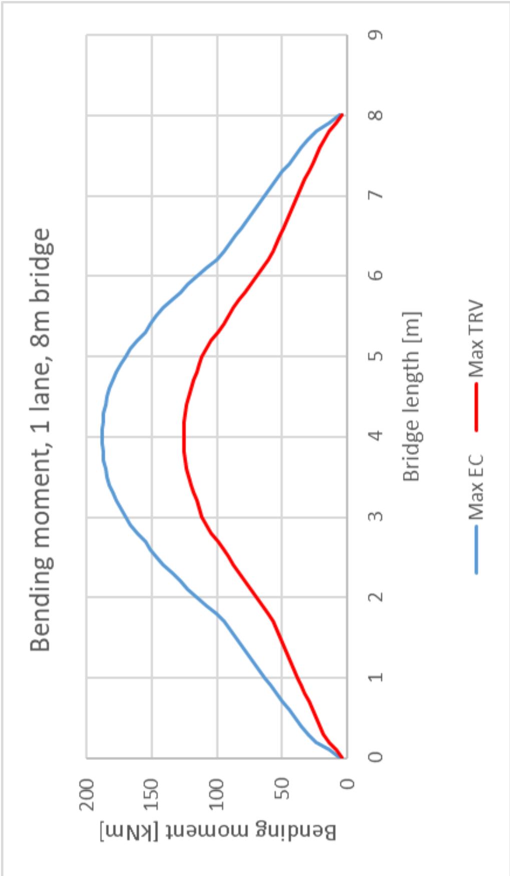
C.1 Lane 1

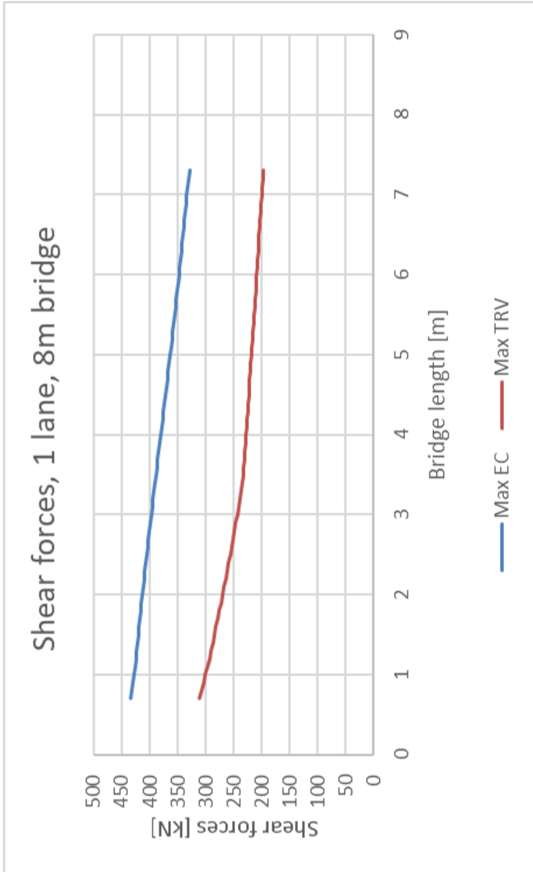


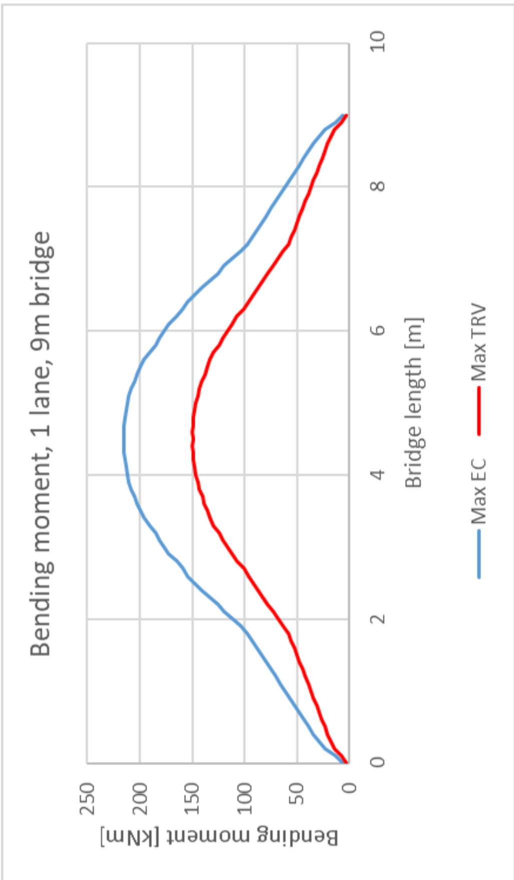


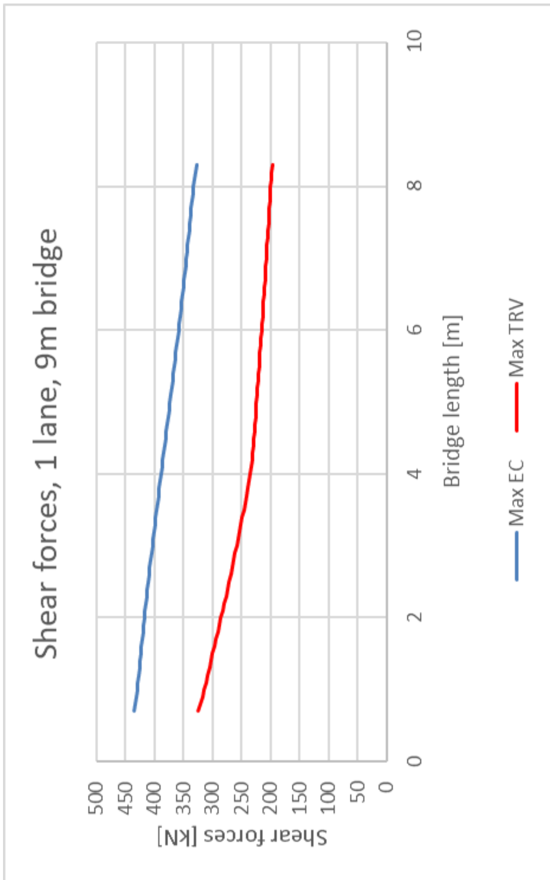


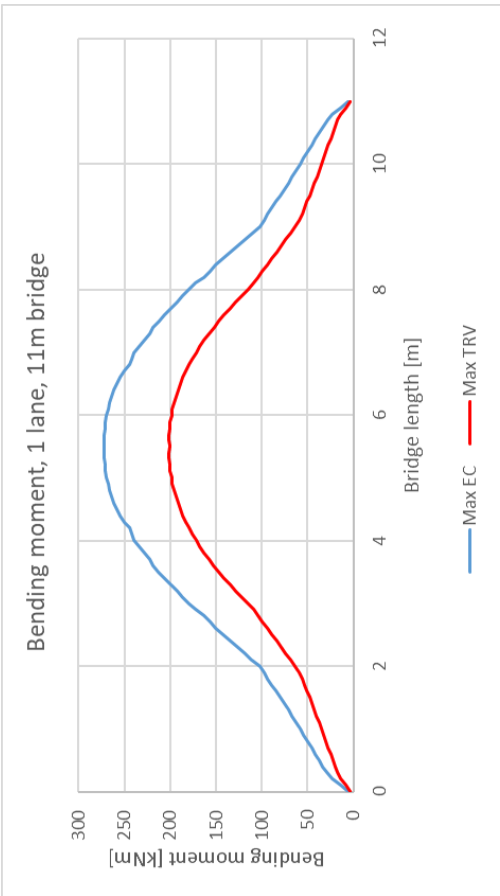


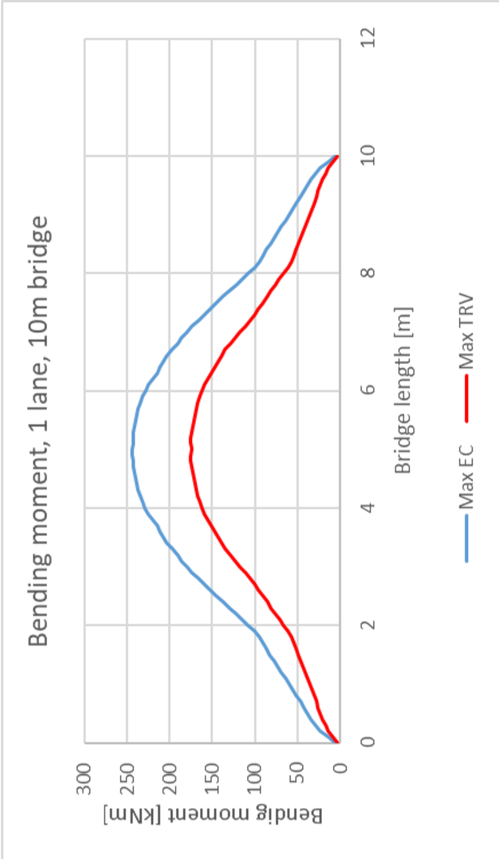

Bending moment, 1 lane, 8m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV

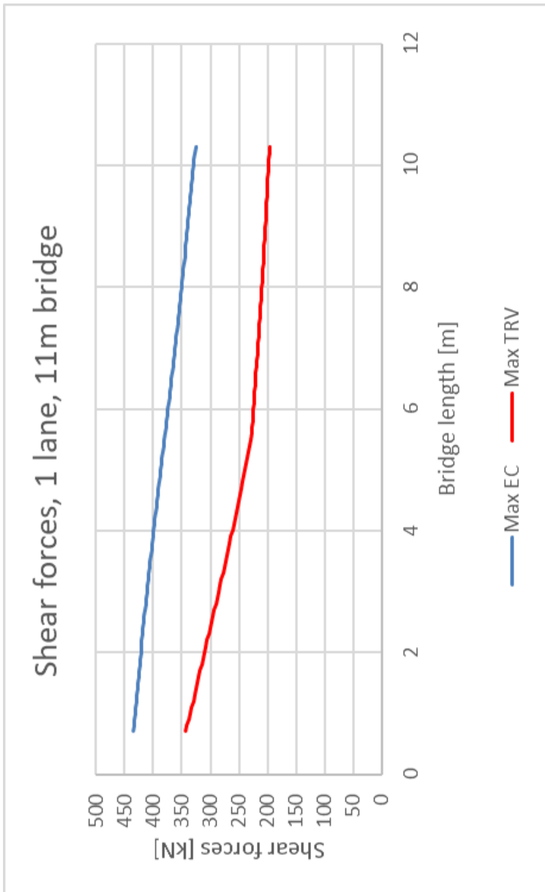

Shear forces, 1 lane, 8m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV

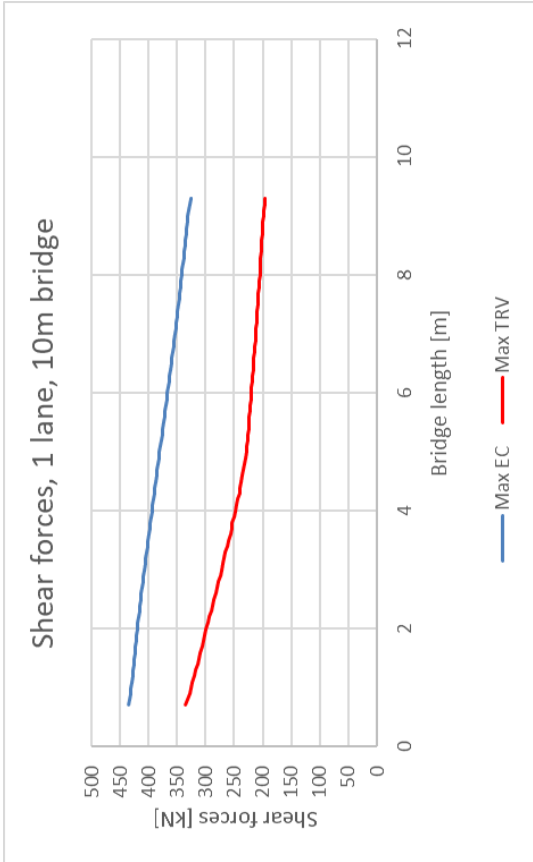

Bending moment, 1 lane, 9m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV

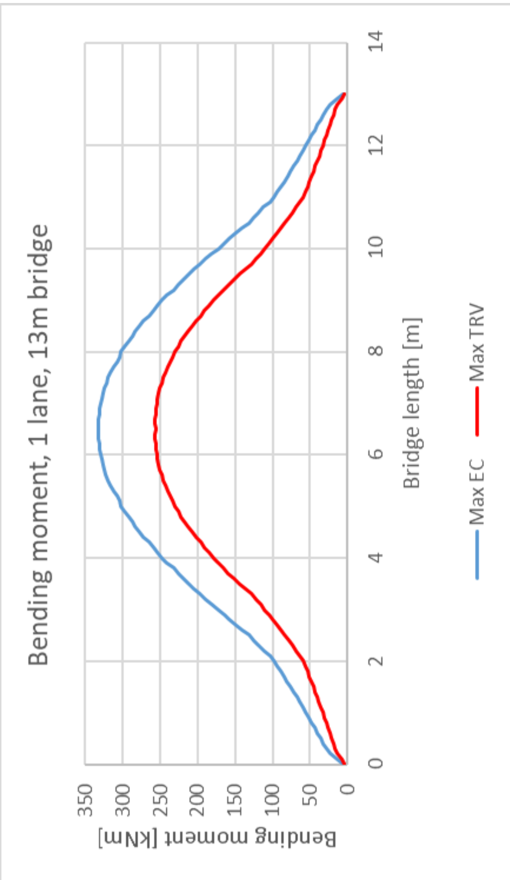

Shear forces, 1 lane, 9m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV


Bending moment, 1 lane, 11m bridge
Bendig moment [kNm]
300
250
200
150
100
50
0
0
2
4
6
8
10
12
Bridge length [m]
Max EC
Max TRV


Bending moment, 1 lane, 10m bridge
Bendig moment [kNm]
300
250
200
150
100
50
0
0
2
4
6
8
10
12
Bridge length [m]
Max EC
Max TRV


Shear forces, 1 lane, 11m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
Bridge length [m]
Max EC
Max TRV


Shear forces, 1 lane, 10m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
Bridge length [m]
Max EC
Max TRV


Bending moment, 1 lane, 13m bridge
Bending moment [kNm]
Bridge length [m]
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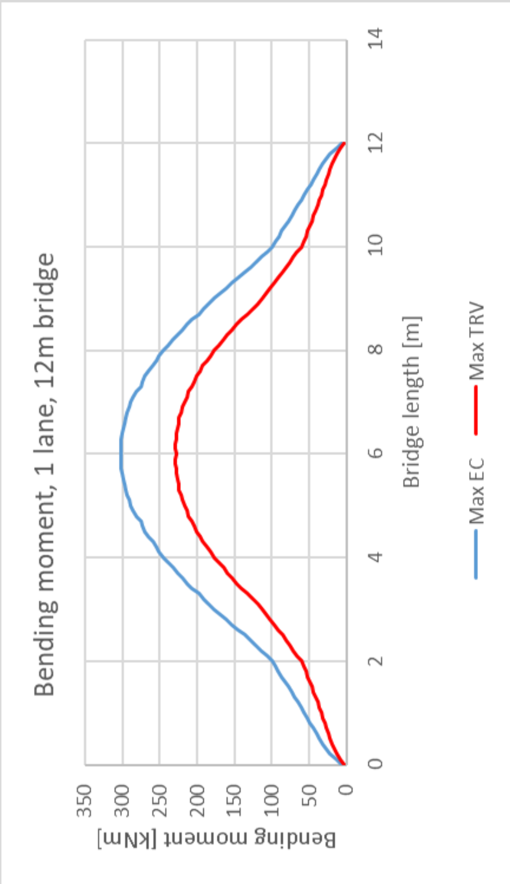
100
150
200
250
300
350
0
2
4
6
8
10
12
14
Max EC
Max TRV


Bending moment, 1 lane, 12m bridge
Bending moment [kNm]
Bridge length [m]
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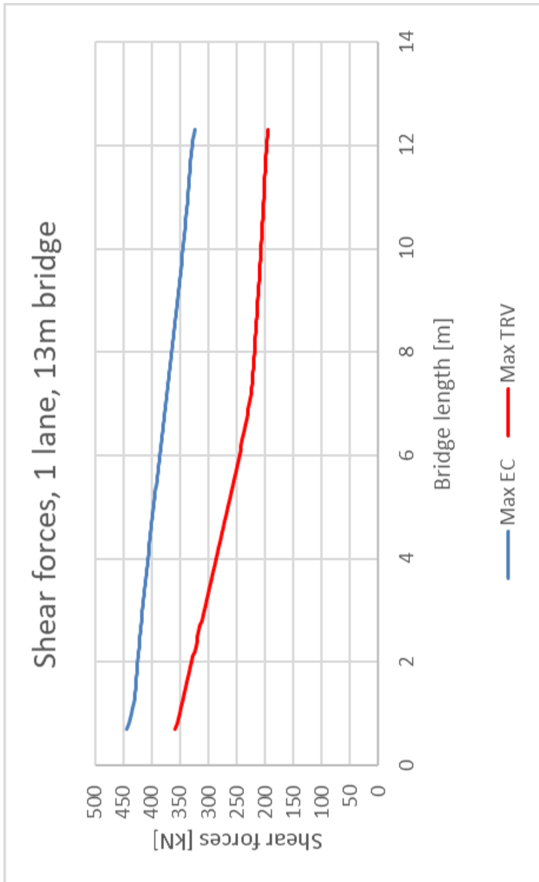
100
150
200
250
300
350
0
2
4
6
8
10
12
14
Max EC
Max TRV


Shear forces, 1 lane, 13m bridge
Shear forces [kN]
Bridge length [m]
0
50
100
150
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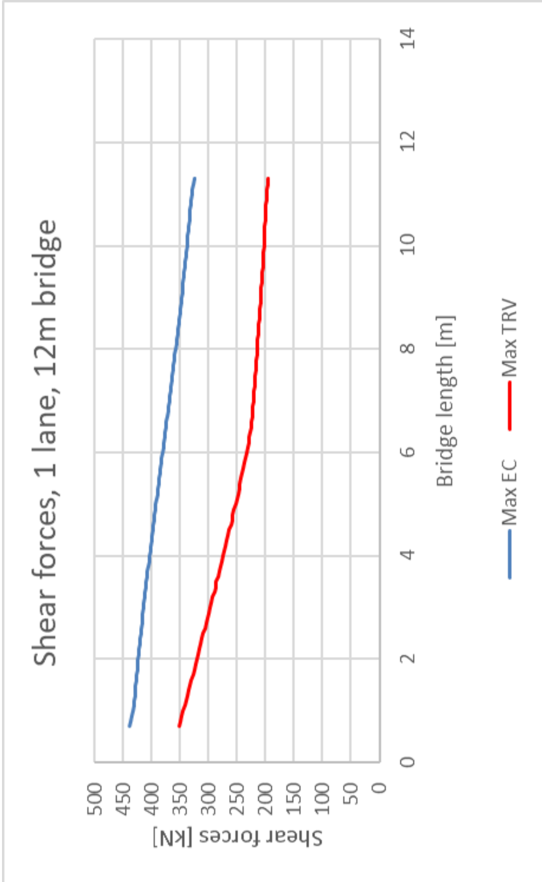
250
300
350
400
450
500
0
2
4
6
8
10
12
14
Max EC
Max TRV


Shear forces, 1 lane, 12m bridge
Shear forces [kN]
Bridge length [m]
0
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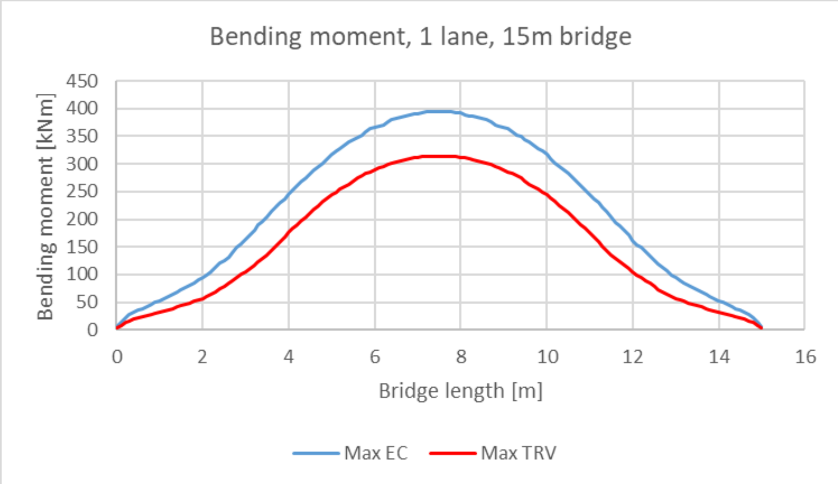
100
150
200
250
300
350
400
450
500
0
2
4
6
8
10
12
14
Max EC
Max TRV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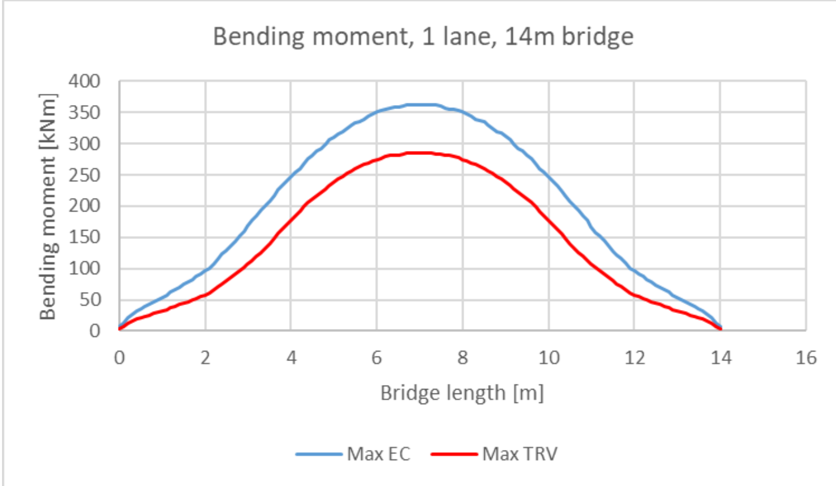
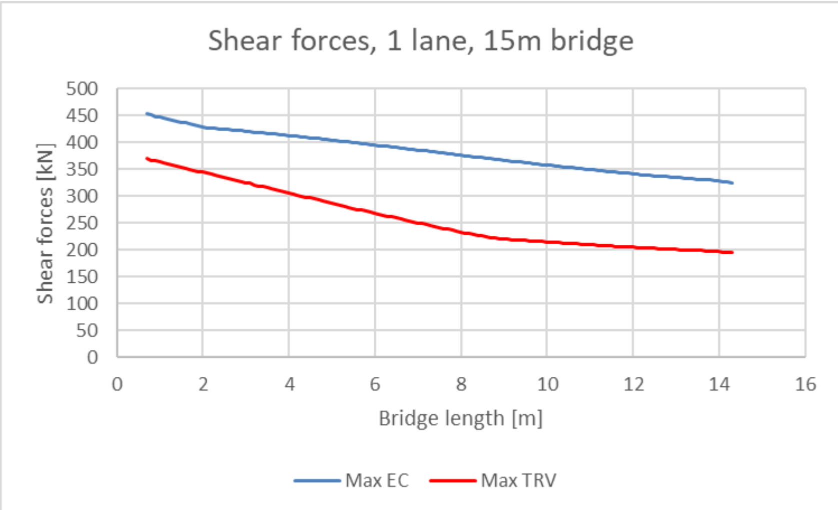
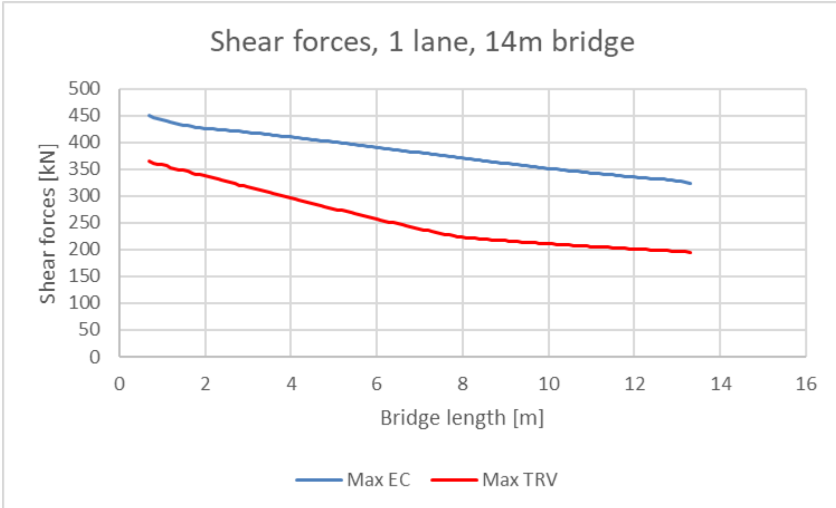
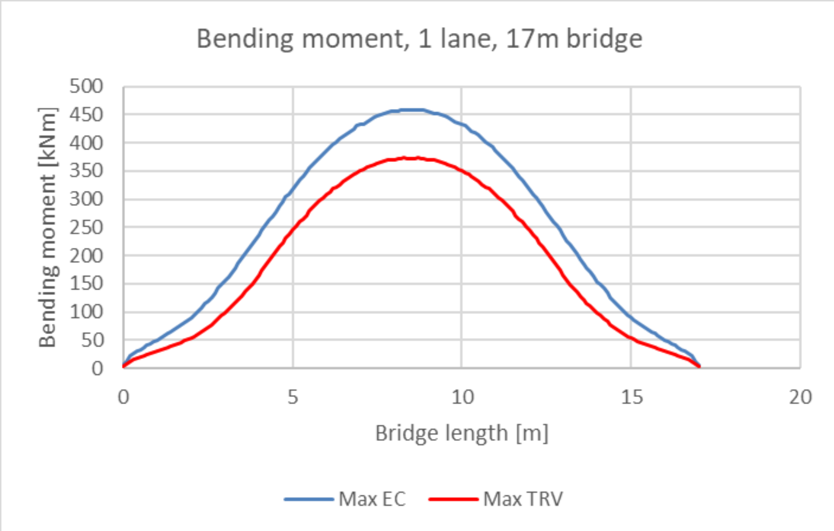
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV


Bending moment, 1 lane, 14m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV


Shear forces, 1 lane, 15m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV


Shear forces, 1 lane, 14m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV


Bending moment, 1 lane, 17m bridge
Bending moment [kNm]
500
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400
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300
250
200
150
100
50
0
0
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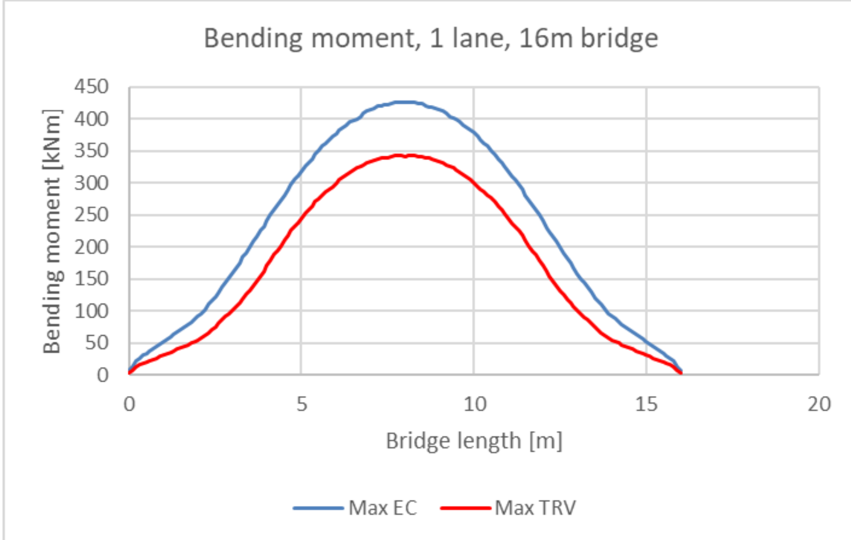
10
15
20
Bridge length [m]
Max EC
Max TRV


Bending moment, 1 lane, 16m bridge
Bending moment [kNm]
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50
0
0
5
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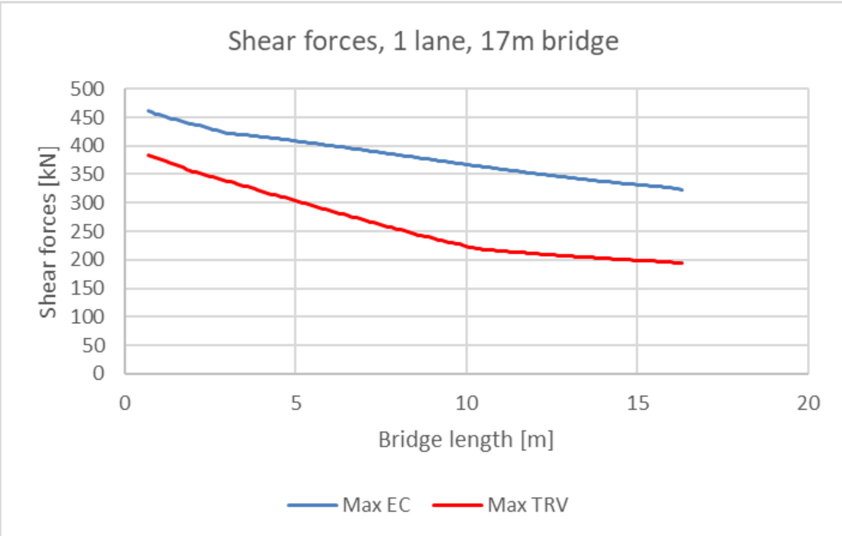
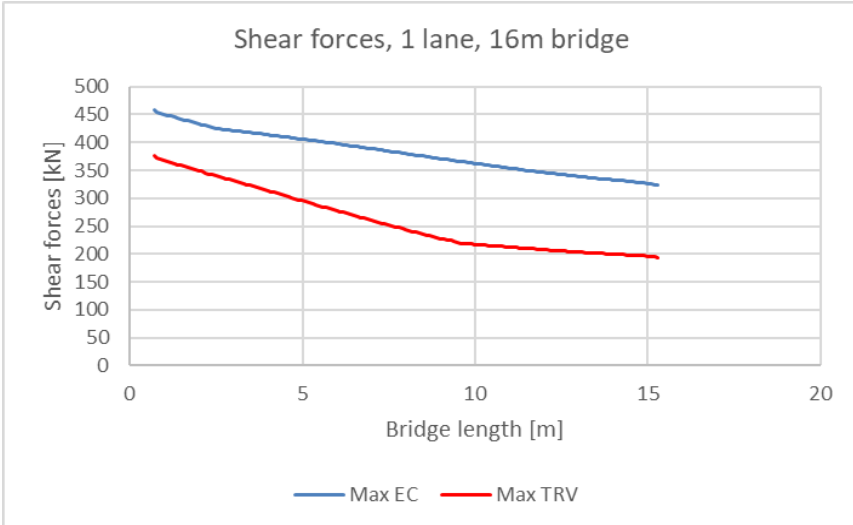
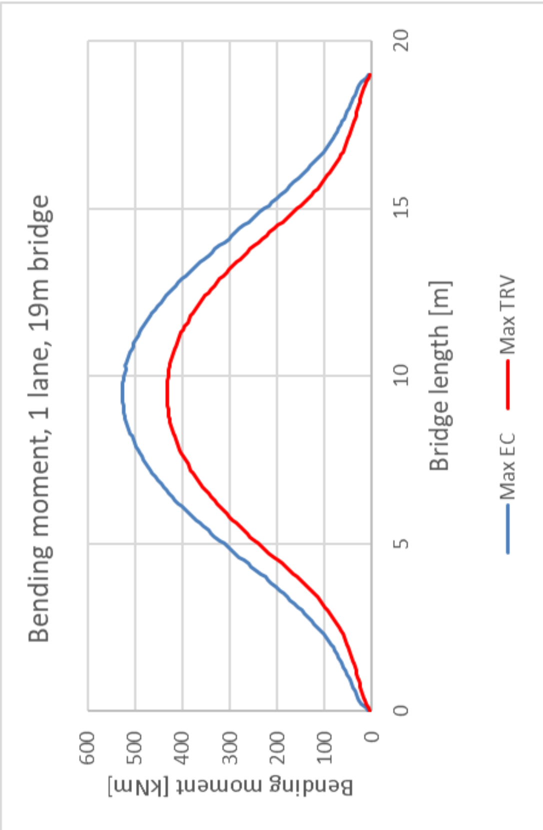
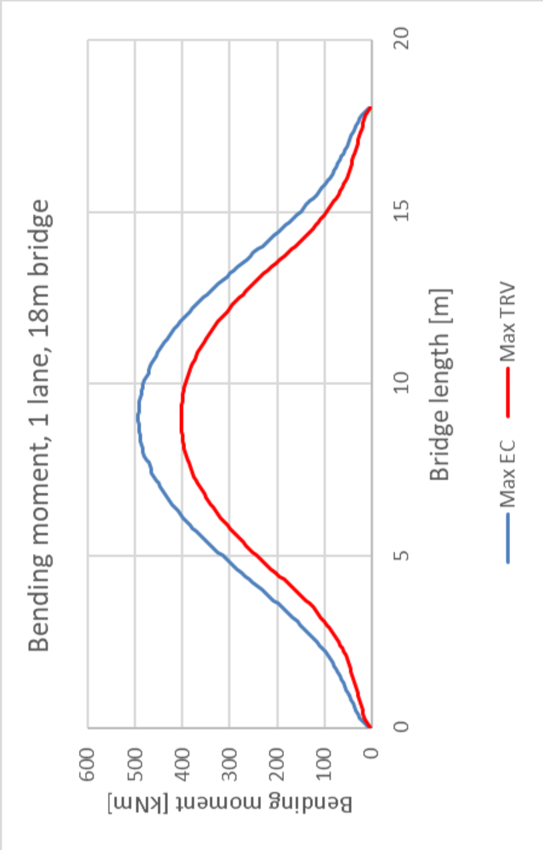
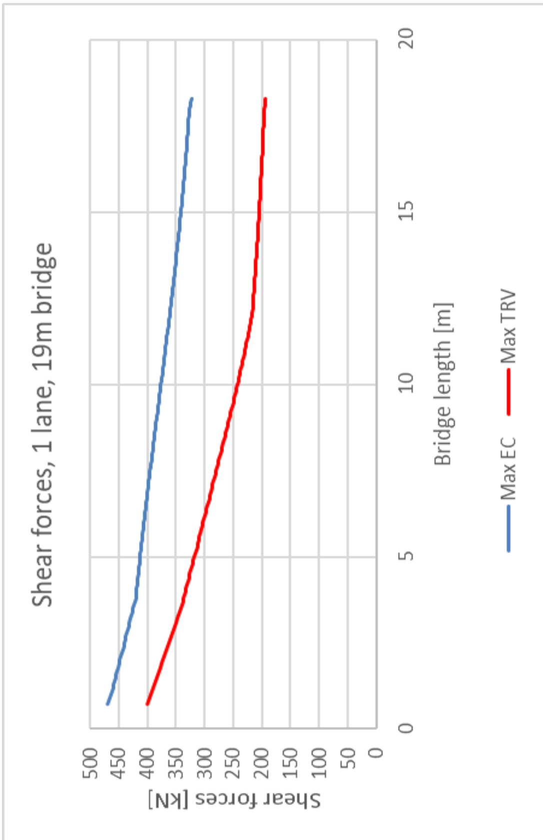
Bridge length [m]
Max EC
Max TRV

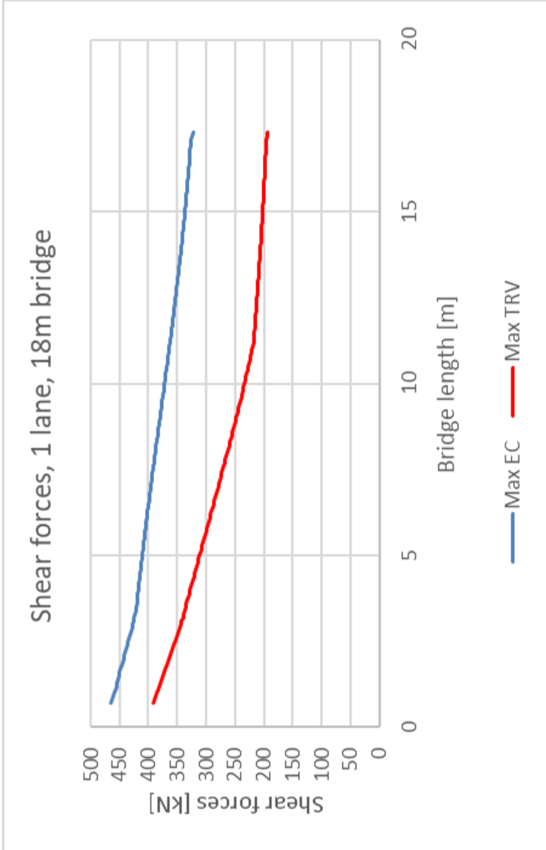

Shear forces, 1 lane, 17m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV

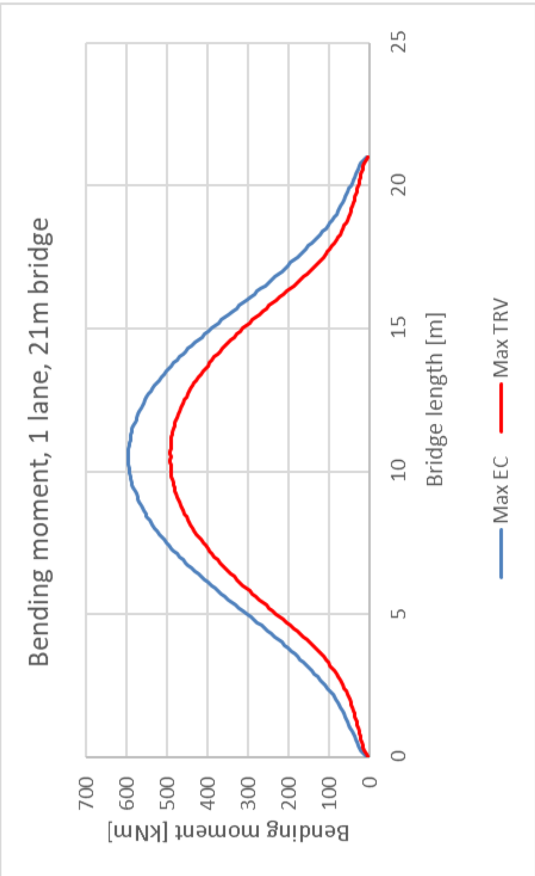

Shear forces, 1 lane, 16m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV

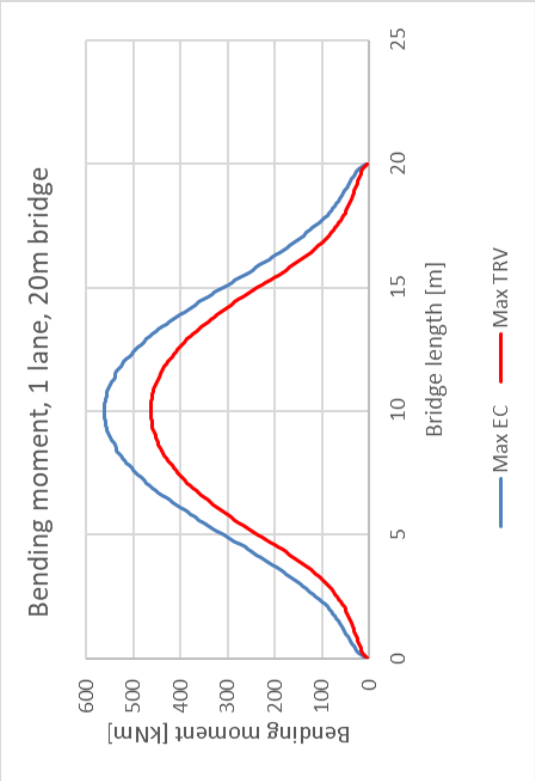

Bending moment, 1 lane, 19m bridge
Bending moment [kNm]
0
100
200
300
400
500
600
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV

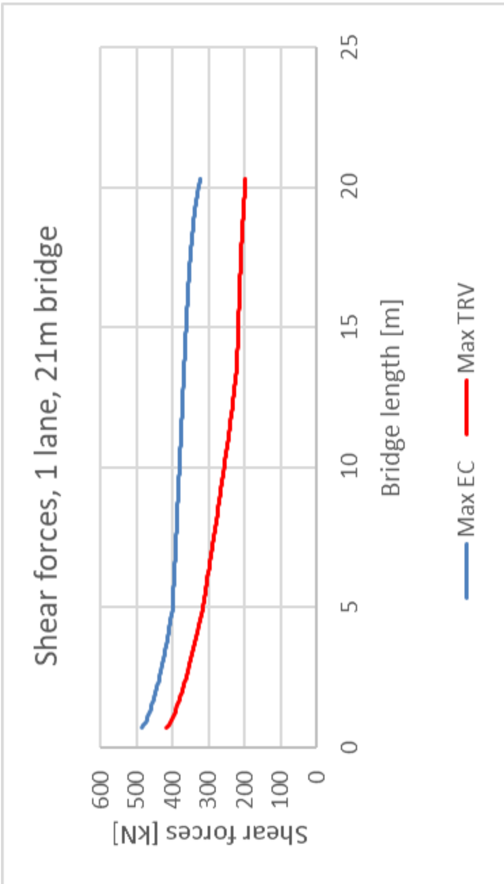

Bending moment, 1 lane, 18m bridge
Bending moment [kNm]
0
100
200
300
400
500
600
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV

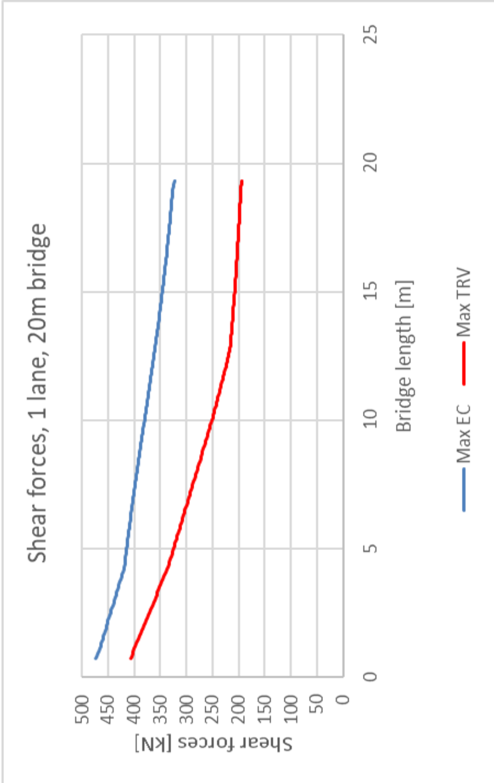

Shear forces, 1 lane, 19m bridge
Shear forces [kN]
0
50
100
150
200
250
300
350
400
450
500
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV

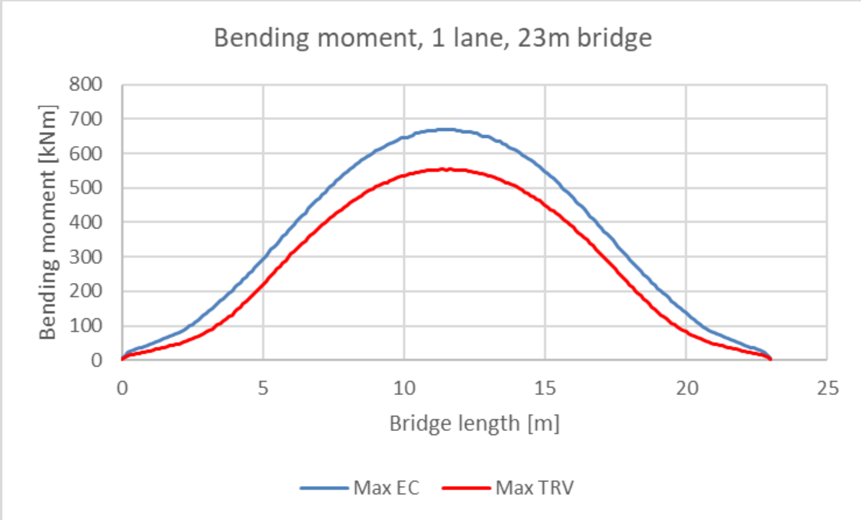

Shear forces, 1 lane, 18m bridge
Shear forces [kN]
0
50
100
150
200
250
300
350
400
450
500
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV

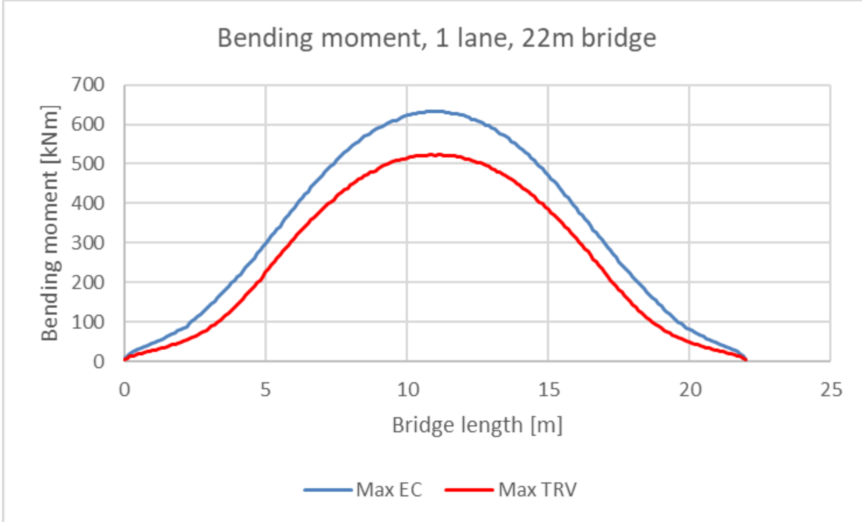

Bending moment, 1 lane, 21m bridge
Bending moment [kNm]
700
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV

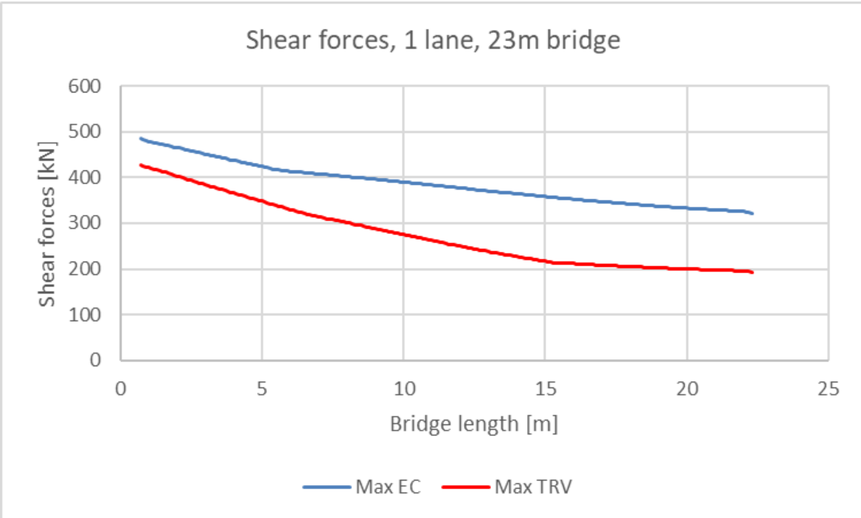

Bending moment, 1 lane, 20m bridge
Bending moment [kNm]
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV

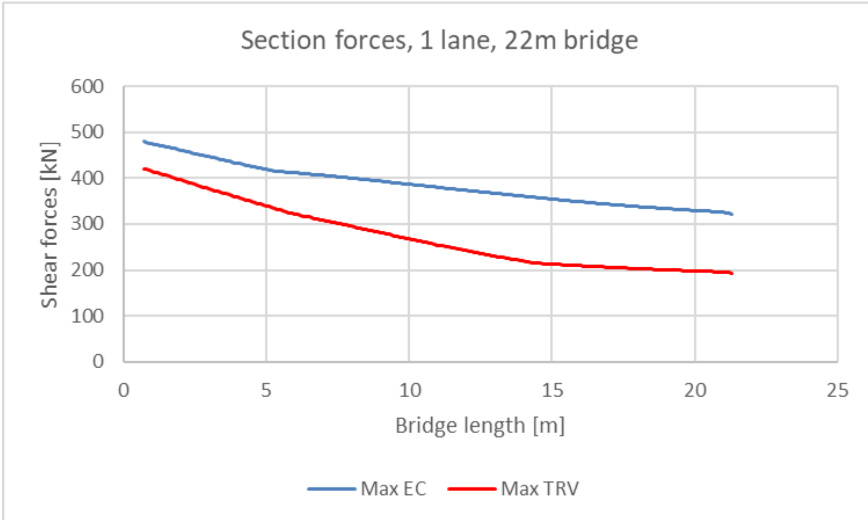

Shear forces, 1 lane, 21m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV

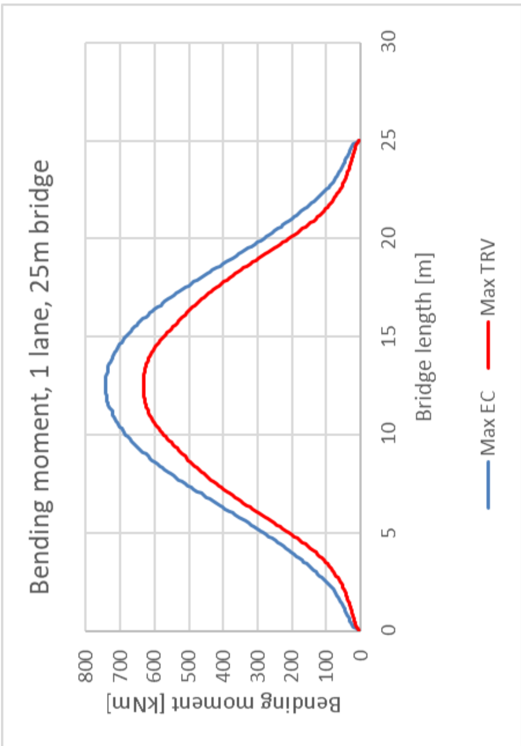

Shear forces, 1 lane, 20m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV

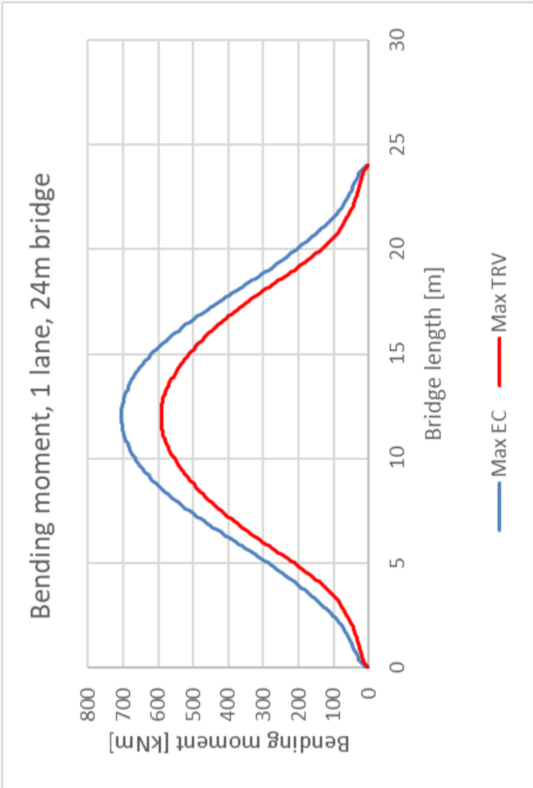

Bending moment, 1 lane, 23m bridge
Bending moment [kNm]
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV

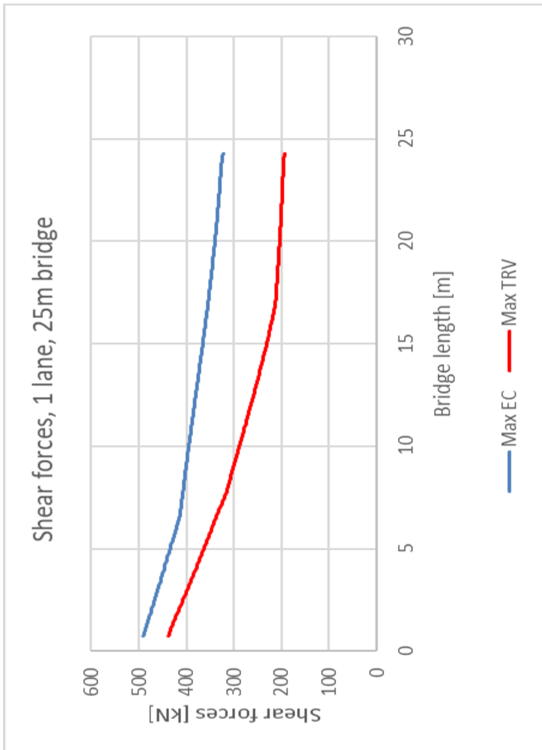

Bending moment, 1 lane, 22m bridge
Bending moment [kNm]
700
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV

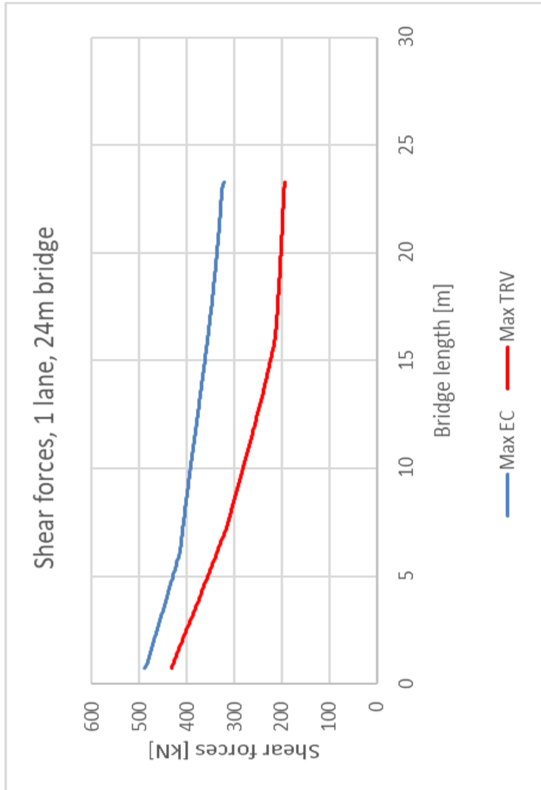

Shear forces, 1 lane, 23m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV


Section forces, 1 lane, 22m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV

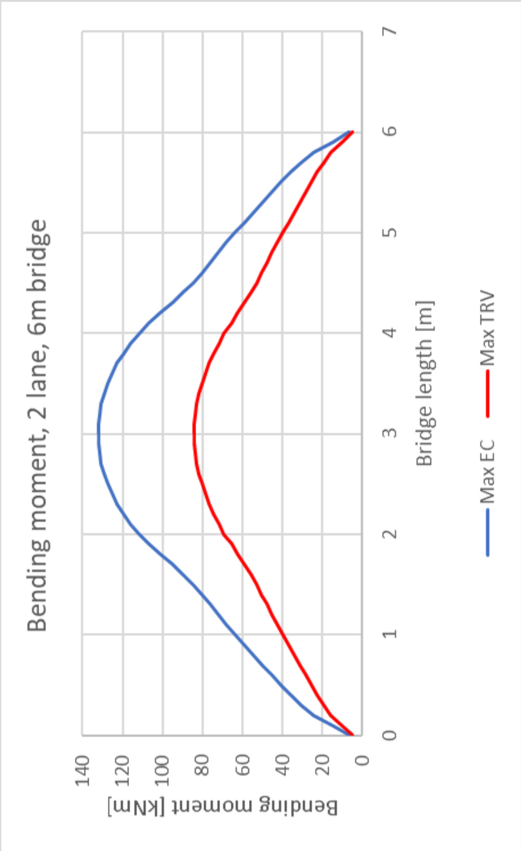

Bending moment, 1 lane, 25m bridge
Bending moment [kNm]
0
100
200
300
400
500
600
700
800
0
5
10
15
20
25
30
Bridge length [m]
Max EC
Max TRV

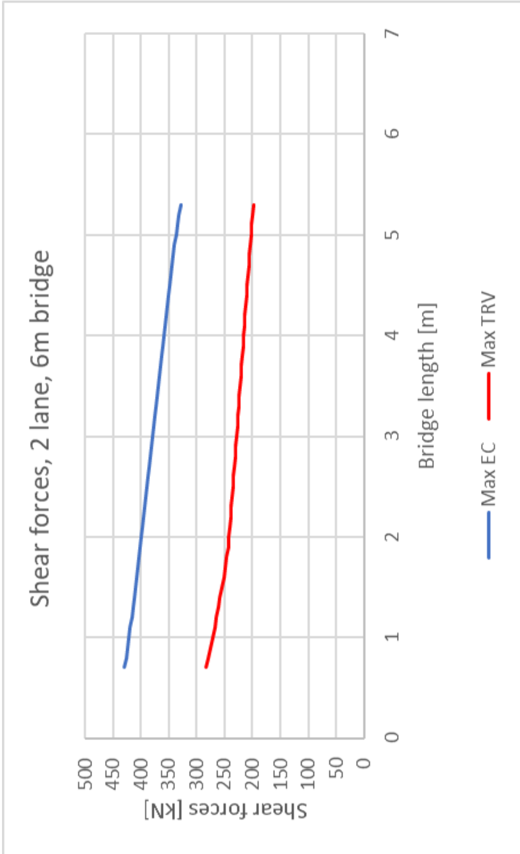

Bending moment, 1 lane, 24m bridge
Bending moment [kNm]
0
100
200
300
400
500
600
700
800
0
5
10
15
20
25
30
Bridge length [m]
Max EC
Max TRV

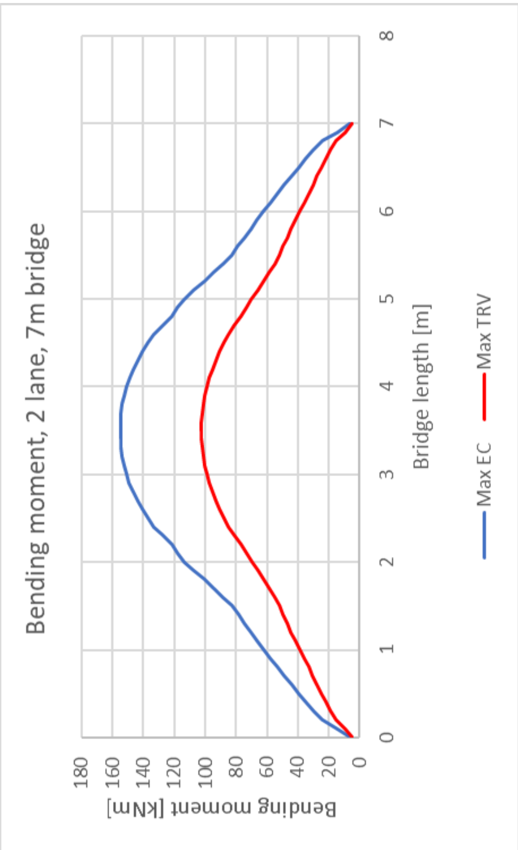

Shear forces, 1 lane, 25m bridge
Shear forces [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
Bridge length [m]
Max EC
Max TRV

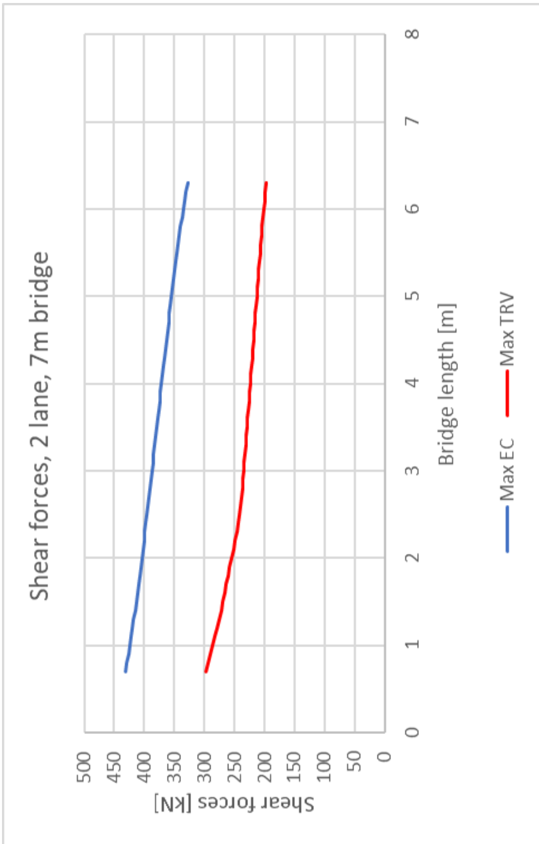

Shear forces, 1 lane, 24m bridge
Shear forces [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
Bridge length [m]
Max EC
Max TRV

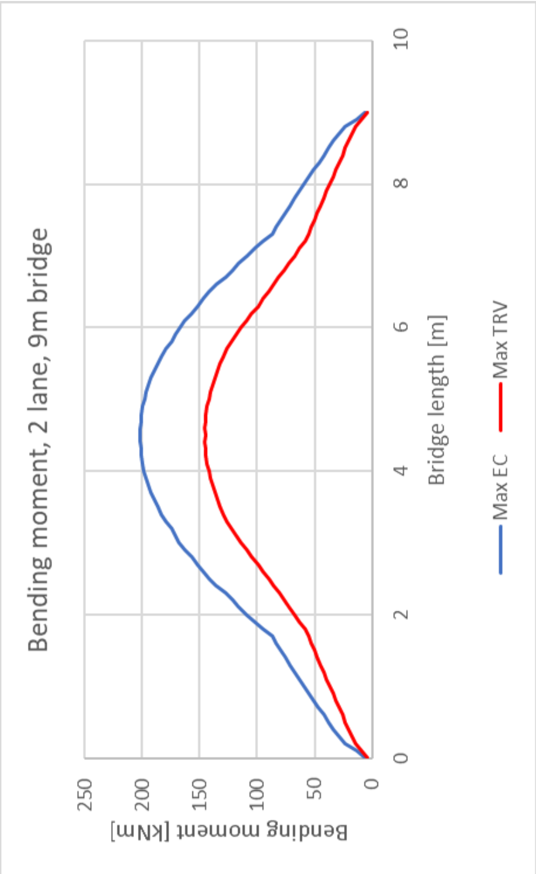
C.2 Lane 2

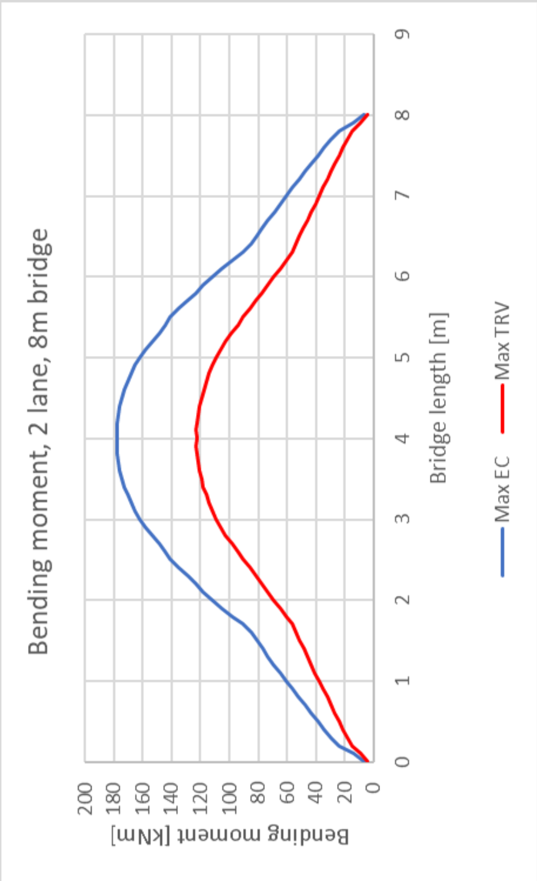

Bending moment, 2 lane, 6m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV

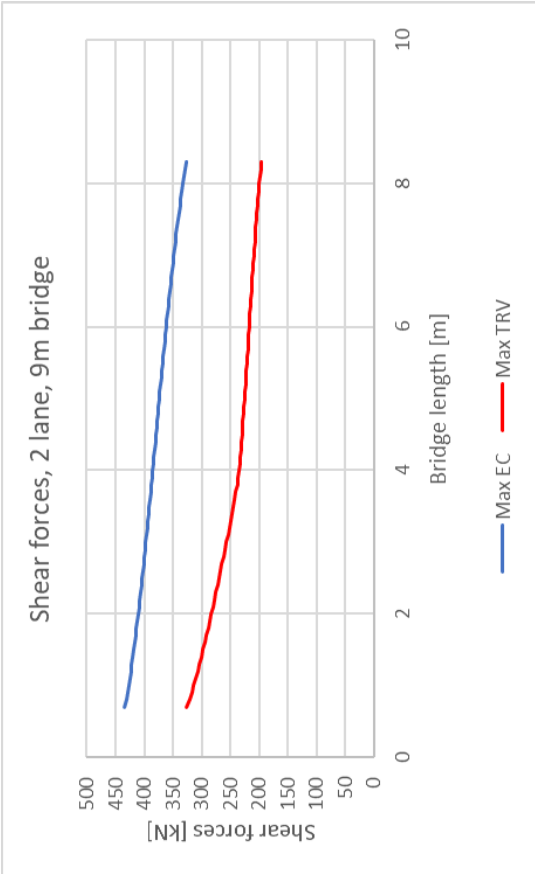

Shear forces, 2 lane, 6m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV

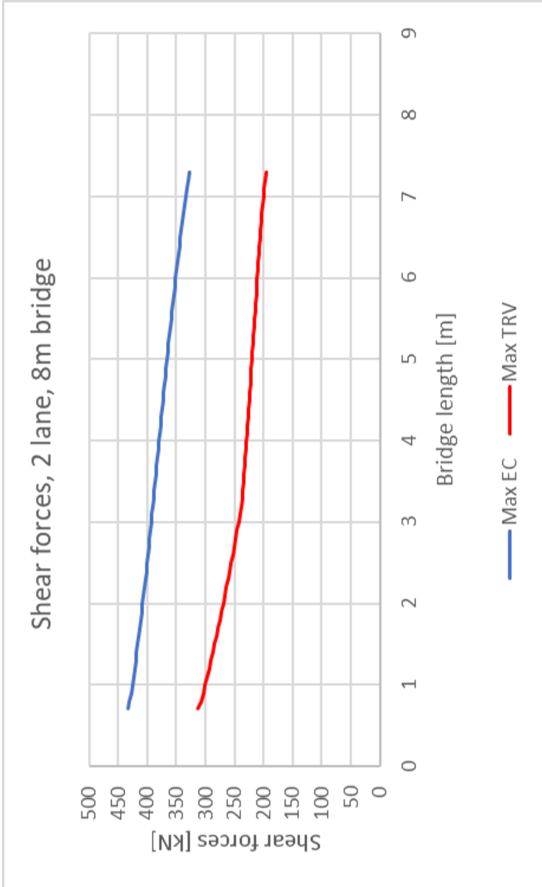

Bending moment, 2 lane, 7m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV

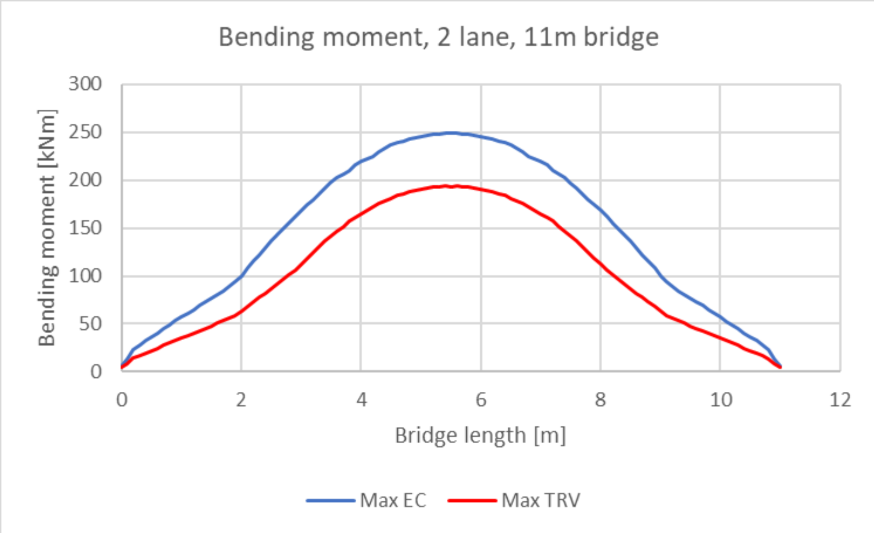

Shear forces, 2 lane, 7m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV

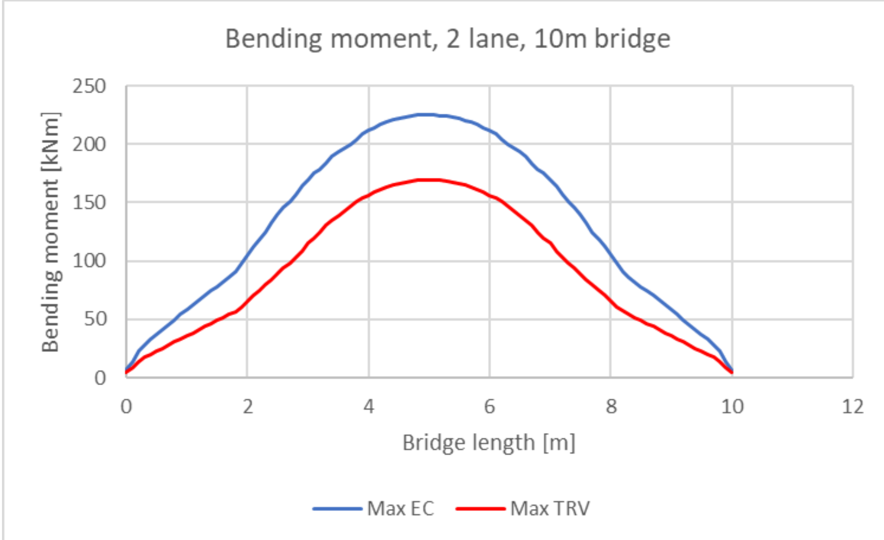

Bending moment, 2 lane, 9m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV

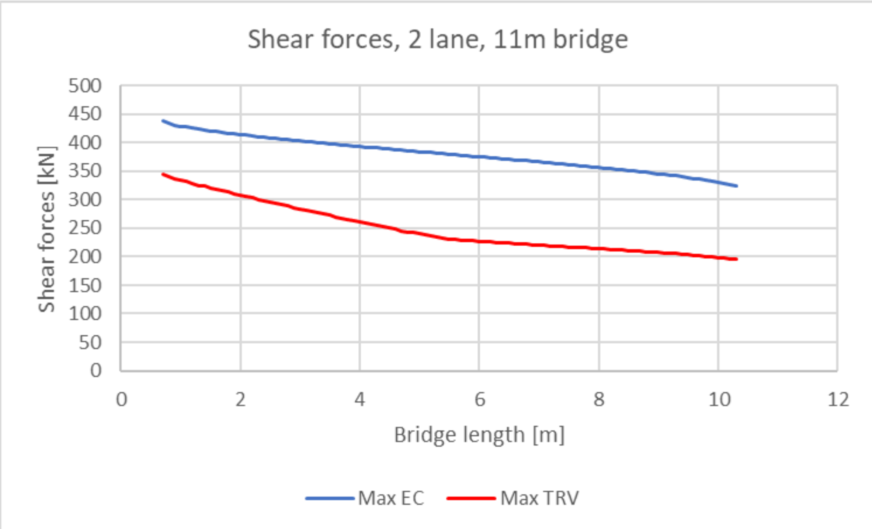

Bending moment, 2 lane, 8m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV


Shear forces, 2 lane, 9m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV

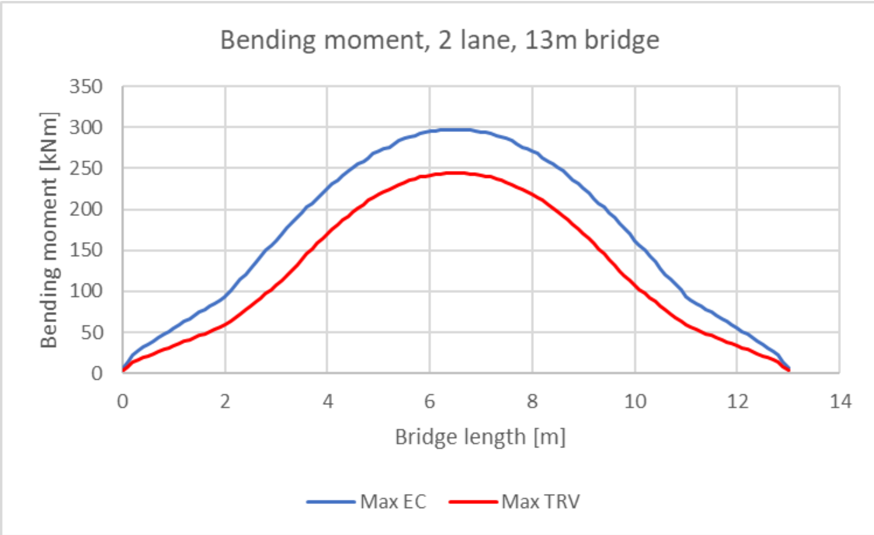

Shear forces, 2 lane, 8m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV


Bending moment, 2 lane, 11m bridge
Bending moment [kNm]
300
250
200
150
100
50
0
0
2
4
6
8
10
12
Bridge length [m]
Max EC
Max TRV

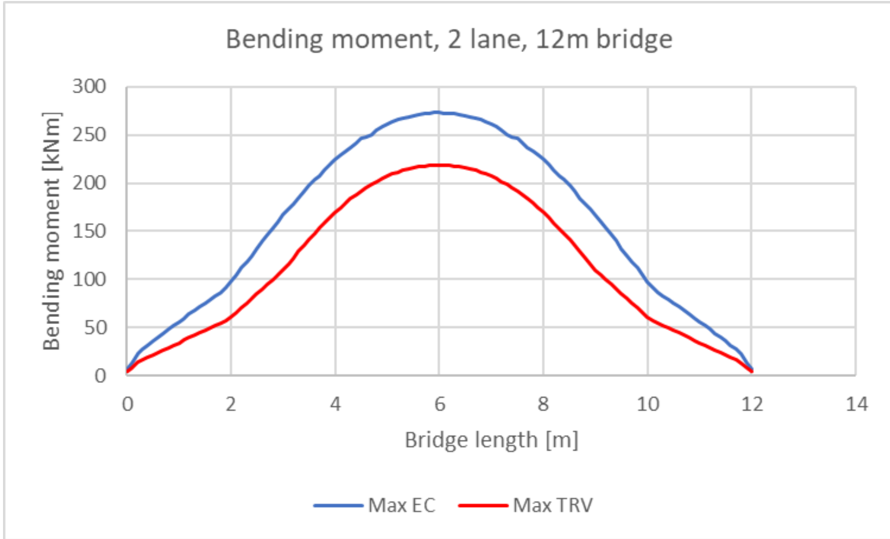

Bending moment, 2 lane, 10m bridge
Bending moment [kNm]
250
200
150
100
50
0
0
2
4
6
8
10
12
Bridge length [m]
Max EC
Max TRV


Shear forces, 2 lane, 11m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
Bridge length [m]
Max EC
Max TRV


Shear forces, 2 lane, 10m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
Bridge length [m]
Max EC
Max TRV

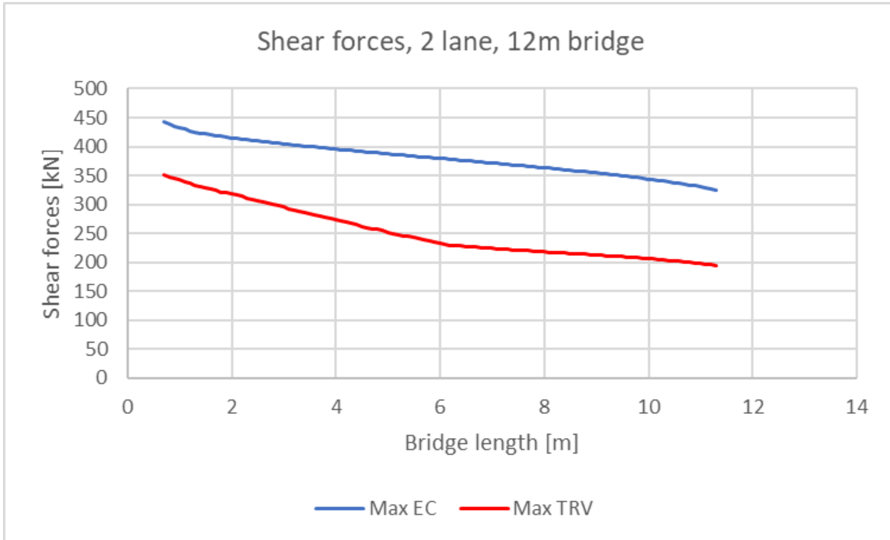


Bending moment, 2 lane, 13m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV

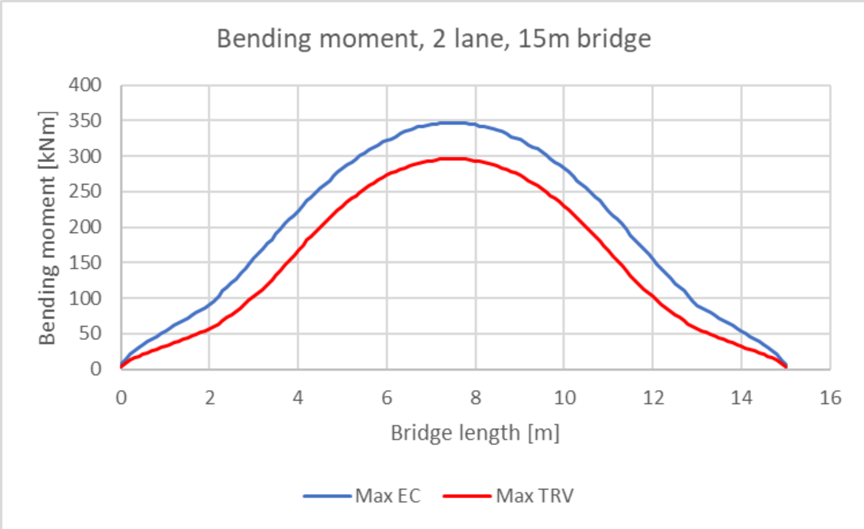


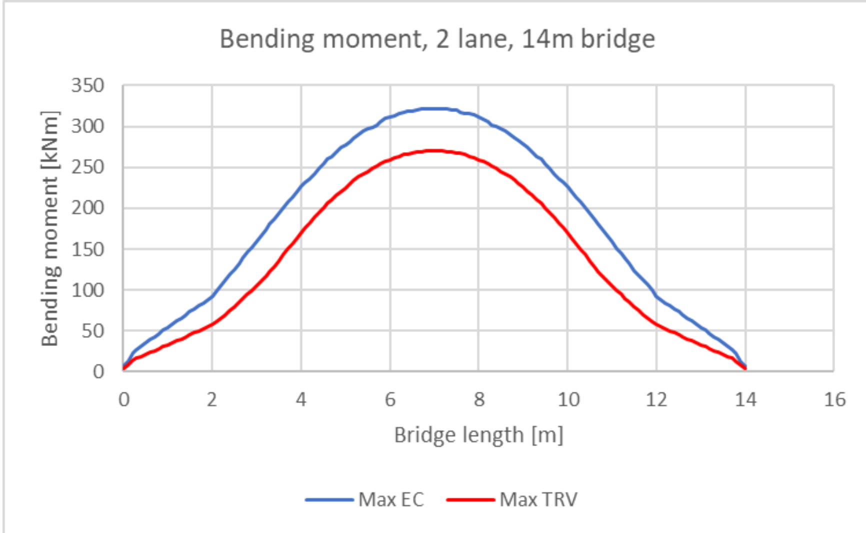
Bending moment, 2 lane, 12m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV

Shear forces, 2 lane, 13m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV

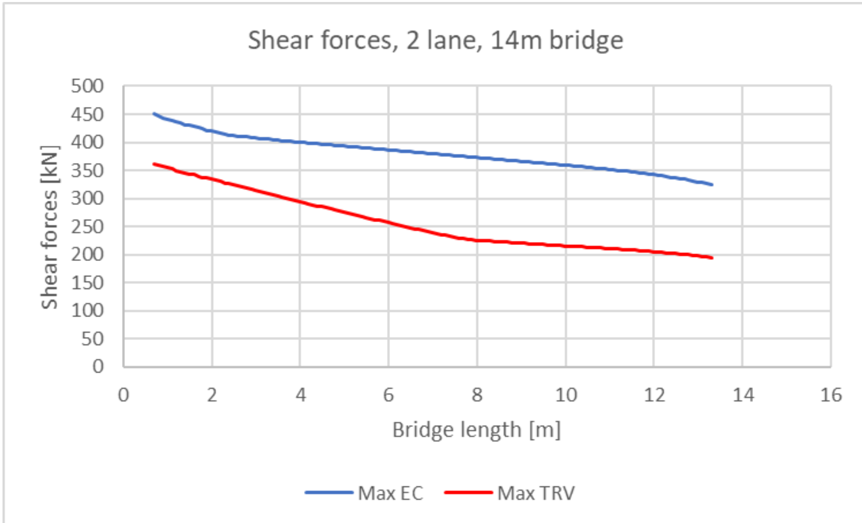


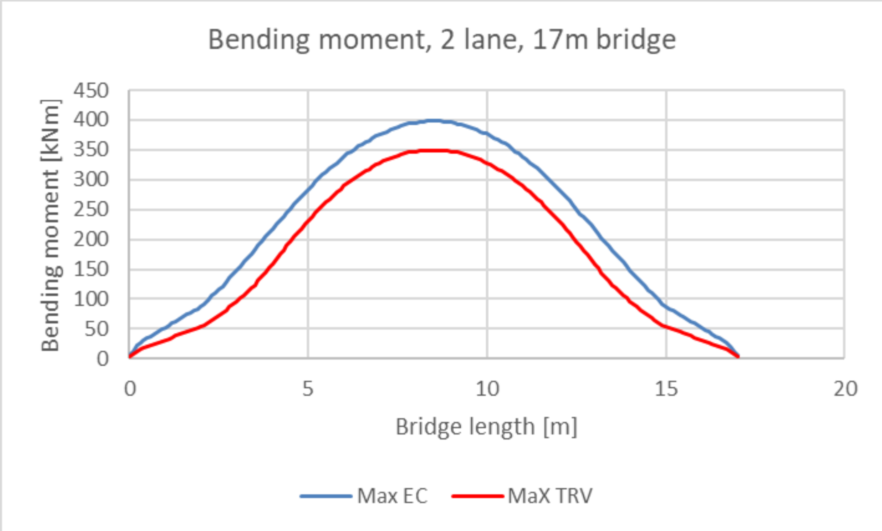
Shear forces, 2 lane, 12m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV

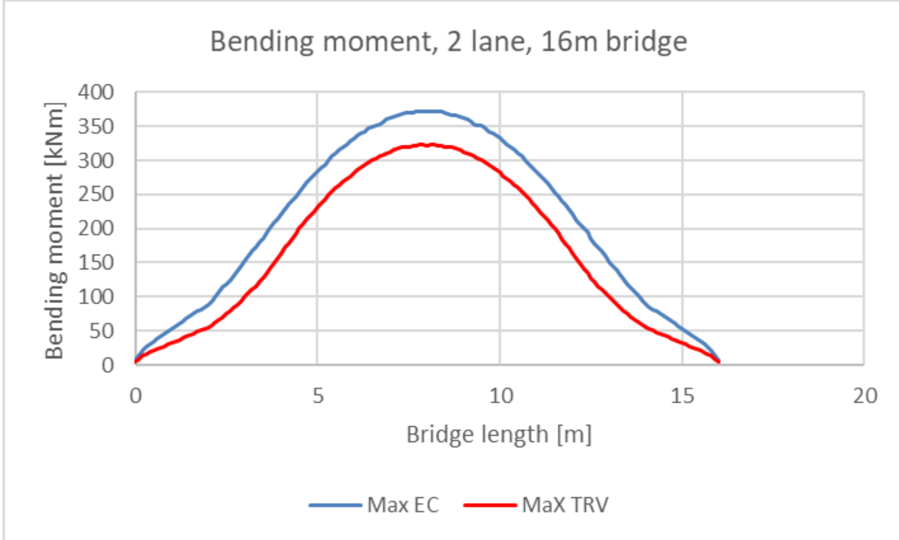

Bending moment, 2 lane, 15m bridge
Bending moment [kNm]
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
Bridge length [m]
Max EC
Max TRV

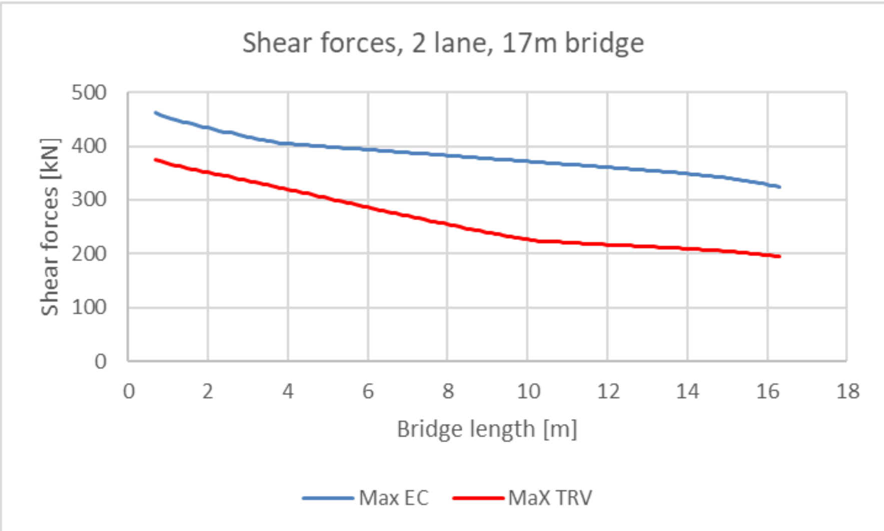

Bending moment, 2 lane, 14m bridge
Bending moment [kNm]
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
Bridge length [m]
Max EC
Max TRV

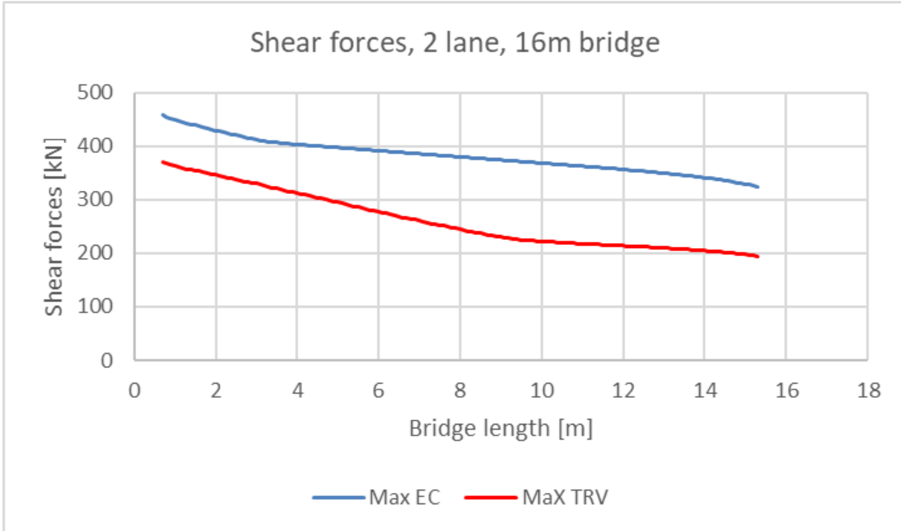

Shear forces, 2 lane, 15m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
Bridge length [m]
Max EC
Max TRV

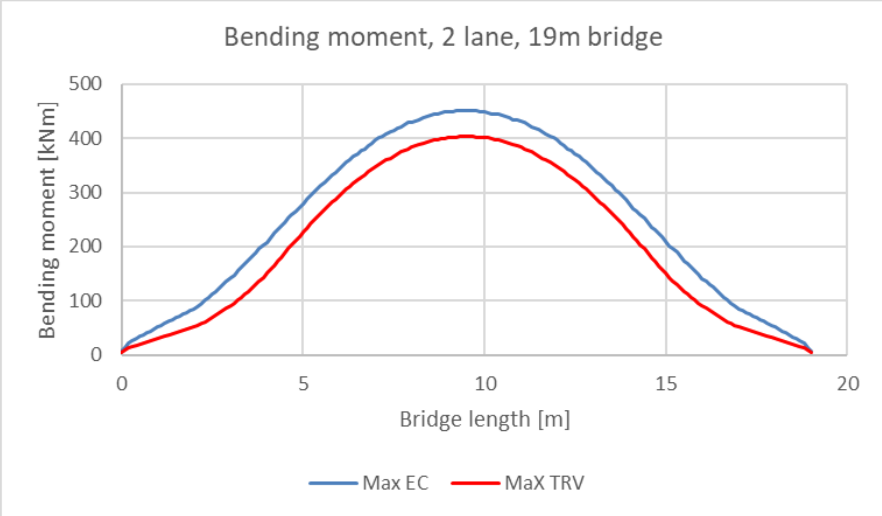

Shear forces, 2 lane, 14m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
Bridge length [m]
Max EC
Max TRV

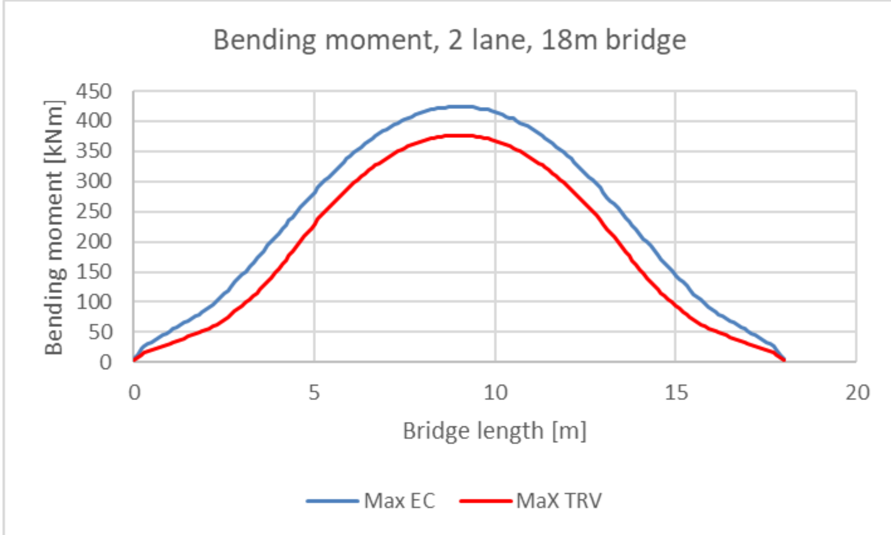

Bending moment, 2 lane, 17m bridge
Bending moment [kNm]
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
Bridge length [m]
Max EC
MaX TRV


Bending moment, 2 lane, 16m bridge
Bending moment [kNm]
400
350
300
250
200
150
100
50
0
0
5
10
15
20
Bridge length [m]
Max EC
MaX TRV

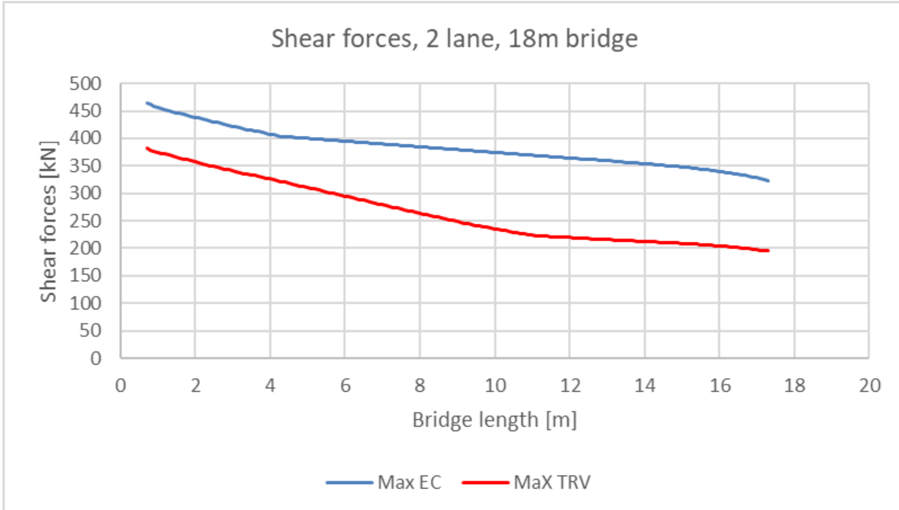

Shear forces, 2 lane, 17m bridge
Shear forces [kN]
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
Bridge length [m]
Max EC
MaX TRV

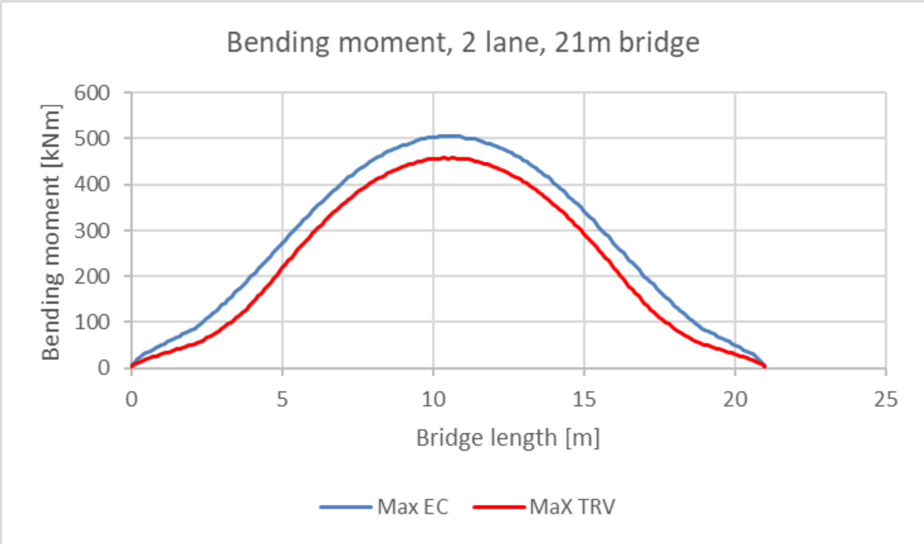

Shear forces, 2 lane, 16m bridge
Shear forces [kN]
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
Bridge length [m]
Max EC
MaX TRV

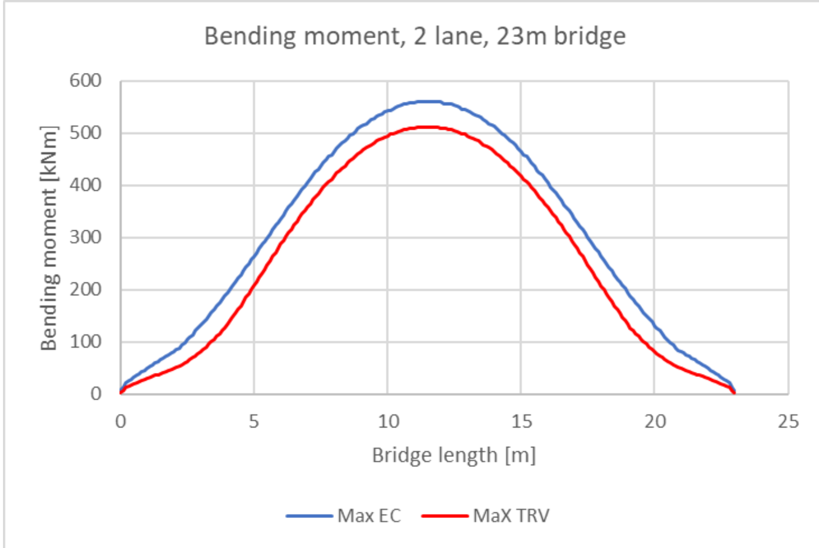

Bending moment, 2 lane, 19m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
MaX TRV

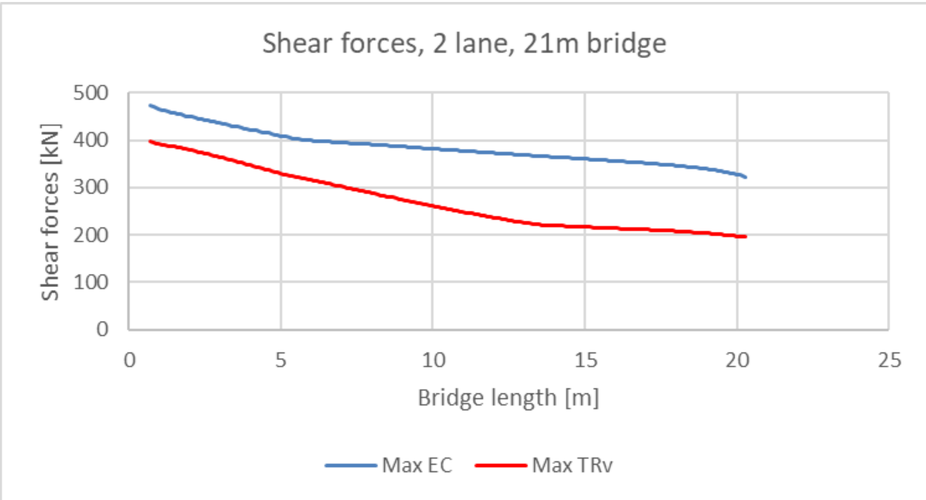

Bending moment, 2 lane, 18m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
MaX TRV

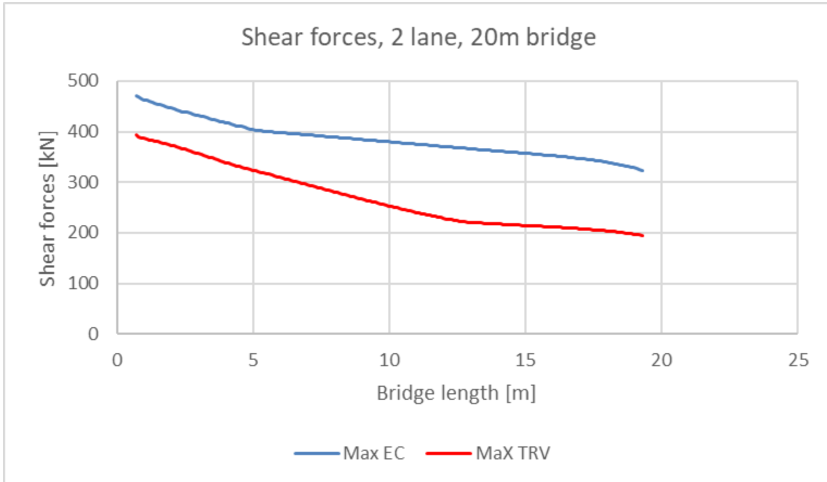

Shear forces, 2 lane, 19m bridge
Shear forces [kN]
Bridge length [m]
Max EC
MaX TRV

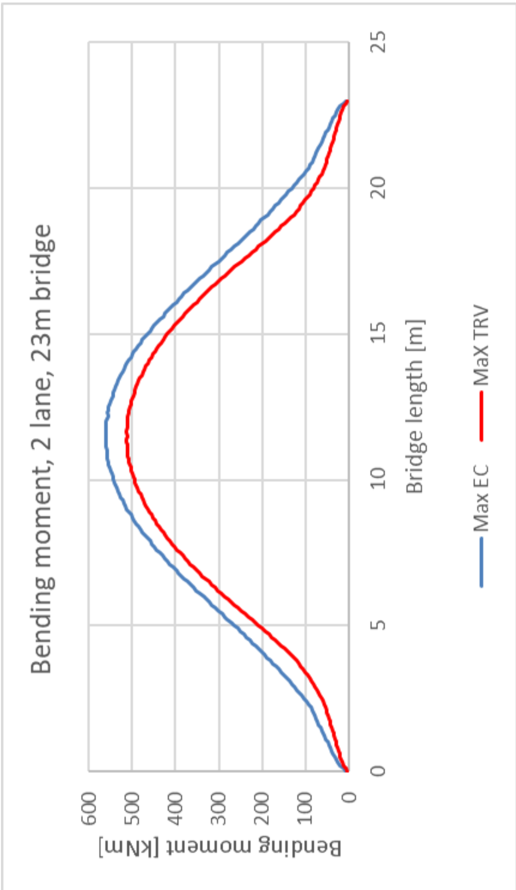

Shear forces, 2 lane, 18m bridge
Shear forces [kN]
Bridge length [m]
Max EC
MaX TRV

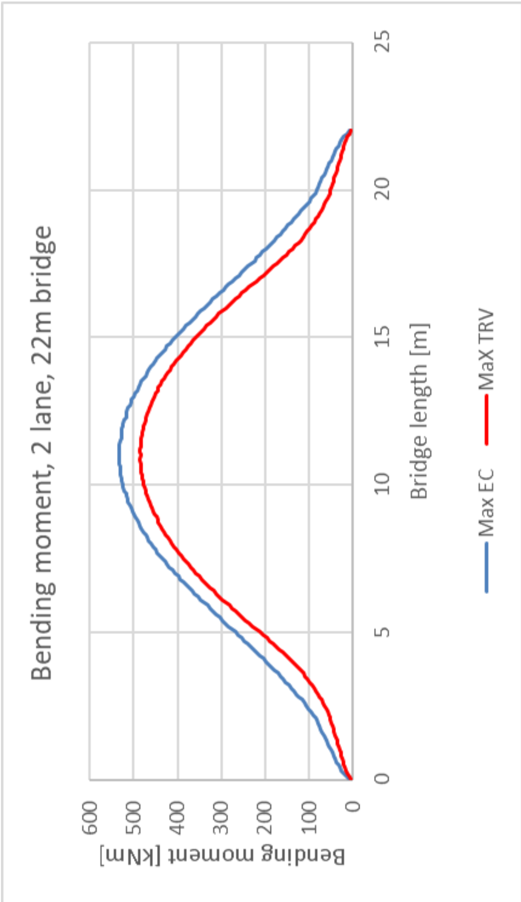

Bending moment, 2 lane, 21m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
MaX TRV

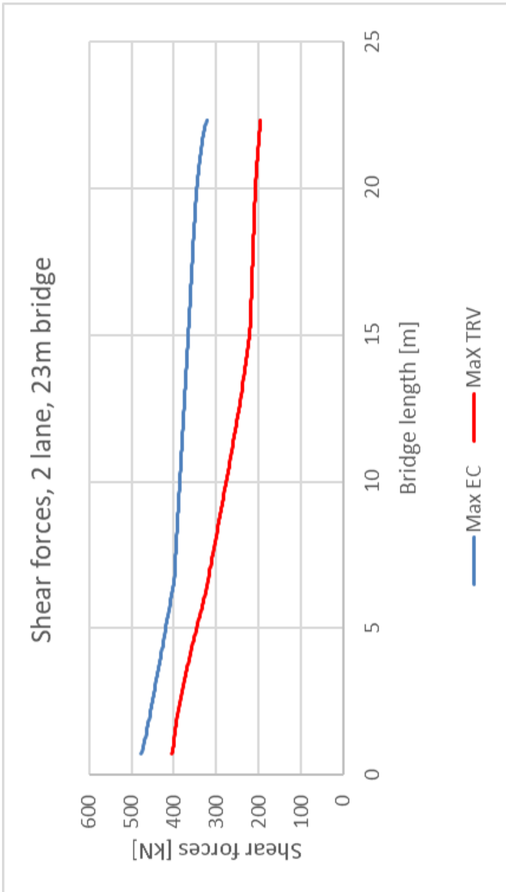

Bending moment, 2 lane, 23m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
MaX TRV

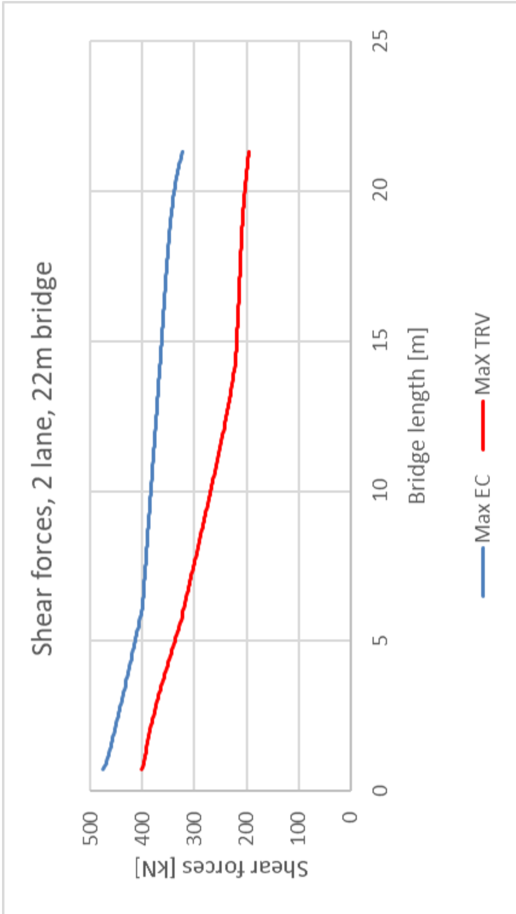

Shear forces, 2 lane, 21m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRv

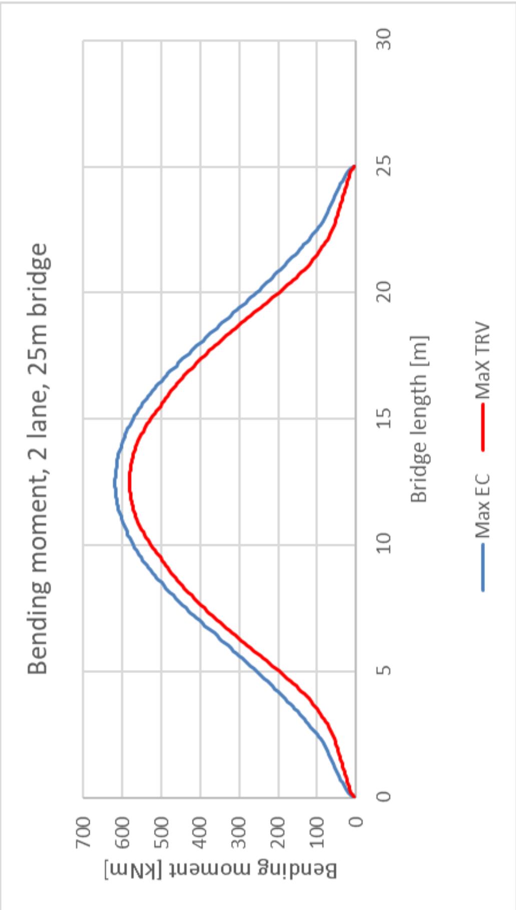

Shear forces, 2 lane, 20m bridge
Shear forces [kN]
Bridge length [m]
Max EC
MaX TRV

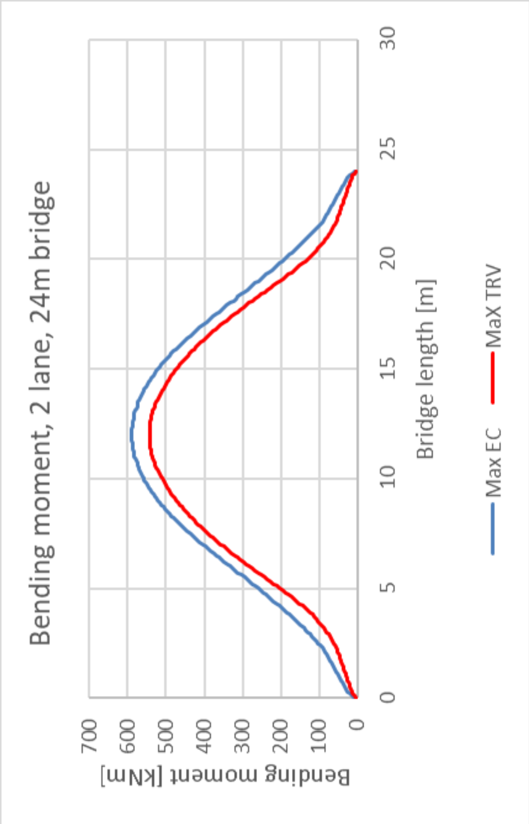

Bending moment, 2 lane, 23m bridge
Bending moment [kNm]
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
MaX TRV

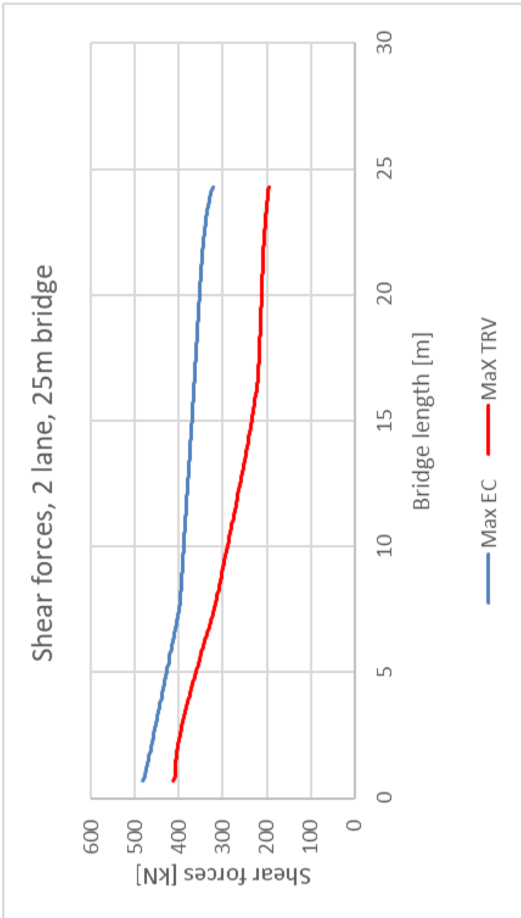

Bending moment, 2 lane, 22m bridge
Bending moment [kNm]
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
MaX TRV

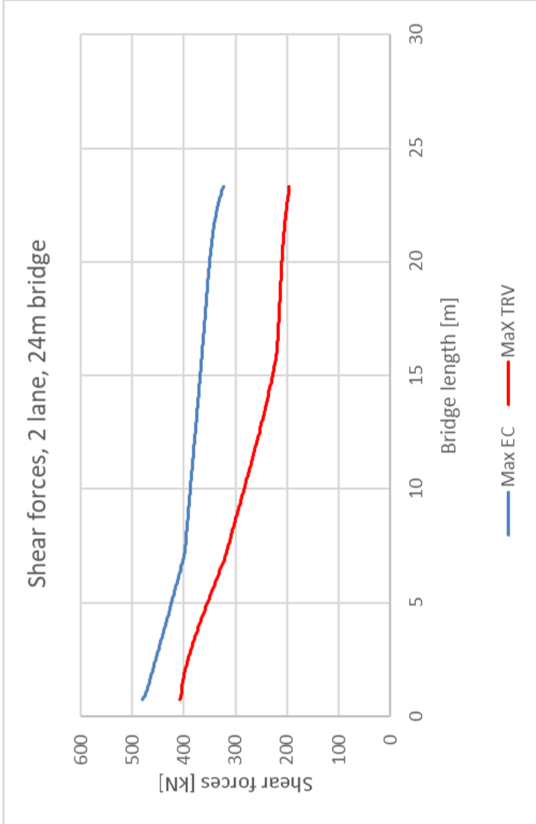

Shear forces, 2 lane, 23m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
MaX TRV


Shear forces, 2 lane, 22m bridge
Shear forces [kN]
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
MaX TRV

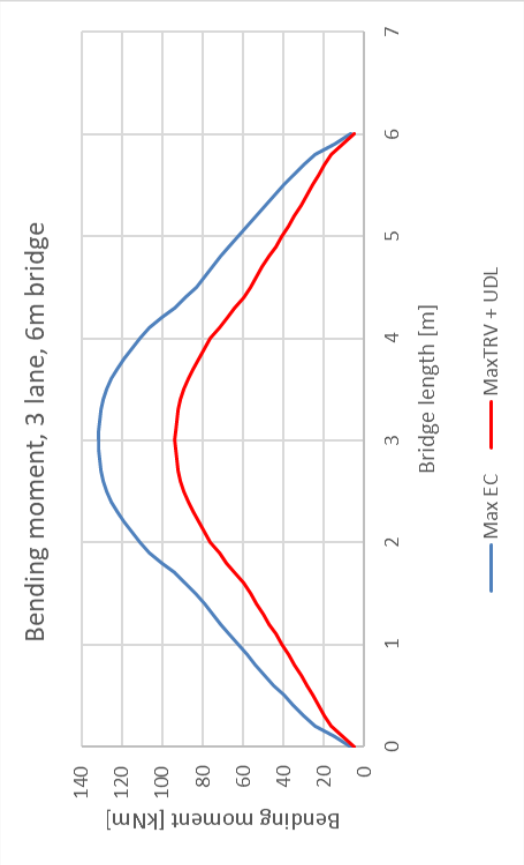

Bending moment, 2 lane, 25m bridge
Bending moment [kNm]
0
100
200
300
400
500
600
700
0
5
10
15
20
25
30
Bridge length [m]
Max EC
MaX TRV

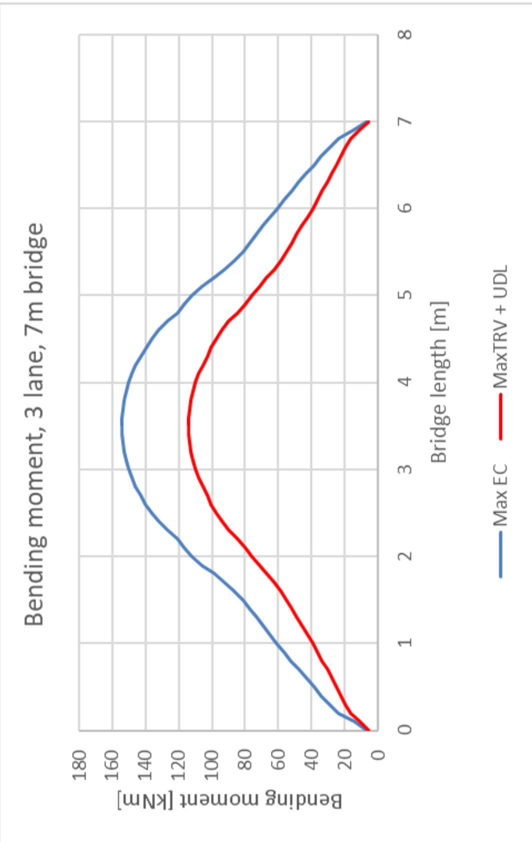

Bending moment, 2 lane, 24m bridge
Bending moment [kNm]
0
100
200
300
400
500
600
700
0
5
10
15
20
25
30
Bridge length [m]
Max EC
MaX TRV

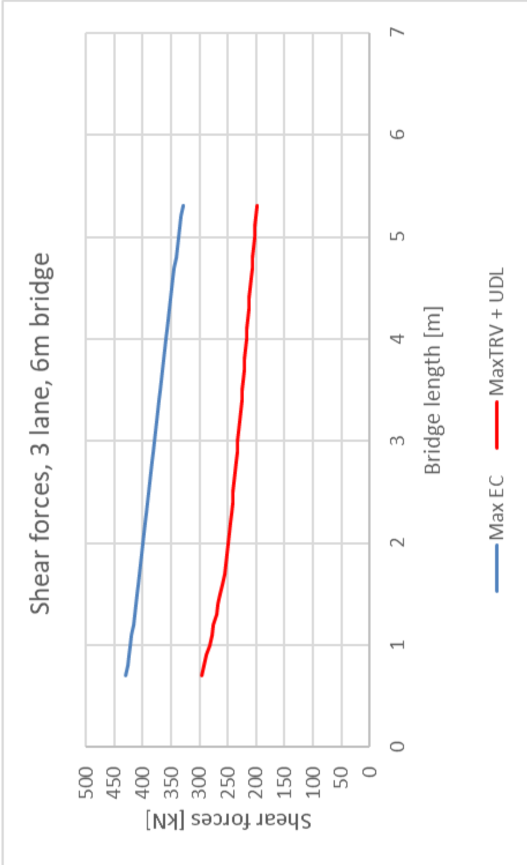

Shear forces, 2 lane, 25m bridge
Shear forces [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
Bridge length [m]
Max EC
MaX TRV

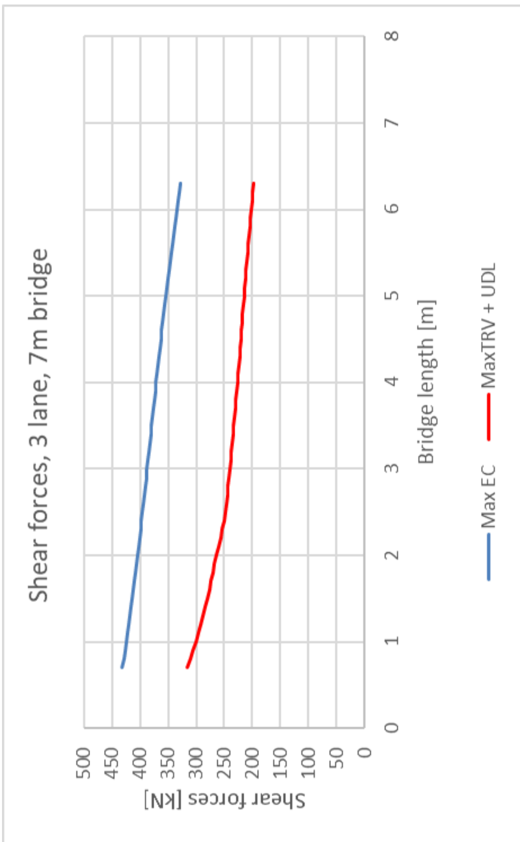

Shear forces, 2 lane, 24m bridge
Shear forces [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
Bridge length [m]
Max EC
MaX TRV

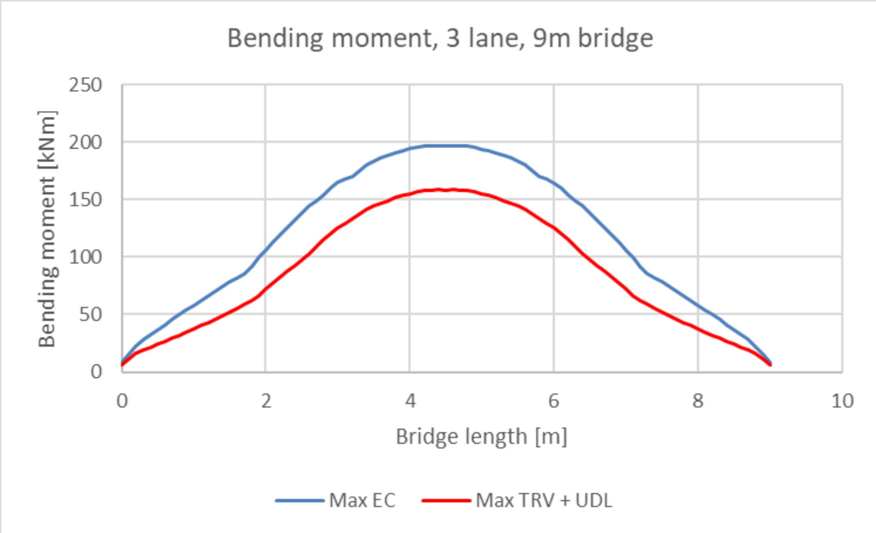
C3. Lane 3

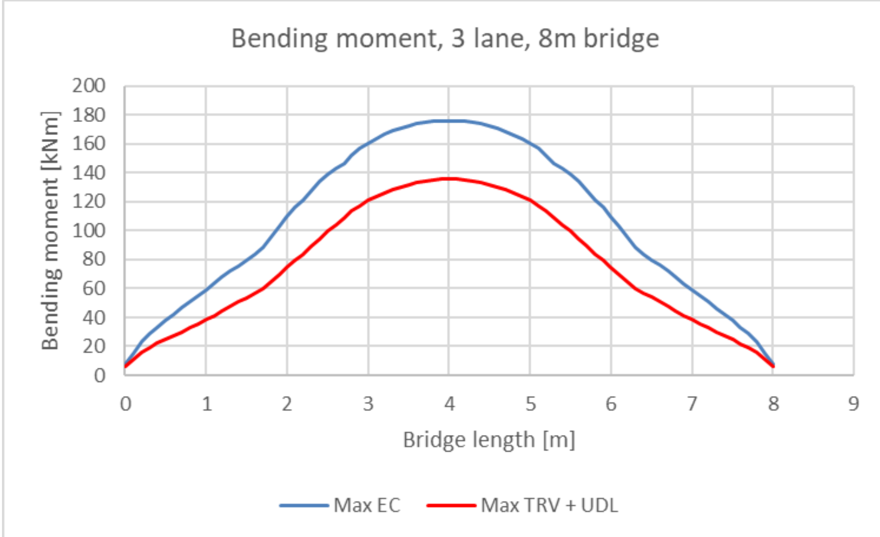

Bending moment, 3 lane, 6m bridge
Bending moment [KNm]
Bridge length [m]
Max EC
MaxTRV + UDL

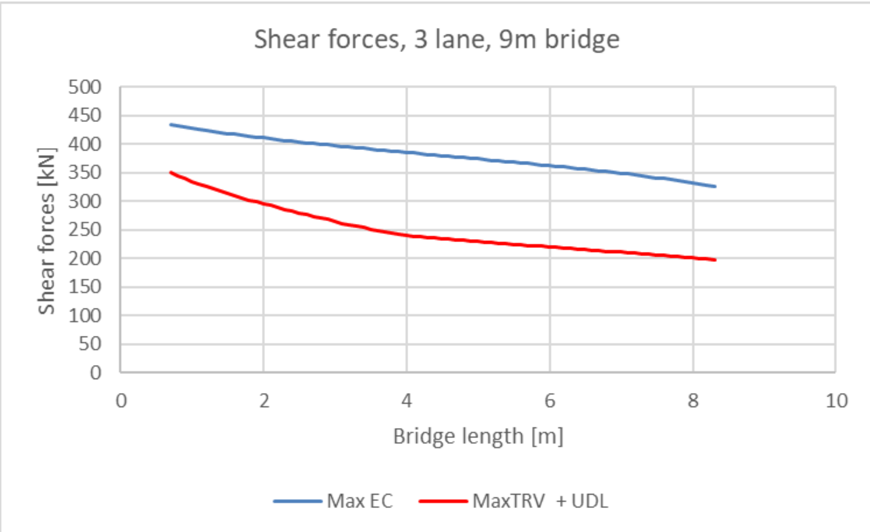

Bending moment, 3 lane, 7m bridge
Bending moment [KNm]
Bridge length [m]
Max EC
MaxTRV + UDL

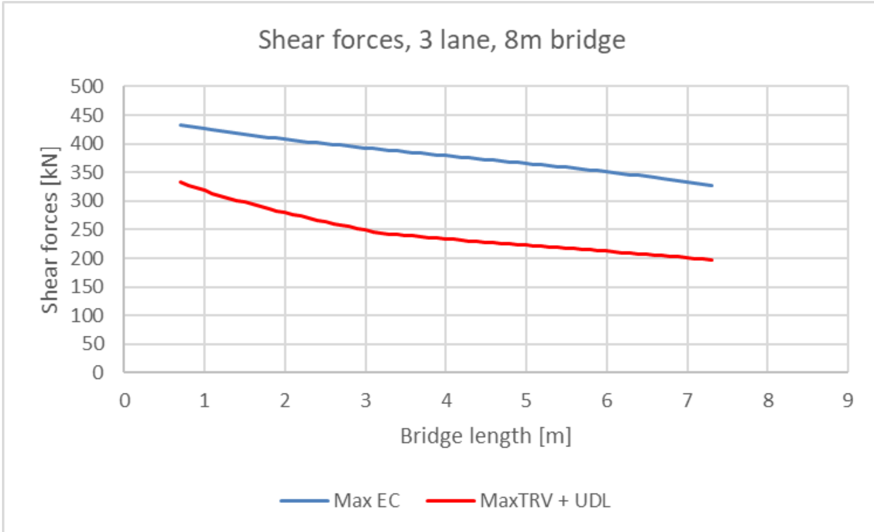

Shear forces, 3 lane, 6m bridge
Shear forces [KN]
Bridge length [m]
Max EC
MaxTRV + UDL

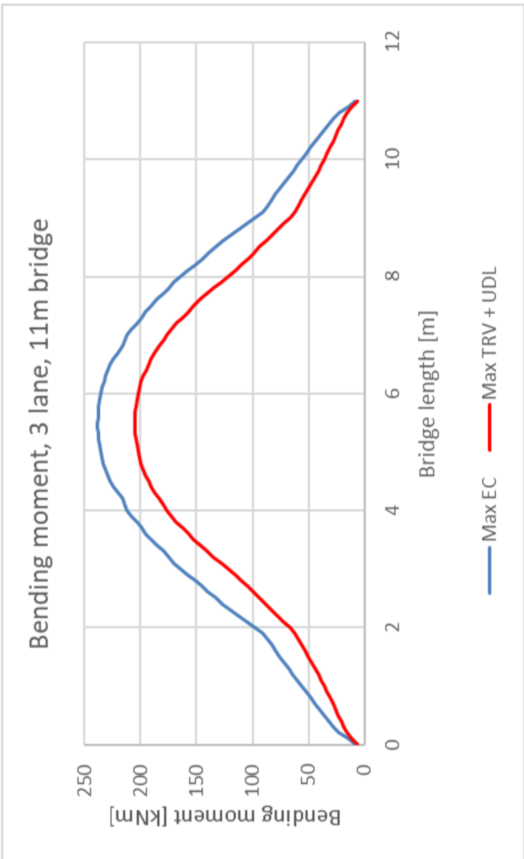

Shear forces, 3 lane, 7m bridge
Shear forces [KN]
Bridge length [m]
Max EC
MaxTRV + UDL

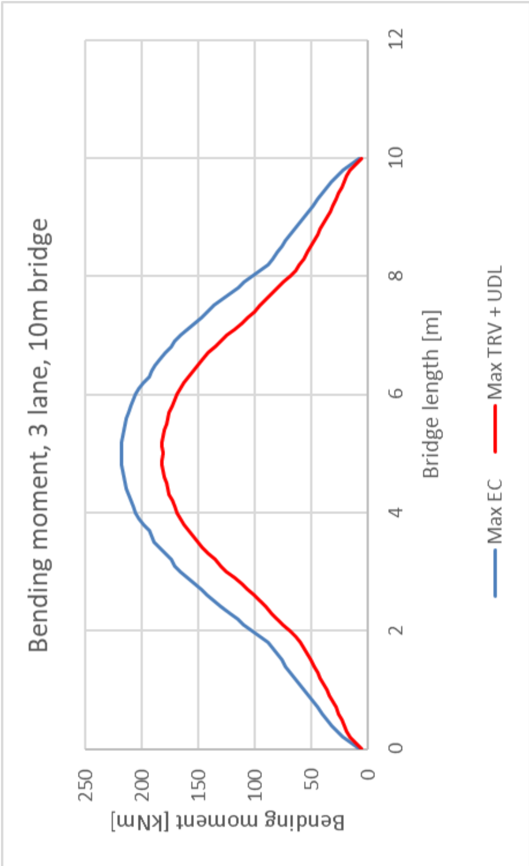

Bending moment, 3 lane, 9m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV + UDL

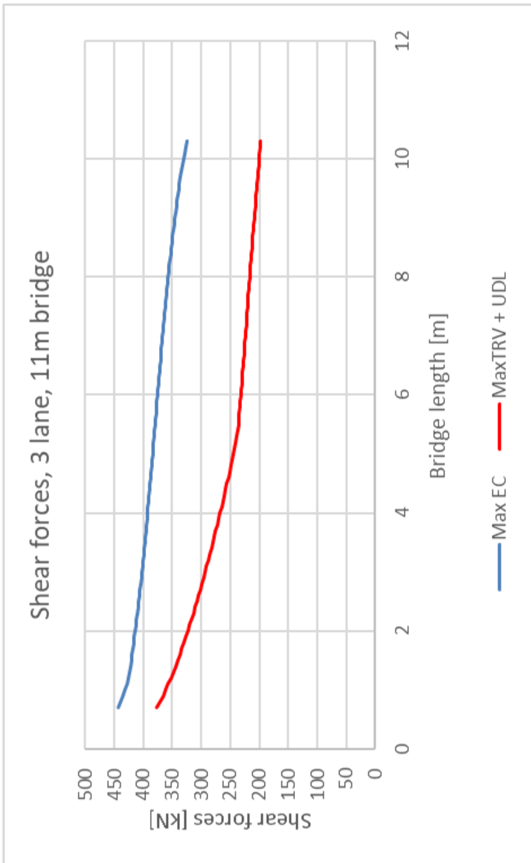

Bending moment, 3 lane, 8m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV + UDL

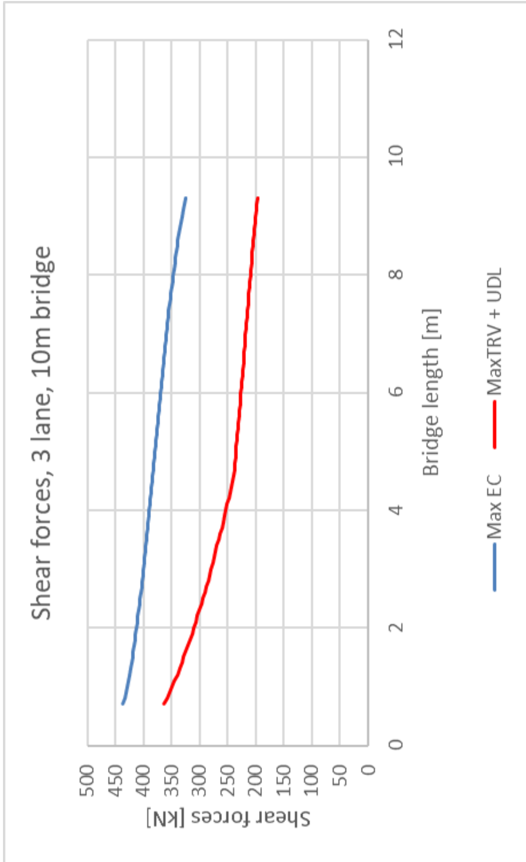

Shear forces, 3 lane, 9m bridge
Shear forces [kN]
Bridge length [m]
Max EC
MaxTRV + UDL

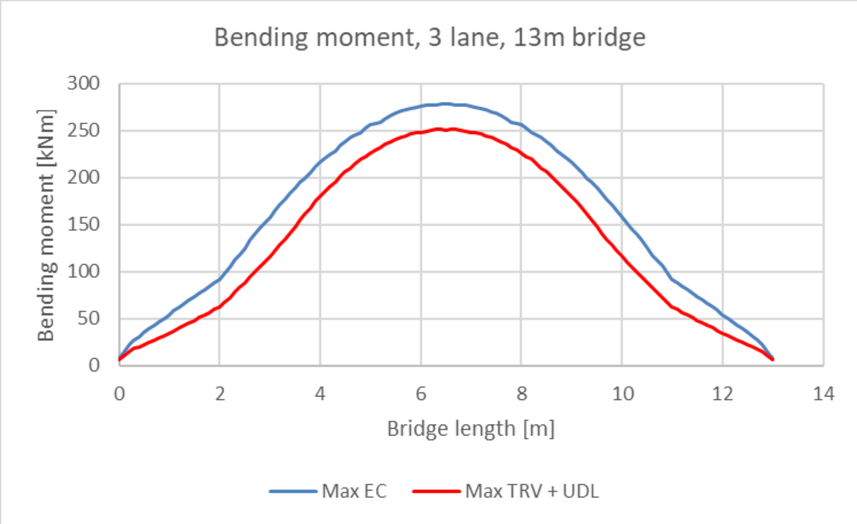

Shear forces, 3 lane, 8m bridge
Shear forces [kN]
Bridge length [m]
Max EC
MaxTRV + UDL

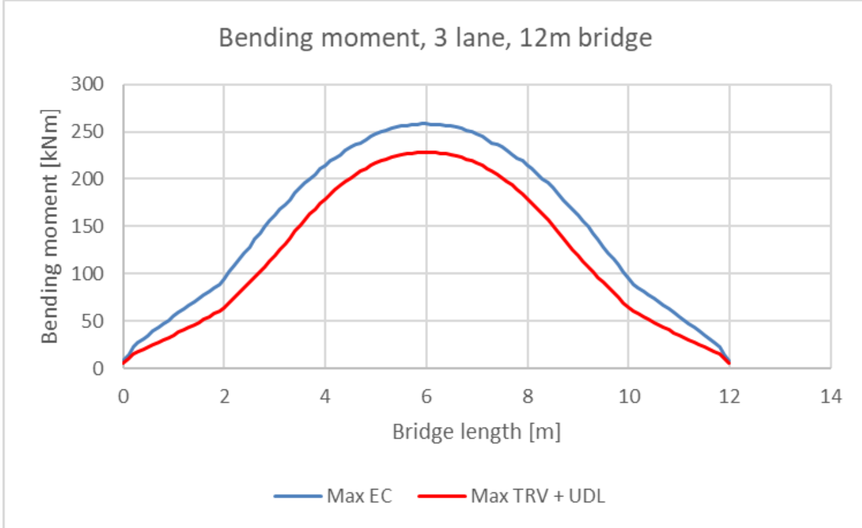

Bending moment, 3 lane, 11m bridge
Bending moment [KNm]
Bridge length [m]
Max EC
Max TRV + UDL


Bending moment, 3 lane, 10m bridge
Bending moment [KNm]
Bridge length [m]
Max EC
Max TRV + UDL


Shear forces, 3 lane, 11m bridge
Shear forces [kN]
Bridge length [m]
Max EC
MaxTRV + UDL

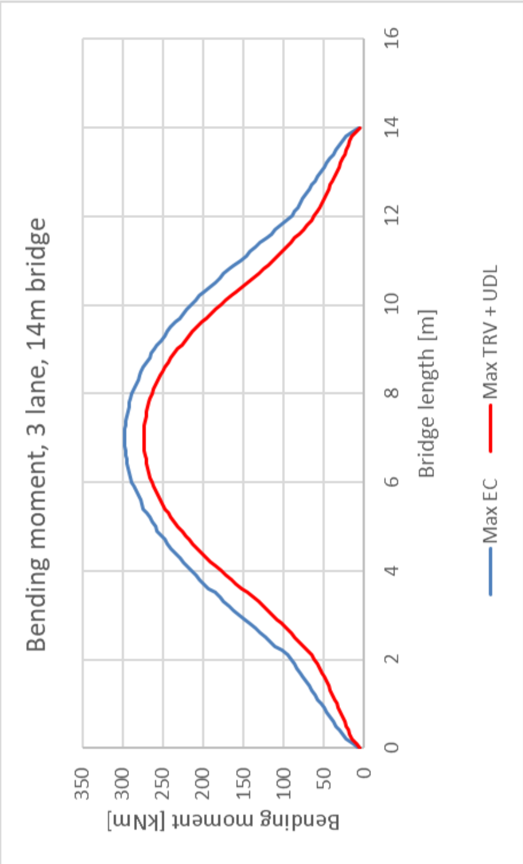

Shear forces, 3 lane, 10m bridge
Shear forces [kN]
Bridge length [m]
Max EC
MaxTRV + UDL

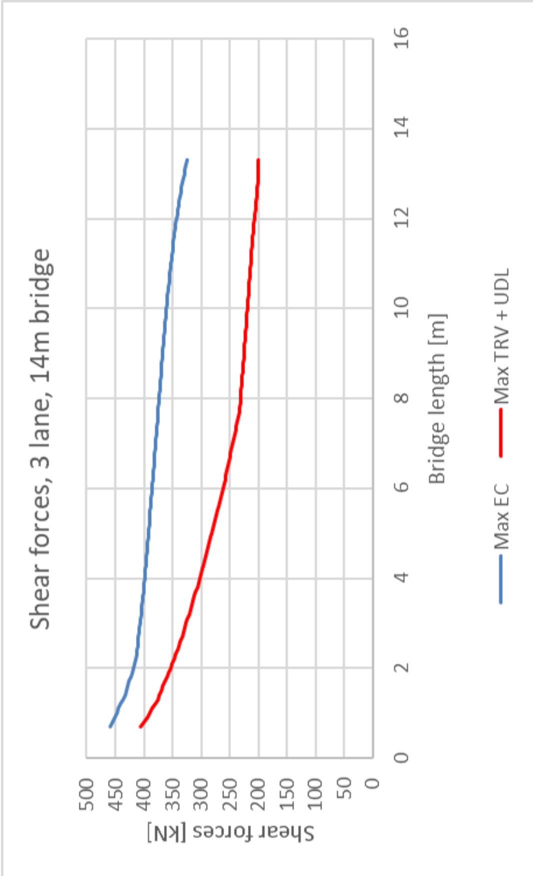

Bending moment, 3 lane, 13m bridge
Bending moment [kNm]
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
Bridge length [m]
Max EC
Max TRV + UDL

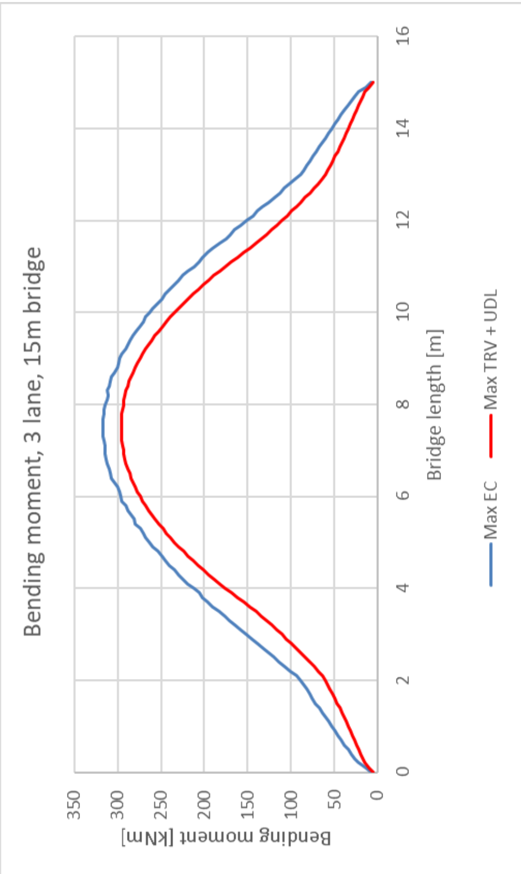

Bending moment, 3 lane, 12m bridge
Bending moment [kNm]
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
Bridge length [m]
Max EC
Max TRV + UDL

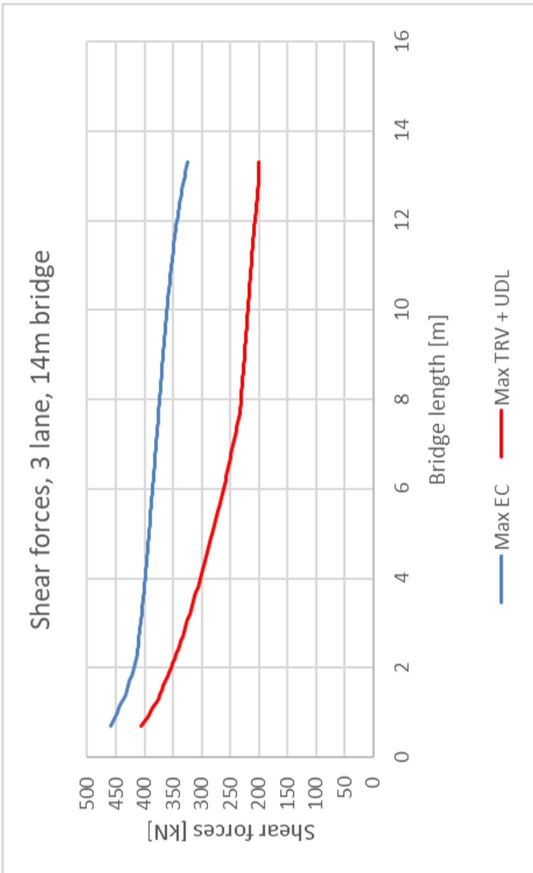

Shear forces, 3 lane, 13m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
Bridge length [m]
Max EC
Max TRV + UDL

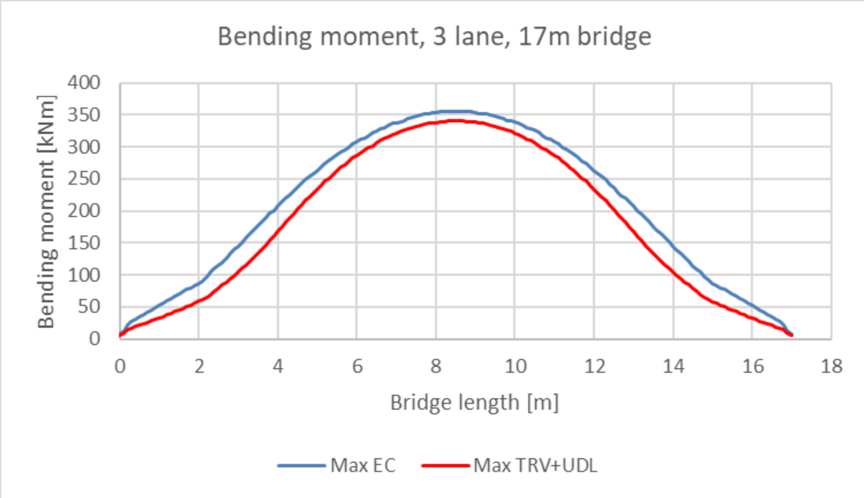

Shear forces, 3 lane, 12m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
Bridge length [m]
Max EC
Max TRV + UDL

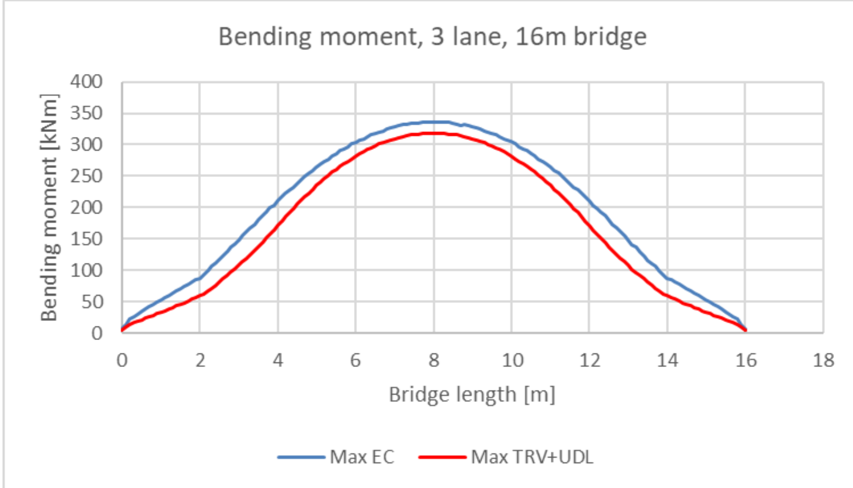

Bending moment, 3 lane, 14m bridge
Bending moment [KNm]
Bridge length [m]
Max EC
Max TRV + UDL

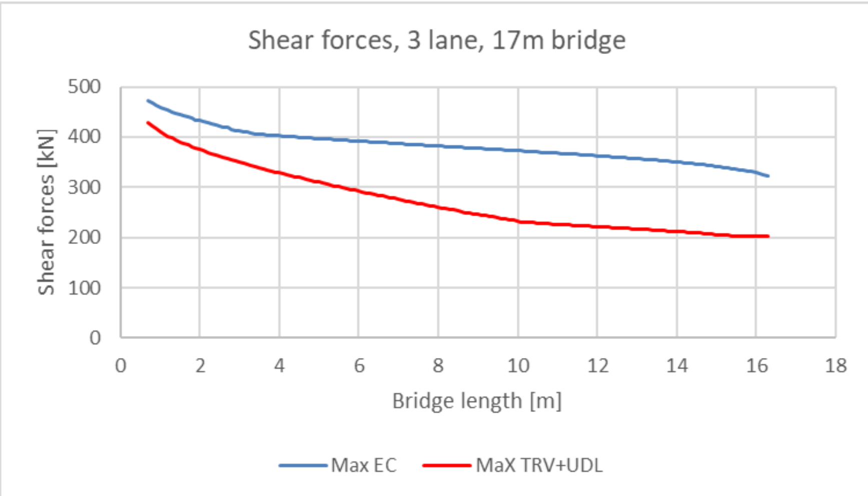

Shear forces, 3 lane, 14m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV + UDL


Bending moment, 3 lane, 15m bridge
Bending moment [KNm]
Bridge length [m]
Max EC
Max TRV + UDL

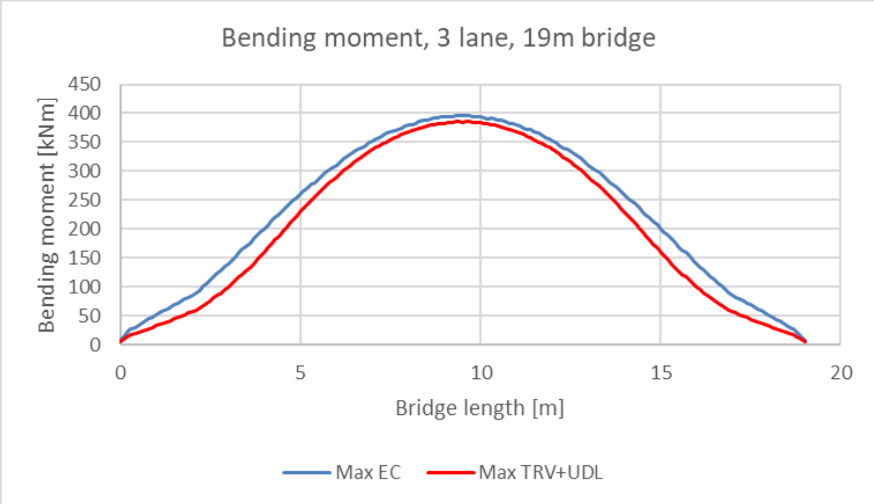

Shear forces, 3 lane, 14m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV + UDL

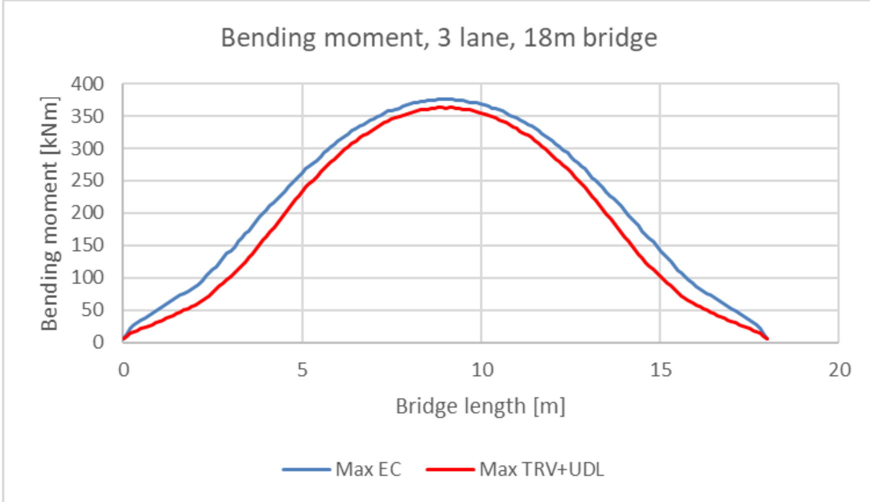

Bending moment, 3 lane, 17m bridge
Bending moment [kNm]
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
18
Bridge length [m]
Max EC
Max TRV+UDL

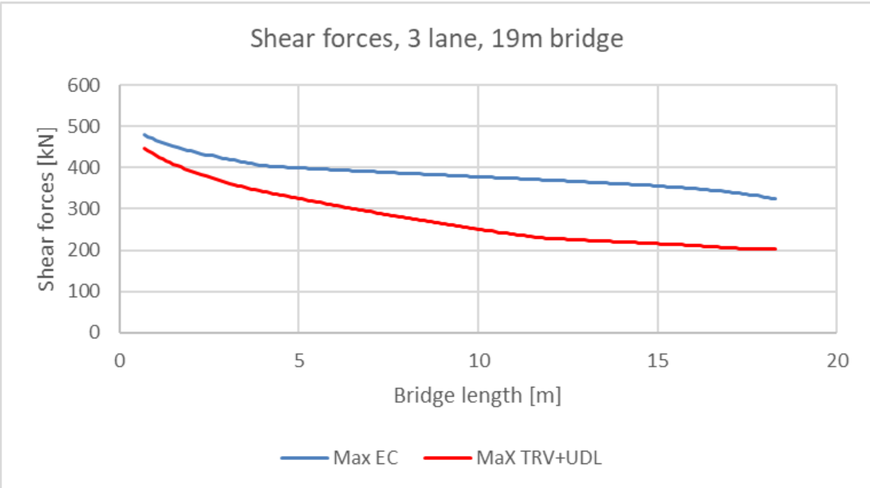

Bending moment, 3 lane, 16m bridge
Bending moment [kNm]
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
18
Bridge length [m]
Max EC
Max TRV+UDL

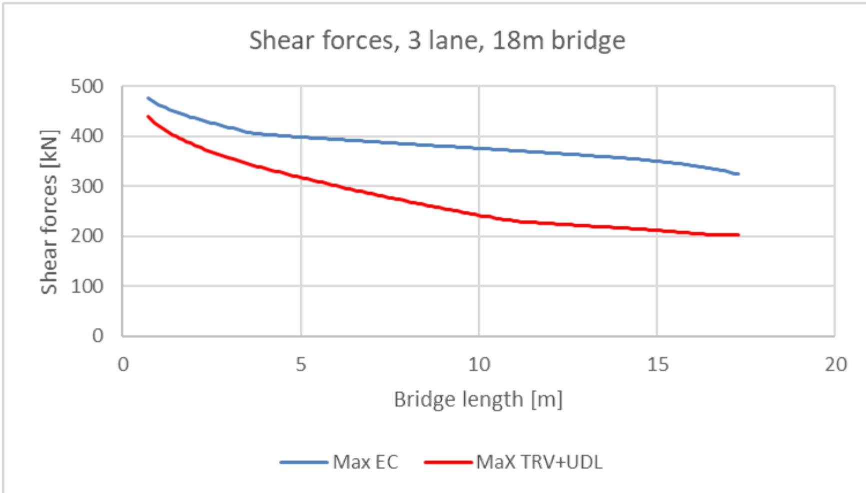

Shear forces, 3 lane, 17m bridge
Shear forces [kN]
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
Bridge length [m]
Max EC
MaX TRV+UDL

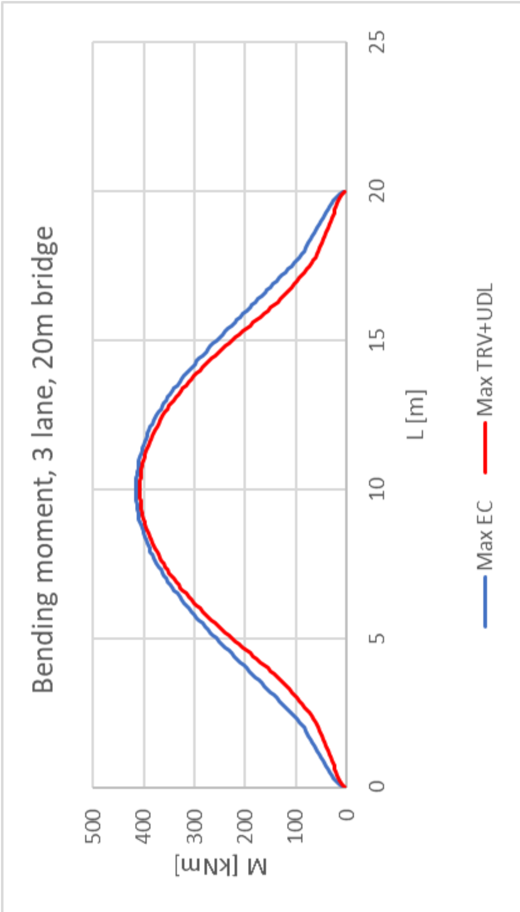

Shear forces, 3 lane, 16m bridge
Shear forces [kN]
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
Bridge length [m]
Max EC
MaX TRV+UDL

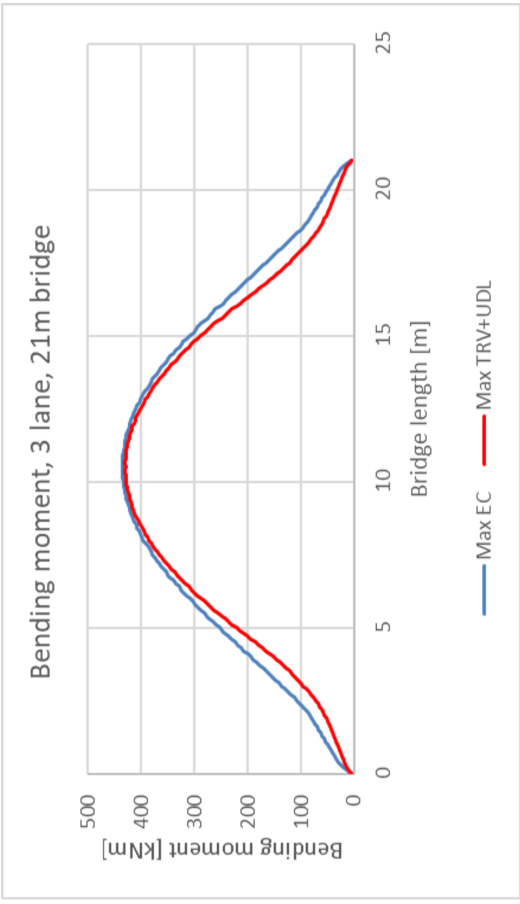

Bending moment, 3 lane, 19m bridge
Bending moment [kNm]
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV+UDL

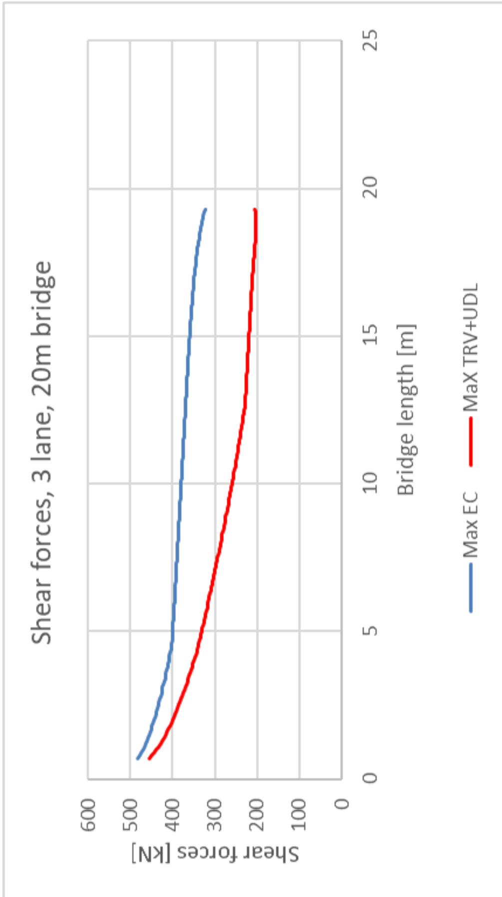

Bending moment, 3 lane, 18m bridge
Bending moment [kNm]
400
350
300
250
200
150
100
50
0
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV+UDL

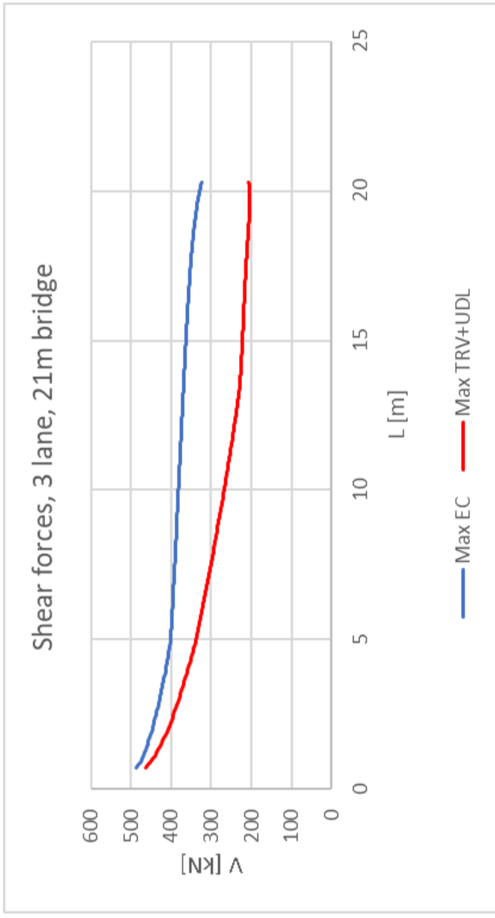

Shear forces, 3 lane, 19m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
Bridge length [m]
Max EC
MaX TRV+UDL

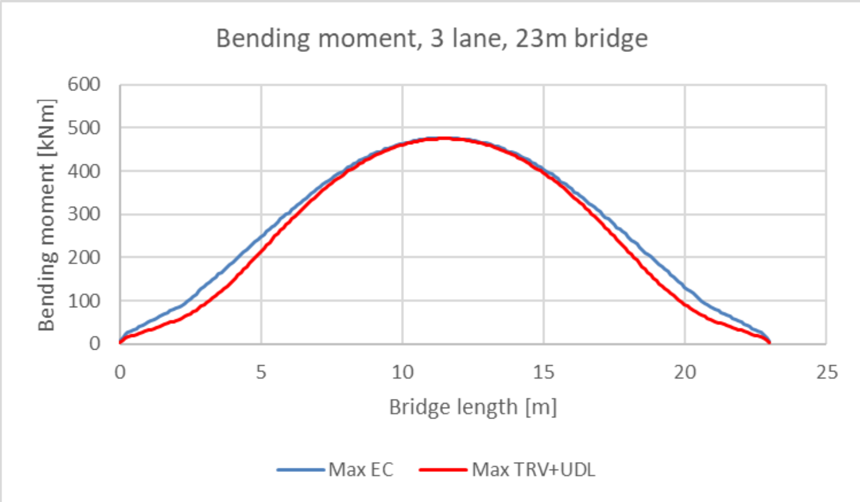

Shear forces, 3 lane, 18m bridge
Shear forces [kN]
500
400
300
200
100
0
0
5
10
15
20
Bridge length [m]
Max EC
MaX TRV+UDL

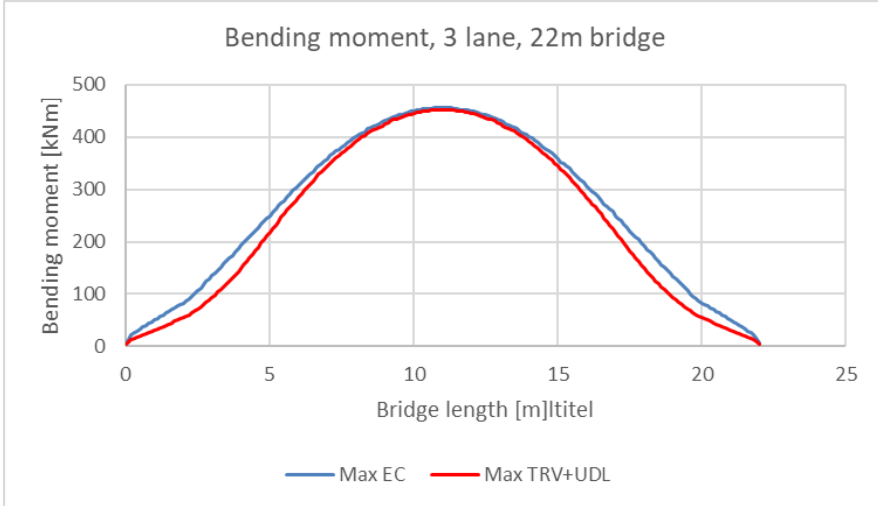

Bending moment, 3 lane, 20m bridge
M [kNm]
0
100
200
300
400
500
0
5
10
15
20
25
L [m]
Max EC
Max TRV+UDL

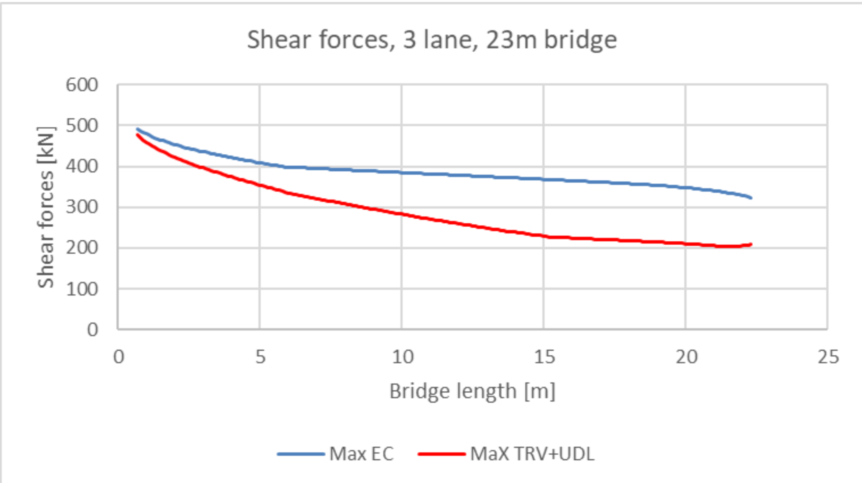

Bending moment, 3 lane, 21m bridge
Bending moment [kNm]
0
100
200
300
400
500
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV+UDL

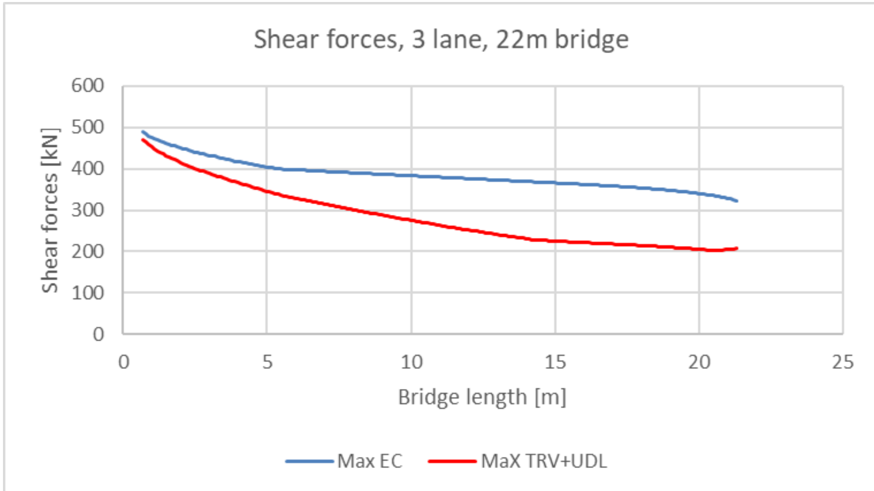

Shear forces, 3 lane, 20m bridge
Shear forces [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
Bridge length [m]
Max EC
MaX TRV+UDL

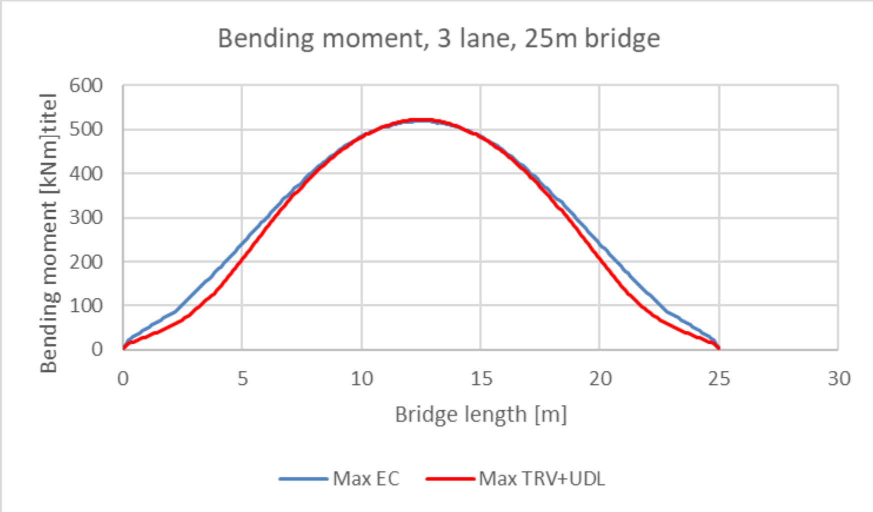

Shear forces, 3 lane, 21m bridge
V [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
L [m]
Max EC
Max TRV+UDL

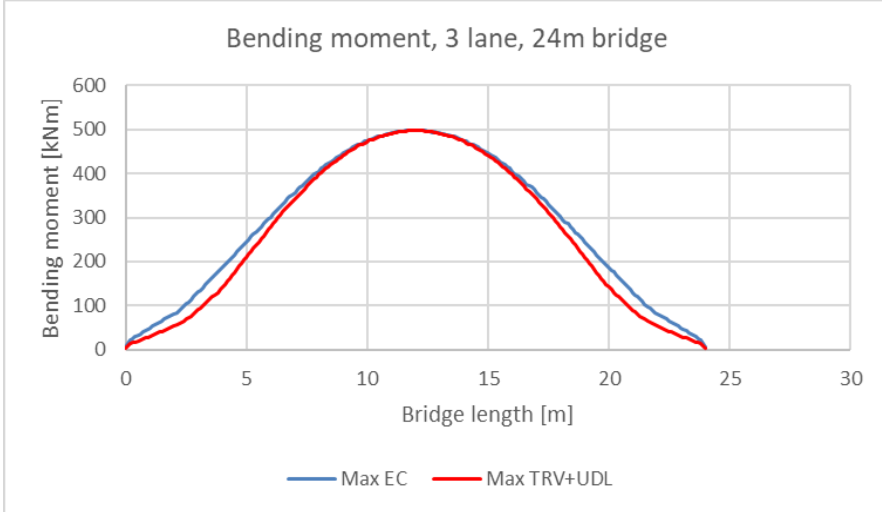

Bending moment, 3 lane, 23m bridge
Bending moment [kNm]
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV+UDL

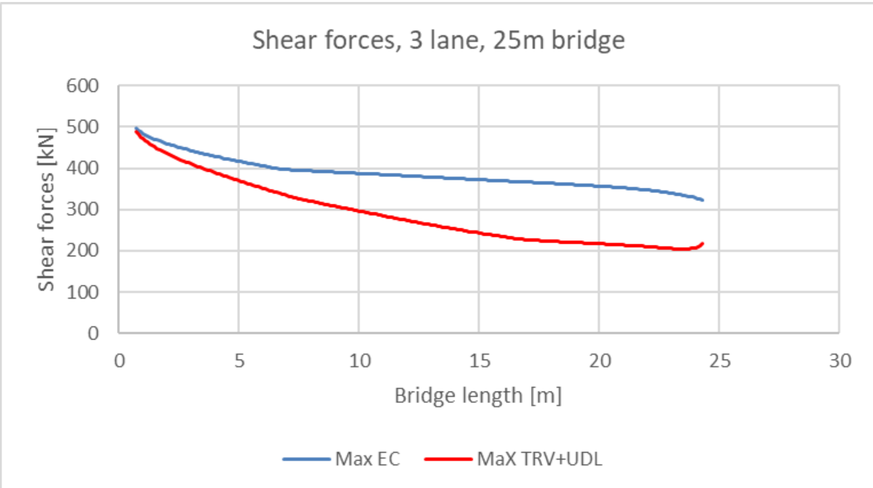

Bending moment, 3 lane, 22m bridge
Bending moment [kNm]
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]ltitel
Max EC
Max TRV+UDL

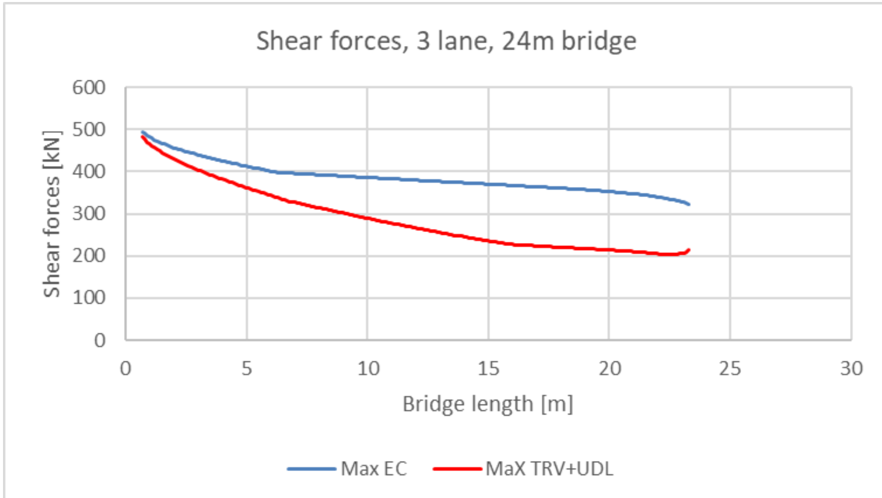

Shear forces, 3 lane, 23m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
MaX TRV+UDL


Shear forces, 3 lane, 22m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
25
Bridge length [m]
Max EC
MaX TRV+UDL

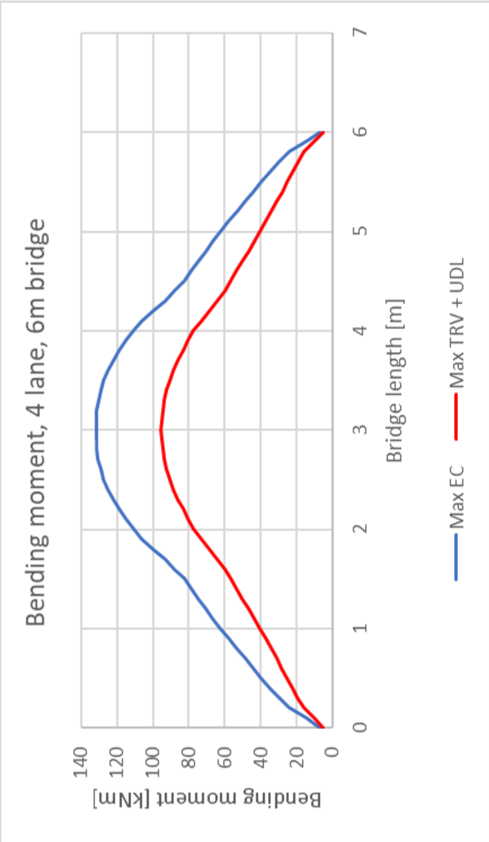

Bending moment, 3 lane, 25m bridge
Bending moment [kNm]titel
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Bridge length [m]
Max EC
Max TRV+UDL


Bending moment, 3 lane, 24m bridge
Bending moment [kNm]
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Bridge length [m]
Max EC
Max TRV+UDL

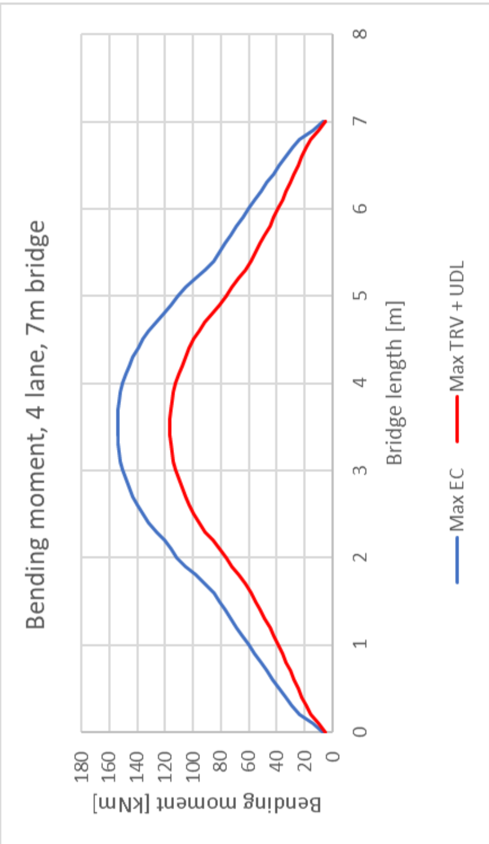

Shear forces, 3 lane, 25m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Bridge length [m]
Max EC
MaX TRV+UDL


Shear forces, 3 lane, 24m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Bridge length [m]
Max EC
MaX TRV+UDL

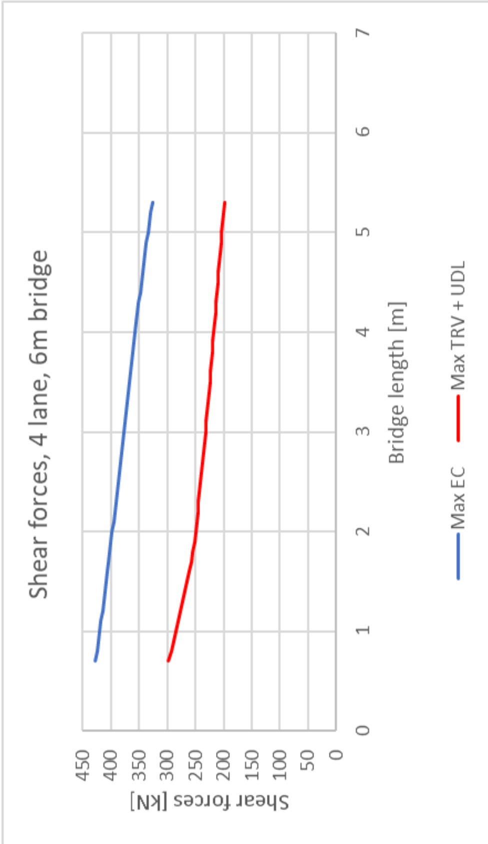
C.4 Lane 4



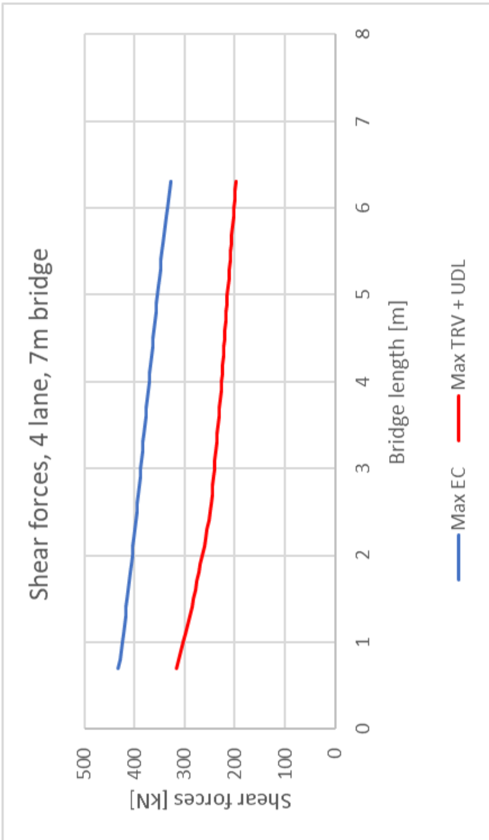
Bending moment, 4 lane, 6m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV + UDL



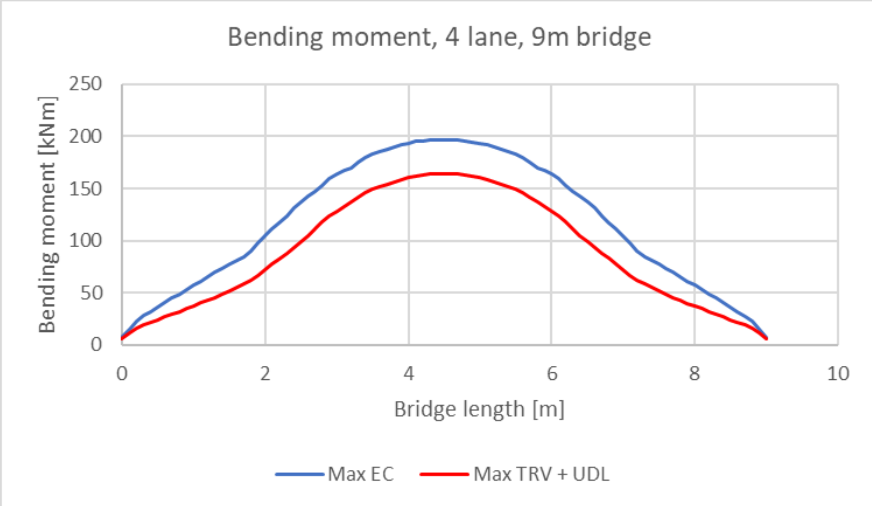
Bending moment, 4 lane, 7m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV + UDL

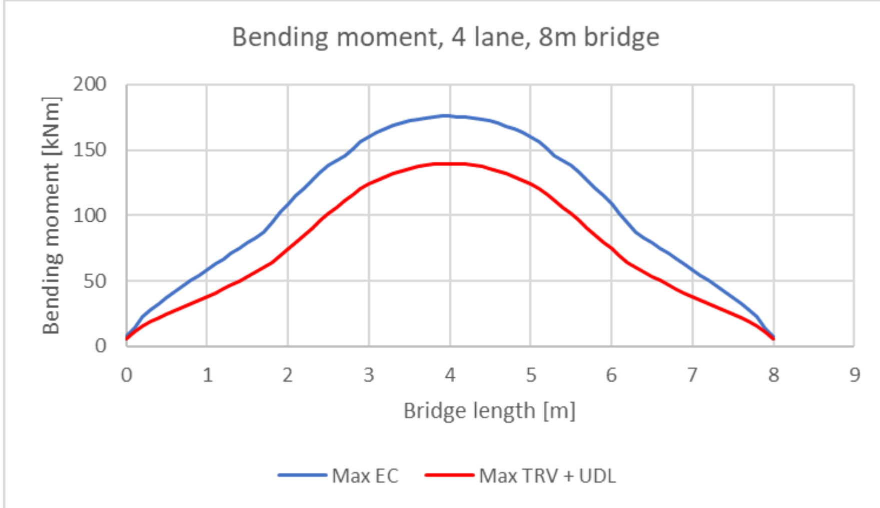


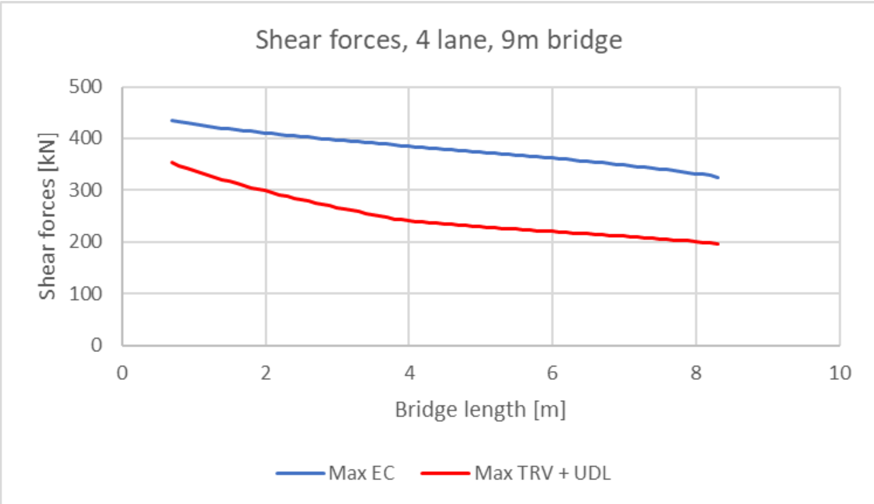
Shear forces, 4 lane, 6m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV + UDL

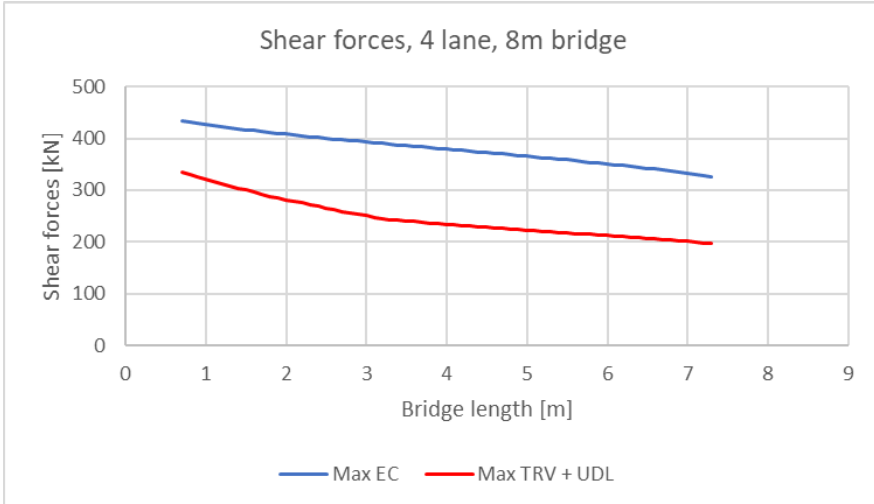


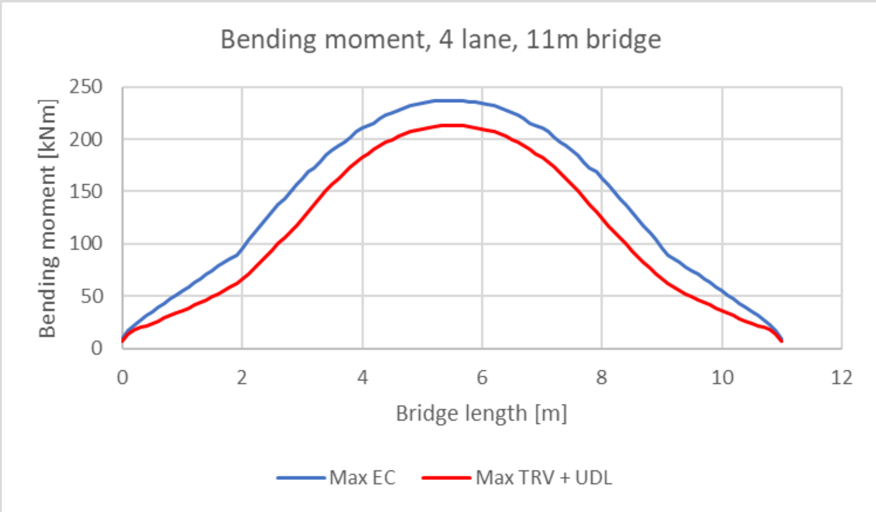
Shear forces, 4 lane, 7m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV + UDL


Bending moment, 4 lane, 9m bridge
Bending moment [kNm]
250
200
150
100
50
0
0
2
4
6
8
10
Bridge length [m]
Max EC
Max TRV + UDL

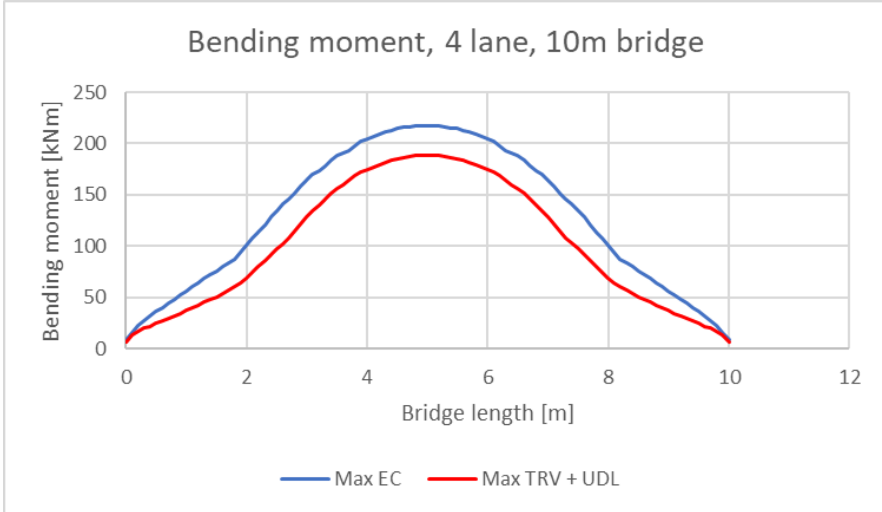

Bending moment, 4 lane, 8m bridge
Bending moment [kNm]
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
Bridge length [m]
Max EC
Max TRV + UDL


Shear forces, 4 lane, 9m bridge
Shear forces [kN]
500
400
300
200
100
0
0
2
4
6
8
10
Bridge length [m]
Max EC
Max TRV + UDL

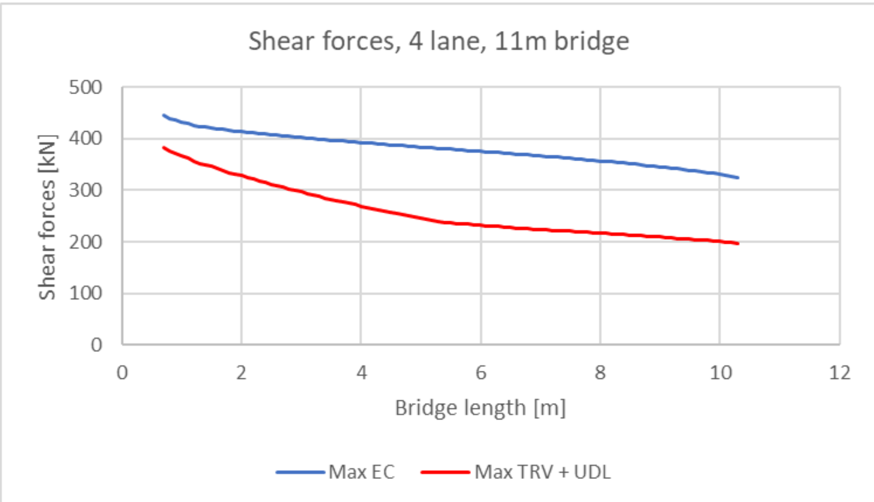

Shear forces, 4 lane, 8m bridge
Shear forces [kN]
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
Bridge length [m]
Max EC
Max TRV + UDL



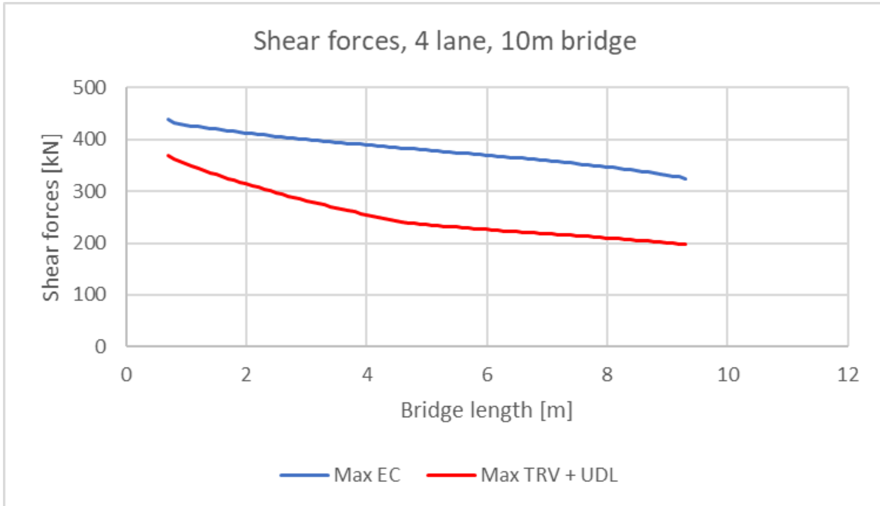
Bending moment, 4 lane, 11m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV + UDL



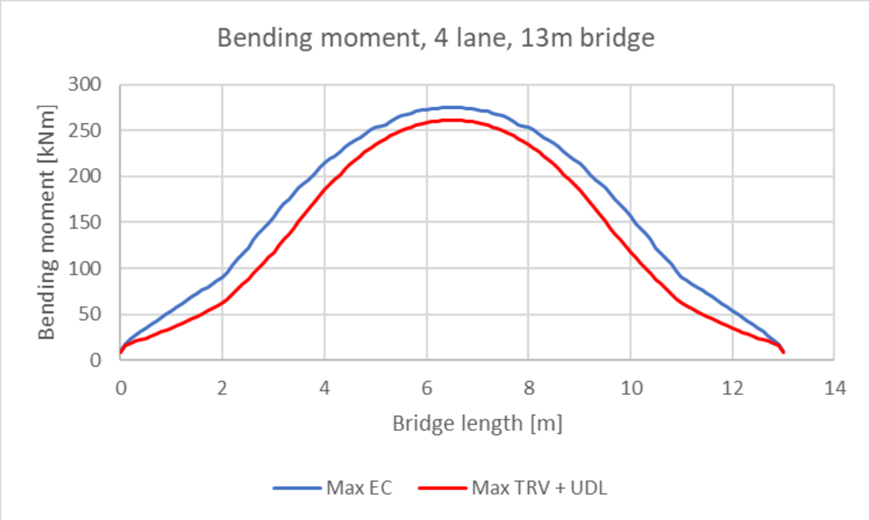
Bending moment, 4 lane, 10m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV + UDL

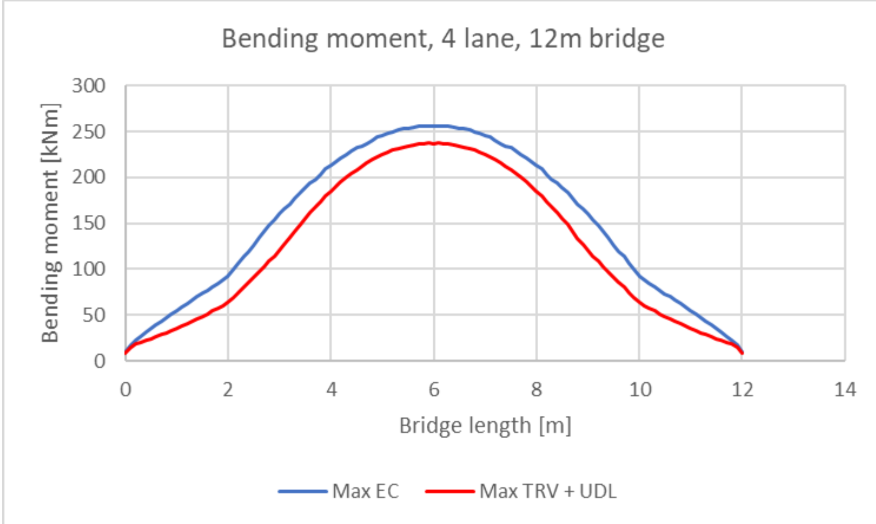


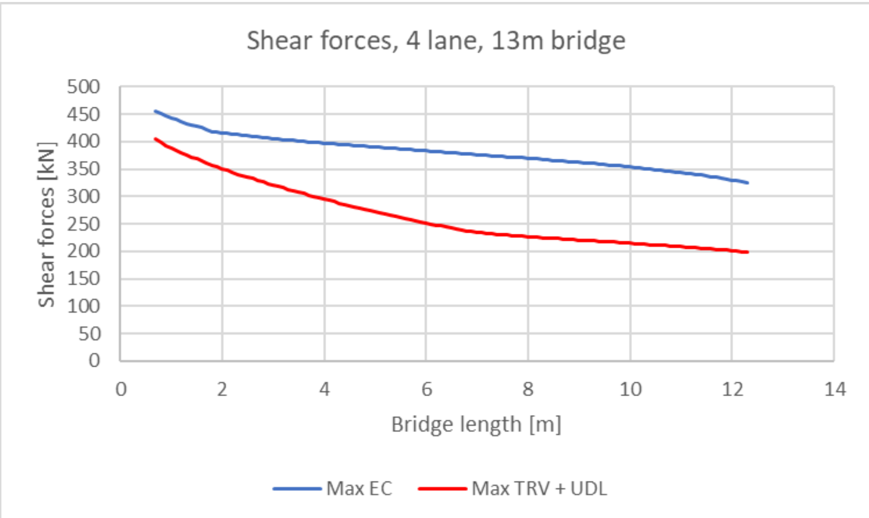
Shear forces, 4 lane, 11m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV + UDL



Shear forces, 4 lane, 10m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV + UDL

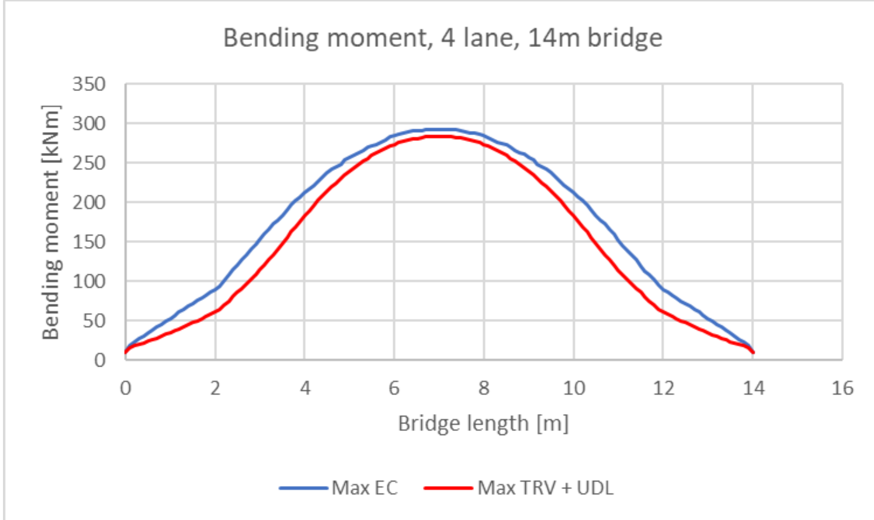

Bending moment, 4 lane, 13m bridge
Bending moment [kNm]
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
Bridge length [m]
Max EC
Max TRV + UDL


Bending moment, 4 lane, 12m bridge
Bending moment [kNm]
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
Bridge length [m]
Max EC
Max TRV + UDL

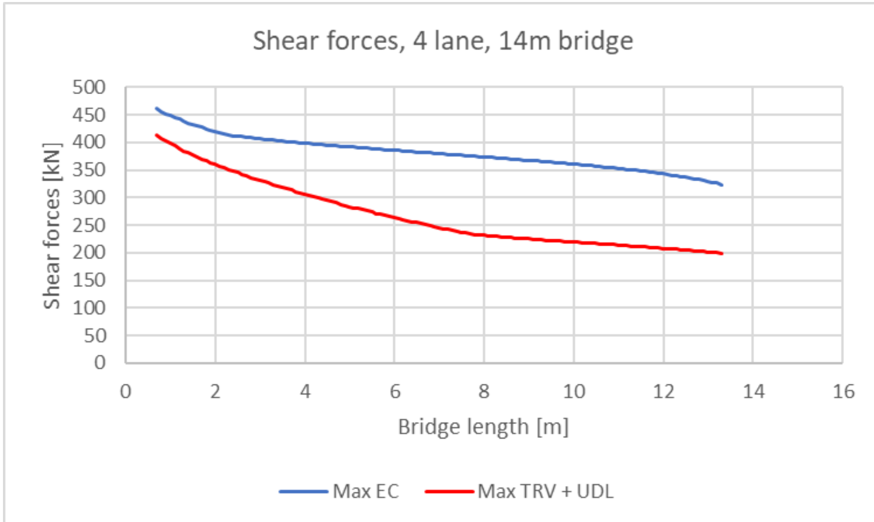

Shear forces, 4 lane, 13m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
Bridge length [m]
Max EC
Max TRV + UDL

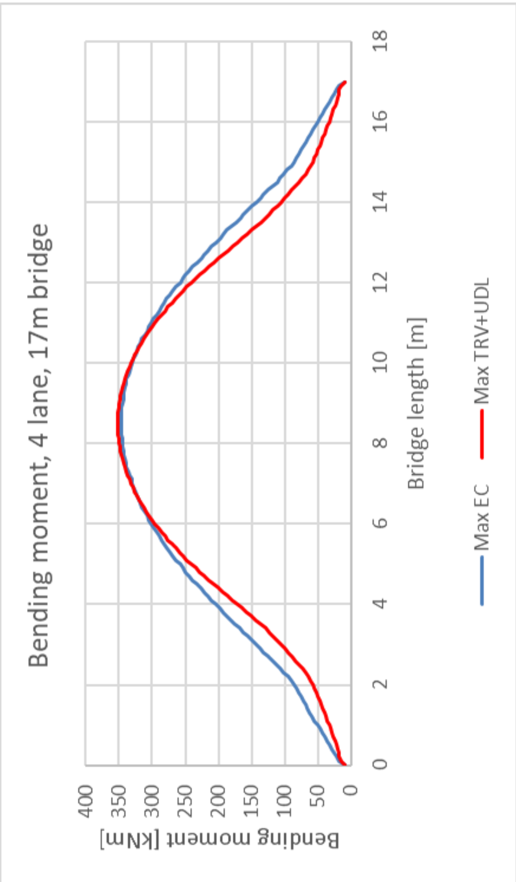

Shear forces, 4 lane, 12m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
Bridge length [m]
Max EC
Max TRV + UDL

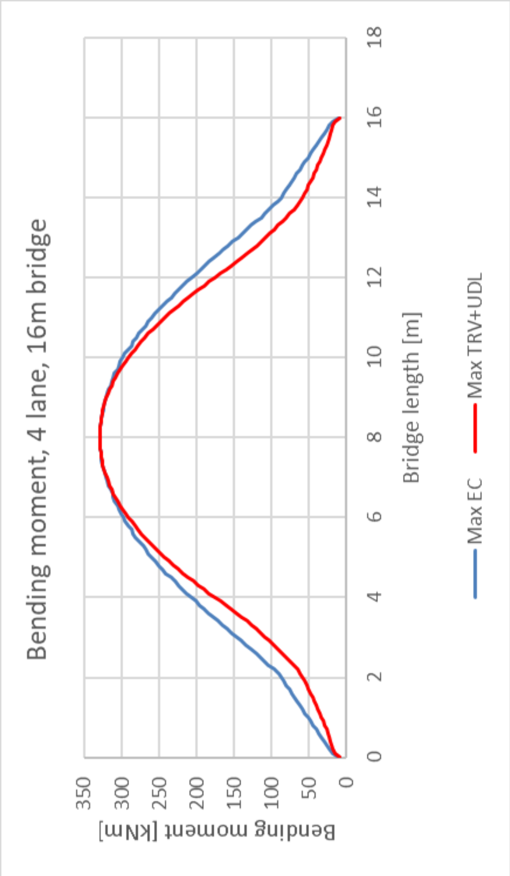

Bending moment, 4 lane, 15m bridge
Bending moment [kNm]
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
Bridge length [m]
Max EC
Max TRV + UDL

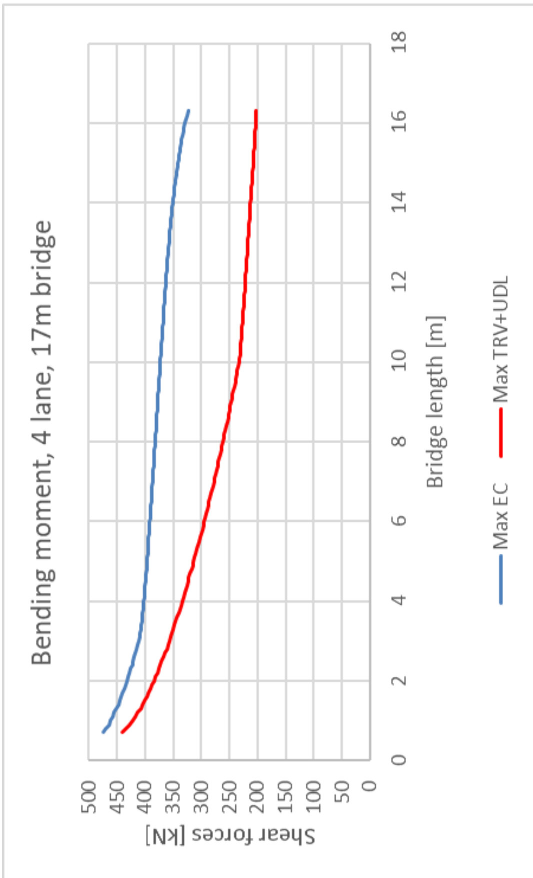

Bending moment, 4 lane, 14m bridge
Bending moment [kNm]
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
Bridge length [m]
Max EC
Max TRV + UDL

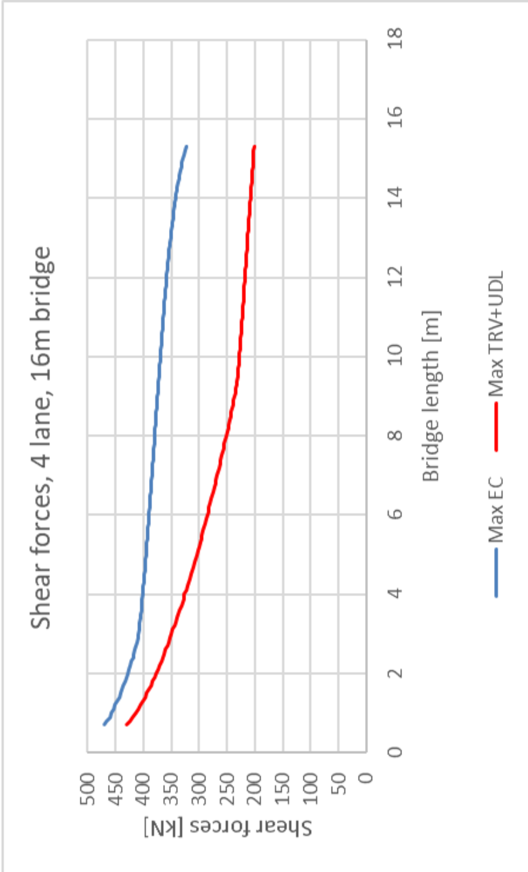

Shear forces, 4 lane, 15m bridge
Shear forces [kN]
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
Bridge length [m]
Max EC
Max TRV + UDL

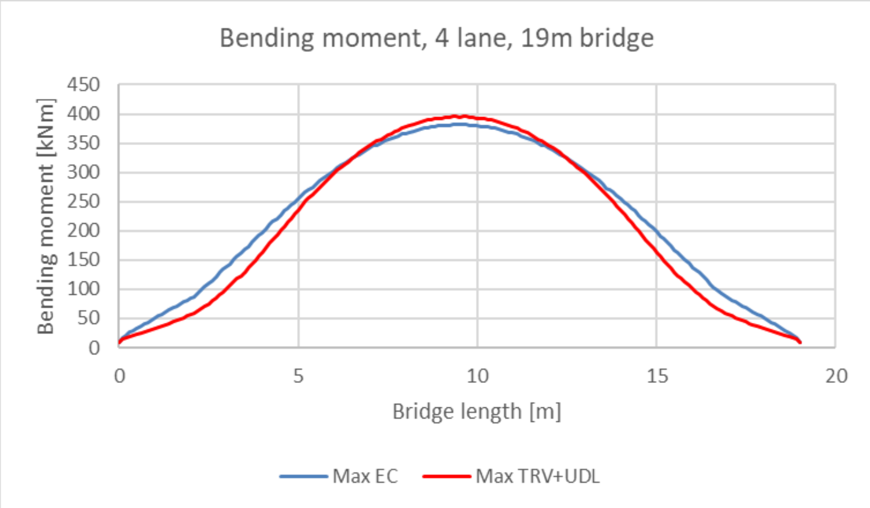

Shear forces, 4 lane, 14m bridge
Shear forces [kN]
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
Bridge length [m]
Max EC
Max TRV + UDL


Bending moment, 4 lane, 17m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV+UDL

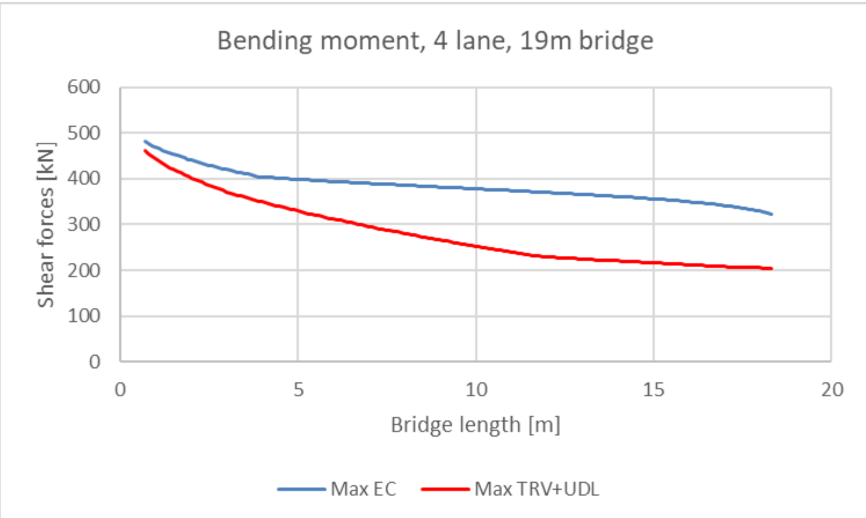

Bending moment, 4 lane, 16m bridge
Bending moment [kNm]
Bridge length [m]
Max EC
Max TRV+UDL

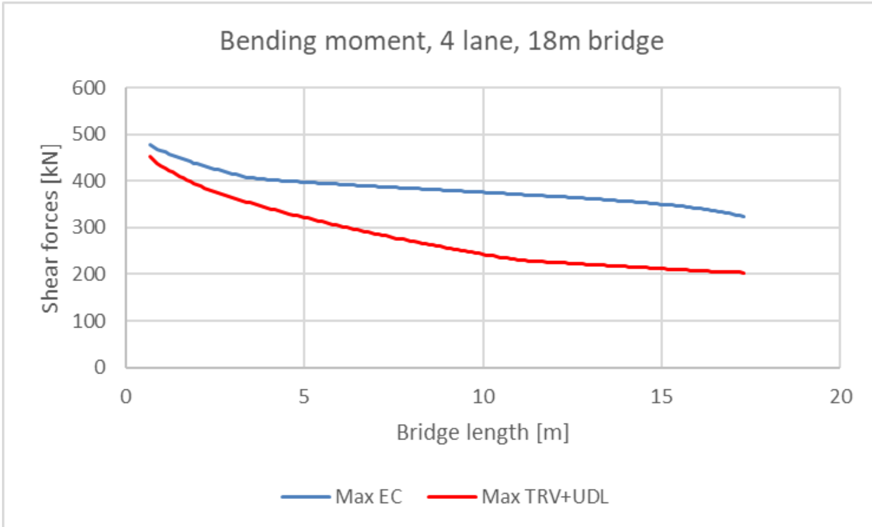

Bending moment, 4 lane, 17m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV+UDL

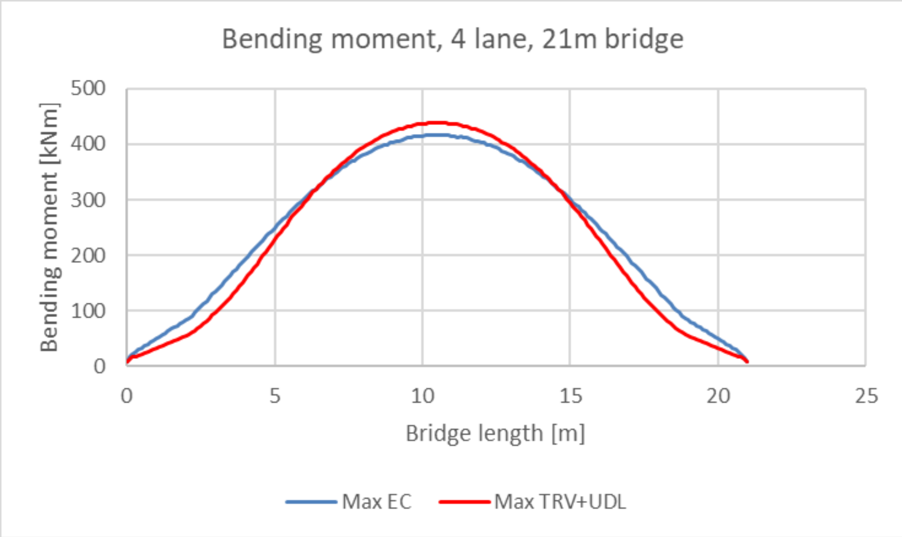

Shear forces, 4 lane, 16m bridge
Shear forces [kN]
Bridge length [m]
Max EC
Max TRV+UDL

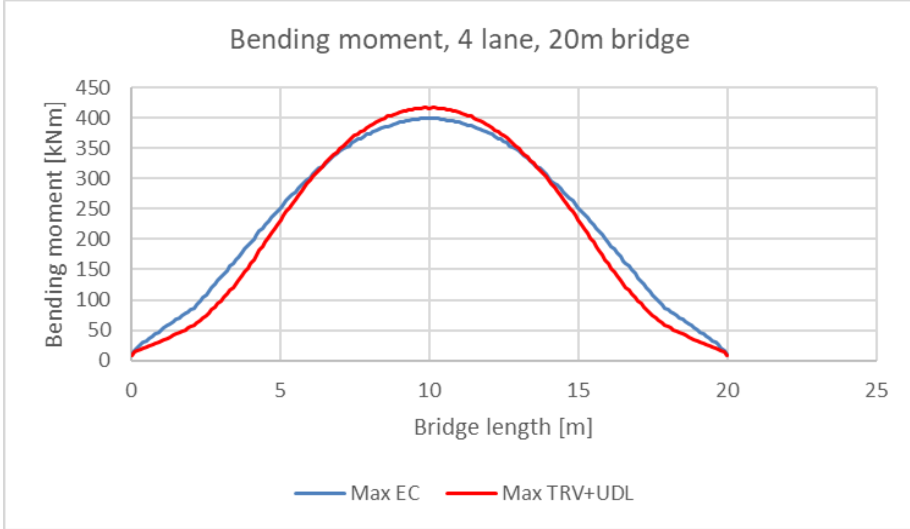

Bending moment, 4 lane, 19m bridge
Bending moment [kNm]
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV+UDL

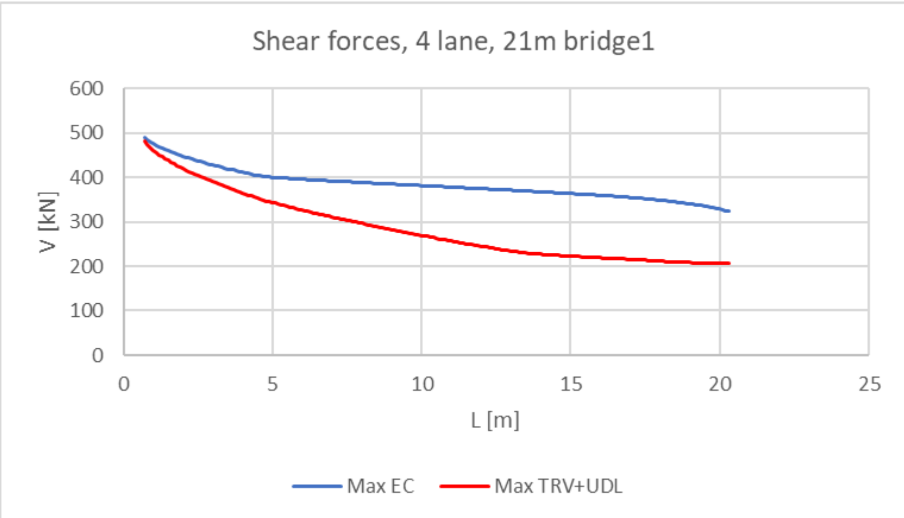

Bending moment, 4 lane, 18m bridge
Bending moment [kNm]
400
350
300
250
200
150
100
50
0
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV+UDL

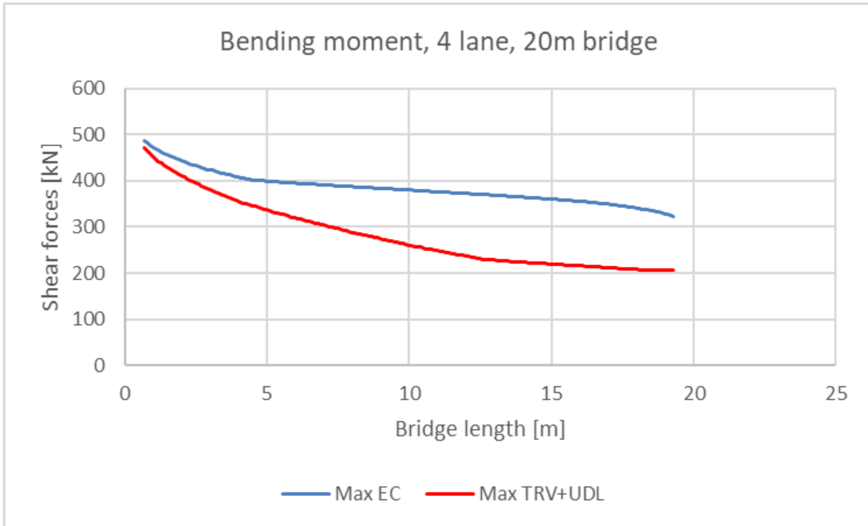

Bending moment, 4 lane, 19m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV+UDL

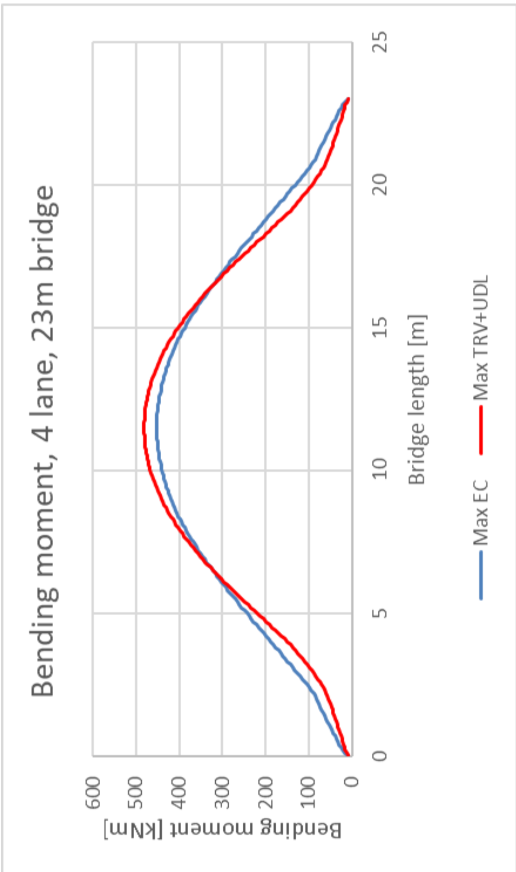

Bending moment, 4 lane, 18m bridge
Shear forces [kN]
600
500
400
300
200
100
0
0
5
10
15
20
Bridge length [m]
Max EC
Max TRV+UDL

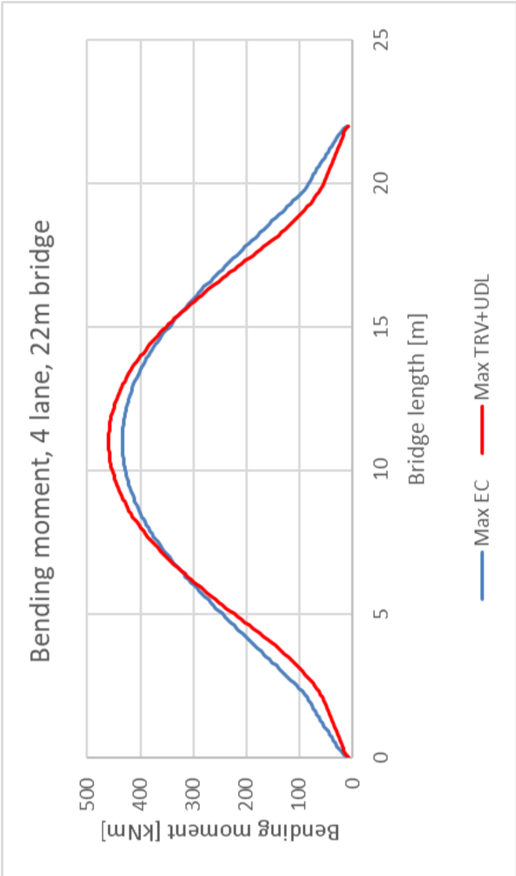

Bending moment, 4 lane, 21m bridge
Bending moment [kNm]
0
100
200
300
400
500
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV+UDL

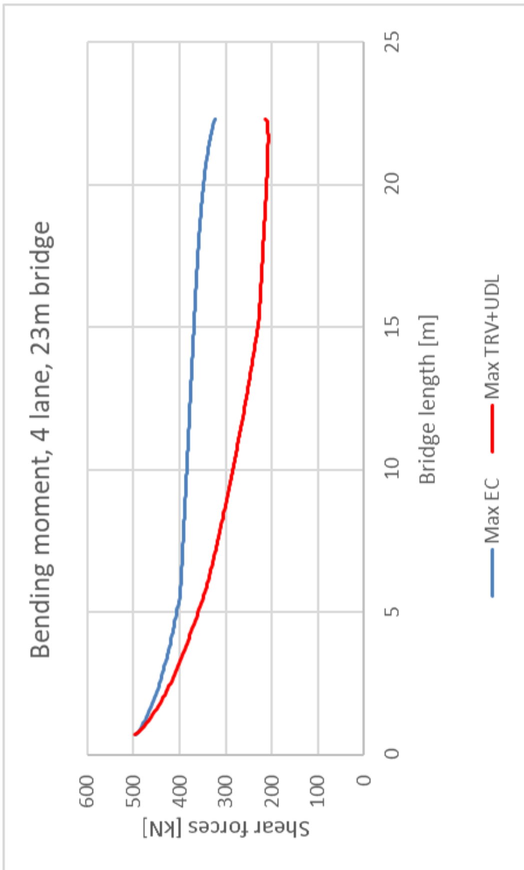

Bending moment, 4 lane, 20m bridge
Bending moment [kNm]
0
50
100
150
200
250
300
350
400
450
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV+UDL

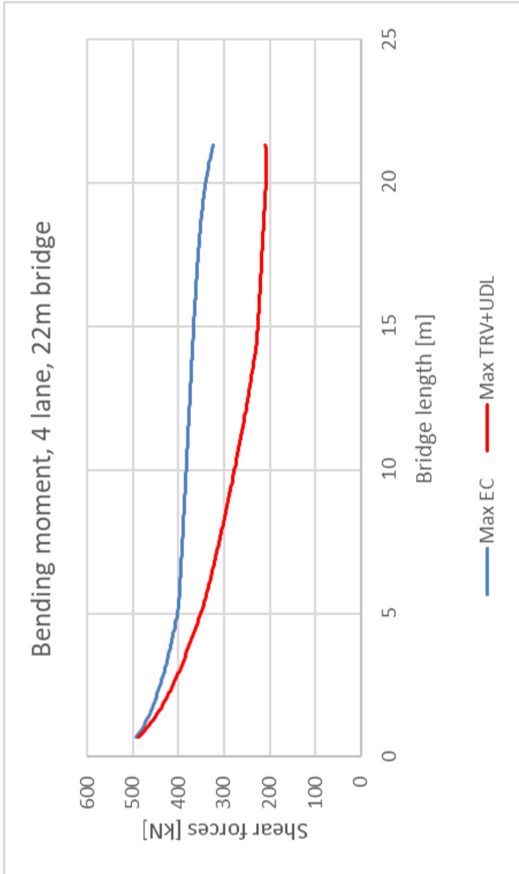

Shear forces, 4 lane, 21m bridge1
V [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
L [m]
Max EC
Max TRV+UDL

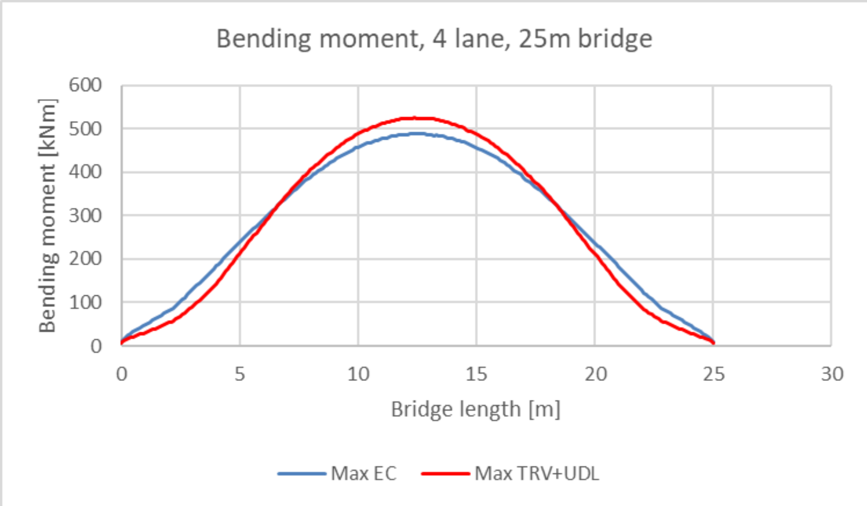

Bending moment, 4 lane, 20m bridge
Shear forces [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV+UDL

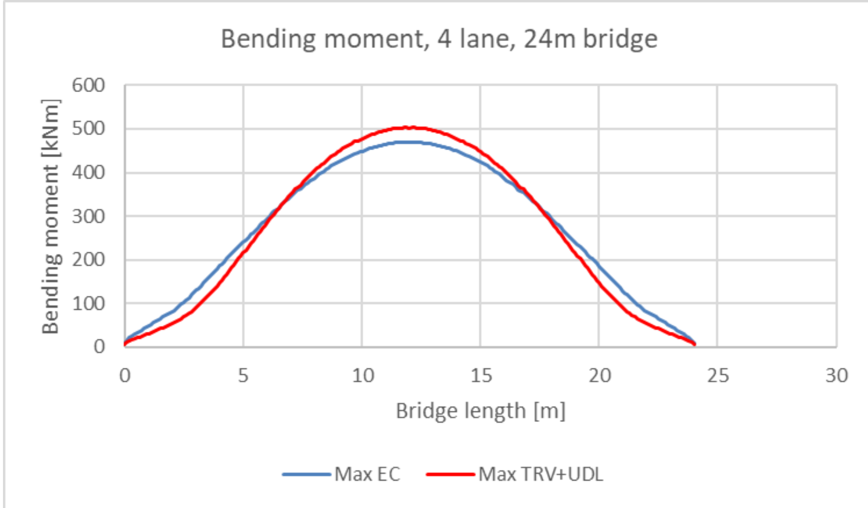

Bending moment, 4 lane, 23m bridge
Bending moment [kNm]
0
100
200
300
400
500
600
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV+UDL

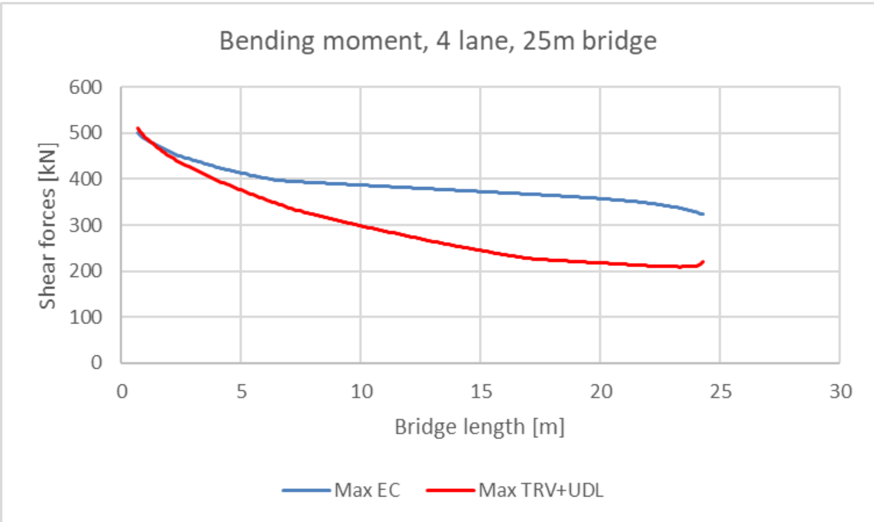

Bending moment, 4 lane, 22m bridge
Bending moment [kNm]
0
100
200
300
400
500
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV+UDL

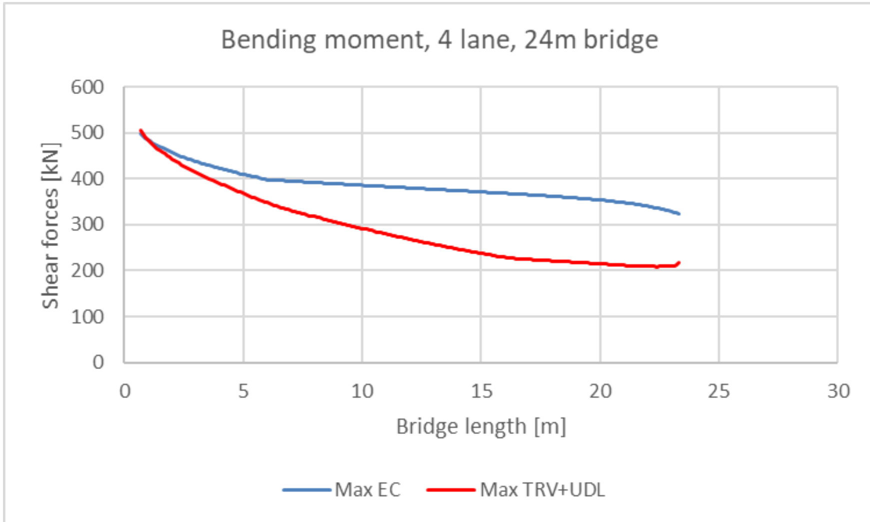

Bending moment, 4 lane, 23m bridge
Shear forces [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV+UDL


Bending moment, 4 lane, 22m bridge
Shear forces [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
Bridge length [m]
Max EC
Max TRV+UDL


Bending moment, 4 lane, 25m bridge
Bending moment [kNm]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
Bridge length [m]
Max EC
Max TRV+UDL


Bending moment, 4 lane, 24m bridge
Bending moment [kNm]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
Bridge length [m]
Max EC
Max TRV+UDL


Bending moment, 4 lane, 25m bridge
Shear forces [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
Bridge length [m]
Max EC
Max TRV+UDL


Bending moment, 4 lane, 24m bridge
Shear forces [kN]
0
100
200
300
400
500
600
0
5
10
15
20
25
30
Bridge length [m]
Max EC
Max TRV+UDL

C.5 Deck Surface Results

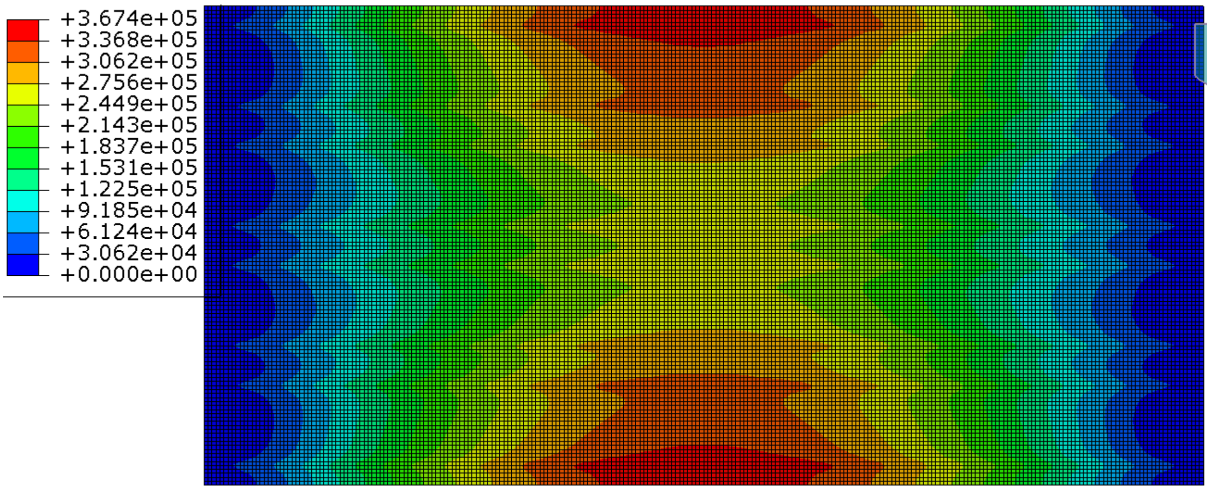


Figure C.1: 2D bending moment result for LM 1_TS, maximum envelope

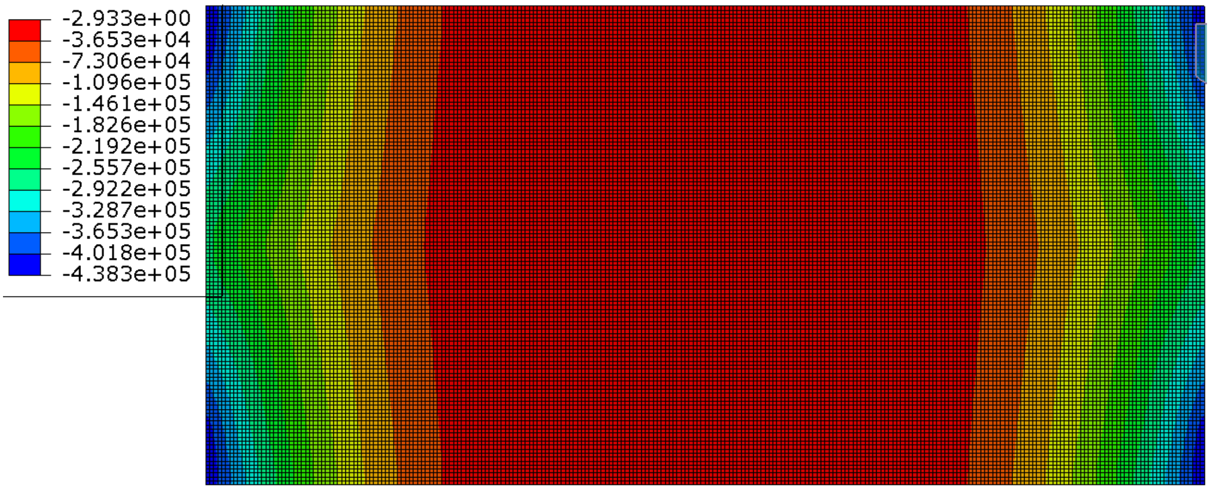


Figure C.2: 2D bending moment result for LM 1_TS, minimum envelope

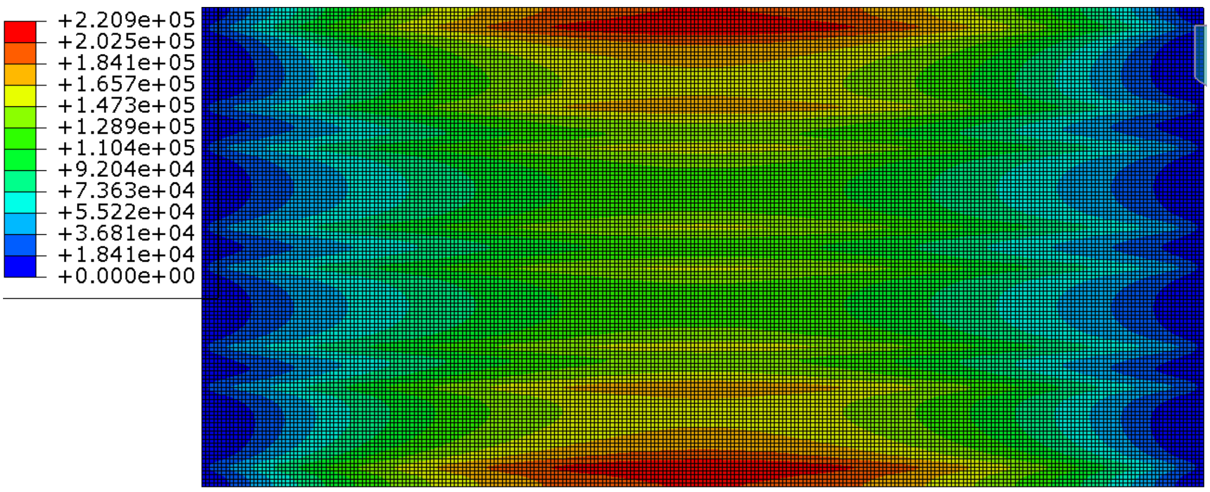


Figure C.3: 2D bending moment result for LM 2, maximum envelope

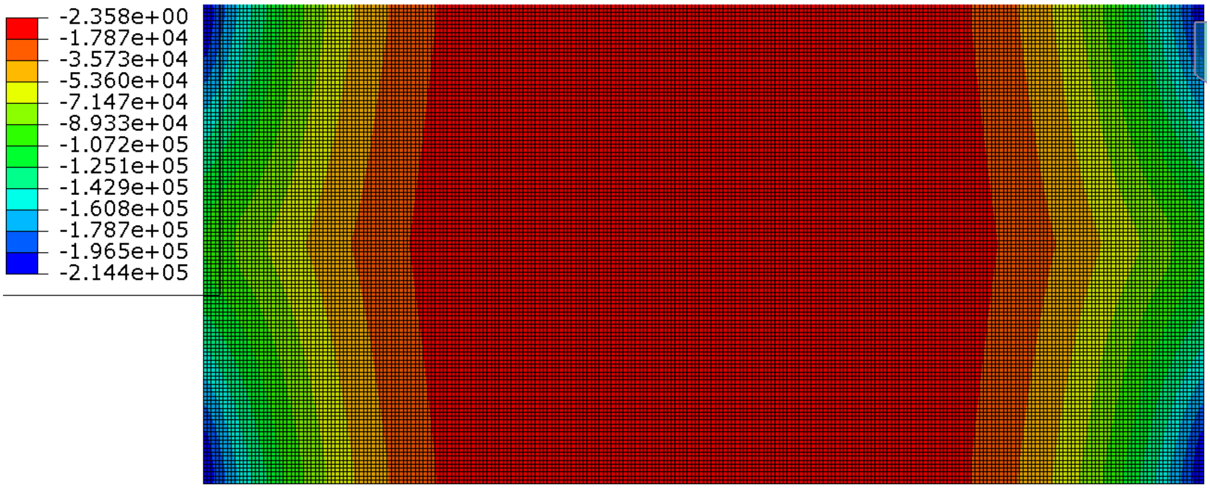


Figure C.4: 2D bending moment result for LM 2, minimum envelope

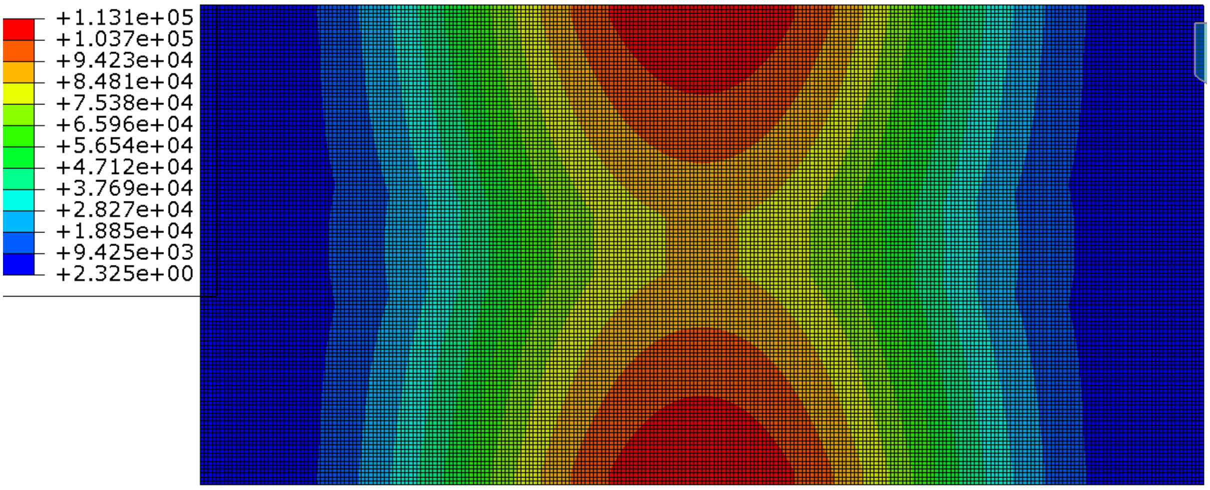


Figure C.5: 2D bending moment result for LM 1_UDL, maximum envelope

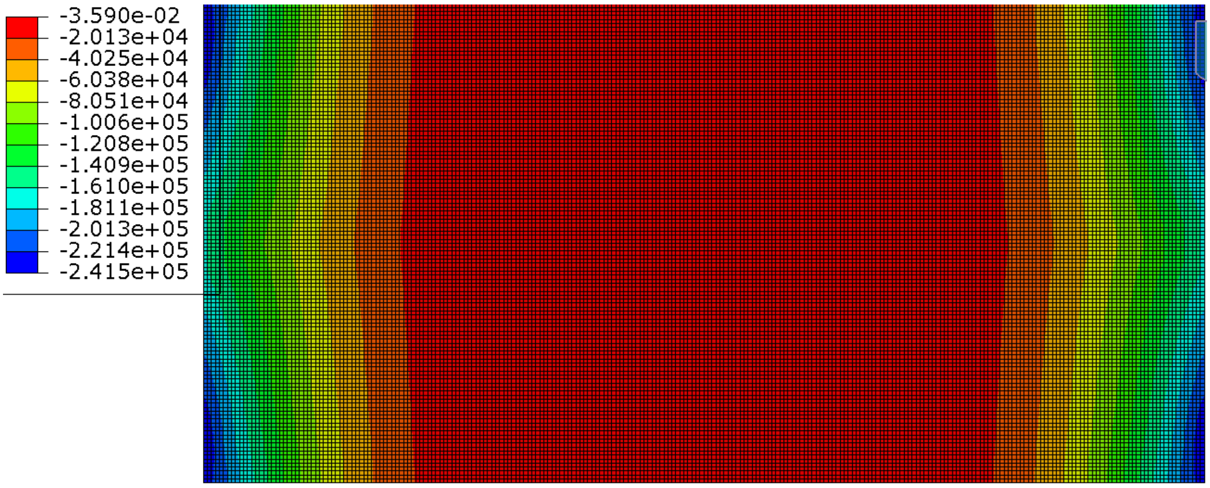


Figure C.6: 2D bending moment result for LM 1_UDL, minimum envelope

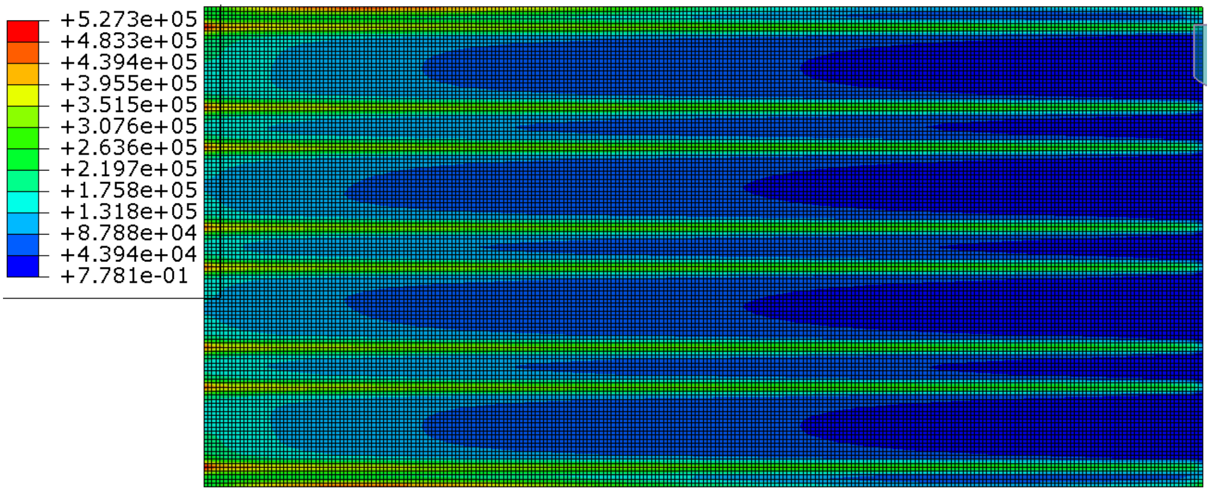


Figure C.7: 2D shear force result for LM 1_TS, maximum envelope

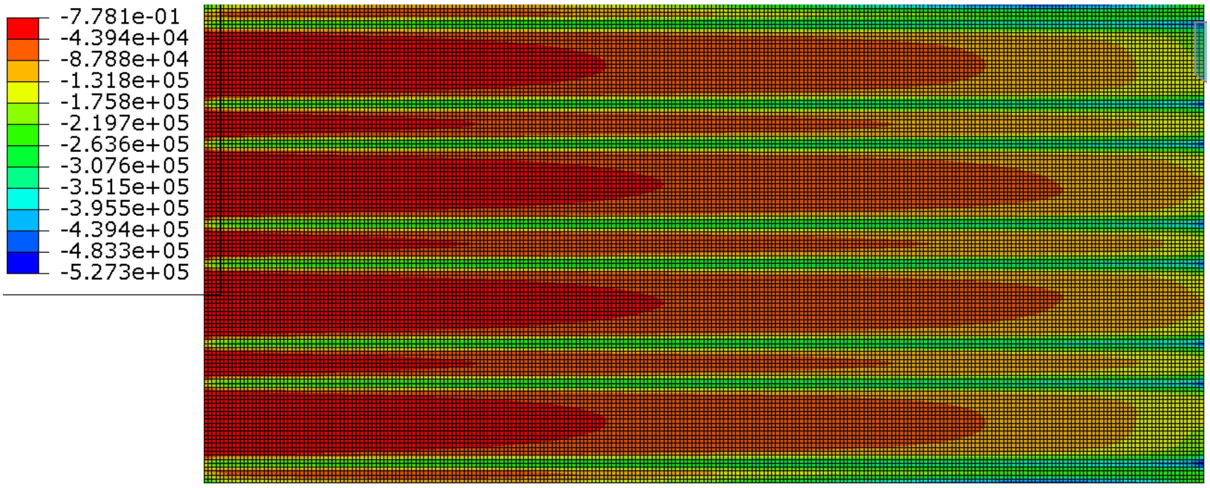


Figure C.8: 2D shear force result for LM 1_TS, minimum envelope

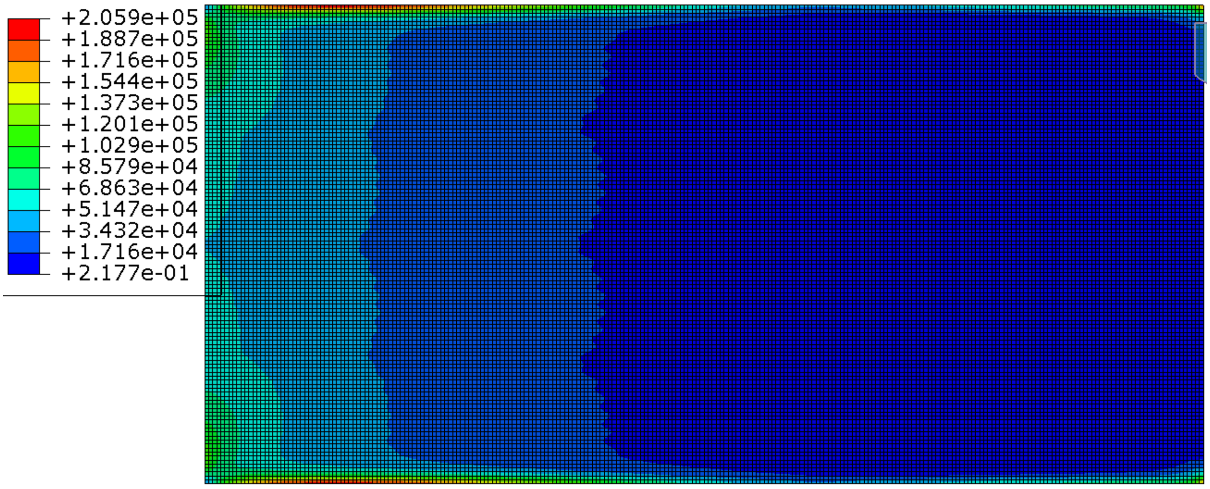


Figure C.9: 2D shear force result for LM 1_UDL, maximum envelope

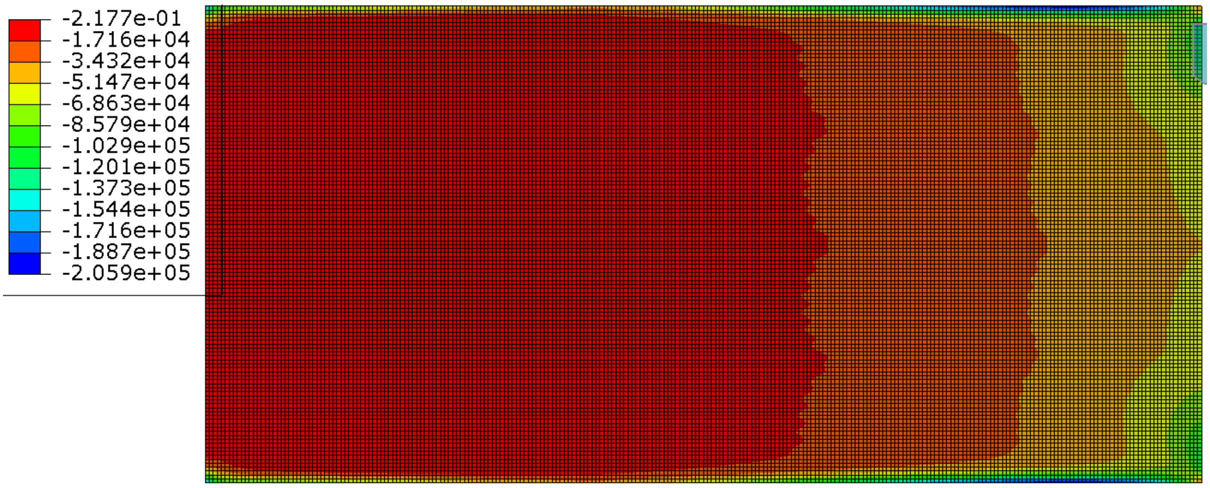


Figure C.10: 2D shear force result for LM 1_UDL, minimum envelope

C.6 Regression Line