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Methods for analysing heavy transports on existing bridges

Metoder för att analysera tung transport på existerande broar

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2020

Abstract

The main purpose of this thesis is to evaluate two current methods, Brokontrollen and TungTransport, used in Sweden for analysing heavy transport on existing bridges. It was investigated how the two methods compare, how bridge types affect the differences, if other variables impact the results and how, and if the methods can be improved. To answer these questions, first, a set of vehicles (which were used to analyse every bridge) were created and yielded the bridges response to varying numbers of axles and varying axle distances. Secondly, a Theoretical Method was programmed to create a reference for slab bridges. Lastly, a further evaluation of the methods was performed through varying input data and creating adjusted models in TungTransport and the Theoretical Method. It was found that the difference between the two Swedish methods was significant, ranging from Brokontrollen permitting loads 33 % lower to 50 % higher than TungTransport. Brokontrollen tends to be more conservative for tensioned structures. In addition, Brokontrollen varies less than TungTransport for changes regarding length and width. Furthermore, it was found that certain models in TungTransport, results were inconsistent; statements about Brokontrollen could generally not directly be made due to it being a “black box”. Furthermore, it was found that the axle width of permit vehicles significantly impacts the results given by TungTransport and, due to Brokontrollen not allowing axle width as input data, also the difference between the two methods. More importantly, it was found that TungTransport does not account for the prescribed range of axle widths for classification vehicles, which are used to determine the capacity of a bridge, and in so doing missing out on extra capacity of the bridge.

Rapport TVBK-5279
ISSN 0349-4969
ISRN: LUTVDG/TVBK-20/5279+63

Master's thesis
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May 2020

Preface

The basis for this thesis lies in my passion for the art that is bridges. In that passion lies not only the drive for new creation, but also preservation. This thesis is my contribution to improve methods that ensure that preservation. Furthermore, this project concludes my master's in Civil Engineering with a specialization in Structural Analysis and Design.

I would like to thank my supervisors: Hassan Mehri for the initial idea and the valuable input throughout the process, Pontus Christensson for discussing ideas and his help with practical parts, and Ivar Björnsson for giving new perspectives. In addition, I would like to thank Jaqueline Hinz for bearing with me through these months.

Lund, May 2020

Remco de Bruijn

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1. Introduction

1.1. Background

According to the Swedish traffic regulations, SFS 1998:1276, motor vehicles may only pass public motorways if certain axle or bogie-axle (double-axle) loads are not surpassed (Svensk författningssamling, 1998). These loads are defined in four carrying capacity classes (bärighetsklasser in Swedish), and in short referred to as BK1, BK2, BK3, and BK4. Traffic structures get assigned one of these classes which is then used to determine if vehicles may pass or not. Determining the carrying class of the structure in question can be done in multiple ways (The Swedish Transport Administration, 2018a). First, load effect classification; the design traffic load is compared to the allowable traffic load for the structure (assuming this is given). Second, design capacity classification; the capacity in relevant cross-sections is used in order to investigate and determine the class. Third, pattern classification; based on statistics of the bridge type, the class is determined. Fourth, general classification; a temporary classification where the bridge is assigned the same class as the road it is connected to or the class that the designers intended it to have.

However, the Swedish Transport Administration may give permission for vehicles to pass despite surpassing the requirements of the carrying class. To give such dispensation, computations for the specific case are performed (The Swedish Transport Administration, 2017). The computations that are required to judge if permission can be given is performed using different strategies. Sweden adopts an approach that uses so called classification vehicles (see Annex B). These classification vehicles have axle- and bogie-axle-values (A/B-values) that for a certain bridge are calibrated such that their load effects are the highest possible without surpassing the capacity of the bridge (The Swedish Transport Administration, 2018b). This calibration is performed once for a bridge (and passage criteria, see subsection 2.1.1) and the A/B-values are saved. These A/B-values are later used in combination with the classification vehicles in order to efficiently produce a modelled capacity of the bridge by taking the maximum load effects of the classification vehicles' load effects. This modelled capacity can thereafter be compared to load effects of real vehicles in order to determine if they can pass a certain bridge. For the computation of the modelled capacity and the load effects, different methods are implemented; Brokontrollen and TungTransport.

Brokontrollen is one of the Swedish methods. It is accessible through an online Bridge Management System (BMS) called the Bridge and Tunnel Management system (BaTMan) and is owned by the Swedish Transport Administration. Currently, little information is public about the algorithms used in this method. Only one thing is known; the computed load effects (of the classification vehicles and the permit vehicle) are based on influence lines and lane-factors. Nevertheless, Brokontrollen gives an immediate response displaying if passage across e.g. a bridge is possible as well as specific instruction on how to cross. Furthermore, it requires little input data and can be used directly by the public (provided they have a BaTMan account).

TungTransport is another Swedish method, owned by Tyréns AB, which uses finite element models to evaluate if dispensation can be given. TungTransport is ABAQUS based and available on an online server. It requires a little more input data than Brokontrollen and has a computation time ranging from a few minutes to up to an hour. On the other hand, load effects for classification vehicles (the modelled capacity) and the real vehicle are usually computed for all possible positions along a bridge.

1.2. Aim

The aim of this thesis is to evaluate current methods, commonly used in Sweden for the analysis of heavy transports on existing bridges, as well as giving an account for methods used in other countries. Furthermore, it aims to clarify the Swedish approach. The evaluation is partially performed by creating and using a Theoretical Method. In full, it aims to answer the following questions:

- What methods are used in practice regarding heavy transport on existing bridges?
- How do the methods TungTransport and Brokontrollen compare to each other?
- What does the Theoretical Method indicate about the methods TungTransport and Brokontrollen?
- Does the type of bridge affect the difference between the methods?
- Can any other variables be identified that causes the difference? If yes, what are those variables and how do they affect the results?
- Can the methods be improved? If yes, how?

The previous questions are answered through creating a set of permit vehicles called test-trucks which will vary in either the number of axles or axle distance. A certain set of bridges will be analysed for passage by these test-trucks. The results of these analyses will be in the form of maximum total load for certain criteria. These criteria and loads might vary between the two methods and will therefore be compared. The Theoretical Method will provide upper- and lower-bound solutions for slab bridges in order to further evaluate the comparison between the methods. These upper- and lower-bounds are based on analytical influence surfaces for plates (see subsection 3.2), where certain assumptions are made to create a lower- and upper-bound model of each bridge, respectively (see subsection 4.1). Based on the results of the passage analyses, variables that might play a role in the differences between the methods are identified and analysed. Thereafter, based on all results and discussions around them, improvements are suggested.

1.3. Limitations

This thesis will analyse methods for heavy transport on existing bridges from the perspective of the computation of the load effects from the classification vehicles (which yield the modelled capacity) and the real vehicle that passes a bridge. Another perspective would be that of the calibration of the classification vehicles' A/B-values to the real load carrying capacity; this topic will be briefly mentioned.

Regarding the comparison between Brokontrollen, TungTransport and the Theoretical Method the evaluation will be based on the highest permissible load (P) according to each method for a certain test-truck and passage criteria. This is due to Brokontrollen not providing any output regarding moment and shear utilizations or similar. Furthermore, only a limited amount of existing bridges are available in both programs. Therefore, the bridges to be analysed must be chosen from the list of in common bridges, see Annex A; this limits the types of bridges that can be analysed. Regarding the Theoretical Method, only the simplest bridge type (from the list of common bridges) will be implemented.

2. Swedish and international methods for handling heavy transports

Different countries employ different strategies to deal with heavy transports. Nevertheless, some strategies have similarities such as the use of classification vehicles (defined in section 2.1.1). Furthermore, many methods are implemented in a larger system called a Bridge Management System (BMS). A BMS is made up of a database with information about a register of bridges used by bridge managers to monitor and manage the current state of their bridges (Ryall, 2010).

2.1. Swedish methods

Holmstrand (2011) states that dispensation for heavy transport over a bridge is only given if the passage is deemed safe with no risk of damage or other inconvenience. Moreover, he argues that dispensation for heavy transport should only be considered in special cases. These cases include when a loaded truck cannot have its load distributed to reduce high axle loads, if an unloaded vehicle exceeds the maximum capacity, or if a vehicle with a distributable load needs to cross a road with multiple traffic-lanes. Therefore, in most cases of heavy transport, dispensation should not be given; instead, alternative ways of transportation should be considered. If a case fulfils the requirements to be considered for dispensation, an analysis is performed to determine if the heavy transport does not exceed the capacity of the bridge it needs to pass.

2.1.1. Classification of bridges – Determining the A/B-values of the classification vehicles

In order to understand the Swedish methods and gain perspective from methods of other countries, it is important to have a concise review of the classification of bridges in Sweden. The classification of bridges is in current Swedish practice performed deterministically. For a certain bridge and different passage criteria, different axle and bogie-axle values (A/B-values) are calibrated which are later used to compute a modelled capacity that is used in dispensation cases (The Swedish Transport Administration, 2018b). The different passage criteria are (The Swedish Transport Administration, 2018b):

- Normal passage, no special restrictions;
- mid-road, alone on bridge;
- mid-road, traffic on the opposing road.

The A/B-values are calibrated using the classification vehicles (Swedish: typfordon) shown in Annex B as previously mentioned in subsection 1.1. This is done following the criteria that the load effects of the classification vehicles cannot surpass any of the limit state design capacities. The load effects are computed by placing the axle-loads of the classification vehicles in one lane, while parallelly on the second – fourth lane the same classification vehicles are placed but with axle loads scaled with a factor 0.8. The remaining lanes carry a distributed adverse load of 5 kN/m. A schematic of the general classification procedure is shown in a flowchart, see Figure 2.1.

As mentioned in the limitations, to analyse the correctness of this process is not within the scope of the thesis. However, for completeness, subsection 2.1.1.1 is dedicated to the impact of having a deterministic classification system compared to a probabilistic approach.

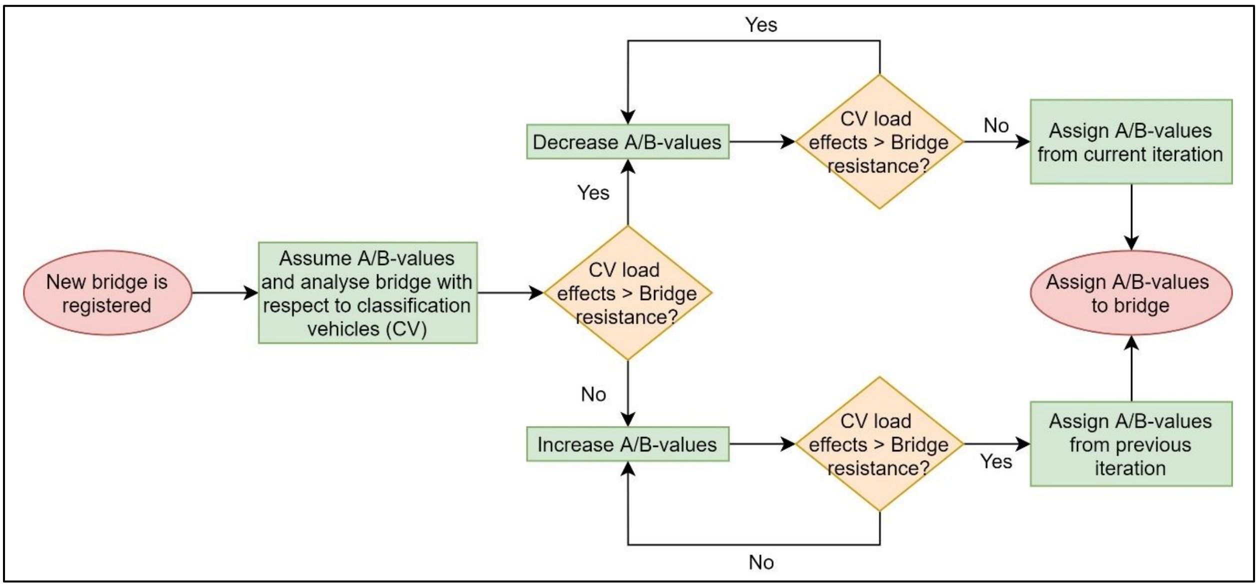


Figure 2.1: Flowchart of the classification process (determining A/B values for a bridge). Note, different passage criteria are taken into account by the placement of the classification vehicles when computing their load effects.

2.1.1.1. Deterministic vs. probabilistic approach to classification

In a deterministic approach safety factors for load effects and resistances are used. These factors are calibrated using structural reliability theory where assumptions about uncertainties include distribution functions, the mean value and standard deviation (μ, σ), and the definition of characteristic values (Steenbergen, 2017). Safety factors are found in design codes and are generalized for application to a wide range of loads and structures (Connor & Enevoldsen, 2007).

In a probabilistic approach, probabilistic distributions are determined for a specific load and structure. The approach is therefore less conservative while remaining safe. From the distributions, safety indexes are computed (see equation (2.1)) (Lauridsen, Jensen, & Enevold, 2007). In other words, safety indexes are functions of the probabilities of failure and can therefore be used to evaluate structural safety. Codes provide limits for probabilities of failures that vary for different cases. These limit probabilities yield safety indexes which are then compared to the safety index of the structure in question.

$$\beta = -\Phi^{-1}(p_f) = -\Phi^{-1}(P(R - S > 0)) \tag{2.1}$$

where $\Phi^{-1}(\cdot)$ is the inverse function of the standardized normal distribution,
p_f is the probability of failure,
R is the capacity,
and S is the load effect.

When classification vehicles are used, each specific loading of the classification vehicles would yield a different modelled capacity. Each modelled capacity in turn yields a different safety index. In Denmark, where one classification vehicle per a certain truckload is used (see subsection 2.2.1), the truckload that does not exceed the relevant safety index provided by the codes is the truckload (also called class) that is assigned to the bridge.

In an interview with Fredrik Carlsson (2020), who wrote a dissertation called "Probabilistic modelling and safety principles for existing bridges" in Sweden, Carlsson stated that the preferred method for classification of bridges (from an economic point of view) depends on the investment costs of the bridge. In other words, longer bridges or bridges that are more heavily used benefit more from a probabilistic classification.

If a probabilistic approach is chosen, in the case of small Swedish bridges, reference can be taken from the probabilistic values for typical small Swedish bridges in Carlsson's and Thelandersson's (2006) report. For larger, more atypical bridges, Carlsson (2020) states that stochastic loads must be determined for every bridge independently. An example given by Carlsson of the magnitude of difference between using deterministic or stochastic variables is regarding the 0.8 factor used for the truckload of the classification vehicles on the second – fourth lane. According to Carlsson, this factor could go down to 0.5 in certain cases, meaning the A/B-values for the bridge could go up.

Furthermore, as is mentioned in subsection 2.2.1 the Danish system, DANBRO, utilizes a rather similar approach compared to the Swedish system. It is therefore relevant to mention Connor and Enevoldsen's (2007) findings on the comparison of a post-tensioned concrete slab bridge analysed both deterministically and probabilistically. They found that when using a deterministic approach, the bridge required strengthening in order to be able to register it into the Danish special road network for heavy transports (The Blue Road Network, see subsection 2.2.1). However, when using a probabilistic approach, they found the capacity to be sufficient.

2.1.2. Computation of dispensation cases.

Once the A/B-values for the classification vehicles have been determined in the classification of a bridge (see subsection 2.1.1), the classification vehicles can be used to compute dispensation cases. This computation is performed in different methods (Brokontrollen and TungTransport, see subsection 2.1.3 and 2.1.4, respectively). What mainly sets the methods apart is the models that are used to represent the bridges. What is interesting when it comes to using classification vehicles is that the actual capacity of the bridge is not used in the computation of a dispensation case. Instead, a modelled capacity is used; this modelled capacity is based on the load effects produced by the classification vehicles (calculated with a model of ones choosing). During the computation of load effects, once again the axle-loads of the classification vehicles are placed in one lane, while on the second – fourth lane the same classification vehicles are placed but with axle loads scaled with a factor 0.8. The remaining lanes carry a distributed adverse load of 5 kN/m. A schematic of the general dispensation case computation procedure is shown in a flowchart, see Figure 2.2.

The modelled capacity for a certain location of a bridge is set as the maximum load effect of all classification vehicles placed in the most adverse position (with respect to that certain location and limited by the different passage criteria, see subsection 2.1.1). Once this capacity is set, it can be compared to load effects produced by permit vehicles (a real vehicle that has requested dispensation to pass a bridge). The permit vehicles are also placed in the most adverse position (limited by the different passage criteria). If the load effects from the permit vehicle do not surpass the modelled capacity, permission is given for that vehicle to pass the bridge in question.

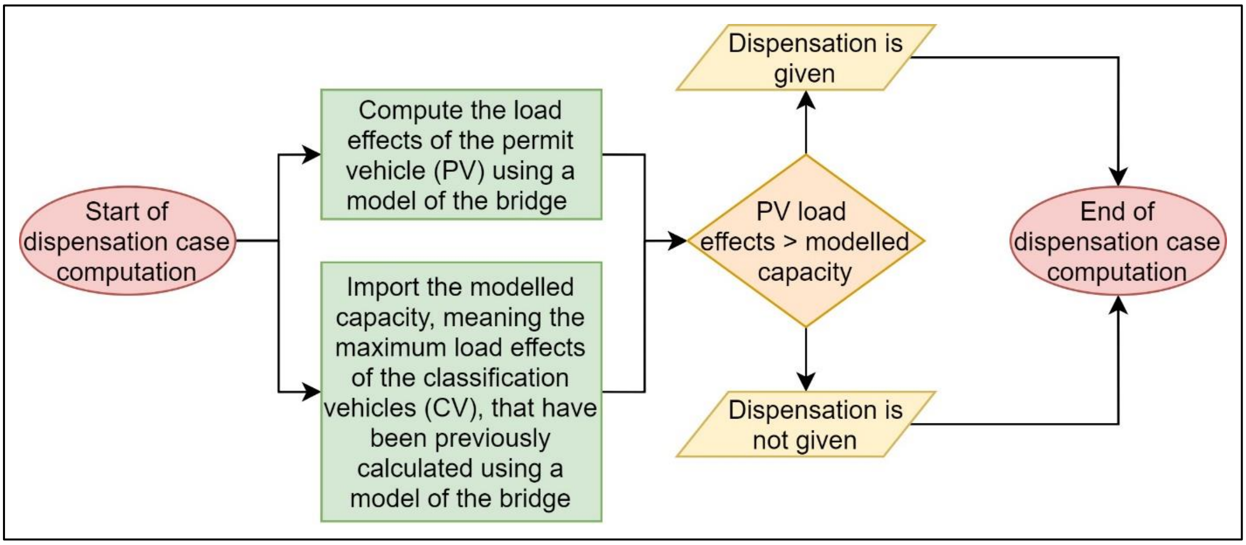


Figure 2.2: Flowchart of the dispensation case computation process (determining if a vehicle can pass a certain bridge). Note, different passage criteria are taken into account by the placement of the classification vehicles and permit vehicle when computing their load effects. For the classification vehicles, the A/B-values produced in the classification process (see subsection 2.1.1) are used.

2.1.3. Brokontrollen

The Swedish methodology, which is the assignment and comparison of classes, is among others implemented in Brokontrollen, a web-based program part of the Swedish Transport Administration's BMS, the Bridge and Tunnel Manager (BaTMan).

Brokontrollen works in two steps (The Swedish Transport Administration, 2017):

1. Load intensity calculation: In this step, the vehicle inputted into Brokontrollen is compared to the carrying capacity class of a bridge (BK1, BK2, BK3, or BK4).
2. Load effect calculation: If step 1 grants passage with limitations regarding velocity, where to drive, etc., a second step is performed in an attempt to grant lesser limitations. In this step the load effects due to the classification A/B values are compared to the load effects due to the vehicle in question. The load effects are determined for a number of classification vehicles shown in Annex B.

For the computation of load effects, use is made of influence lines (see subsection 3.1) and lane factors (The Swedish Transport Administration, 2017). More details about the algorithms in Brokontrollen are not disclosed by the Swedish Transport Administration.

2.1.3.1. Input

The input that Brokontrollen requires to perform the above given computations are mentioned below. The vehicle and how it passes over bridges are defined with the following information:

- Where, transversally, the vehicle will pass on the bridge (optional);
- velocity;
- number of axles;
- axle loads;
- and distances between axles.

The input for loads and distances are given in tons and meters. Information concerning existing bridges is found in BaTMan; this includes bridge dimensions, A/B-values, and which classification vehicles that are relevant for the analysis of the bridge.

2.1.3.2. Output

A generalization of the output of Brokontrollen in form of indexes and their corresponding passage description is given by the Swedish Transport Administration (2017) as follows (translated from swedish; information might be lost in translation):

10-11	Vehicle drives in normal lane. Possible restrictions on velocity.
20-21	Vehicle drives in normal lane. Weighing required. Possible restrictions on velocity.
30-31	Vehicle drives mid road. Restrictions on velocity.
40-41	Vehicle drives mid road. Weighing required and restrictions on velocity.
50-51	Vehicle drives mid road. Restrictions on velocity. No other traffic on the bridge during passage (counts for all lanes).
60-61	Vehicles drives mid road. Weighing required and restrictions on velocity. No other traffic on the bridge during passage (counts for all lanes).
19	Vehicle drives according to the dispensation description.
90-96	Transport cannot be permitted.

An example of output from Brokontrollen is presented in Annex C

2.1.4. TungTransport

TungTransport is an ABAQUS based online service; i.e. the computations are finite element based. Furthermore, the results are post-processed in excel. A detailed description is provided in Annex D. Based on the selection of input, TungTransport loads the relevant model of the bridge into Brigade (a FEM-software that uses the ABAQUS solver); this is a finite-element model of the actual bridge. Thereafter, TungTransport runs the analyses with the defined permit vehicle along predefined traffic-lines. These traffic-lines vary depending on if the model is for passage on a normal traffic lane or on the middle of the road. The analysis is performed through the usage of numerical influence lines. When the analyses are done, the maximum load effects along certain result-lines are compared to the previously calculated load effects due to classification vehicles. These effects are usually bending moments and shear but depending on the bridge, additional effects such as punching shear or edge stresses due to tensioning. Below, Figure 2.3 shows the traffic- and results-lines for a bridge in the TungTransport database. Note, the traffic-lines do not necessarily coincide with the result-lines.

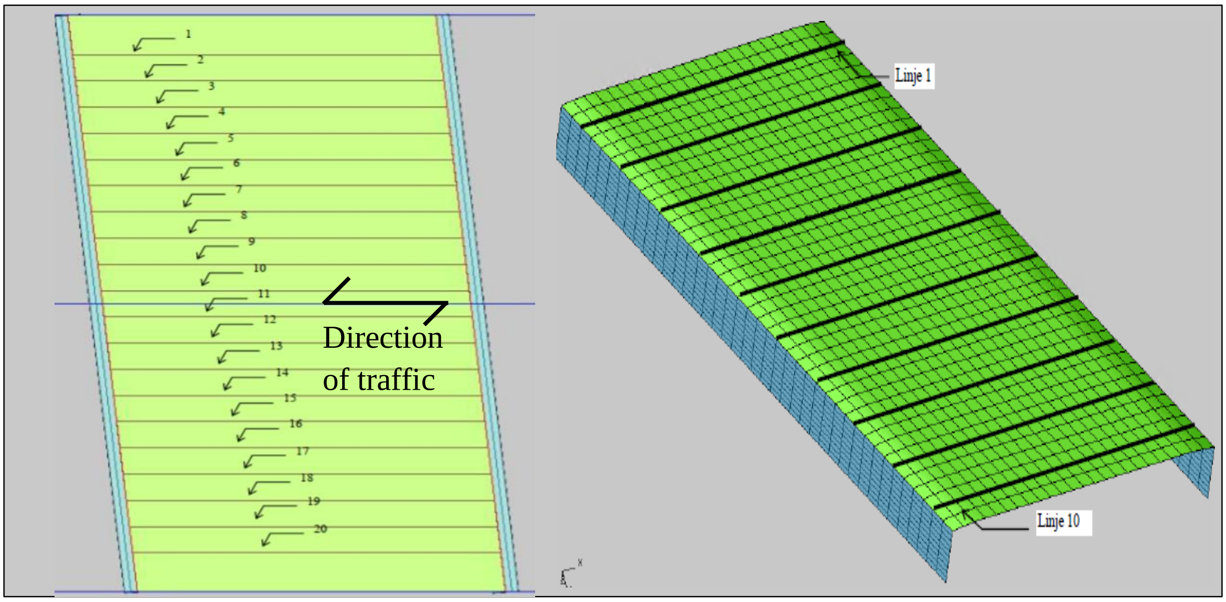


Figure 2.3: A typical illustration of traffic-lines on the left and result-lines on the right for a bridge registered in TungTransport. Note, the traffic- and result-lines go in the longitudinal direction of the bridge.

2.1.4.1. Input

In order to perform calculations in TungTransport, the bridge is selected provided it is in the system. Thereafter, the permit vehicle is defined which requires the following input:

- The vehicle name;
- axle loads;
- distance between axle loads;
- axle width;
- and vehicle width.

Furthermore, information about the passage is required; where on the bridge (the whole bridge is an option) and at which velocity the vehicle will pass.

2.1.4.2. Output

TungTransport provides the results as degrees of utilization for each load effect that has been computed as well as the location of the highest utilization. If the maximum utilization is less than 1.0 (or 100 %), permission is given for the vehicle in question to pass the bridge. An example of the output of TungTransport is presented in Annex C.2.

2.2. Other methods

2.2.1. Danish method – DANBRO

DANBRO is a Danish BMS, designed by Ramboll and currently implemented in Denmark, Thailand, Mexico and many other countries (Yari, 2018). Included in DANBRO is a method for managing dispensations of heavy transport that follows an approach not dissimilar to the Swedish one (Directorate-General for Energy, 2008). DANBRO uses a classification system including four classes per bridge. The general classification describes the modelled capacity where a class 100 has the modelled capacity produced by a classification vehicle with a total weight of 100 tons (gross) (Connor & Enevoldsen, 2007). The remaining three classifications are optional and have additional conditions regarding velocity, traffic situation, etc. (Directorate-General for Energy, 2008). There is a distinction between the use of classification vehicles in Sweden and Denmark. The Swedish classification vehicles are a set of vehicles that are always used together to determine the modelled capacity (see subsection 2.1.2) and all have axle-loads based on the A/B-values multiplied with certain factors (see Annex B). The Danish system uses only one classification vehicle at a time, each having a specific gross weight, also called class (class 70, 80, 90, etc), which yield different modelled capacities. An interesting feature of DANBRO is the Blue Road Network; a special network for heavy transport where every structure has a capacity corresponding to class 100 (Connor & Enevoldsen, 2007).

2.2.2. Finnish method

Similar to the Blue Road Network in DANBRO, the Finnish Road Administration has included a specific network especially designed for heavy transport (Directorate-General for Energy, 2008). This method allows for efficient transport with less influence on regular traffic. However, information about how the classification of the bridges on this network is performed has not been found (in English) by the author of this thesis.

2.2.3. US method – American Association of State Highway (AASHTO): Load Rating Factor (LRF)

According to the National Academies of Sciences, Engineering and Medicine (2006), for the evaluation of heavy transports, the United States uses a Load Rating Factor to evaluate a certain permit vehicle on a bridge. The National Academies give the LRF as

$$LRF = \frac{R - A_1 DL}{A_2 LL}, \tag{2.2}$$

where R is the total resistance of the bridge,

DL is the total dead load,
LL is the total live load,
A_1 is the dead load factor (accounts for uncertainties in the estimation of DL), and A_2 is the live load factor (accounts for the uncertainties in the estimation of LL).

They continue to explain that the LRF is used both in evaluating general transport traffic and permit vehicles. If the LRF is larger than zero in all sections along a bridge means dispensation can be given. How the different components are calculated is not shown in this thesis. However, the National Academies study shows the great variety in the determination of DL and LL (in the case of non-electronic computations/models). This, according to them, is due to that DL and LL contain factors, e.g. impact factors, that can be determined in a multitude of ways, increasing the variety of possible results. The study therefore points out the usefulness of computational models. Note that the study was published in 2006 and both the use and usefulness of computational models has surely increased.

Different states use different programs to implement this general methodology. Nord & Hovey (2000) explain that the state of Colorado has implemented a software, Fast Truck Routing and Credentialing System (FASTRACS), capable of issuing single trips permits, annual permits, fleet permits, longer combination vehicles permits, and special permits (different permits with different requirements and different timeframes for which they can be used). Furthermore, they state that algorithms have been put in place that, based on historical and special truck ratings, select which structures should be checked when evaluating a route, decreasing the overall time to issue a permit.

2.2.4. Spanish method – SGI

Casas, Aparicio, Ramos, and Sánchez-Rey (2000) explain the, at the time still in development, permission system to be implemented in the Spanish BMS, SGI. They describe that the approach for the system is to use representative bridges to represent the real bridges that are a part of the Strategic Spanish Highway Network. Casas et al. (2000) continue to explain that this approach is chosen due to the possibility to include all bridges, old and new, and at the same time minimize the cost of the study. Furthermore, they mention that the decrease in reliability and inaccuracy will require overconservative models. However, in a later more detailed article by Casas & Aparicio (2001), an adjusted methodology is described which will be explained in short below.

In the updated methodology, Casas & Aoaricio (2001) explain different analyses will be used for old and new bridges, however, for both old and new, the orthotropic deck theory and grillage method are used. They continue to describe that for new (well-documented) bridges the following criteria is decisive for the passage permit (without restrictions):

$$\Phi_i E_{st} + \Phi_j k E_{ct} < RCE_{des} \tag{2.3}$$

where ϕ_i is the impact coefficient of the permit vehicle,
ϕ_j is the impact coefficient of the accompanying traffic,

k is the percentage of accompanying traffic (defined by the highway agency),
RC is the rating coefficient (equal to or less than 1.0) regarding bridge deterioration (defined by the highway agency after inspection and evaluation),
E_{st} is the bending or shear forces from the permit vehicle,
E_{ct} is the bending or shear forces from accompanying traffic,
and E_{des} is the bending or shear forces from the design live load (including impact) from the design codes.

Passage permits with restrictions can be tried by omiting the accompanying traffic components (Casas & Aparicio, 2001).

For old (ill-documented) bridges equation (2.3) cannot be applied due to E_{des} (Casas & Aparicio, 2001). E_{des} comes from new codes; therefore, older bridges where other codes were used cannot be evaluated this way. Instead, the following criteria is implemented (Casas & Aparicio, 2001):

$$\beta_{ot} \geq \beta_{rt} \tag{2.4}$$

where β_{ot} is the reliability index for the permit vehicle and, if applicable, the accompanying traffic,
and β_{rt} is the reliability index for normal traffic.

Casas & Aparicio (2001) explain that, in other words, due to uncertainties around the actual resistance of the bridge, the safety level is set to the known (measured) level due to normal traffic that passes the bridge on a daily basis. For more details regarding the statistics behind the reliability index, the reader is refered to section 2.1.1.1 and the source material.

2.2.5. Hungarian method

Kolozsi, Szilassy, Agárdy, and Gáspár (2000) explain the permission system used in Hungary is used either for passage of a bridge or finding a route from one point to another. For the passage computation, they explain the actual capacity of the bridge is used. Furthermore, the computation is performed with an idealized static model and neglecting features such as the actual cross-section. Kolozsi et al. (2000) state that the adaption of the actual bridges into the idealized models yield conservative results with up to 30-40% increased safety. Regarding the routing possibility, they explain the program checks every possible route between two points and only performs checks for capacity in special cases.

2.2.6. South Korean method – OPERAS

OPERAS, the South Korean BMS makes use of a modified probability-based Load Rating Factor (LRF) analysis for the computation of single- and multi-trip permit (Choi, Lim, Seo, & Jung, 2006). The probabilistic approach is used in the determination of the load factors, see equation (2.2). Based on, among others, the average daily truck traffic (AADT) for certain areas; the permit condition (routine permit or special permit, such as single trip, multiple trip or escorted trip); and the permit vehicle weight, the load factors (A_1 and A_2) for the specific case can be computed which can then be used to compute the LRF.

Similar to the strategies of some other countries, South Korea implemented a road network for heavy transports in Seoul (Choi, Lim, Seo, & Jung, 2006). This network is built up of nine routes. It is for bridges on these nine routes that the above described method has been implemented.

3. Influence lines and surfaces

Influence lines and surfaces are a great tool to efficiently compute load effects and find the most adverse loading positions. As previously mentioned, Brokontrollen makes use of influence lines. Furthermore, TungTransport uses Brigade, which employs numerical influence surfaces. Moreover, the Theoretical Method (see subsection 4.1 and Annex D.2) was developed using theoretical influence surfaces. Therefore, this section is dedicated to shortly introducing influence lines and surfaces. It provides the mathematical basis needed for the development of the Theoretical Method which was used in this thesis.

3.1. Influence lines

An influence line is a function/graph showing the variation of a load effect at a fixed position in a structure due to a concentrated unit load (Karnovsky & Lebed, 2010). It is therefore a powerful tool to use in situations where structures are subjected to moving loads than can take any arbitrary position along the structure. Moreover, influence lines help when combining loads in such a way that the most adverse effects are achieved.

To the author's knowledge, there are three common methods for the construction of influence lines. The Müller-Breslau principle is one of them and uses the load effect's corresponding unit deformation to graphically determine the shape of an influence line. Furthermore, influence lines can be determined either crudely, by computing and plotting multiple points along a structure, or by creating a function for the load effect with a variable load position (Karnovsky & Lebed, 2010). The derivation of a support reaction influence line from a simply supported beam is shown below (see Figure 3.1).

$$\sum M_B = R_A \cdot L - P \cdot (L - x) = 0 \rightarrow R_A = P \cdot \frac{L - x}{L} \rightarrow Influence(R_A) = \frac{(L - x)}{L} \quad (3.1)$$

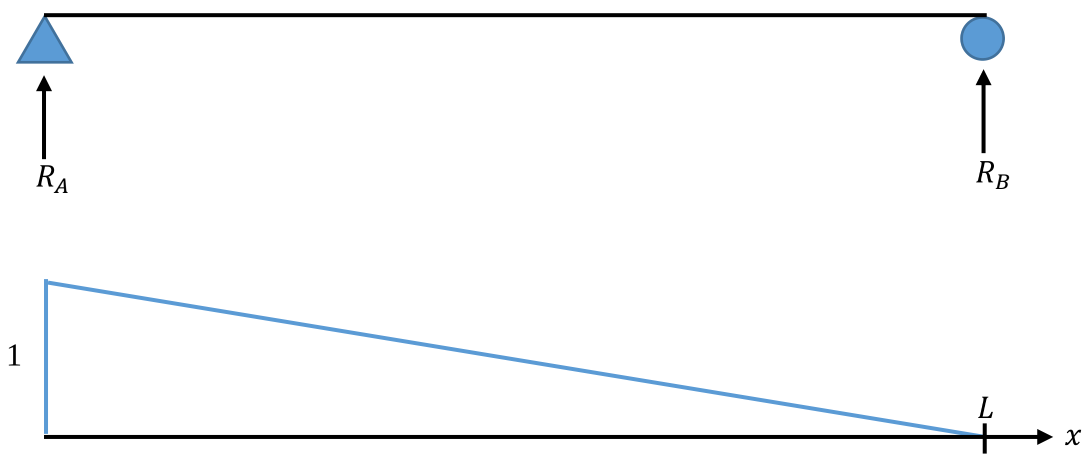


Figure 3.1: A simply supported beam and its reaction force influence line.

3.2. Influence surfaces

Influence surfaces were developed as a tool to compute plates, especially reinforced concrete slabs, after the increased usages of plates in structures due to their load-bearing behaviour (Pucher, 1964). At this time, use of influence lines had become a preferable method to compute the effects of loads on linear members, which made the progression to plates natural (Kawai, 1957).

Influence surfaces are based on the same assumptions as thin plate theory, which are not directly applicable to reinforced concrete (Pucher, 1964). Nevertheless, history has shown the theory to be sufficiently trustworthy for the calculation of internal forces of reinforced concrete. Therefore, also the influence surfaces derived from plate theory are applicable.

Pucher (1964) found the following theorem to hold:

> "One obtains the influence surface for all of the internal forces, which are computed by differentiation of the deflection surface, by differentiating the deflection influence surface – the deflection surface due to a concentrated load – with respect to the coordinates of the reference point."

This thesis has adopted Pucher's (1964) mathematical description of the influence surface, which is shown in short below, with the plate deflection (see equation (3.2)) as a starting point. Note, (u, v) is the reference point for the load effect and (x, y) is the position of the load.

$$w(u,v) = \sum_i P_i K(u,v;x_i;y_i) + \iint p(x,y)\, K(u,v;x,y)\, dx\, dy\,, \tag{3.2}$$

where $w(\cdot)$ is the plate deflection,
P_i is a point load,
$p(\cdot)$ is a distributed load,
And $K(\cdot)$ is the influence function.

Based on the plate deflection, moments are described as:

$$\begin{cases} m_u = -D\left(\dfrac{\partial^2 w}{\partial u^2} + \nu \cdot \dfrac{\partial^2 w}{\partial^2 v}\right) \\ m_v = -D\left(\dfrac{\partial^2 w}{\partial v^2} + \nu \cdot \dfrac{\partial^2 w}{\partial^2 u}\right), \\ m_{uv} = -D\,(1-\nu)\left(\dfrac{\partial^2 w}{\partial u \partial v}\right) \end{cases} \tag{3.3}$$

where m_u, m_v and m_{uv} are the plate moments,
D is the plate stiffness,
and ν is Poison's ratio.

If Poison’s ratio is equated to zero and (3.2) is inserted into (3.3) it yields:

$$m_u = -D\left(\sum_i P_i \frac{\partial^2 K(u,v;x_i;y_i)}{\partial u^2} + \iint p(x,y)\frac{\partial^2 K(u,v;x,y)}{\partial u^2}\, dx\, dy\right). \qquad (3.4)$$

The moment influence surfaces, χ_u, for the moment m_u can then be identified as

$$\chi_u = -D\,\frac{\partial^2 K}{\partial u^2}, \qquad (3.5)$$

which is in line with Pucher’s theorem.

Pucher used this method to develop 93 moment influence charts, treating rectangular and circular plates with different boundary conditions. The formulas used for these charts have not been stated explicitly but may be found back in the sources referenced by Pucher. Timoshenko (1953) shows the implementation of this theorem on several plates as well as a more detailed methodology for usage. However, of special interest for this thesis are plates with free edges in the longitudinal direction; this is due to the fact that bridges are usually supported on two opposite edges and free on the other two edges. Molkenthin (1971) provides a thorough description of the implementation and application of single span plates with two parallel free edges. Furthermore, an exhaustive list of 165 charts with different geometries and boundary cases are provided. This was a significant development as it moved the usability of influence surfaces into the domain of bridge engineering.

Influence surfaces can be used for distributed loads, line loads, and concentrated loads (Pucher, 1964); nevertheless, Molkenthin (1971) recommends wheel loads to be integrated over a contact area. He suggests integration for distributed loads to be performed by using the trapezoidal rule, Simpson’s rule, or Newton’s rule; going from lowest to highest accuracy.

Molkenthin’s (1971) influence surfaces have a certain limitation. Influence surfaces exist only for moments with the reference point along the center-line of the slab as well as along the free edge (see Figure 3.2). For the case of simple line supports along the transverse edges, the equations given below yield the influence lines for middle and edge moments in x- and y-directions.

The equations are derived with the non-dimensional coordinates (ξ, η) (Molkenthin, 1971). The plate in the non-dimensional coordinate system is shown in Figure 3.2. Note, dashed lines represent free edges and solid lines represent simply supported edges.

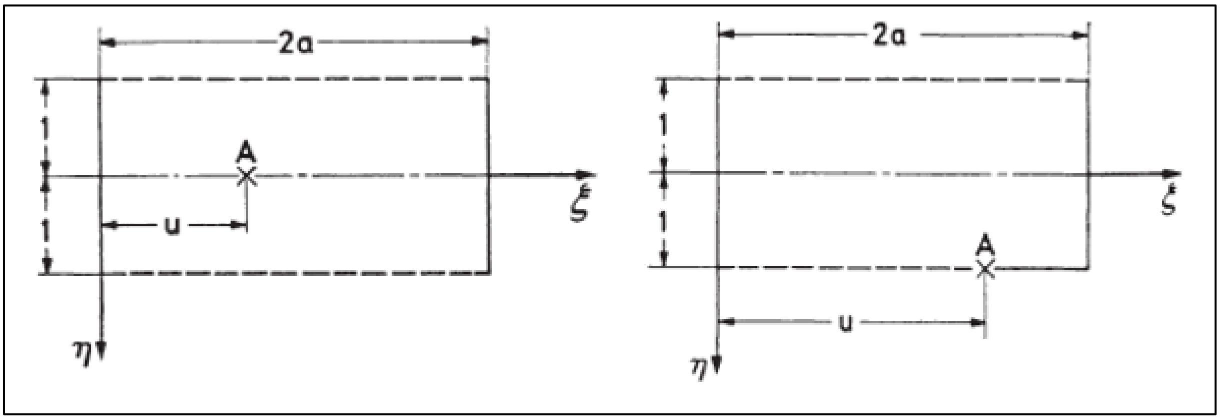


Figure 3.2: Plates with reference for the moment influence surface along the middle (left) and edge of the plate (right) in the non-dimensional coordinate system (ξ, η). Reprinted from Influence Surfaces of Two-Span Continuous Plates with Free Longitudinal Edges (p. 32), by A. Molkenthin, 1971, Springer-Verlag.

Regarding the centreline moment influence surface (point A in Figure 3.2 on the left) (Molkenthin, 1971):

$$\begin{cases} 8\pi\, m_x^F \\ 8\pi\, m_y^F \end{cases} = \ln \frac{X_1^F}{X_2^F} \mp \frac{\pi}{2a} \eta \sinh \frac{\pi}{2a} \eta \cdot \left(\frac{1}{X_1^F} - \frac{1}{X_2^F} \right)$$

$$+4 \sum_n \frac{1}{n} (A_n \cosh \omega\eta + B_n \omega\eta \sinh \omega\eta) \sinh \omega u \sin \omega\xi \,, \tag{3.6}$$

where

$$\begin{cases} X_1^F = \cosh \frac{\pi}{2a} \eta - \cosh \frac{\pi}{2a} (\xi + u) \\ X_2^F = \cosh \frac{\pi}{2a} \eta - \cosh \frac{\pi}{2a} (\xi - u) \end{cases}, \tag{3.7}$$

and where for $8\pi\, m_x^F$

$$\begin{cases} A_n = \dfrac{3 \cosh \omega e^{-\omega} + 1 + \omega + \omega^2}{3 \cosh \omega \sinh \omega - \omega} \\ B_n = \dfrac{-3 \cosh \omega e^{-\omega} + 1 - \omega}{3 \cosh \omega \sinh \omega - \omega} \end{cases}, \tag{3.8}$$

and where for $8\pi\, m_y^F$

$$\begin{cases} A_n = \dfrac{-3 \sinh \omega e^{-\omega} + \omega - \omega^2}{3 \cosh \omega \sinh \omega - \omega} \\ B_n = \dfrac{-3 \sinh \omega e^{-\omega} + \omega}{3 \cosh \omega \sinh \omega - \omega} \end{cases}, \tag{3.9}$$

with $\omega = \frac{n\pi}{2a}$ and where $n = 1, 2, 3, \ldots.$

Note that in case of the double sign $\mp$, the upper sign is used for m_x^F and the lower sign is used for m_y^F.

Regarding the free-edge moment influence surface (point A in Figure 3.2 on the right) (Molkenthin, 1971):

$$8\pi\, m_x^F = \frac{8}{3}\ln\frac{X_1^E}{X_2^E} - \frac{8}{6}\frac{\pi}{2a}(\eta-1)\sinh\frac{\pi}{2a}(\eta-1)\cdot\left(\frac{1}{X_1^E}-\frac{1}{X_2^E}\right)$$

$$+\frac{8}{3}\sum_n \frac{1}{n}(A_n\cosh\omega\eta + B_n\omega\eta\sinh\omega\eta)\sinh\omega u\sin\omega\xi$$

$$-\frac{8}{3}\sum_n \frac{1}{n}(C_n\sinh\omega\eta + D_n\omega\eta\cosh\omega\eta)\sinh\omega u\sin\omega\xi\,, \qquad (3.10)$$

where

$$\begin{cases} X_1^E = \cosh\frac{\pi}{2a}(\eta-1) - \cosh\frac{\pi}{2a}(\xi+u) \\ X_2^E = \cosh\frac{\pi}{2a}(\eta-1) - \cosh\frac{\pi}{2a}(\xi-u) \end{cases}, \qquad (3.11)$$

and where

$$\begin{cases} A_n = \dfrac{2\omega(\omega\cosh\omega - \sinh\omega) + (3+2\omega)(2\cosh\omega + \omega\sinh\omega)}{3\cosh\omega\sinh\omega - \omega}e^{-2\omega} \\ B_n = -\dfrac{2\omega\sinh\omega + (3+2\omega)\cosh\omega}{3\cosh\omega\sinh\omega - \omega}e^{-2\omega} \\ C_n = \dfrac{2\omega(\omega\sinh\omega - \cosh\omega) + (3+2\omega)(2\sinh\omega + \omega\cosh\omega)}{3\cosh\omega\sinh\omega + \omega}e^{-2\omega} \\ D_n = -\dfrac{2\omega\cosh\omega + (3+2\omega)\sinh\omega}{3\cosh\omega\sinh\omega + \omega}e^{-2\omega} \end{cases}, \qquad (3.12)$$

with $\omega = \frac{n\pi}{2a}$ and where $n = 1, 2, 3$ ....

For the case of one simple line support and one clamped line support along the transverse edges or two clamped line support along the transverse edges, additional surfaces are added, see equations (3.13) (Molkenthin, 1971). The first additional surface is for a simple-clamped plate and the second for a clamped-clamped plate.

$$\begin{cases} m_{add1} = \dfrac{8\pi}{2a}(2a-u)\left(-x + \dfrac{3}{4}\dfrac{x^2}{a} - \dfrac{x^3}{8a^2}\right) \\ m_{add2} = \dfrac{8\pi}{2a}\left[(2a-u)\left(-x + \dfrac{x^2}{a} - \dfrac{x^3}{4a^2}\right) + u\left(-\dfrac{x^2}{2a} + \dfrac{x^3}{4a^2}\right)\right] \end{cases}. \qquad (3.13)$$

If a clamped support is added, Molkenthin (1971) states certain limitations are required regarding the dimensions of the plate (see equation (3.14)).

$$\begin{cases} \dfrac{l_y}{l_x} \leq 1.0 \text{ for a moment reference along the middle of the plate} \\ \dfrac{l_y}{l_x} \leq 1.2 \text{ for a moment reference point along the edge of the plate} \end{cases} . \quad (3.14)$$

These limitations are set based on the shape of the influence surfaces for the two sided simply supported cases. In Figure 3.3 the contour lines for a centreline moment at mid-span of a quadratic plate (side ratio of 1.0) with two simply supported and two free edges is shown. Molkenthin argues that if the contour lines close to the simply supported edges are parallel with the edges, the added surface will yield a good approximation of a plate with one or two clamped supports. This is the case for the plate in Figure 3.3. For cases where the length in x-direction increases, the same requirement is met.

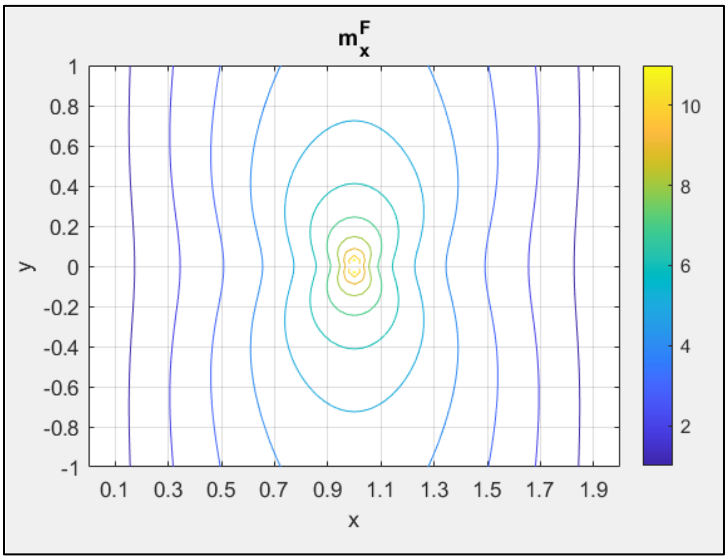


Figure 3.3: Influence surface for the centreline moment at mid-span of a quadratic plate with the edges at x = 0 and x = 2 simply supported and the other two edges free.

4. Methodology

The general methodology employed in this thesis is presented in a flowchart, see Figure 4.1. The thesis was primarily divided into three main tasks; literature research, the comparison of Brokontrollen and TungTransport, and the development of the Theoretical method and its use in the evaluation of Brokontrollen and TungTransport.

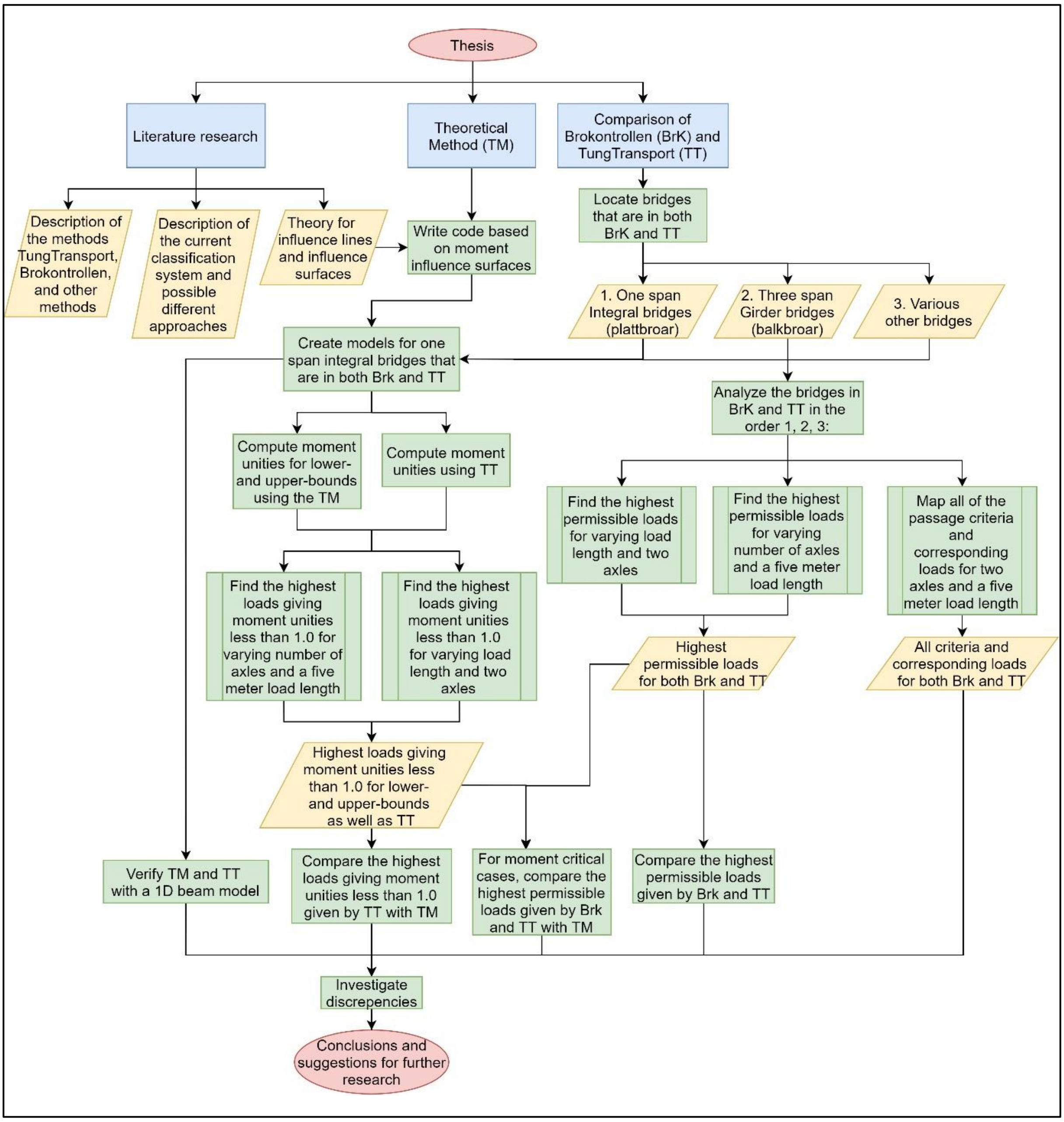


Figure 4.1: Flowchart of the general thesis methodology.

4.1. Development of the Theoretical Method

The Theoretical Method was developed to provide a reference in the evaluation of Brokontrollen and TungTransport in the form of upper- and lower-bounds. It was programmed to be capable of analysing moment critical dispensation cases for integral slab bridges ("plattbroar" in Swedish). Integral slab bridges were chosen due to it being the simplest bridge type that was available in both Brokontrollen and TungTransport. Furthermore, the Theoretical Method was limited to the evaluation of moments because no shear influence surfaces with the same conditions were found. Also, looking only at one load effect limits the complexity of analysing the results to some degree. How the Theoretical Method is used and its limitations are presented in subsection 4.2.7.2.

To create the Theoretical Method, three scripts were made; one for creating new bridges, another for calculating moment load effects of classification vehicles, and a third for analysing dispensation cases for bridges that are in the system (created and classified). For the classification and dispensation scripts, theoretical influence surfaces for moments were used. The influence surface formulas were adopted from Molkenthin (1971) for single span plates, see subsection 3.2.

The Theoretical Method was programmed in such a way that once data about the bridge and vehicle have been inputted, it computes the influence surfaces for both the center-line and free-edge moments of the slab, taking into account the dimensions and support conditions of the bridge, see section 3.2. Once the influence surfaces are computed, the program starts looping over a predefined number of moment locations (different values for u, see Figure 3.2) where moment load effects are computed. In each loop, the front axle of the vehicle takes gradual steps along the bridge (different values for ξ, see Figure 3.2). The remaining axles are placed with the predefined distance behind it. Furthermore, surface loads are placed in accordance with the guidelines provided by The Swedish Transport Administration (2018b). For each position, load effects are computed. If any axle or surface load is not on the bridge, values are not computed for this axle. Once the load effects have been computed for each vehicle position, the maximum and minimum load effects are found and assigned to the current moment location. The details regarding the exact algorithm are found in Annex D.2.

As previously mentioned, the Theoretical Method evaluates bridges in the form of upper- and lower-bounds. For the lower-bound only one lane of each bridge was modelled (see Figure 4.2). This simplification is conservative because if multiple lanes would have been used, the modelled capacity would have been higher since the classification vehicle would have been used (with a factor of 0.8) on up to four lanes. Furthermore, since it will be shown that none of the bridges contain traffic lanes directly at the edge of the bridge, only centreline moments are computed.

For the upper-bound two lanes of each bridge were modelled (see Figure 4.2). This is due to that all bridges where the Theoretical Method is used only have two lanes. Furthermore, more lanes would not be possible in most cases due to the limitations set by the additional surface for the clamped supports (see equations (3.13)). The two-lane upper-bound model is more similar to the methods Brokontrollen and TungTransport; this is due to the contribution to the modelled capacity from the classification vehicles on the second lane (with 80 % of the axle-loads, see subsection 2.1.1). The two-lane models are upper-bound models since the moments can only be computed at the centreline or free-edge of the bridge (which might not be the most critical line along the bridge). Furthermore, again only the centreline moments were computed since none of the analysed bridges have lanes directly at the edge of the bridge.

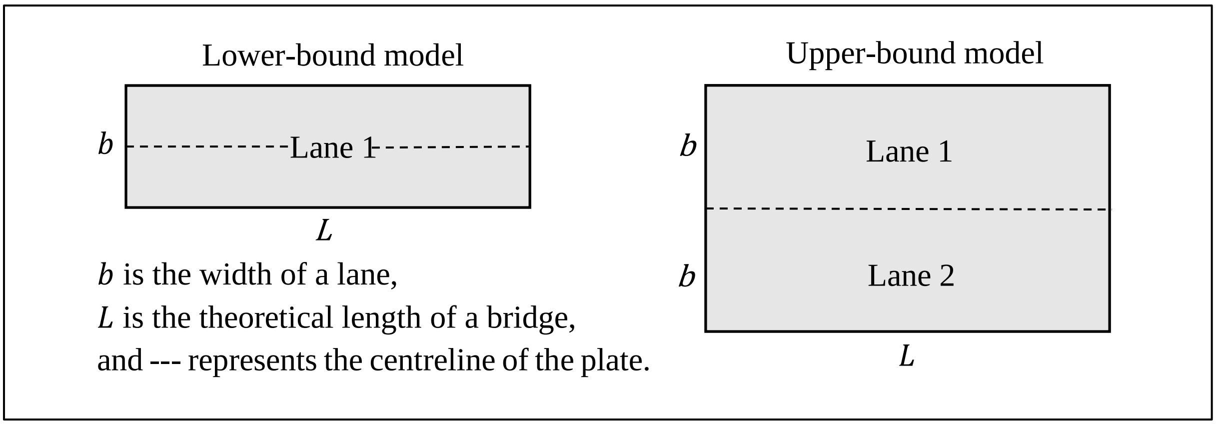


Figure 4.2: Visualization of the difference between the upper- and lower-bound models. For the lower-bound model, both the classification vehicle and permit vehicle drive on Lane 1. For the upper-bound, the classification vehicle drives on both Lane 1 and Lane 2 whereas the permit vehicle only drives on Lane 1; the classification vehicle on Lane 2 has its axle-loads scaled with a factor 0.8.

In order for the Theoretical Method to run efficiently, a few simplifications were made. First, although integration over a contact area for point loads is recommended (Molkenthin, 1971), due to computation speed limitations, the decision was made to evaluated them directly with the value of the ordinate under the point load.

Secondly, regarding the classification vehicles (see Annex B), each vehicle contains one axle distance which can be equal to or larger than a certain value. For the Theoretical Method, these axle distances will be put equal to that certain value. Since the program will only be used to analyse single span slabs, the impact of this simplification is deemed to be small to non-existent. Moreover, in cases where there is an impact, it causes a reduction of the bridge capacity. Therefore, it is a conservative simplification.

4.2. Analyses of dispensation cases

In this subsection, first, the strategy is described (subsection 4.2.1). Secondly, a set of permit vehicles (test-trucks) that were used in the analyses are defined (subsection 4.2.2). Thirdly, how dispensation cases are computed with each method respectively is described (subsection 4.2.3 – 4.2.5). Lastly, a description of how the methods were compared and further evaluated is presented (subsection 4.2.6 – 4.2.8).

4.2.1. Strategy

First, an identification of all bridges existing in both Brokontrollen and TungTransport was performed through contact with Malmö Stad. Out of the bridges a selection was made into categories based on bridge type and order of indeterminacy. The categories were based on the available bridge types in the selection. Category 1 was chosen as single span integral slab bridges; this was due to it being one of the simplest bridge types and at the same time highly available in the selection. Category 2 was chosen as three span continuous girder bridges; this type was chosen mainly due to the logical succession from Category 1. The reason for three spans was due to availability. Category 3 was chosen as various other bridges, which includes tensioned and higher indeterminate structures, often in combination.

Secondly, the main comparison of the methods was performed by analysing each Category separately, starting with Category 1. For Category 1, the Theoretical Method was used to create upper- and lower-bounds to define a region where the results of the methods should reasonably land within. More details about this is shown in subsection 4.2.5.

Thirdly, a further evaluation is performed of bridges in Category 1, 2, and 3 in order to find the variables that have a significant impact on the results. It is important to identify such variables in case of inconsistencies in the results because these variables might be chosen differently depending on the method. More details about this step are shown in subsection 4.2.7 and 4.2.8.

4.2.2. Test-trucks used in the analyses

For the comparison of the methods (see subsection 4.2.6), a few test-trucks were defined that represent possible permit vehicles. These test-trucks have an axle-load (F) and a total truckload (P). As a starting point, a test-truck with two axles and a load length of five meters was chosen, see Figure 4.3. Furthermore, an axle width of two meters and a total width of three meters were assigned. The axle width and total width are the same as those of the classification vehicles in TungTransport (and the classification vehicles used in the Theoretical Model). Based on adjustments to this test-truck, other test-trucks were defined and divided into two groups. The first group contained test-trucks with a varying number of axles. In this group, test-trucks with 2, 3, 4, or 5 axles were distributed evenly over the load length of five meters. A second group contained test-trucks with varying load length. In this group, test-trucks have two axles spaced 5, 4, 3, or 2 meters. All test-trucks kept a velocity of 10 km/h in order to remove the impact of the dynamic factor in Brokontrollen (it is set to zero if it acts in accordance with The Swedish Road Administration’s (2018b) regulations).

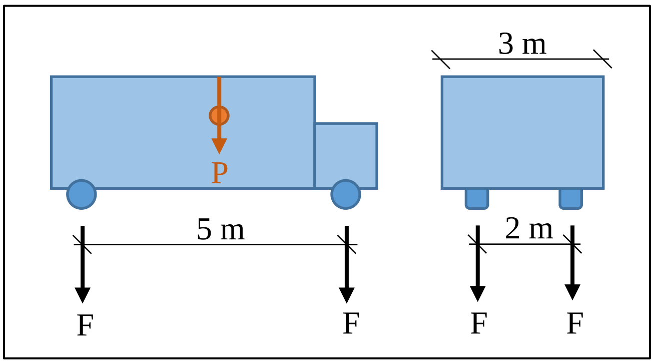


Figure 4.3: Test-truck with varying total weight, 5 meter distance between axles, 2 meter between wheels and 3 meters total width. F is the axle load and P is the total load of the test-truck

4.2.3. Computing dispensation cases with Brokontrollen

The computation of dispensation cases with Brokontrollen was very straightforward. First, the test-trucks were defined and saved into Brokontrollen; for this, editing in the source code was needed to input decimal numbers due to limitations set on the input dialogues. Secondly, axle loads (F) were assumed; A/B-values were used as a first indicator for this. Thirdly, the bridge was selected and the computation was executed; as previously mentioned, the tasks performed during the computation are unknown. The computation yielded output in the form of if the passage was allowed or not and if yes, with what limitations (see Annex C.1 for an example). Based on the output, the process was iterated until the Highest permissible load (P) for a desired passage criterion was found (for example, the highest load (P) that is allowed to pass a certain bridge if it drives in the middle of the bridge and there is no other traffic).

4.2.4. Computing dispensation cases with TungTransport

The computation of dispensation cases with TungTransport was performed directly on the computer running the software instead of going through the online portal. First, the "correct model" was identified, see the paragraphs below. Secondly, a text-file for the input was created where the model and the relevant test-truck was described including a first estimate of the axle loads (F); for this, the highest loads found with Brokontrollen were used as an indicator. Thirdly, the text-file was placed into a working folder where the TungTransport script found the file and initiated the computation. For the computation, the inputted permit vehicle/test-truck was analysed in Brigade and the results were extracted to excel. Fourthly, the excel-file containing all results (raw and post-processed) was extracted and saved. This excel-file compared the maximum load effects from the classification vehicles (the modelled capacity) to the load effects of the permit vehicle/test-truck. Lastly, based on the output, the process was iterated until the highest permissible load (P) for a desired passage criterion (in this case already determined by the model, see the paragraph below) was found.

As hinted above, multiple models exist for some bridges in TungTransport, a model for normal passage and a model for mid-bridge passage without other traffic on the bridge. As explained in subsection 2.1.4.1, in order to run a dispensation case in TungTransport, input is required regarding where on the bridge the passage will occur; this is in order for the program to use the "correct model". The difference between the models lies in the number and placement of the traffic- and result-lines (see subsection 2.1.4), where the mid-bridge model places the lines only near the middle of the bridge.

On top of using the current models in TungTransport, new models were also made in order to identify the impact of certain variables or to verify TungTransport against a 2D beam model. The specifics of these models are mentioned in the relevant subsections 4.2.7.1 and 4.2.7.2. In general, in order to perform the above-mentioned computation steps for new models, a few things needed to be done. First, a new folder was created in the TungTransport directory for bridges. Secondly, all relevant files were inserted such as the Brigade bridge model and a result excel-file. Lastly, the bridge model was analysed with respect to the load effects of the classification vehicles and the results are saved in a text-file.

4.2.5. Computing dispensation cases with the Theoretical Method

The computation of dispensation cases with the Theoretical Method was programmed to be straightforward. Similar to the creation of a new model in TungTransport, the load effects due to classification vehicles were calculated once and saved. Thereafter, the computation of the bridge for different test-trucks was performed in the following steps. First, the program was initiated and the relevant bridge model was inputted. Secondly, the test-truck was inputted. Lastly, based on the output, the process was iterated until the highest permissible load (P) for a desired passage criterion (in this case only determined by the change in A/B-values) was found.

4.2.6. Main comparison of methods

To start out, information about the bridges were found through the Swedish Transport Administration’s BMS, BaTMan, and the directories in TungTransport. This information included: bridge types, dimensions, A/B-values, etc.. Thereafter, a starting point was defined using the previously defined test-truck shown in Figure 4.3. For this test-truck a mapping was performed, showing the total truckload (P) for different levels of permission. Due to the computation speed of Brokontrollen being much faster than that of TungTransport, bridges were first mapped using Brokontrollen and then TungTransport in order to narrow down the number of computations using TungTransport.

Once the complete mapping of the starting point test-truck was completed, the number of axles was varied. For these test-trucks only the highest permissible load for a certain criterion was found and documented. The criterion was either that the test-truck passes the bridge in the normal lane with other traffic or in the middle of the bridge with no other traffic; which criterion depends on the availability of a mid-bridge model in TungTransport. The same procedure was performed for test-trucks with two axles and a varying axle distance. For Category 3, the variation of the number of axles and the axle distance was limited to two or five axles and five or two meters, respectively. This is due to the long computation time need for bridges in this Category computed in TungTransport.

4.2.7. Further evaluation of Category 1

4.2.7.1. Verification of TungTransport and the Theoretical Method with a 2D beam model

An evaluation of TungTransport and the Theoretical Method was performed through a comparison with a simplified 2D beam model. In order to do this, strip models were created for the bridges in Category 1 for both TungTransport and the Theoretical Method. The strip models are slender plate strips with a width of 0.1 meters (see Figure 4.4 for a strip model in TungTransport). Furthermore, the model was analysed for one traffic-line in the middle of the strip (meaning a one-lane model) and the transverse dimensions of the test-trucks and classification vehicles were set to zero. With these characteristics the strip models should yield results in line with the 2D beam model. The 2D beam model was based on moment influence lines for one span (see subsection 3.1 about influence lines) where the load effects were computed at a clamped support and mid-span (longitudinal mid). Therefore, in this verification TungTransport and the Theoretical Method were also only checked for moments at a clamped support and mid-span (longitudinal mid).

For the 2D beam model, the previously mentioned classification vehicles were used, however with some modifications. The heaviest part of the vehicle was identified and the remainder, which falls outside the bridge or is deemed to not contribute significantly, was cut off. The most adverse placement of each vehicle (modified classification vehicle or permit vehicle) was assumed to be the following; for load effects at a clamped support the middle of the vehicle was placed at 0.40 times the total length of the bridge, for mid-span load effects, 0.50 times the total length. These placements were based on the influence lines for the moment locations (see Figure 4.5), where for the clamped support the asymmetry around the extreme value of the influence line was considered. Note, these placements might not always be the most adverse but were deemed a good enough approximation. If the results showed significant difference in capacity from TungTransport and the Theoretical Method to the 2D beam model, the placement of the permit vehicle will be adjusted to the real most adverse location for that case. No adjustment is made to the placement of the classification vehicles. Instead, this is taken into consideration when evaluating the results.

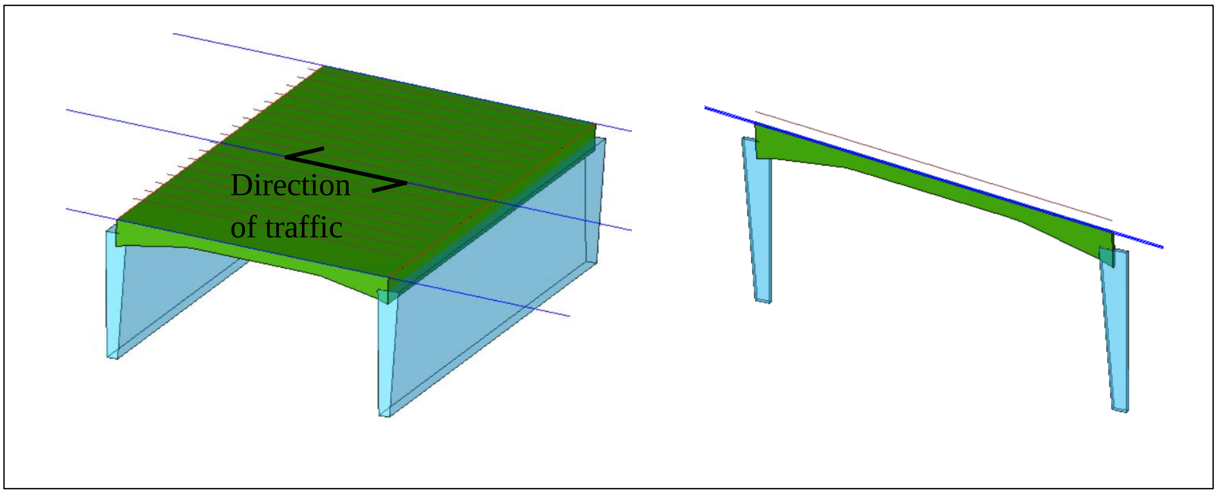


Figure 4.4: A normal model in TungTransport (left) and a 0.1 meter wide strip model created in Brigade for use in TungTransport (right). Note, the red lines are traffic-lines.

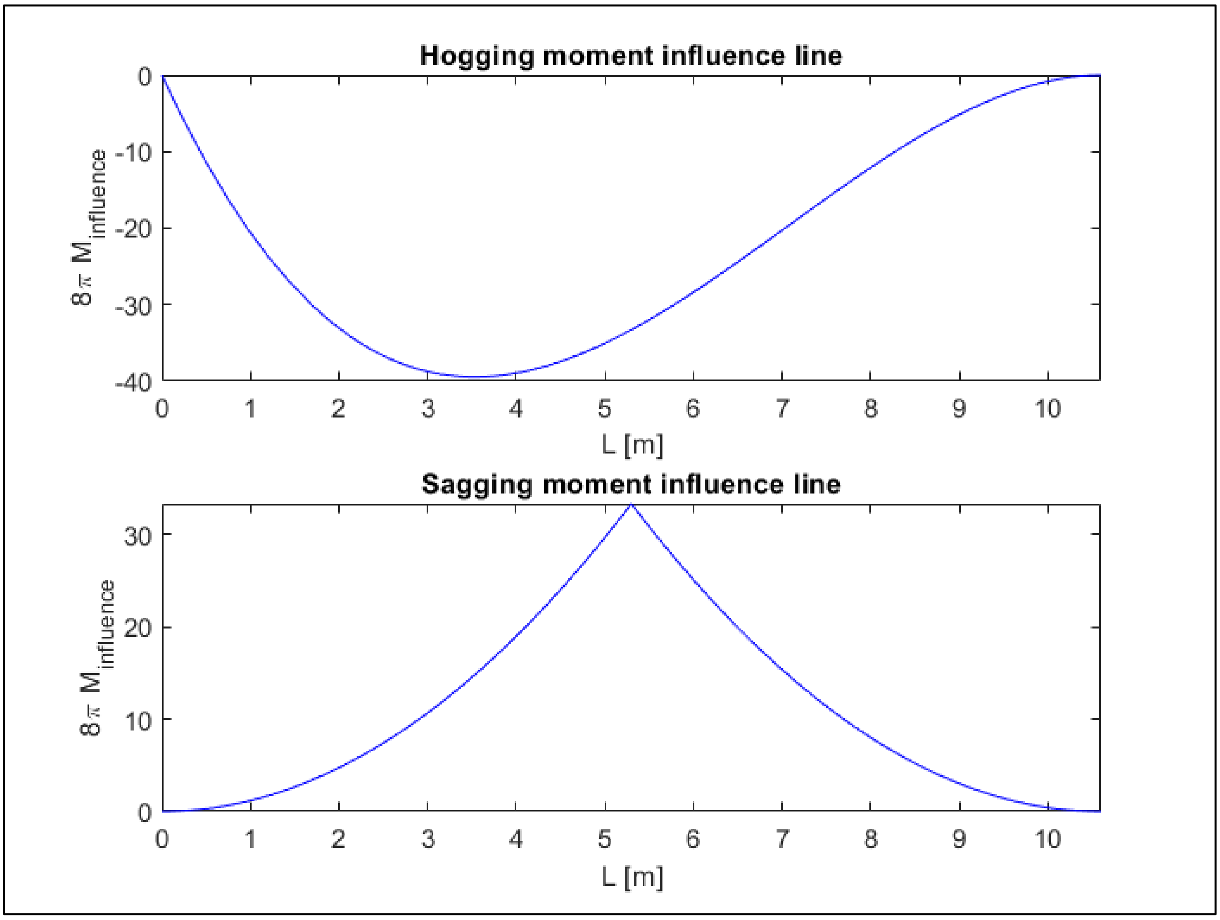


Figure 4.5: Influence lines for a 2D beam model (of Bridge 1) at the clamped support (hogging moment) and mid-span (sagging moment).

4.2.7.2. Lower- and upper-bound analysis

Part of the methodology unique to Category 1 was the use of the upper- and lower-bounds created from the Theoretical Method. The assessment was not based on the highest permissible load but on the highest load that gives a moment utilization less than 1.0; this is due to that the Theoretical Method only computes moments (see subsection 4.1). Due to the limitations of the output provided by Brokontrollen, the assessment of Brokontrollen with the Theoretical Method was limited to moment critical cases, i.e. when the moment utilization is governing. Since Brokontrollen does not include degrees of utilization in their output, the assumption was made that when TungTransport shows that the moment degree of utilization is governing (i.e. moment critical) for a certain case, that Brokontrollen also is moment critical. Note, this might not always be the case.

4.2.7.3. Impact of using mid-bridge models

In order to compute if a permit vehicle passes the criteria for driving over a bridge in the middle of the bridge with no other traffic, TungTransport uses a different model than if it calculates normal passage with other traffic (see Figure 4.4). The difference lies in the number of traffic-lines (E.g. 15 → 3) and result-lines (E.g. 10 → 5), as well as their location. The result-lines are not shown in Figure 4.4, however, they are placed only around the middle of the bridge. The impact of the differences in these models was analysed in order to better understand the impact of them in TungTransport's but also Brokontrollen's results. In order to analyse this, the highest permissible load was found for each model (for different dispensation cases). Furthermore, the highest permissible load was found for the normal model but when only looking at the result-lines in the middle of the bridge. In other words, three alternatives are considered:

- Alternative 1: The mid-bridge model;
- alternative 2: The normal model, only looking at the result-lines in the middle of the bridge;
- alternative 3: The normal model.

Note, alternative 2 has no real practical relevance; however, its results should be close to that of the mid-bridge model and is therefore a good tool for evaluation purposes.

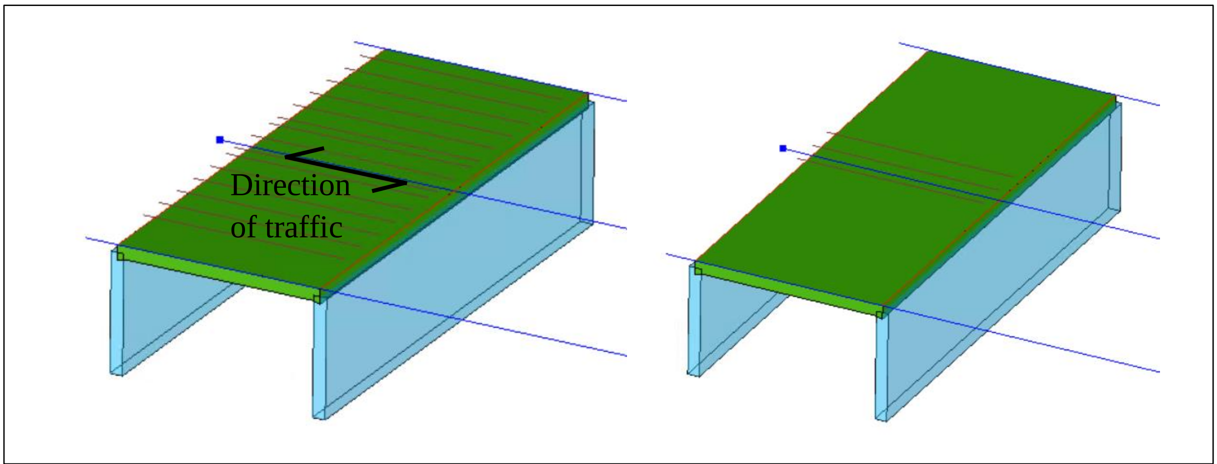


Figure 4.6: A normal model in TungTransport (left) and a mid-bridge in TungTransport (right). Note, the red lines are traffic-lines.

4.2.8. Further evaluation of Category 1, 2 and 3

4.2.8.1. Impact of varying axle width

The impact of the axle width was analysed both for TungTransport and the Theoretical Method. The reason for this was because Brokontrollen does not require axle width as input and must therefore put it to a constant. Furthermore, the classification vehicles in TungTransport have an axle width of two meters. According to the Swedish Transport Administration (2018b), the axle width of classification vehicles is assumed to vary arbitrarily between 1.7 and 2.3 meters. For these reasons, it is important to estimate the impact of these simplifications.

The variable was analysed for the five-meter two-axle test-truck and the five-axle test-truck as well as for the classification vehicles. While the axle width was varied, the total load was kept constant and equal to the highest permissible load for the specific case with the axle width of two meters. For the various axle widths, the utilization ratios were obtained and plotted for moment and shear respectively (only moment for the Theoretical Method). The axle width of the test-truck was varied from one to three meters. The axle width of the classification vehicles was varied from 1.7 to 2.3 meters.

4.2.8.2. Impact of failure modes

In order to better judge Brokontrollen, the utilization ratios of load effects computed by TungTransport for all cases were noted and plotted. This allowed for a visualization of when cases are shear or moment (or stress) critical.

5. Analysis and results

The results are divided into three subsections. First, the main comparison between Brokontrollen and TungTransport is presented. This subsection contains the complete mapping of bridges (subsections 5.1.1.1, 5.1.2.1, and 5.1.3.1) as well as the highest permissible loads for varying numbers of axles and axle distances (subsections 5.1.1.2, 5.1.2.2, and 5.1.3.2) for Category 1, 2, and 3. Secondly, a further evaluation of Category 1 is presented, see subsection 5.2. This subsection contains the verification of TungTransport and the Theoretical Model and analyses of key variables. Lastly, a further evaluation of Category 1, 2, and 3 is presented, see subsection 5.3. This subsection contains analyses of key variables. Before these results are shown, a list of relevant bridges identified in both Brokontrollen and TungTransport is presented in Table 5.1. The bridge numbers are based on the numbers the bridges have in both Brokontrollen and TungTransport (see Annex A for a full list of all bridges available in both Brokontrollen and TungTransport, provided by Malmö Stad).

Table 5.1: Selection of bridges used in the analyses of this thesis. Note, TungTransport only contains mid-bridge (mid-road) models for bridges 79 and 128. For the full list of bridges that are available in both Brokontrollen and TungTransport, see Annex A (provided by Malmö Stad). The Bridge numbers are based on the numbers that the bridges have in both Brokontrollen and TungTransport. Brk stands for Brokontrollen and TT stands for TungTransport

Bridge	Category	Nr. of spans	Type	A/B-Values	
				Normal passage	Mid-road passage
1	1	1	Integral slab bridge	290/220	290/220
2	1	1	Integral slab bridge	300/220	300/220
79	1	1	Integral slab bridge	160/180	195/235
128	1	1	Integral slab bridge	165/190	205/245
12	2	3	Girder bridge	180/180	500/420
404	2	3	Girder bridge	258/301	342/378
273	3	6	Integral slab bridge	Brk: 210/180	210/180
				TT: 235/185	-
361	3	4	Tensioned girder bridge	310/310	310/310
347	3	2	Tensioned girder bridge	210/280	280/470
270	3	1	Tensioned girder bridge	255/215	300/230
28	3	5	Tensioned simple slab bridge	495/300	891/540
324	3	1	Tensioned integral slab bridge	264/290	352/387

5.1. Main comparison between Brokontrollen and TungTransport

5.1.1. Category 1 – One span integral slab bridges (plattrambroar)

As previously mentioned, Category 1 represents one span integral bridges. The results in subsection 5.1.1.1 and 5.1.1.2 show that in general for Category 1, Brokontrollen permits equal or higher loads for the same bridges in comparison to TungTransport. In other words, TungTransport is in general more conservative for these bridges.

5.1.1.1. Mapping of passage criteria

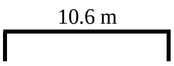
Table 5.2 – Table 5.5 show the mapping of passage criteria for bridges 1, 2, 79, and 128. Furthermore, the tables include a rough side- and top-view sketch of the bridge in question. The results for Bridge 2 in Table 5.3 show that the permission statements overlap exactly. Table 5.2, Table 5.4 and Table 5.5, on the other-hand, show a shift in the permission statements between Brokontrollen and TungTransport, where Brokontrollen gives permission for higher total loads.

When using Brokontrollen, the mappings for Bridge 1 and 2 as well as 79 and 128 are almost the same. However, when using TungTransport the mappings are not as similar anymore. It seems logical that the mapping of Bridge 1 and 2 is similar when looking at the similar A/B-values. On the other hand, when looking at the difference in length and/or width between Bridge 1 and 2 as well as 79 and 128, it might seem less logical. This is further discussed in subsection 6.2.

Table 5.2: Bridge 1 – one span integral slab bridge (plattrambro). Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale!

<table>
<tr><th colspan="2">Load [kN]</th><th rowspan="2">Brokontrollen</th><th rowspan="2">TungTransport</th></tr>
<tr><th>Total (P)</th><th>Per axle (F)</th></tr>
<tr><td>500</td><td>250</td><td rowspan="3">Permitted, normal passage</td><td>Permitted, normal passage</td></tr>
<tr><td>510</td><td>255</td><td rowspan="3">Not permitted</td></tr>
<tr><td>560</td><td>280</td></tr>
<tr><td>570</td><td>285</td><td>Not permitted</td></tr>
</table>

Side view



Top view

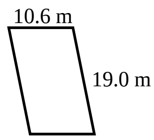
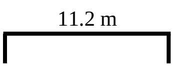


Table 5.3: Bridge 2 – one span integral slab bridge (plattrambro). Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale!

<table>
<tr><th colspan="2">Load [kN]</th><th rowspan="2">Brokontrollen</th><th rowspan="2">TungTransport</th></tr>
<tr><th>Total (P)</th><th>Per axle (F)</th></tr>
<tr><td>560</td><td>280</td><td>Permitted, normal passage</td><td>Permitted, normal passage</td></tr>
<tr><td>570</td><td>285</td><td>Not permitted</td><td>Not permitted</td></tr>
</table>

Side view



Top view

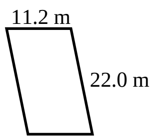
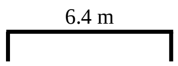


Table 5.4 Bridge 79 – one span integral slab bridge (plattrambro). Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale!

<table>
<tr><th colspan="2">Load [kN]</th><th rowspan="2">Brokontrollen</th><th rowspan="2">TungTransport</th></tr>
<tr><th>Total (P)</th><th>Per axle (F)</th></tr>
<tr><td>310</td><td>155</td><td rowspan="4">Permitted, normal passage</td><td>Permitted, normal passage</td></tr>
<tr><td>320 – 440</td><td>160 – 220</td><td>Permitted, mid-bridge, alone on bridge</td></tr>
<tr><td>450</td><td>225</td><td rowspan="4">Not permitted</td></tr>
<tr><td>470</td><td>235</td></tr>
<tr><td>480 – 510</td><td>240 – 255</td><td>Permitted, mid-road, alone on road, opposing traffic allowed</td></tr>
<tr><td>520</td><td>260</td><td>Not permitted</td></tr>
</table>

Side view



Top view

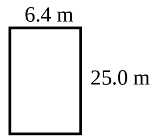
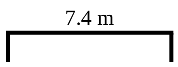


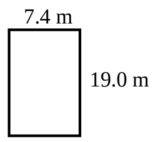
Table 5.5: Bridge 128 – one span integral slab bridge (plattrambro). Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale!

<table>
<tr><th colspan="2">Load [kN]</th><th rowspan="2">Brokontrollen</th><th rowspan="2">TungTransport</th></tr>
<tr><th>Total (P)</th><th>Per axle (F)</th></tr>
<tr><td>350</td><td>175</td><td rowspan="4">Permitted, normal passage</td><td>Permitted, normal passage</td></tr>
<tr><td>360 – 370</td><td>180 – 185</td><td>Permitted, mid-bridge, alone on bridge</td></tr>
<tr><td>380</td><td>190</td><td rowspan="4">Not permitted</td></tr>
<tr><td>500</td><td>250</td></tr>
<tr><td>510 – 520</td><td>255 – 260</td><td>Permitted, mid-road, alone on bridge</td></tr>
<tr><td>530</td><td>265</td><td>Not permitted</td></tr>
</table>

Side view



Top view



5.1.1.2. Varying numbers of axles and axle distances

Similar to the previous subsection, bridges were evaluated for a higher number of axles and different axle distances. However, up to this point, the data presented is identical to what a general user of either software would find. For analysis purposes a small adjustment is made to the data from TungTransport; the values from TungTransport have been scaled by a dynamic factor of 1.082 (see Annex C.2) to take into account the velocity of the vehicle. However, at the velocity of 10 km/h, the dynamic factor should be set to zero according to the Swedish

Transport Administration (2018b). Therefore, the data from TungTransport for this is divided by the dynamics factor to remove its influence. The original data is found in Annex E.1.

The highest permissible load (P) for bridges 1, 2, 79, and 128 are given for 2, 3, 4, and 5 axles with five-meter load length in Table 5.6 and for two-axles with axle distances of 5, 4, 3, and 2 meters in Table 5.7. Furthermore, each table shows the difference between Brokontrollen and TungTransport. The remaining dimensions of the test-truck are the same as in Figure 4.3. The data presented in Table 5.6 and Table 5.7 are presented graphically in Figure 5.1 and Figure 5.2, respectively.

For varying numbers of axles, the results show good agreement between Brokontrollen and TungTransport for Bridge 1 and 2; discrepancies are however found for Bridge 79 and 128. Especially for Bridge 128, Brokontrollen permits between 30 to 40 % higher total loads for varying axles in comparison to TungTransport. Note that for Bridge 79 and 128, the highest permissible loads are regarding the mid-bridge model.

For varying axle distances, the results show good agreement between Brokontrollen and TungTransport for Bridge 1 and decent agreement for Bridge 79. Less good agreement is found for Bridge 2 and strong discrepancies are found for Bridge 128 where Brokontrollen permits between 30 to 35 % higher total loads for varying axles in comparison to TungTransport. Note once again that for Bridge 79 and 128, the highest permissible loads are regarding the mid-bridge model (vehicles pass in the middle of the bridge without other traffic on the bridge).

Table 5.6: Highest permissible load (P) for different one-span integral slab bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data is without the influence of the dynamic factor. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]								(Brk – TT) / TT [%]			
	Brokontrollen				TungTransport							
Nr. of axles	2	3	4	5	2	3	4	5	2	3	4	5
Bridge 1	560	580	570	550	540	550	540	530	4	5	6	4
Bridge 2	560	570	560	550	600	590	560	540	-7	-3	0	2
Bridge 79	510	630	660	620	470	570	570	570	9	11	16	9
Bridge 128	520	650	660	630	400	470	470	460	30	38	40	37

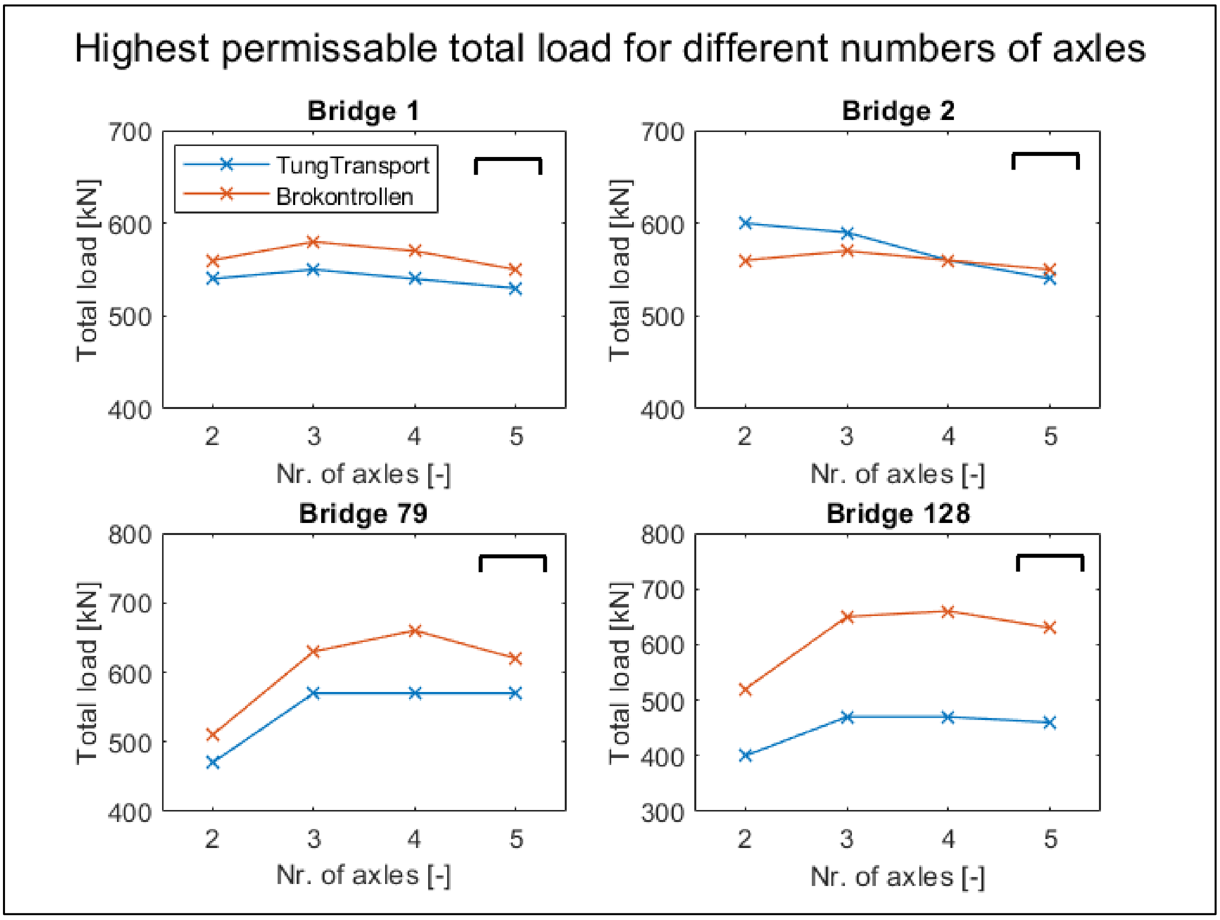


Figure 5.1: Highest permissible load (P) for different integral slab bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data is without the influence of the dynamic factor. Furthermore, a small side-view sketch of each bridge is provided (top right, not to scale).

Table 5.7 Highest permissible load (P) for different integral slab bridges and test-trucks a total load length of 5, 4, 3, or 2 meters; each test-truck has two axles. TungTransport data is without the influence of the dynamic factor. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]								(Brk – TT) / TT [%]			
	Brokontrollen				TungTransport							
Axle dist. [m]	5	4	3	2	5	4	3	2	5	4	3	2
Bridge 1	560	460	460	410	540	490	450	410	4	-6	2	0
Bridge 2	560	470	470	400	600	560	500	450	-7	-16	-6	-11
Bridge 79	510	470	470	410	470	470	430	370	9	0	-9	11
Bridge 128	520	480	480	430	400	370	350	320	30	30	35	34

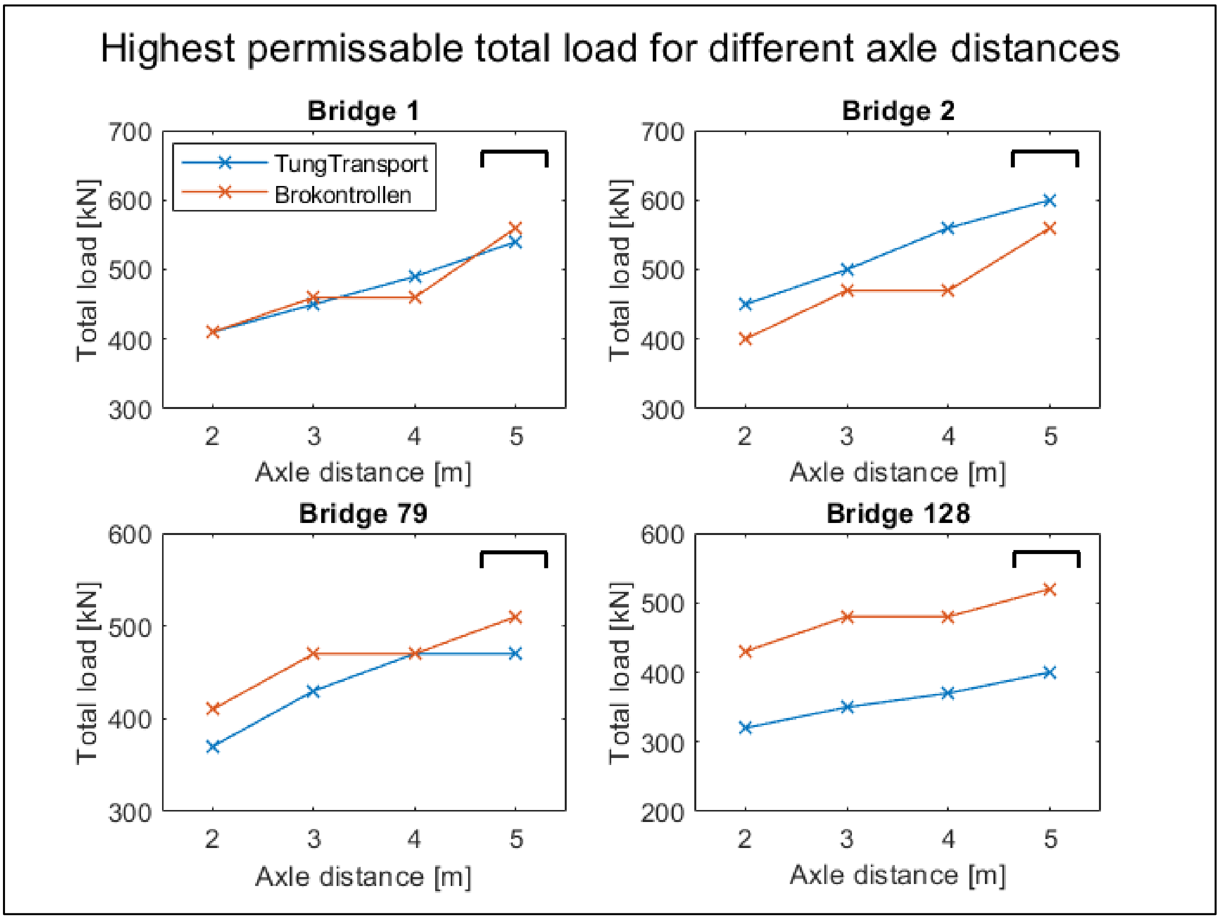


Figure 5.2: Highest permissible load (P) for different integral slab bridges and test-trucks a total load length of 5, 4, 3, or 2 meters; each test-truck has two axles. TungTransport data is without the influence of the dynamic factor. Furthermore, a small side-view sketch of each bridge is provided (top right, not to scale).

5.1.2. Category 2 – Three span girder bridges (balkbroar)

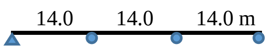
5.1.2.1. Mapping of passage criteria

Analogous with subsection 5.1.1.1, Table 5.8 and Table 5.9 show a complete mapping for Bridge 12 and 404 for the two axle test-truck shown in Figure 4.3. Both tables show that Brokontrollen gives permission for higher total loads (when the dynamic factor influence has not been removed). Furthermore, for Bridge 12, Brokontrollen controls the passage criteria “mid-road, alone on bridge”. In TungTransport, no mid-bridge model is available for Bridge 12. It is highly likely that Bridge 404 also has a “mid-road, alone on bridge” passage criteria in Brokontrollen but that it is not visible in this mapping due to that the highest axial load was reached (no permission for higher loads was given due to local rather than global effects).

Table 5.8: Bridge 12 – three span girder bridge. Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale! The grey lines represent the girders.

Load [kN]		Brokontrollen	TungTransport
Total (P)	Per axle (F)		
320	160	Permitted, normal passage	Permitted, normal passage
330 – 470	165 – 235		Not permitted
480 – 570	240 – 285	Permitted, mid-road, alone on bridge	
580	290	Not permitted	

Side view



Top view

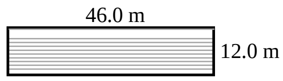
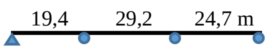


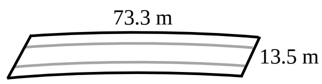
Table 5.9: Bridge 404 – three span girder bridge. Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale! The grey lines represent the girders.

Load [kN]		Brokontrollen	TungTransport
Total (P)	Per axle (F)		
800	400	Permitted, normal passage	Permitted, normal passage
810	405		Not permitted
820	410		
830	415	Not permitted[1]	

Side view



Top view



[1]Not permitted due to too high axial loads.

5.1.2.2. Varying numbers of axles and axle distances

The highest permissible load (P) for Bridge 12 and 404 are given for 2, 3, 4, and 5 axles with five-meter load length in Table 5.10 and for two-axles with axle distances of 5, 4, 3, and 2 meters in Table 5.11. Furthermore, each table shows the difference between Brokontrollen and TungTransport. The remaining dimension of the test-truck are the same as in Figure 4.3. The data presented in Table 5.10 and Table 5.11 are presented graphically in Figure 5.3 and Figure 5.4, respectively. Note, once again the data from TungTransport has been adjusted for the dynamic factor (the data is multiplied 1.082), and therefore differs slightly from the previous subsection. Furthermore, the loads are with regards to the passage criteria "normal passage" because TungTransport does not have any mid-bridge models for Bridge 12 and 404.

Regarding varying numbers of axles, for Bridge 12, Brokontrollen permitted loads between 22 – 38 % higher than TungTransport. However, for Bridge 404, Brokontrollen permitted maximally 5 – 19 % lower loads. Regarding varying axles distances, for Bridge 12, Brokontrollen permitted total loads between 35 – 50 % higher than TungTransport. For Bridge 404, Brokontrollen permitted maximally 2 – 5 % lower total loads.

As previously mentioned, for the case of Bridge 404 being passed by a test-truck with two axles, the highest permissible load is based on local effects rather than global (in Brokontrollen) and shows good agreement; this is consistent for all axle distances. By looking at Bridge 404 in Table 5.10 and Figure 5.3 it is shown that the difference between Brokontrollen and TungTransport is a lot larger when the Brokontrollen limit is based on global effects than local effects. The reason for this is unclear.

Table 5.10: Highest permissible load (P) for different three span girder bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data is without the influence of the dynamic factor. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]								(X – TT) / TT [%]			
	Brokontrollen				TungTransport				X = Brk			
Nr. of axles	2	3	4	5	2	3	4	5	2	3	4	5
Bridge 12[1]	470	460	450	460	340	360	370	350	38	28	22	31
Bridge 404[1]	820[2]	810	810	790	860	1000	990	960	-5	-19	-18	-18

[1] The highest permissible loads are regarding the "normal passage".
[2] No higher load allowed due local effects, not (or not only) global effects.

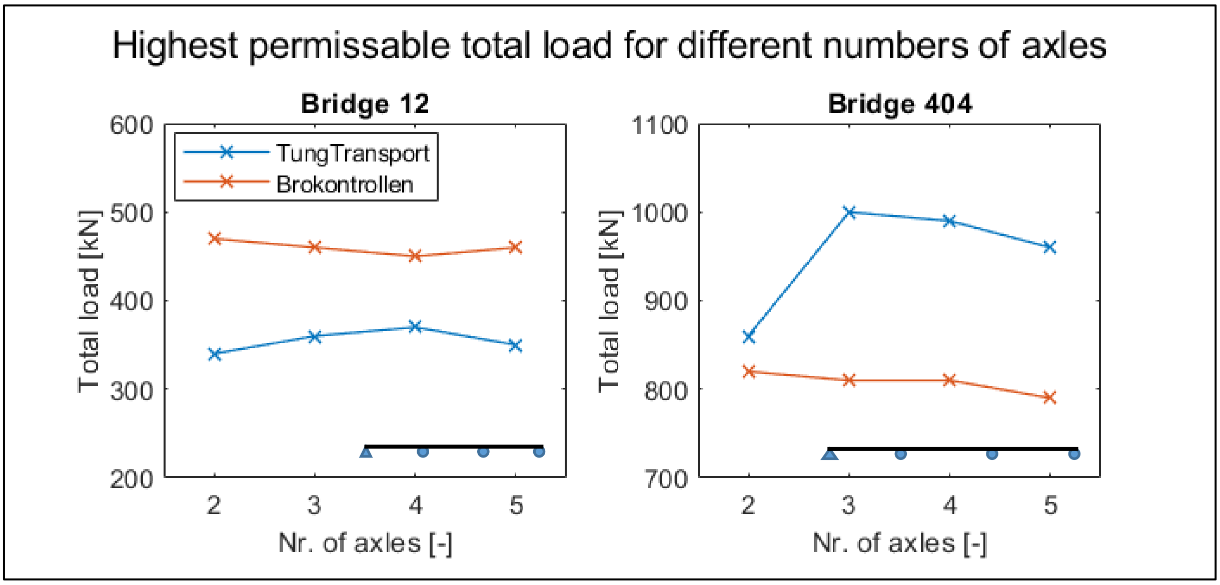


Figure 5.3: Highest permissible load (P) for different three span girder bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data is without the influence of the dynamic factor. The highest permissible loads are regarding the "normal passage". Furthermore, a small side-view sketch of each bridge is provided (bottom right, not to scale).

Table 5.11: Highest permissible load (P) for different multi-span girder bridges and test-trucks with 5, 4, 3, or 2 meters between two axles of the truck; each test-truck has only two axles. TungTransport data is without the influence of the dynamic factor. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]								(Brk – TT) / TT [%]			
	Brokontrollen				TungTransport							
Axle dist. [m]	5	4	3	2	5	4	3	2	5	4	3	2
Bridge 12[1]	460	440	420	390	340	320	280	270	35	38	50	50
Bridge 404[1]	820[2]	820[2]	820[2]	820[2]	860	850	840	850	-5	-4	-2	-4

[1] The highest permissible loads are regarding the "normal passage".

[2] No higher load allowed due local effects, not (or not only) global effects.

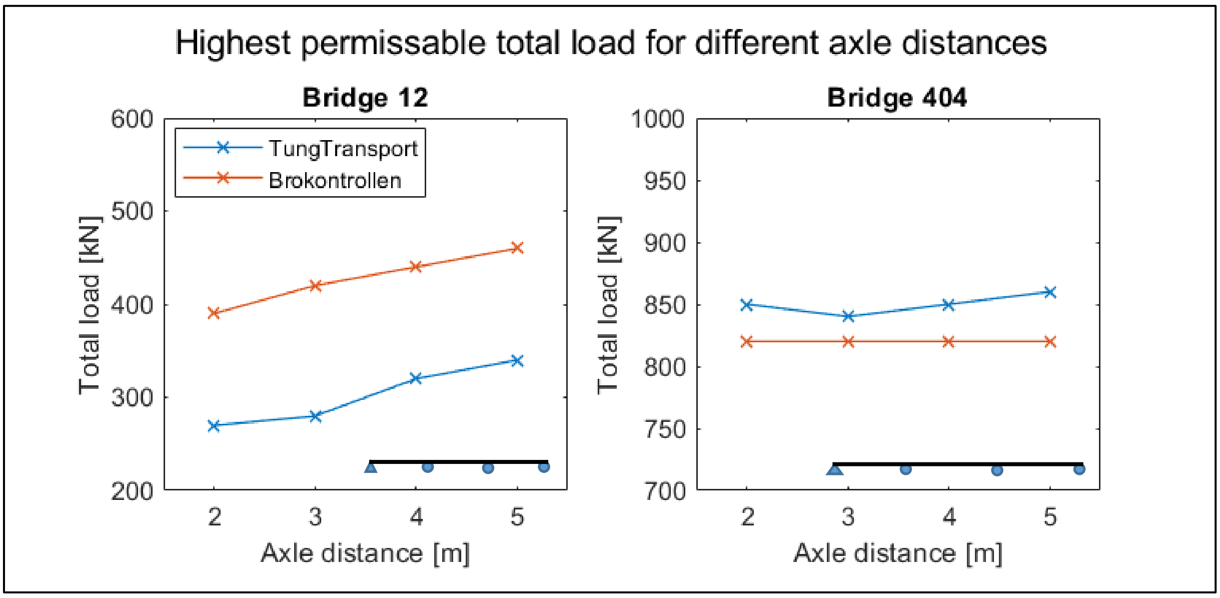


Figure 5.4: Highest permissible load (P) for different multi-span girder bridges and test-trucks with 5, 4, 3, or 2 meters between two axles of the truck; each test-truck has only two axles. TungTransport data is without the influence of the dynamic factor. The highest permissible loads are regarding the "normal passage". Furthermore, a small side-view sketch of each bridge is provided (bottom right, not to scale).

5.1.3. Category 3 – Various other bridges

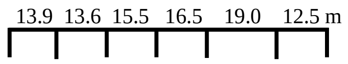
5.1.3.1. Mapping of passage criteria

Analogous with subsection 5.1.1.1 and 5.1.2.1, Table 5.12 – Table 5.17 show a complete mapping for bridges 273, 361, 347, 270, 28, and 324 for the two axle test-truck shown in Figure 4.3. Which method that permits higher total loads varies. Furthermore, for all bridges except Bridge 347, Brokontrollen checks the passage criteria "mid-road, alone on bridge". In TungTransport, no mid-bridge model is available for any of the bridges. It is highly likely that Bridge 347 also has a "mid-road, alone on bridge" passage criteria in Brokontrollen but that it is not visible in this mapping due to that the highest axial load was reached (no permission for higher loads was given due to local rather than global effects).

Table 5.12: Bridge 273 – six span integral slab bridge. Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale!

<table>
<tr><th colspan="2">Load [kN]</th><th rowspan="2">Brokontrollen</th><th rowspan="2">TungTransport</th></tr>
<tr><th>Total (P)</th><th>Per axle (F)</th></tr>
<tr><td>350</td><td>175</td><td rowspan="2">Permitted, normal passage</td><td>Permitted, normal passage</td></tr>
<tr><td>360 – 420</td><td>180 – 210</td><td rowspan="3">Not permitted</td></tr>
<tr><td>430 – 460</td><td>215 – 230</td><td>Permitted, mid-road, alone on bridge</td></tr>
<tr><td>470</td><td>235</td><td>Not permitted</td></tr>
</table>

Side view



Top view

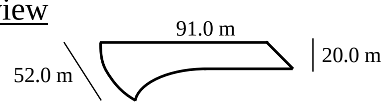
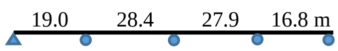


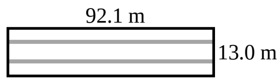
Table 5.13: Bridge 361 – four span tensioned girder bridge. Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale! The grey lines represent the girders.

<table>
<tr><th colspan="2">Load [kN]</th><th rowspan="2">Brokontrollen</th><th rowspan="2">TungTransport</th></tr>
<tr><th>Total (P)</th><th>Per axle (F)</th></tr>
<tr><td>820</td><td>410</td><td>Permitted, normal passage</td><td rowspan="3">Permitted, normal passage</td></tr>
<tr><td>830 – 980</td><td>415 – 490</td><td>Permitted, mid-road, alone on bridge</td></tr>
<tr><td>990 – 1120</td><td>495 – 560</td><td rowspan="2">Not permitted[1]</td></tr>
<tr><td>1130</td><td>565</td><td>Not permitted</td></tr>
</table>

Side view



Top view



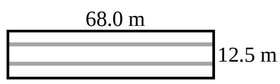
[1]Not permitted due to too high axial loads.

Table 5.14: Bridge 347 – two span tensioned girder bridge. Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale! The grey lines represent the girders.

<table>
<tr><th colspan="2">Load [kN]</th><th rowspan="2">Brokontrollen</th><th rowspan="2">TungTransport</th></tr>
<tr><th>Total (P)</th><th>Per axle (F)</th></tr>
<tr><td>660</td><td>330</td><td>Permitted, normal passage</td><td rowspan="2">Permitted, normal passage</td></tr>
<tr><td>670 – 730</td><td>335 – 365</td><td rowspan="2">Not permitted[1]</td></tr>
<tr><td>740</td><td>370</td><td>Not permitted</td></tr>
</table>

Side view

Top view

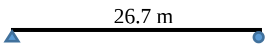


[1]Not permitted due to too high axial loads.

Table 5.15: Bridge 270 – one span tensioned girder bridge. Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale! The grey lines represent the girders.

Load [kN]		Brokontrollen	TungTransport
Total (P)	Per axle (F)		
510	255	Permitted, normal passage	Permitted, normal passage
520	260		Not permitted
560 – 650	280 – 325	Permitted, mid-road, alone on bridge	
660	330	Not permitted	

Side view



Top view

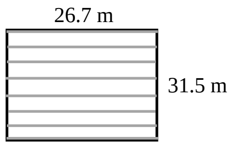
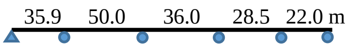


Table 5.16: Bridge 28 – five span tensioned simple slab bridge. Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale!

Load [kN]		Brokontrollen	TungTransport
Total (P)	Per axle (F)		
800	400	Permitted, normal passage	Permitted, normal passage
810 – 1010	405 – 505	Permitted, mid-road, alone on bridge	
1020	510		Not permitted
1450	725		
1460	730	Not permitted	

Side view



Top view

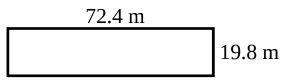
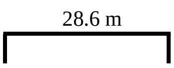


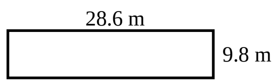
Table 5.17: Bridge 324 – one span tensioned integral slab bridge. Permission results for a two-axle truck with an axle distance of five meters driving at a velocity of 10 km/h. The figure at the bottom shows the geometry of the bridge. Note, not to scale!

Load [kN]		Brokontrollen	TungTransport
Total (P)	Per axle (F)		
650	325	Permitted, normal passage	Permitted, normal passage
660 – 740	330 – 370		Not permitted
750 – 850	375 – 425	Permitted, mid-road, alone on bridge	
860	430	Not permitted[1]	

Side view



Top view



[1]Not permitted due to too high axial loads.

5.1.3.2. Varying numbers of axles and axle distances

The highest permissible load (P) for Bridge 12 and 404 are given for 2, 3, 4, and 5 axles with five-meter load length in Table 5.18 and for two-axles with axle distances of 5, 4, 3, and 2 meters in Table 5.19. Furthermore, each table shows the difference between Brokontrollen and TungTransport. The remaining dimensions of the test-truck are the same as in Figure 4.3. The data presented in Table 5.18 and Table 5.19 are presented graphically in Figure 5.5 and Figure 5.6, respectively. Note, once again the data from TungTransport has been adjusted for the dynamic factor (the data is multiplied 1.082), and therefore differs slightly from the previous subsection. Furthermore, the loads are with regards to the passage criteria “normal passage” because TungTransport does not have any mid-bridge models for the bridges in Category 3. Moreover, only the test-trucks with two axles and five axles were computed due to the long computation time for these bridges in TungTransport.

For Bridge 273 (a multi-span integral slab bridge), Brokontrollen permitted higher loads than TungTransport; for varying numbers of axles between 14 – 18 % and for varying axle distances between (14 – 21 %). However, for the remaining bridges, Brokontrollen permitted lower loads (with some exceptions) up to 36 %; all these bridges are variations of pre- or posttensioned, single- or multi-span, integral or girder bridges.

One interesting case is a two-span tensioned girder bridge, Bridge 347, being passed by the two-axle test-truck, the highest load (P) given by Brokontrollen is based on local effects rather than global. By looking at Bridge 347 in Figure 5.5 and Figure 5.6, it is shown that Brokontrollen permitted a lower load than TungTransport when local effects were critical (in Brokontrollen) but a higher load when global effects (moment and shear) were critical. Furthermore, where the axle distances were larger (five meters), Brokontrollen permitted a significantly lower load (15 %) than TungTransport. Where the axle distance was smaller (two meters), Brokontrollen and TungTransport permitted almost the same load (1 % difference). Note that for the five-axle test-truck case, Bridge 347 is the only tensioned (girder) bridge where TungTransport is more conservative than Brokontrollen.

Another interesting case is Bridge 324 (a single-span tensioned integral slab bridge) where Brokontrollen permits slightly higher loads (6 %) for the two-axle five-meter test-truck but significantly lower loads for the test-truck with five axles (24 %) and for the test-truck with an axle distance of two meters (23 %). Note, this is not due to local effects. It is in subsection 5.3.2 (see also Annex E.5) found that this has to do with the fact that TungTransport checks for edge stresses (axial load due to tensioning) for this bridge.

Table 5.18: Highest permissible load (P) for various others bridges and test-trucks with two or five axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data is without the influence of the dynamic factor. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]				(Brk – TT) / TT [%]	
	Brokontrollen		TungTransport			
Nr. of axles	2	5	2	5	2	5
Bridge 273[1]	420	390	370	330	14	18
Bridge 361[1]	820	770	1210	1070	-32	-28
Bridge 347[1]	660[2]	820	780	740	-15	11
Bridge 270[1]	520	480	550	550	-5	-13
Bridge 28[1]	800	750	1090	1000	-33	-33
Bridge 324[1]	740	640	700	840	6	-24

[1] The highest permissible loads are regarding the "normal passage".
[2] Not permitted due to too high axial loads.

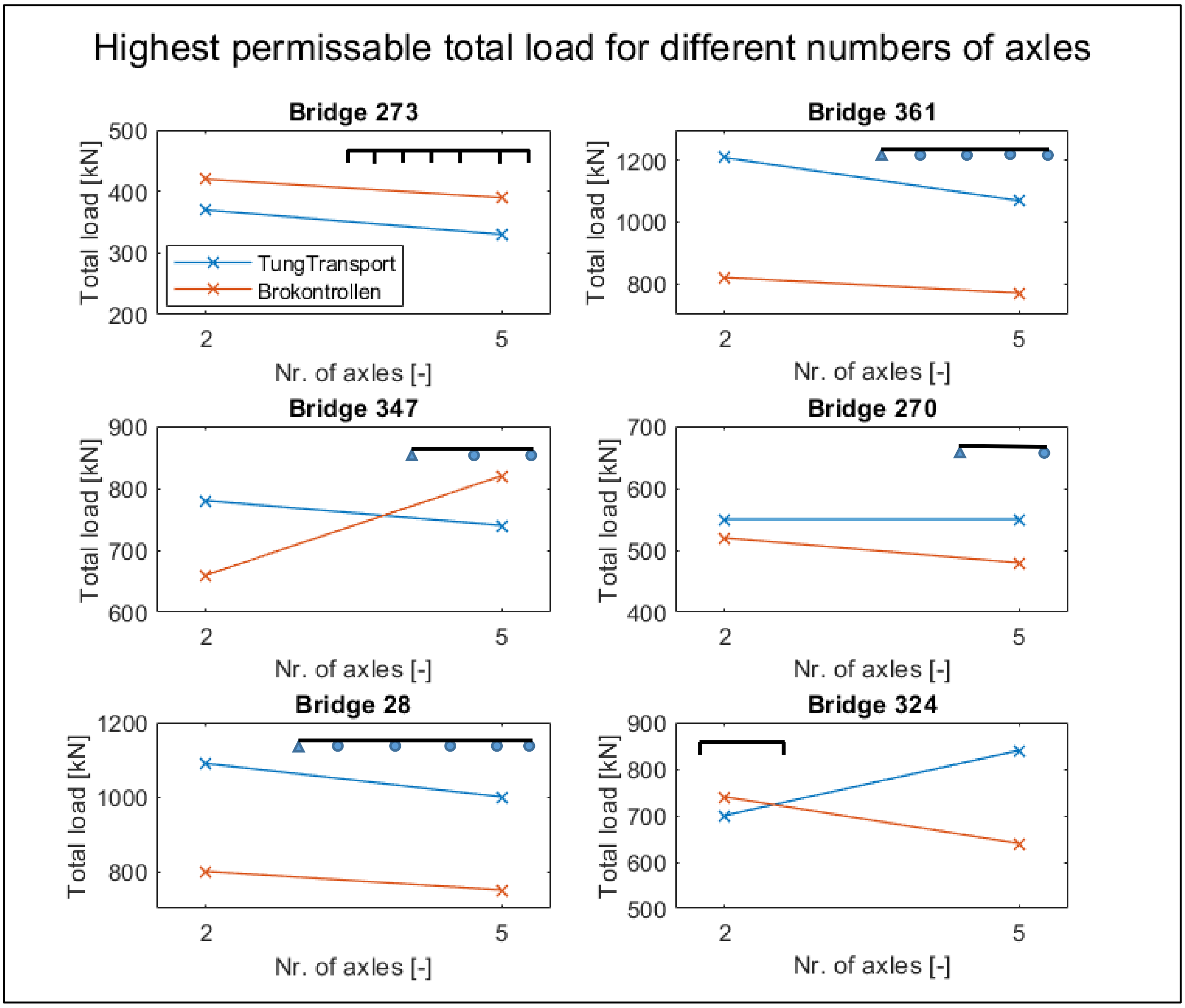


Figure 5.5: Highest permissible load (P) for various others bridges and test-trucks with 2 or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data is without the influence of the dynamic factor. The highest permissible loads are regarding the "normal passage". Furthermore, a small side-view sketch of each bridge is provided (not to scale).

Table 5.19: Highest permissible load (P) for various others bridges and test-trucks five or two meters between two axles of the truck; each test-truck has only two axles. TungTransport data is without the influence of the dynamic factor. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]				(Brk – TT) / TT [%]	
	Brokontrollen		TungTransport			
Axle dist. [m]	5	2	5	2	5	2
Bridge 273[1]	420	340	370	280	14	21
Bridge 361[1]	820	720	1210	900	-32	-20
Bridge 347[1]	660[2]	660[2]	780	680	-15	-1
Bridge 270[1]	520	400	550	460	-5	-15
Bridge 28[1]	800	660	1090	960	-33	-31
Bridge 324[1]	740	540	700	700	6	-23

[1] *The highest permissible loads are regarding the "normal passage".*

[2] *Not permitted due to too high axial loads.*

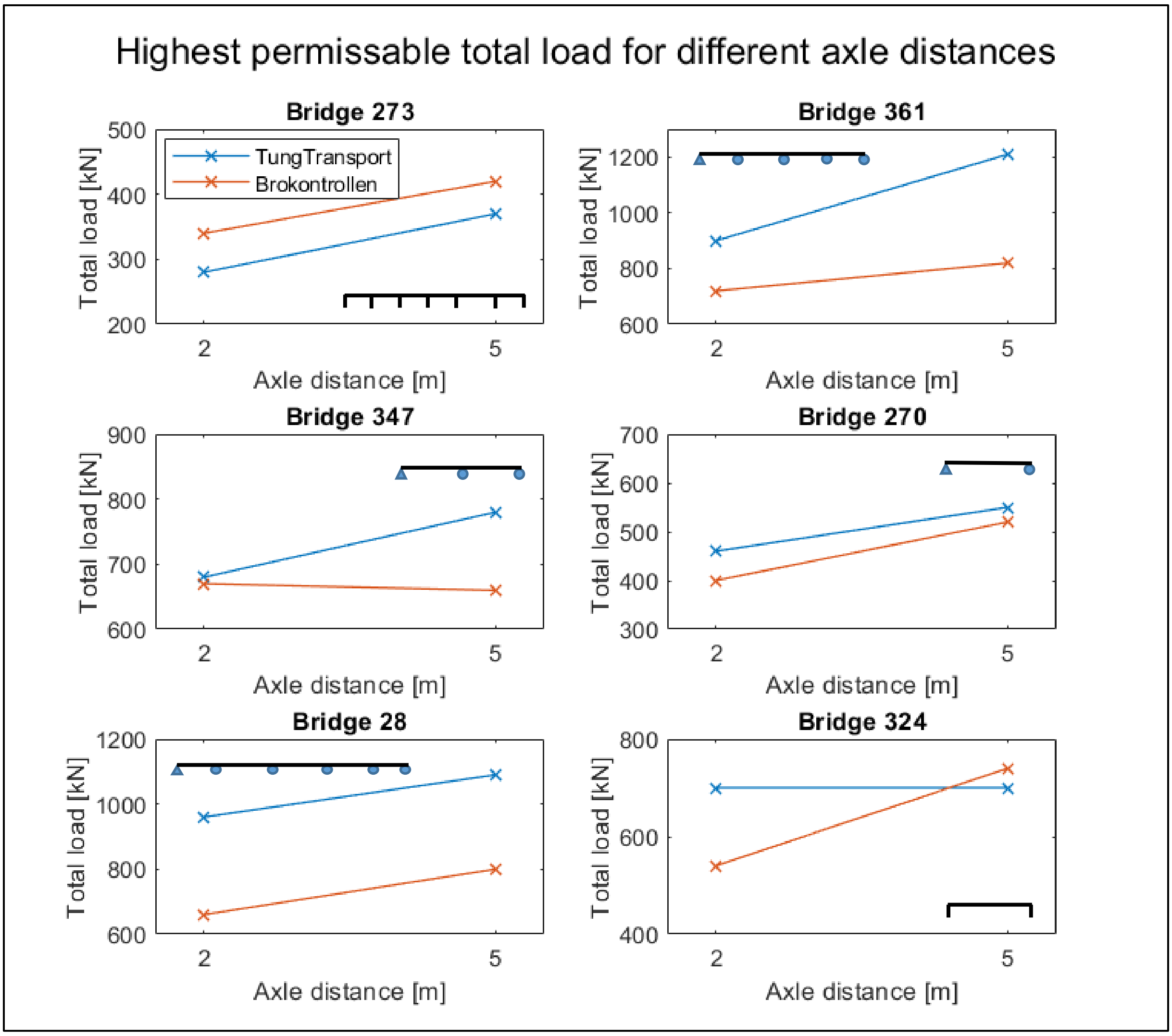


Figure 5.6: Highest permissible load (P) for various others bridges and test-trucks five or two meters between two axles of the truck; each test-truck has only two axles. TungTransport data is without the influence of the dynamic factor. The highest permissible loads are regarding the "normal passage". Furthermore, a small side-view sketch of each bridge is provided (not to scale).

5.1.4. Summary of the main comparison

In this subsection, the results for the main comparison are summarized. In Table 5.20, the Bridge is presented along with some information and the method that on average permitted the highest loads. Furthermore, the average difference between the methods is provided. Note, Table 5.20 provides an overview of general trends but for a full understanding of the differences, the reader is referred to subsections 5.1.1 - 5.1.3. The summarized results show that TungTransport permitted higher loads for tensioned structures. No other general trends were found.

Table 5.20: A summary of the results from the main comparison. Brk stands for Brokontrollen and TT for TungTransport

Bridge	Category	Nr. of spans	Type	Average results	
				Method permitting highest loads	(Brk – TT) / TT [%]
1	1	1	Integral slab bridge	Brk	2
2	1	1	Integral slab bridge	TT	-6
79	1	1	Integral slab bridge	Brk	9
128	1	1	Integral slab bridge	Brk	35
12	2	3	Girder bridge	Brk	36
404	2	3	Girder bridge	TT	-10
273	3	6	Integral slab bridge	Brk	18
361	3	4	Tensioned girder bridge	TT	-27
347	3	2	Tensioned girder bridge	TT	-2
270	3	1	Tensioned girder bridge	TT	-10
28	3	5	Tensioned simple slab bridge	TT	-28
324	3	1	Tensioned integral slab bridge	TT	-14

5.2. Further evaluation of Category 1

5.2.1. Verification of TungTransport and the Theoretical Method with a 2D beam model

The Theoretical Method is applicable on all bridges from Category 1. Therefore, in the verification of the model, 0.1-meter strips of the bridges 1, 2, 79, and 128 were used. In Table 5.21, the highest total load giving a moment utilization less than 1.0 at the clamped support are given for these four strip models. In Table 5.22, the same is given for the middle of the bridge (longitudinal). The results for Bridge 1 and 2 (single span integral bridges) show a good agreement between the two methods and the 2D beam model with an average difference of ~ -0.2 % and a maximum difference of -7 %, with the 2D beam model as reference point. However, the results for Bridge 79 and 128 (single span integral bridges) have large discrepancies.

TungTransport's results for Bridge 79 are up to 36 % higher than the 2D beam model and for Bridge 128 up to 16 % lower. These discrepancies could be indications of mistakes in the mid-bridge models.

Table 5.21: Highest total load giving a moment utilization less than 1.0 at the clamped support of different integral slab bridge strips and test-trucks with four or five axles; each test-truck has a total load length of five meters and equal distances between axles. TM stands for Theoretical Method and 2D for 2D beam model.

	Highest load (P) for moment utilization < 1.0 [kN]						(X – 2D) / 2D [%]			
	TT[1]		TM[1]		2D[1]		X = TT		X = TM	
Nr. of axles	4	5	4	5	4	5	4	5	4	5
Strip Br. 1	380	370	380	370	370	370	3	0	3	0
Strip Br. 2	370	360	380	370	370	370	0	-3	3	0
Strip Br. 79[2]	590	610	450	430	460	450	28	36	-2	-4
Strip Br. 128[2]	370	360	430	410	440	410	-16	-12	-2	0

[1]Evaluating only at clamped support and mid-span.
[2]Mid-road A/B-values are used for consistency.

Table 5.22: Highest total load giving a moment utilization less than 1.0 at the longitudinal middle of different integral slab bridge strips and test-trucks with four or five axles; each test-truck has a total load length of five meters and equal distances between axles. TM stands for Theoretical Method and 2D for 2D beam model.

	Highest load (P) for moment utilization < 1.0 [kN]						(X – 2D) / 2D [%]			
	TT[1]		TM[1]		2D[1]		X = TT		X = TM	
Nr. of axles	4	5	4	5	4	5	4	5	4	5
Strip Br. 1	390	360	410	390	410	370	-5	-3	0	5
Strip Br. 2	400	370	410	390	410	370	-2	0	0	5
Strip Br. 79[2]	570	550	490	470	460	480	16	17	-7	-2
Strip Br. 128[2]	470	450	480	470	490[3]	470	-4	-4	-2	0

[1]Evaluating only at clamped edge and mid-span.
[2]Mid-road A/B-values are used for consistency.
[3]The placement of the permit vehicle has been adjusted to the real most adverse location for this case (see section 4.2.7.1).

5.2.2. Lower- and upper-bound analysis

The data from the Brokontrollen and TungTransport is compared to the upper- and lower-bounds created with the Theoretical Method. For this comparison, only moment critical cases were evaluated. Determining whether a case is moment critical was based on the TungTransport degrees of utilization for shear and moment given in the output of these computations.

The highest permissible loads (P) for moment utilization ratios less than one are presented in Annex E.2, Table E.7 - Table E.11 for varying numbers of axles and Table E.12 - Table E.18 for varying axle distances. The data presented in the tables is presented graphically in Figure 5.7 and Figure 5.8. Note that for the Brokontrollen data, the shear critical cases are left blank (and are not plotted).

All results for Category 1 from Brokontrollen and TungTransport are both within or approximately on the bounds created with the Theoretical Method. In general, both

Brokontrollen's and TungTransport's results are closer to the upper-bound. However, for Bridge 2 passed by a test-truck with four meters load length, the results deviate from the upper-bound and go towards the lower-bound. Furthermore, an interesting case is Bridge 128 where for varying numbers of axles, TungTransport approaches the lower-bound whereas Brokontrollen is close to the upper-bound. Being close to the lower-bound implies that the model is plausibly overly conservative (see the characteristics of the lower-bound in subsection 4.2.7.2).

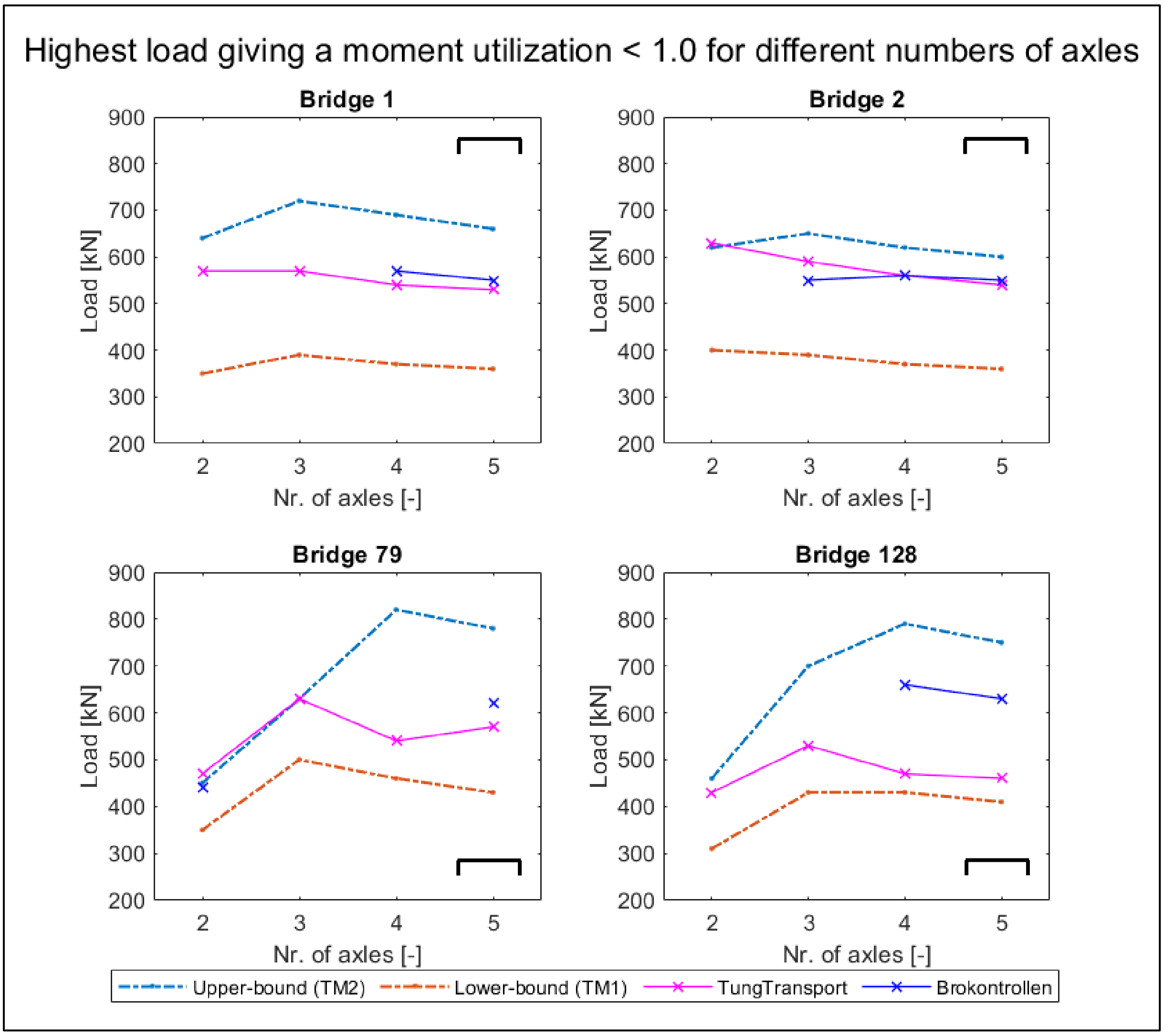


Figure 5.7: Highest permissible load (P) that gives a moment utilization less than 1.0 for different integral slab bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TM1 stands for Theoretical Method with one lane (lower-bound) and TM2 stands for Theoretical Method with two lanes (upper-bound). TungTransport data has been adjusted to remove the dynamic factor. Furthermore, a small side-view sketch of each bridge is provided (not to scale).

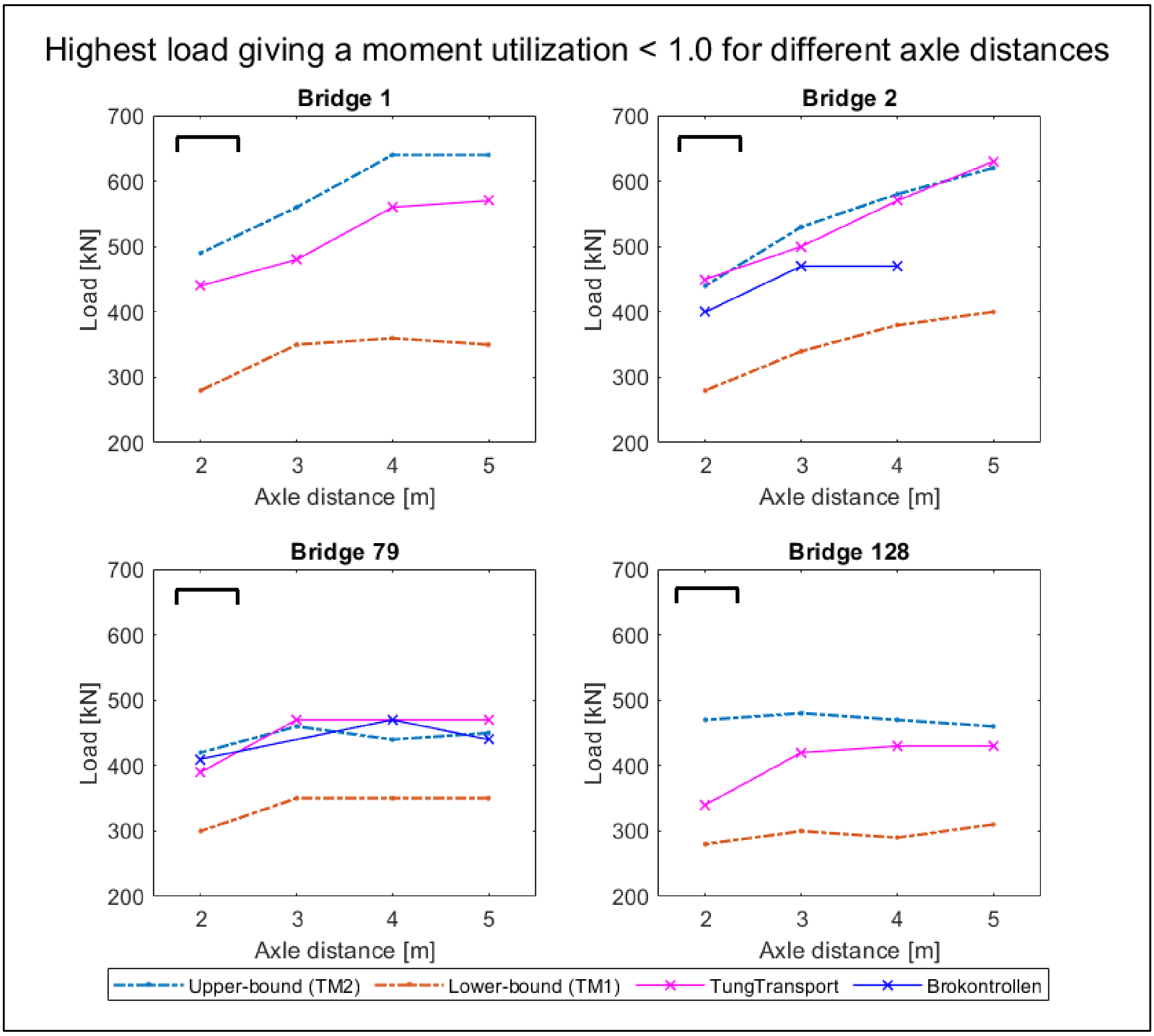


Figure 5.8: Highest permissible load (P) that gives a shear or moment utilization less than 1.0 for different integral slab bridges and test-trucks with a total load length of 5, 4, 3, or 2 meters; each test-truck has only two axles. TM1 stands for Theoretical Method with one lane and TM2 stands for Theoretical Method with two lanes. TungTransport data has been adjusted to remove the dynamic factor. Furthermore, a small side-view sketch of each bridge is provided (top right, not to scale).

5.2.3. Impact of using mid-bridge models

The results from previous sections showed significant differences (up to 40 %) between Brokontrollen and TungTransport regarding Bridge 128, a bridge that uses a mid-bridge model for the highest permissible load. Bridge 79, a similar bridge that also uses a mid-bridge model for the highest permissible load, did not show the same large differences (only up to 16 %). When the mid-bridge models were simplified to strip models and verified against a 2D beam model discrepancies were found for both bridges. These inconsistencies in the differences is shortly further investigated in this subsection through comparing the mid-bridge models with different alternatives based on the normal models.

Figure 5.9 and Figure 5.10 show the highest permissible loads for different alternative models for the integral bridges, Bridge 79 and 128, respectively (see also Annex E.3, Table E.19 – Table E.22). The alternatives are described in subsection 4.2.7.3 and are listed again below.

- Alternative 1: The mid-bridge model;
- alternative 2: The normal model, only looking at the result-lines in the middle of the bridge;
- alternative 3: The normal model.

In general, for both bridges it was expected that alternative 1 and 2 would yield results relatively close to each other. Furthermore, they were expected to allow the highest loads (P) to pass the bridges and that alternative 3 would allow the lowest loads. For Bridge 79, the expectations were met. For Bridge 128, however, alternative 1 permitted the lowest loads. This is unreasonable because alternative 3 should never allow heavier vehicles to pass than alternative 1 (alternative 3 accounts for other traffic on the bridge and places the permit vehicle in the most adverse position). These discrepancies could once again be indications of mistakes in the mid-bridge models.

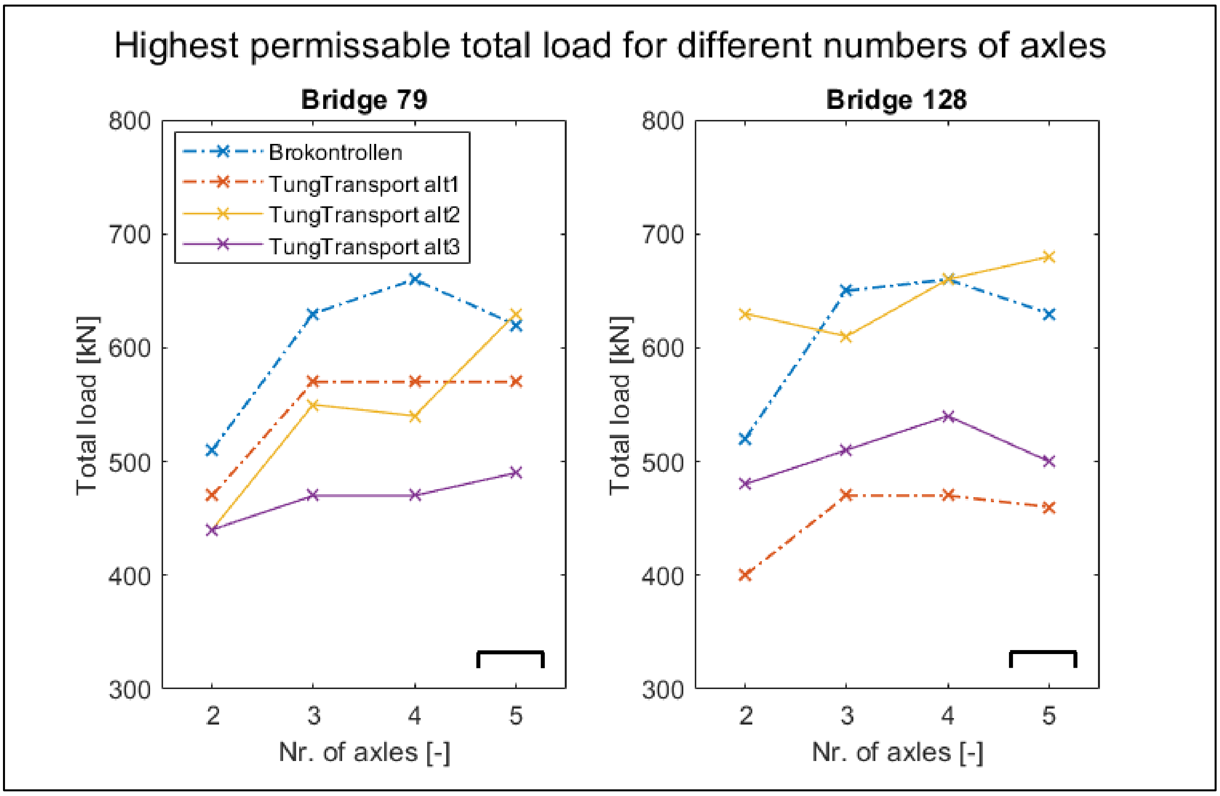


Figure 5.9: Highest permissible load (P) for Bridge 79 and 128 computed with different mid-bridge alternatives and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data is without the influence of the dynamic factor. Furthermore, a small side-view sketch of each bridge is provided (bottom left, not to scale).

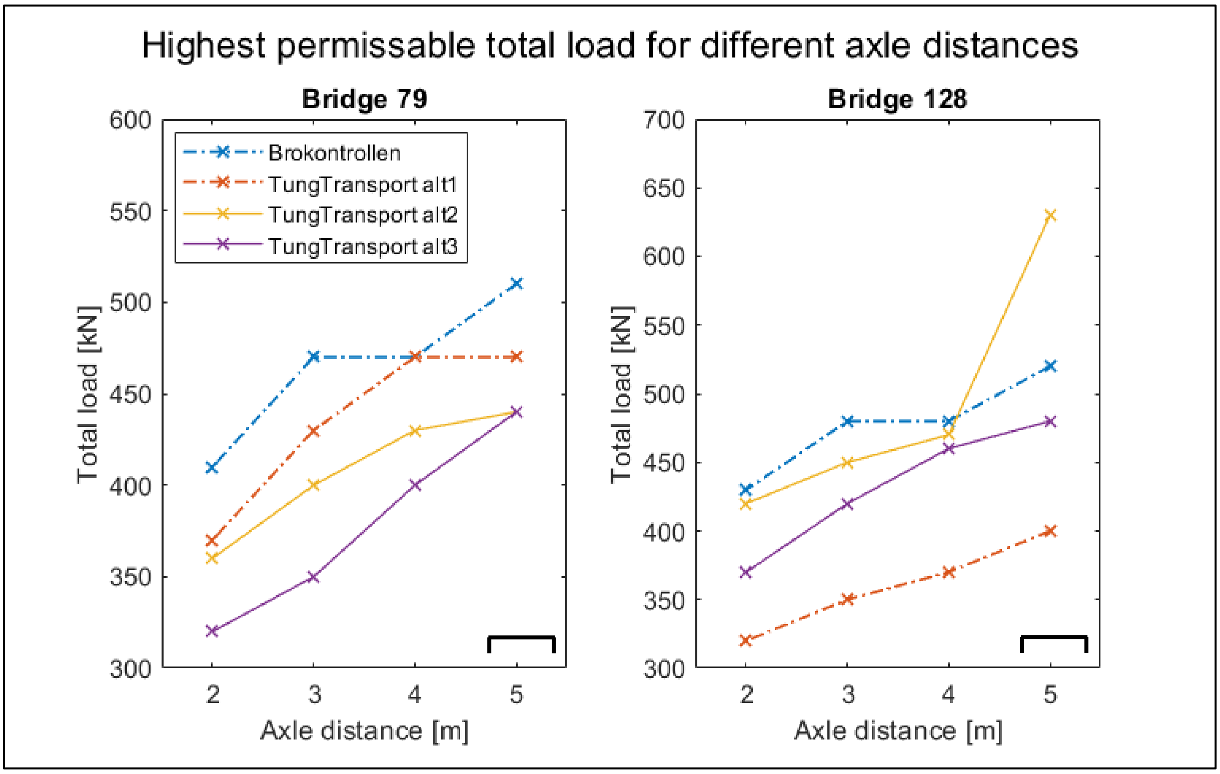


Figure 5.10: Highest permissible load (P) for Bridge 79 and 128 computed with different mid-bridge alternatives and test-trucks a total load length of 5, 4, 3, or 2 meters; each test-truck has two axles. TungTransport data is without the influence of the dynamic factor. Furthermore, a small side-view sketch of each bridge is provided (bottom right, not to scale).

5.3. Further evaluation of all categories

5.3.1. Impact of varying axle width

5.3.1.1. Test-truck

The results from TungTransport for a varying axle width between one and three meters of the five-meter two-axle test-truck are shown for Bridge 1, 79, and 404 in Figure 5.11 – Figure 5.13. The results for the five-axle test truck are shown in Annex E.4, Figure E.2 – Figure E.4. Specifically these bridges were computed to show the impact of this variable due to the differences in location and number of results-lines; Bridge 1 has 10 result-lines where degrees of utilization are computed, the mid-bridge model of Bridge 79 has 4 result-lines, and Bridge 404 only has two (one for each beam). The results show significant change in the utilizations. The shear utilization shows a stronger dependency on the axle width. Furthermore, it is important to keep in mind that it is the highest degree of utilization that is deciding; i.e. the upper curve.

For Bridge 1 (one-span integral slab bridge) being passed by the two-axle five-meter test-truck with an axle width of two meters, the current highest permissible load (P) is 540 kN and yields a (moment) utilization of 0.99. However, if the axle width is changed to three meters, the same load yields a (moment) utilization of 1.16. For Bridge 79 (one-span integral slab bridge) the same change of axle width results in a change of the utilization from 0.98 to 1.63 and for Bridge 404 (three-span girder bridge) from 1.0 to 0.99. When the five-axle test-truck was used (see Annex E.4), the impact from the change of the axle width on the utilization was smaller, but nevertheless significant.

The results from the Theoretical Method for a varying axle width between one and three meters are shown for Bridge 1 in Annex E.4, Figure E.1. The results show a significant impact on the moment utilization, where the utilization decreases for increasing axle width. This is intuitive because moment degrees of utilization are only calculated in the centreline of the lane. Therefore, no further analysis with the Theoretical Method regarding axle width is necessary.

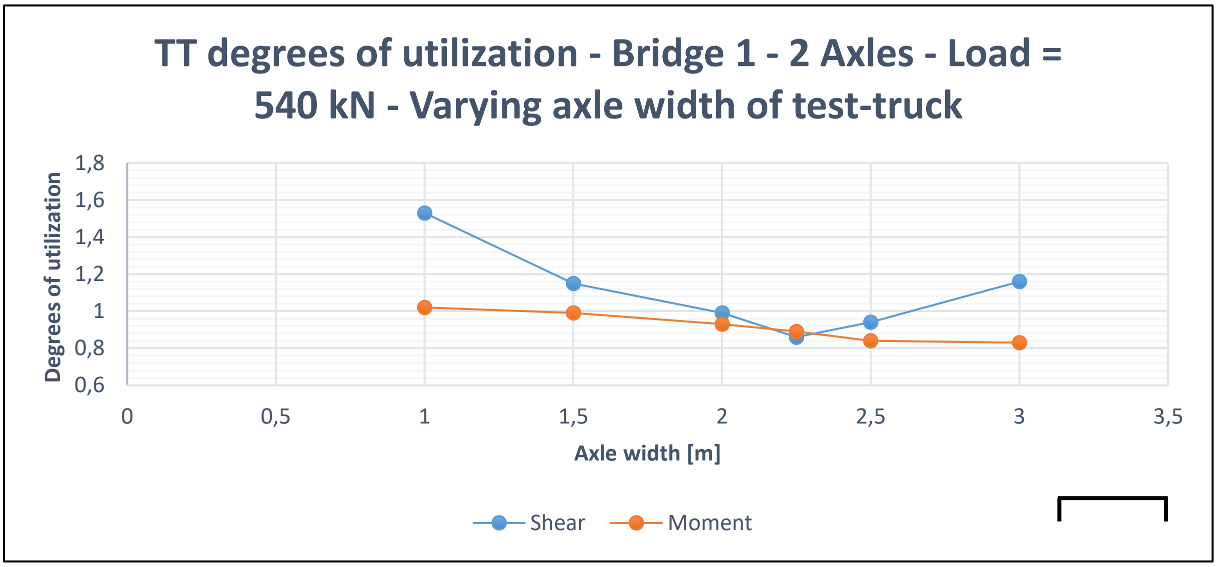


Figure 5.11: Bridge 1 – one span integral slab bridge (plattrambro). Degrees of utilization from TungTransport for varying axle widths of a test-truck with a 540 kN total load distributed over two axles with a total load length of five meters. TT stands for TungTransport. Furthermore, a small side-view sketch of the bridge is provided (bottom right, not to scale).

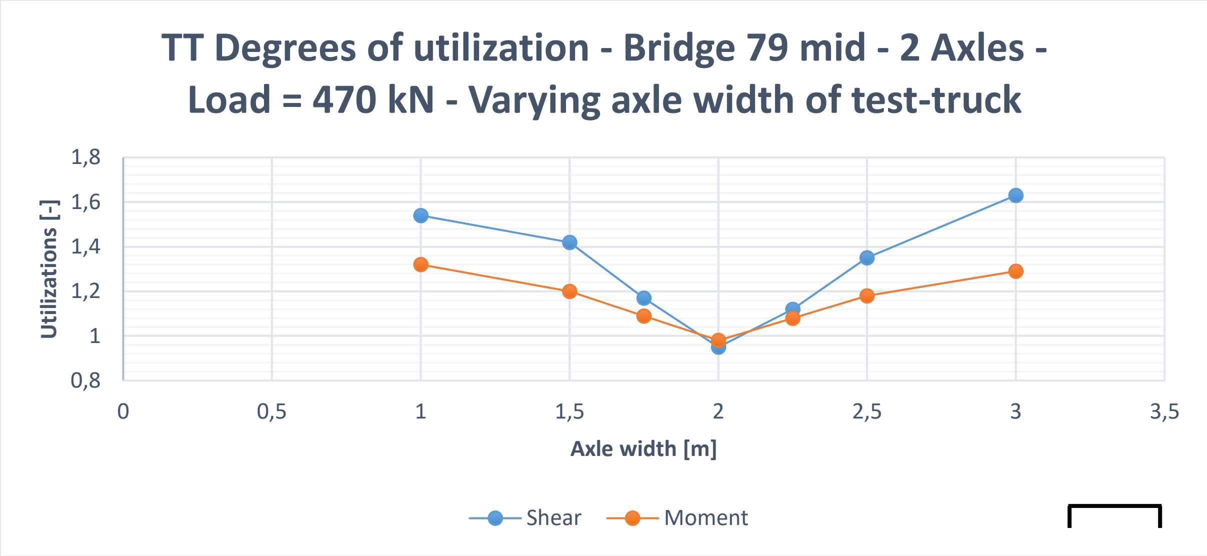


Figure 5.12: Bridge 79 (evaluated mid bridge, alone on bridge) – one span integral slab bridge (plattrambro). Degrees of utilization from TungTransport for varying axle widths of a test-truck with a 470 kN total load distributed over two axles with a total load length of five meters. TT stands for TungTransport. Furthermore, a small side-view sketch of the bridge is provided (bottom right, not to scale).

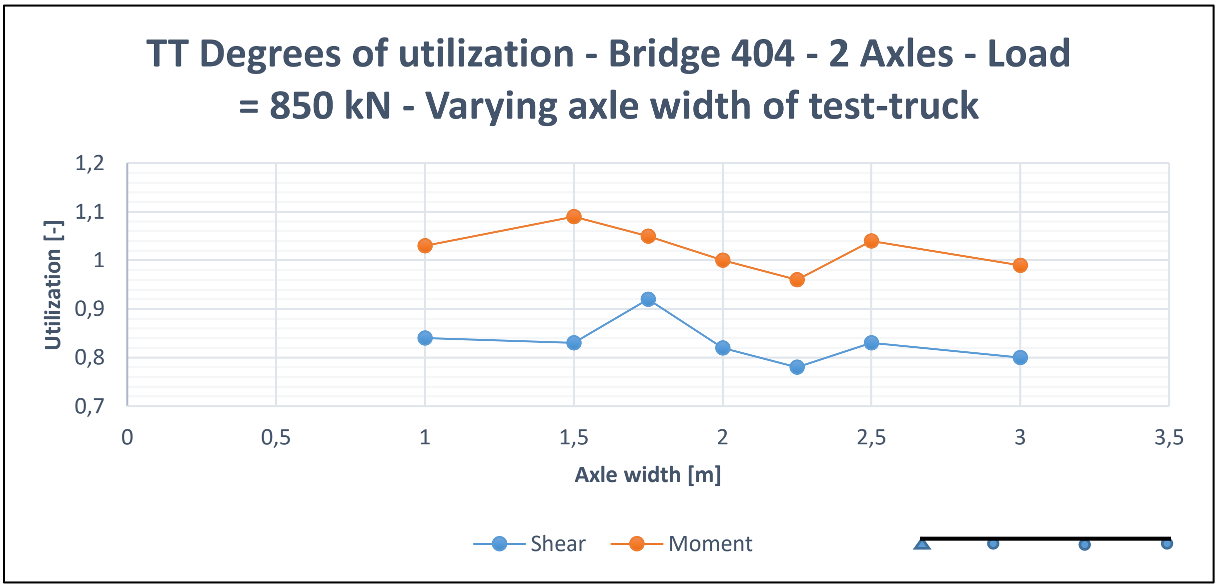


Figure 5.13: Bridge 404 – three span girder bridge (balkbro). Degrees of utilization from TungTransport for varying axle widths of a test-truck with an 850 kN total load distributed over two axles with a total load length of five meters. TT stands for TungTransport. Furthermore, a small side-view sketch of the bridge is provided (bottom right, not to scale).

5.3.1.2. Classification vehicles

The results from TungTransport for a varying axle width of the classification vehicles between 1.7 and 2.3 meters are shown for Bridge 1, 79, and 404 loaded by the five-meter two-axle test truck in Figure 5.14 – Figure 5.16. The reason for the choice of bridges is the same as the previous subsection.

For changes from two meters to 1.7 and 2.3 meters (for the classification vehicles), Bridge 1 changed the utilization from 0.99 to 0.92 and 1.11, Bridge 79 (mid-bridge model) from 0.98 to 1.36 and 1.09, and Bridge 404 from 1.0 to 1.04 and 0.99. Bridge 1 shows that for some bridges, taking into account the 1.7 to 2.3 meter range of axle widths for classification vehicles leads to an increase in capacity.

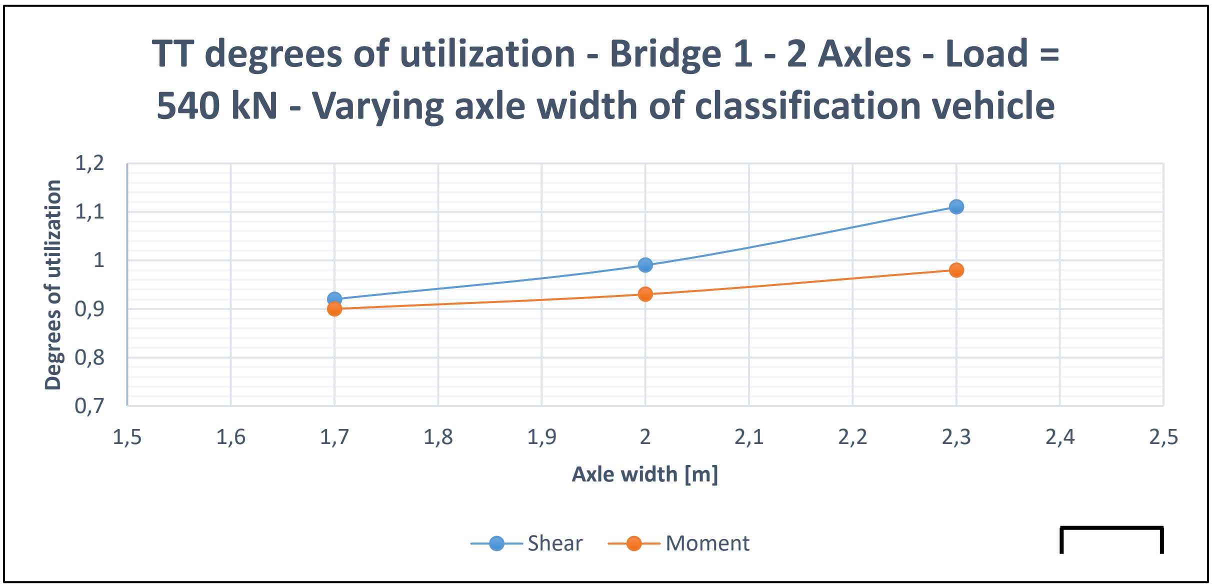


Figure 5.14: Bridge 1 – one span integral slab bridge (plattrambro). Degrees of utilization from TungTransport for varying axle widths of the classification vehicle. The bridge is passed by a test-truck with a 540 kN total load distributed over two axles with a total load length of five meters (and an axle width of two meters). TT stands for TungTransport. Furthermore, a small side-view sketch of the bridge is provided (bottom right, not to scale).

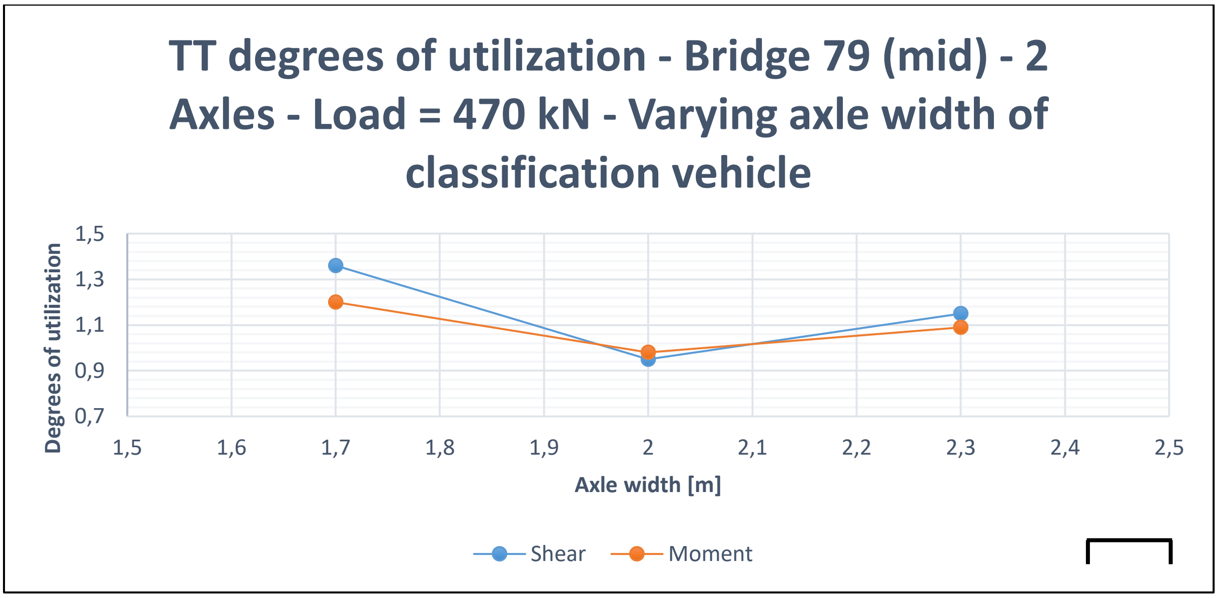


Figure 5.15: Bridge 79 (evaluated mid bridge, alone on bridge) – one span integral slab bridge (plattrambro). Degrees of utilization from TungTransport for varying axle widths of the classification vehicle. The bridge is passed by a test-truck with a 470 kN total load distributed over two axles with a total load length of five meters (and an axle width of two meters). TT stands for TungTransport. Furthermore, a small side-view sketch of the bridge is provided (bottom right, not to scale).

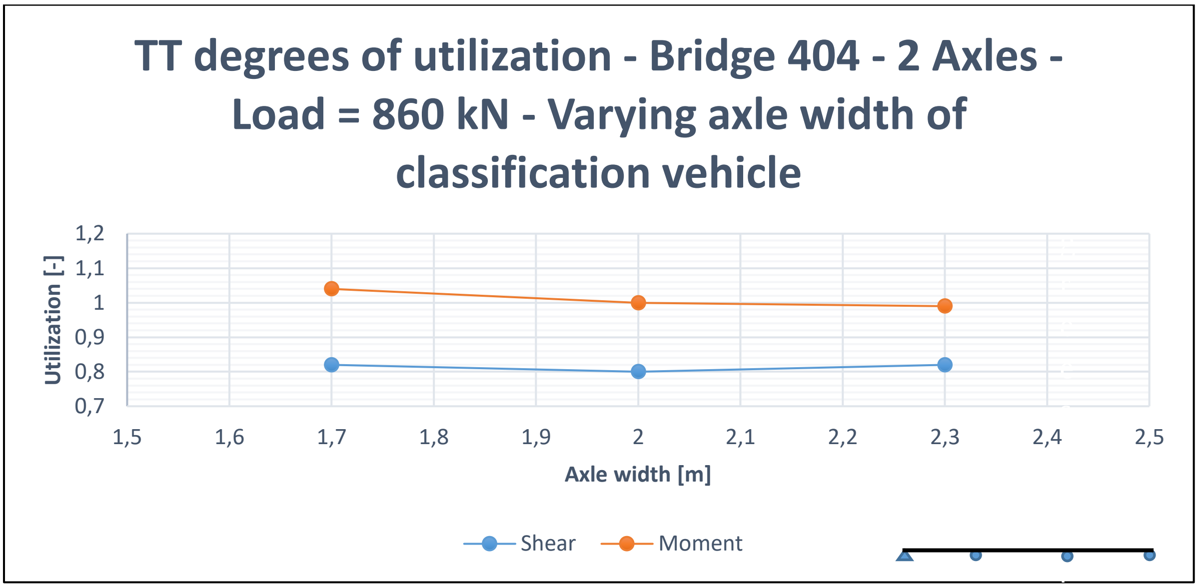


Figure 5.16: Bridge 404 – three span girder bridge (balkbro). Degrees of utilization from TungTransport for varying axle widths of the classification vehicle. The bridge is passed by a test-truck with a 540 kN total load distributed over two axles with a total load length of five meters (and an axle width of two meters). TT stands for TungTransport. Furthermore, a small side-view sketch of the bridge is provided (bottom right, not to scale).

5.3.2. Impact of failure modes

Figure 5.17 and Figure 5.18 show the highest loads for TungTransport with regards to the failure modes shear, moment, and stress of all bridge for varying numbers of axles. In Annex E.5, Figure E.5 and Figure E.6, the same is shown for varying axle distances. Furthermore, the previous highest permissible loads for Brokontrollen and TungTransport are also presented in the figures. No specific trends were identified based on different critical cases. However, for Bridge 324 (one-span tensioned integral slab bridge), some clarity has been given regarding the previously mentioned abnormality in the general trend of Brokontrollen being more conservative than TungTransport for tensioned structures. The reason that TungTransport is more conservative for Bridge 324 passed by a two-axle five-meter test-truck is related to the fact that TungTransport checks for edge stresses (due to tensioning) in some tensioned structures and that for this case, it was critical.

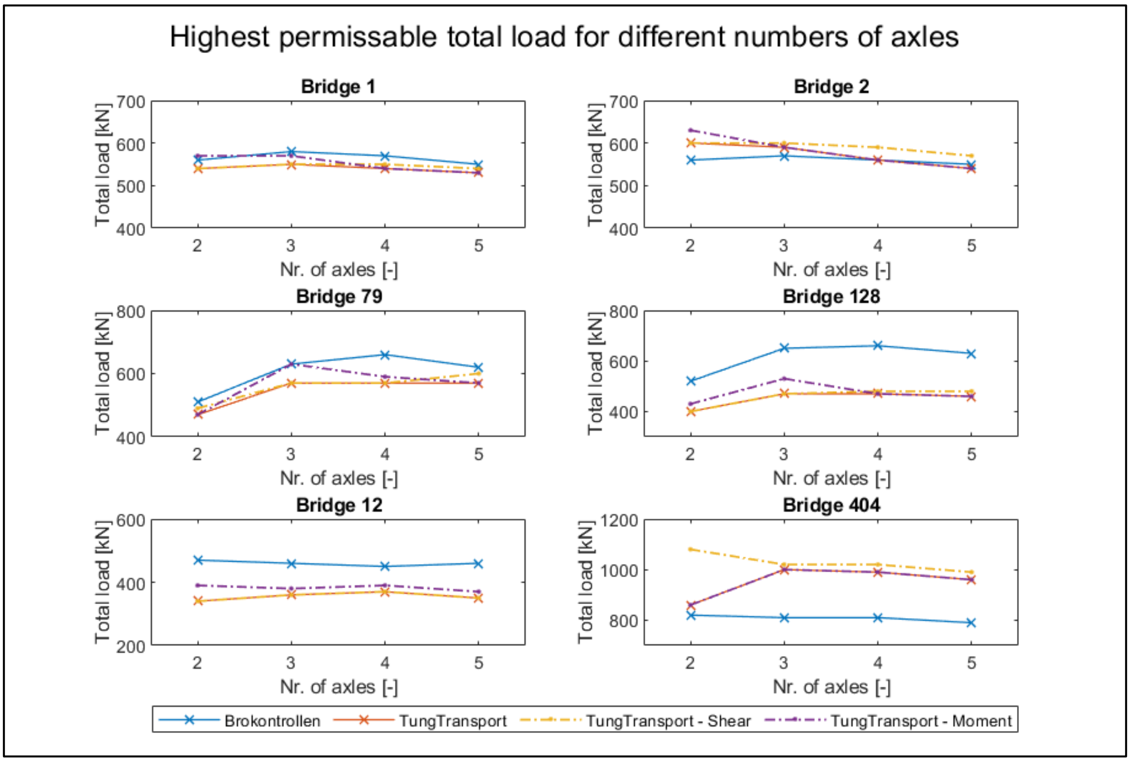


Figure 5.17: Highest permissible load (P) that gives a shear or moment utilization less than 1.0 for different bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data has been adjusted to remove the dynamic factor.

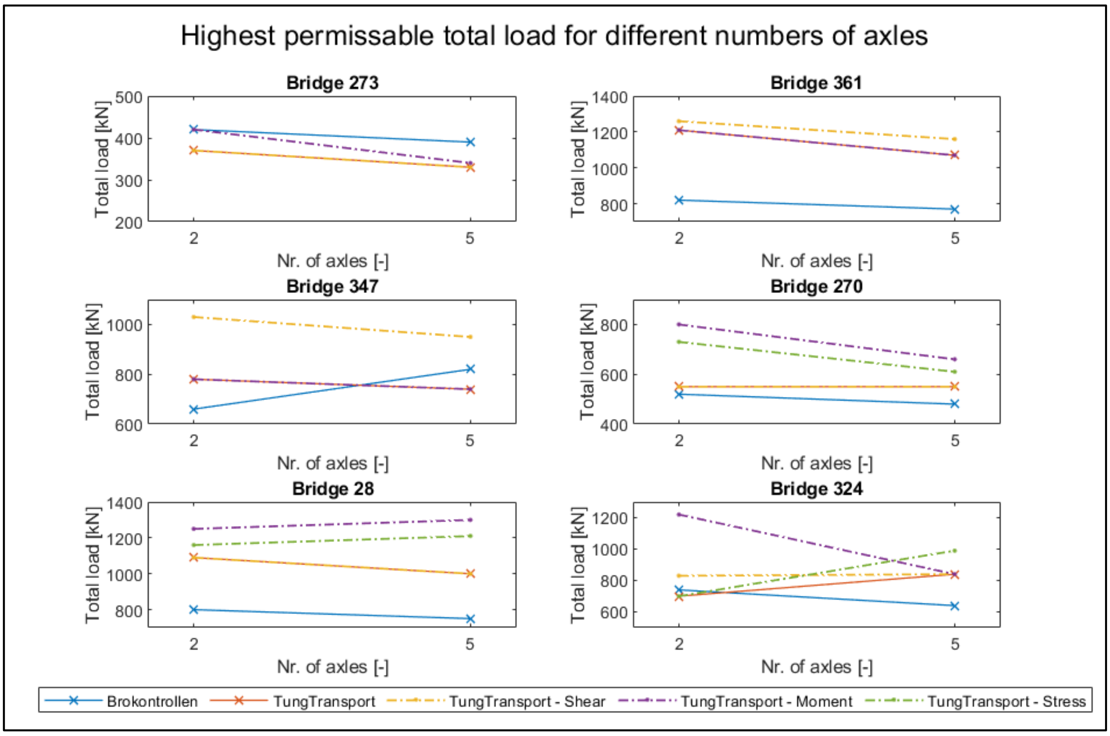


Figure 5.18: Highest permissible load (P) that gives a shear, moment, or stress utilization less than 1.0 for different bridges and test-trucks with two or five axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data has been adjusted to remove the dynamic factor.

6. Discussion

6.1. Swedish and international methods dealing with heavy transports

This thesis provides several methods used in various countries in order to compute permission requests for heavy vehicles. These methods include different variations of classification vehicles, so-called Load Rating Factors (LRF), and probabilistic approaches. Why certain countries choose certain methods might be due to a few things:

- It produces fast results (Swedish Method – Brokontrollen);
- it is based on similar methods for similar problems (US Method – LRF);
- it is simple and based on available information (Hungarian Method);
- it fulfils the specific requirements of local problems such as lack of documentation (Spanish Method);
- or it is an improved adaptation of an already existing method (Korean Method – OPERA)

In other cases, the direct motivation is unclear. What might play a role in the decision is the lack of available research (in English) regarding the topic, where what is available is from older sources (such as the ones used in this thesis). This might be due to the disinclination of governments (and/or companies) regarding sharing information. An example of this is the Swedish Transport Administration who decline to share any information regarding the working algorithms behind Brokontrollen. This is not to say that they do not provide a general methodology or guidelines; however, these can be broadly interpreted. This is also mentioned about the US Method (LRF) in subsection 2.2.3.

Regarding the Swedish method, as mentioned above, when it is implemented as it is in Brokontrollen its ability to evaluate dispensations cases in a matter of seconds is beneficial when time is a critical factor. Another benefit with the method is that it can be implemented using different sorts of models (2D beam models like Brokontrollen or 3D finite-element-models like TungTransport). On the other hand, the more detailed the models become, the more time a single dispensation case computation takes; TungTransport sometimes requires an hour for the computation of a single bridge. When such a long computation time is required using this method, does it then still make sense to use this method? Moreover, would a more traditional approach using a finite-element-model not be equally time consuming while producing more understandable results? This question cannot directly be answered. However, it would be interesting to see a comparison between this method and a more traditional approach, both regarding computation time and final results.

A common trend among the represented countries is the implementation of a heavy transport network where all bridges in the network surpass, for example, a high class (DANBRO). This is beneficial because it lessens the negative impact on normal traffic flow for the remaining roads. In the case of a special heavy transport network, the probabilistic approach is beneficial because a limited amount of bridges has to be analysed; this means that specific data can be gathered for specific (groups of) bridges that leads to less conservativeness because it directly accounts for uncertainties rather than using safety formats such as characteristic values and safety factors.

6.2. Assessment of Brokontrollen and TungTransport

In general, Brokontrollen and TungTransport sometimes gave similar results. However, often, a significant difference of up to 50 % was found. The differences in results are discussed below, first treating each category separately and thereafter together.

The impact of changing length and widths of bridges is more visible in the results from TungTransport than Brokontrollen (the loads change more between bridges when using TungTransport than when using Brokontrollen). Since Brokontrollen is based on 2D beam models with lane-factors (accounting for the transverse placement) while TungTransport is based on 3D models, the following might be of interest: for a 2D beam model, the impact of the length of the bridge is cancelled out. This is because the modelled capacity (computed based on the A/B-values in combination with the classification vehicles) is dependent on the length of a bridge to the same degree as the load effects of a permit vehicle. For a 3D model however, the length and width of the bridge does not influence the modelled capacity and the load effects of a permit vehicle to the same degree. This is because changing the length and/or width impacts the length/width ratio and therefore also the influence surface of the 3D model (see Molkenthin (1971) for influence surfaces of plates with different length/width ratios). A consequence of this is, for example, when the width changes, the spacing between classification vehicles in parallel lanes does not change. This has an impact on the modelled capacity different from the impact on the load effects due to a permit vehicle. Furthermore, what also might play a role is (when it comes to integral slab bridges) that TungTransport distributes 40 mesh elements along the width of the bridge, independent of the width of the bridge. This leads to bridges with smaller widths being more refined (in one direction).

The bridge type might to play a role when comparing tensioned vs. not tensioned structures. It was shown that TungTransport tended to permit higher loads for tensioned structures (with some exceptions) whereas for a multi-span integral bridge, Brokontrollen permitted higher loads. The exceptions for the tensioned structures were Bridge 347 (two-span tensioned girder bridge), passed by a five-axle test-truck and Bridge 324 (one-span tensioned integral slab bridge), passed by a two-meter test-truck. The exception of Bridge 347 might be explained by the edge stress utilization check performed in TungTransport (see subsection 5.3.2 and Annex E.5).

In order to see how tensioning affects the methods, it is interesting to compare bridges with similar geometries and spans. A clear example of this is the difference between Bridge 273 and 28, an integral slab bridge and a tensioned simple slab bridge, respectively, where Brokontrollen permits higher loads for the former and TungTransport for the latter. Another example is the difference between Bridge 12 and 270, a normal and tensioned girder bridge respectively. Other examples such as between Bridge 1, 2 (one-span integral slab bridges) and 324 (one-span tensioned integral slab bridge) show a less pronounced effect. The same is true for the difference between Bridge 404 (three-span girder bridge) and 361 (four-span tensioned girder bridge). Furthermore, the rule does not hold for the difference between Bridge 404 and

347 (two-span tensioned girder bridge). The reason why this general difference exists is unclear. It is possible that, like TungTransport, Brokontrollen checks for edge stresses in tensioned structures and that this check is more conservative than TungTransport's edge stress check.

Another thing to look at is the general response of all bridges to the varying of numbers of axles and axle distances. Regarding this, trends are more easily observed for Category 1 and 2 due to the higher amount of data-points. However, the data for Category 3 still gives some indication. Generally, Brokontrollen and TungTransport do seem to follow similar trends for the same bridges with some exceptions. The first exception is the results from Brokontrollen for the varying of numbers of axles for Bridge 12 (three-span girder bridge); the convex behaviour seems out of place when looking at the behaviour of the other bridges in Category 1 and 2. Especially, since the results from TungTransport are concave, which is more in line with the behaviour other bridges show. The second exception is Bridge 324 (one-span tensioned integral slab bridge), which is due to an additional load effect, edge stresses due to tensioning, which is computed in TungTransport (see subsection 5.3.2 and Annex E.5). Furthermore, two other bridges that stand out are Bridge 404 and 347 (three-span girder bridge and two-span tensioned girder bridge, respectively), which is due to local effect criteria implemented in Brokontrollen. For Bridge 404 the limit for local effects set by Brokontrollen coincides well with the results from TungTransport. For Bridge 347 good agreement between Brokontrollen and TungTransport was found when the axle distance was small; however, Brokontrollen permitted significantly lower loads than TungTransport for larger axle spacing.

The Theoretical Method was used to evaluate the results from the other methods. The upper-bound represents a more accurate (in relation to the requirements by the Swedish Transport Administration) model but is possibly on the unsafe side/unconservative side whereas the lower-bound more represents an overly conservative model that is certainly safe. The Theoretical Method indicates that the results from Brokontrollen and TungTransport for Bridge 1 and 2 (one-span integral slab bridges) are in the vicinity of the upper-bound and are therefore not overly conservative. This, in combination with the good agreement between Brokontrollen and TungTransport as well as the good agreement between the strip models from TungTransport and the Theoretical Method with the 2D beam model suggest that the overall results for Bridge 1 and 2 are reliable.

For Bridge 79 (one-span integral slab bridge), both Brokontrollen's and TungTransport's results sometimes slightly surpass the upper-bound. Furthermore, the verification of a strip model of Bridge 79 in TungTransport shows large discrepancies (too high values from TungTransport) when compared to a 2D beam model of Bridge 79. However, the further investigation of the mid-bridge models does not indicate large discrepancies. Nevertheless, the results for Bridge 79 are questionable. Due to the that Brokontrollen sometimes permitted even higher loads than TungTransport, the results from Brokontrollen are questionable.

Bridge 128 (one-span integral slab bridge), shows results from TungTransport that approach the lower-bound to an extent the other bridges do not. Furthermore, the verification with a 2D beam model showed that TungTransport gave too low values. Moreover, a further investigation of mid-bridge models showed that the mid-bridge model results were too low. Due to these facts, TungTransport is deemed overly conservative for Bridge 128. Brokontrollen gave results up to 40 % higher than TungTransport for Bridge 128. Furthermore, the few datapoints that are available show Brokontrollen’s results fall within the bounds created by the Theoretical Method. However, due to the small dataset, no further conclusions can be drawn about Brokontrollen for this bridge.

For a few bridges, TungTransport was analysed for a test-truck with varying axle width. The results showed that axle width can play a significant role depending on the bridge model. How the degrees of utilization vary with the axle width has to do with that TungTransport evaluates degrees of utilization at many lines along the bridge. Since Brokontrollen does not use axle width as input data, it must use a standard axle width value. If this value is the same for all bridges or optimised to be the most adverse for each bridge is not known. Furthermore, TungTransport was analysed for classification vehicles with varying axle width. The results show a significant impact as well. Especially interesting is that this change in axle width can increase the modelled capacity.

An attempt to assign certain behaviours to which load effect was critical was also made. However, without more output data from Brokontrollen, it was not possible to identify any trends. It did, as discussed previously, help to understand the inconsistencies of the results from Bridge 324 in comparison to the general trends. Furthermore, it shows the use of (edge) stresses for some bridges. Why these stresses are only computed in some cases is unclear. Moreover, it is unclear if the (edge) stresses were taken into account when classifying the bridge; If they were not, the question is if they then still should be included in the dispensation calculations.

6.3. Using Brokontrollen vs. TungTransport

The pros and cons of using either software will shortly be presented in this subsection. Using Brokontrollen yields the benefit of fast computation times and convenient checking of multiple bridges at once. Furthermore, it is less conservative when it comes to integral slab bridges and it allows for more levels of permission (passage criteria) whereas TungTransport only checks for normal passage (for most bridges). There is the option in TungTransport to use certain traffic-lines in a bridge model; however, this does not eliminate other traffic out of the computation and requires extra insight from the user. Brokontrollen was created by the Swedish Transport Administration that also created the Swedish approach. On the other hand, Brokontrollen does not show which algorithms are used; it cannot account for variations in the axle width of the permit vehicle; it does not show the critical degree of utilization and section in the output; also, it tends to be more conservative than TungTransport for tensioned bridges and when accounting for local effects.

Using TungTransport yields the benefit of that it is a Brigade based method, where Brigade is an established finite element software for bridges which uses the ABAQUS solver. This guaranties sophistication in the computations. However, this does not guarantee better results. Furthermore, it shows the critical utilization and section in the output and tends to be less conservative than Brokontrollen for tensioned bridges and when accounting for local effects. On the other hands, the computation time is long; it does not account for varying axle widths of classification vehicles, meaning it sometimes missing out on extra (modelled) capacity; in addition, it has some discrepancies in results from mid-bridge models.

The consequences of using either method varies depending on the bridge. However, if a bridge is checked with both methods, one could go with a risk averse approach and go for the method permitting the lowest load and increase the chance of not damaging the bridge. The other option is taking the higher load, leading to less detours for heavy transport but increasing the risk of damage. However, when taking into account that the original resistance of the bridge, to which the A/B-values are scaled and therefore the modelled capacity is scaled, a lot of safety margin is already built in. Therefore, it is more probable that the methods are in general too conservative rather than unconservative.

7. Conclusions and suggestions for further research

Several methods from different countries for the analysis of heavy transport on existing bridges were shortly presented. Some implement a variation of the classification vehicle methodology, some use a variation of the Load Rating Factor methodology, and others have created a unique methodology that fits the countries specific needs. Both deterministic and probabilistic methods have been found and some methods have been implemented using both a deterministic and a probabilistic approach. For the classification vehicle methodology, research suggests that the switch from a deterministic approach to probabilistic approach, when classifying bridges, might yield economic benefits for more advanced, higher investment cost bridges.

When looking at all analysed categories (1: one-span integral slab bridges, 2: three-span girder bridges, and 3: one- or multi-span, tensioned or not tensioned, girder or slab bridges), the results from Brokontrollen and TungTransport differ greatly ranging from results where Brokontrollen permitted 33 % lower to 50 % higher total loads than TungTransport. However, for some bridges results showed good agreement, such as Bridge 1 and 2 (one-span integral slab bridges) or decent agreement such as Bridge 347 and 270 (two-span and one-span tensioned girder bridges). For Bridge 1 and 2, further verification with the Theoretical Method and a 2D beam model shows that the results for the bridges are reliable. Also, when local effects are critical, the two methods show decent agreement. Nevertheless, in general it is concluded that Brokontrollen and TungTransport show alarming differences in the highest loads (P) for certain criteria. For some cases, such as Bridge 128 (one-span integral slab bridge) it has been shown that this difference is due to problems with the mid-bridge model in TungTransport; this has been done through the use of the Theoretical Method, a 2D beam model, and analysing alternative models for the same bridge.

Regarding the bridge type, for tensioned structures TungTransport generally permitted higher total loads than Brokontrollen for the same passage criteria. No other trends due to bridge type were identified. However, a trend was found regarding length/width changes. TungTransport's results tend to vary from bridge to bridge, even if the change is only primarily the length/width.

Axle width was identified as a variable that significantly impacts the difference in results between Brokontrollen and TungTransport; this regards both the axle width of the classification vehicles and the permit vehicle. Since Brokontrollen does not use axle width as input there is a possibility of under- or overestimating the load effects from permit vehicles. Furthermore, The Swedish Transport Administration (2018b) states that the axle width of the classification vehicles is assumed to vary arbitrarily between 1.7 and 2.3. Since TungTransport keeps the axle width of classification vehicles a constant two meters, it misses out on potential extra capacity when computing dispensation cases (a different axle width sometimes yields higher capacity).

For use in practice, these discrepancies between the methods imply that unnecessary detours or avoidable damage could occur. Both would lead to avoidable costs. due to built-in safety margins in the bridge carrying capacity and additional margins from the implemented approach, one could argue to go for the less conservative results (given the models in the methods are not faulty).

Regarding improvements, the first and most straight forward improvement for TungTransport would be to adjust the dynamic factor computation so that the multiplier is set to 1.0 when the velocity is 10 km/h or less. Including classification vehicles with an axle width of 1.7 and 2.3 meters would be the following improvement. Adjusting/recreating the mid-bridge models would be the next step. Thereafter, remaining bridges that are suspected to be inaccurate can be checked by using the strip model – 2D beam model comparison methodology as a first check.

Bearing in mind that these methods are used to compute dispensation cases to make sure if heavy transport can or cannot pass a bridge, and that they are based on the same approach, further research should be performed to check if after these adjustments, the differences persist. If they do persist, it should be identified why.

For TungTransport, the effect of varying the axle width could be studied for the same bridges with an altered number of result lines (where degrees of utilization are computed). Furthermore, a comparison between TungTransport and a traditional finite-element-approach, both regarding computation time and highest permissible loads would be interesting. For Brokontrollen, no direct improvement can be suggested due to that it is a black box. Nevertheless, suggestions can be made regarding what to look at if developers at the Swedish Transport Administration were to be interested in improving Brokontrollen. The first suggestion is to analyse how their choice of axle width impacts the results. The second suggestion is to make use of the failure criterion figures provided by this thesis to investigate if the trends for shear, moment, and stress failure criterion from TungTransport align with the trends from Brokontrollen.

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Annex A: In common bridges in Brokontrollen and TungTransport

Table A.1: List of all bridges that are available both in Brokontrollen and TungTransport. Provided by Malmö Stad.

Bridge		Bridge name and/or description
1		Varvsbron. VB för V. Varvsg ö Turbinkanalen
2		Västerbron. VB för Citadellsv ö Turbinkanalen
8	a	Fersens bro. Vägbro för Fersens väg över Parkkanalen
12	a	Östra Amiralsbron. Vägbro för Amiralsgatan
12	b	Västra Amiralsbron. Vägbro för Amiralsgatan
14		Carolibron. Vägbro för Stora Kvarngatan
16		Slussbron. Vägbro för Norra Vallgatan
28		Sjölundaviadukten. Vägbro över jvg-bg
64		Vägbro för ...över gångväg (gångtunnel) vid Dalaplan
77		Vägbro för Tvärförbindelsen nya väg 101
78		Vägbro för Regementsg över GC-väg vid Thottsg
79		Vägbro för Trelleborgsv över Söderkullastigen
121		VB för J. Ericssons väg ö transportv vid MAS
128	a	VB för Lorensborgsg över Bellevueallén.V.bron
128	b	VB för Lorensborgsg över Bellevueallén.Ö. bron
148		VB för Limhamnsv ör GC-väg vid Köpenhamnsv
211		Vägbro för väg 101/Käglingev över väg E65/14
234		VB för Västkustv ö GC-väg vid Spillep. Tpl. V. bron
235		VB för Västkustv ö GC-väg vid Spillep Tpl. S. bron
236		VB för Västkustv ö GC-väg vid Spillep Tpl. Ö bron
264		Hovrättsbron. VB för Slottsg ö V. Hamnkanalen
270		VB för väg 8004 - Västkustv över Jörgen Kocksgatan
271		VB för väg 8004 -Västkustv över Frihamnens Rbg
272		VB för väg 8004 -Västkustv ö hamnspår vid Sjölunda
273		VB för väg 8064 -Flinttränneg ö väg 8062 -Borrg och jvg
284	a	Vägbro för Föreningsg över GC-väg. S bron
284	b	Vägbro för Föreningsg över GC-väg. N bron
322		Vägbro för Nobelvägen över GC-väg
324		VB för Lorensborgsg, s. delen,ö GCR-väg,Eko-stråket.
347	y	Vägbro för Käglingev - väg 101 över Yttre Ringv
361	y	VB för Lockarpsvägen ö Y. Ringv. Broläge 10.
364		Västra VB i cirkulationsplatsen för Lorensborgsgatan/ Annetorpsv över GCR-väg
365		Östra VB i cirkulationsplatsen för Lorensborgsgatan/ Annetorpsv över GCR-väg
404		Vägbro för Arrievägen över

Annex B: Classification vehicles (Swedish: Typfordon)

Below, classification vehicles used in the Swedish methodology are presented (see Figure B.1). More classification vehicles exist but are not used in any of the bridges used in this thesis.

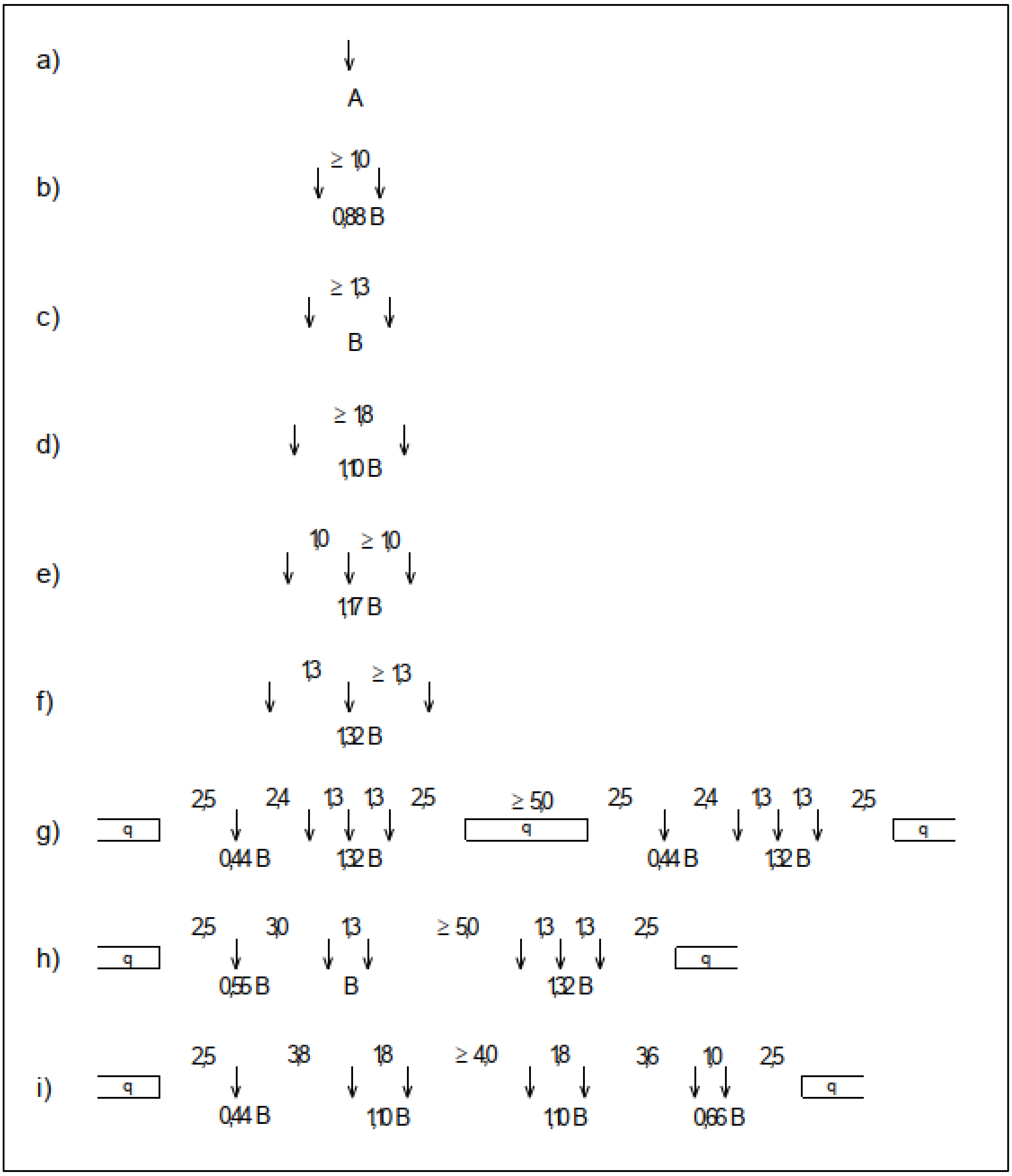


Figure B.1: Classification vehicles used to compute bridge capacities where the A/B-values are calibrated to the actual capacity of the bridge in question. Reprinted from Bärighetsberäkning av broar (p. 112), by the Swedish Transport Administration, 2013, Trafikverket.

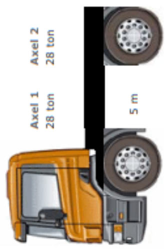
Annex C: Output examples

C.1. Example of output from Brokontrollen

Brokontroll - Resultat

Beräkningsdatum 2020-03-02 15:11

Vägsedel finns ☐
Delbart gods ☐
Enbart vägbanemitt ☐
Konstruktiv hastighet 10 Km/h



Summa axellast 56 ton

Summa axelavstånd 5 m

Resultat

Knr/IdNr2	Längdsystem	Namn	Funktionstyp	Ägare	Förvaltare	KonstrTyp	Riktningsanm	VillkorNr	Villkor	Hastighet	BeräknUrsprung
1280-1-1	Hela bron	Varvsbron. Vägbro för västra Varvsgatan över Turbinkanalen.	Vägbro	Malmö stad	Malmö stad		Överfart Dubbelriktad trafik, konstruktionens riktning mot Malmö Centralstation	10	Eget körfält (konstruktiv hastighet)	10	Lastintensitetsberäkning
1280-2-1/M354	Hela bron	Västerbron. Vägbro för Citadellsvägen över Turbinkanalen.	Vägbro	Malmö stad	Malmö stad		Överfart Dubbelriktad trafik, konstruktionens riktning mot Malmö Centralstation	10	Eget körfält (konstruktiv hastighet)	10	Lastintensitetsberäkning
1280-79-1/M558	Hela bron	Vägbro för Trelleborgsvägen över Söderkullastigen	Vägbro	Malmö stad	Malmö stad		Överfart Körning mot söder	90	Transport kan ej medges		Lasteffektberäkning
1280-79-1/M558	Hela bron	Vägbro för Trelleborgsvägen över Söderkullastigen	Vägbro	Malmö stad	Malmö stad		Överfart Körning mot norr	90	Transport kan ej medges		Lasteffektberäkning
1280-128-1/M697	Hela bron	Vägbro för Lorensborgsgatan över Bellevueallén, västra bron	Vägbro	Malmö stad	Malmö stad		Överfart Enkelriktad (mot), konstruktionens riktning mot Mot Malmö centralstation	90	Transport kan ej medges		Lasteffektberäkning
1280-148-1	Hela bron	Vägbro för Limhamnsvägen över GC-väg vid Köpenhamnsvägen - Smedsterassen	Vägbro	Malmö stad	Malmö stad		Överfart Inkl stödremsan	10	Eget körfält (konstruktiv hastighet)	10	Lastintensitetsberäkning
1280-234-1/M855	Hela bron	Vägbro för västkustvägen över gc-väg vid spillepengens trafikplats, västra bron	Vägbro	Malmö stad	Malmö stad		Överfart Körning mot Malmö C	90	Transport kan ej medges		Lasteffektberäkning
1280-235-1/M856	Hela bron	Vägbro för västkustvägen över gc-väg vid spillepengens trafikplats, södra bron	Vägbro	Malmö stad	Malmö stad	Plattram 2-leds	Överfart Körning mot Gbg	10	Eget körfält (konstruktiv hastighet)	10	Lastintensitetsberäkning
1280-236-1/M857	Hela bron	Vägbro för västkustvägen över gc-väg vid spillepengens trafikplats, östra bron	Vägbro	Malmö stad	Malmö stad	Plattram 2-leds	Överfart Körning mot Gbg	10	Eget körfält (konstruktiv hastighet)	10	Lastintensitetsberäkning
1280-270-1/M175	Hela bron	Vägbro för väg 8004 - västkustvägen över jörgen kocksgatan	Vägbro	Malmö stad	Malmö stad		Överfart Körning mot Malmö C	51	Vägbanemitt. Hastighet 10 km/tim. Ensam på bron, motriktad trafik stängs av (har mitträcke/refug)	10	Lasteffektberäkning
1280-270-1/M175	Hela bron	Vägbro för väg 8004 - västkustvägen över jörgen kocksgatan	Vägbro	Malmö stad	Malmö stad		Överfart Körning mot Gbg	51	Vägbanemitt. Hastighet 10 km/tim. Ensam på bron, motriktad trafik stängs av (har mitträcke/refug)	10	Lasteffektberäkning
1280-271-1/M352	Hela bron	Vägbro för väg 8004 - västkustvägen över frihamnens rangerbangård	Vägbro	Malmö stad	Malmö stad	Plattram 2-leds	Överfart Körning mot Malmö C	10	Eget körfält (konstruktiv hastighet)	10	Lasteffektberäkning
1280-271-1/M352	Hela bron	Vägbro för väg 8004 - västkustvägen över frihamnens rangerbangård	Vägbro	Malmö stad	Malmö stad	Plattram 2-leds	Överfart Körning mot Gbg	10	Eget körfält (konstruktiv hastighet)	10	Lasteffektberäkning
1280-272-1/M534	Hela bron	Vägbro för väg 8004 - västkustvägen över hamnspår vid sjölunda	Vägbro	Malmö stad	Malmö stad		Överfart Mot Sjölundaviadukten	10	Eget körfält (konstruktiv hastighet)	10	Lastintensitetsberäkning
1280-324-1	Hela bron	Vägbro för lorensborgsg, södra delen, över gcr-väg, eko-stråket.	Vägbro	Malmö stad	Malmö stad		Överfart Dubbelriktad trafik, konstruktionens riktning mot Mot Malmö centralstation	10	Eget körfält (konstruktiv hastighet)	10	Lastintensitetsberäkning
1280-364-1	Hela bron	Vägbro för Annetorpsv över GC-väg. v. bron i rondellen	Vägbro	Malmö stad	Malmö stad		Överfart Varierande bredd 12,1 til	10	Eget körfält (konstruktiv hastighet)	10	Lastintensitetsberäkning

Figure C.1: Example of output from Brokontrollen for multiple bridges being passed by a five-meter two-axle test-truck with a total load of 560 kN Note the different passage criteria.

C.2. Example of output from TungTransport

Malmö Stad
Broenheten
Gatukontoret

Bro 1
2020-03-02T15:17:41
Remco de Bruijn/TYR

Allmänt

Bronamn:	Varvsbron. Bro över Turbinkanalen
Brotyp:	Sned plattram (89gon) fri öppning = 10.0 m
Byggnadsår:	1961
EG A/B:	BK1 290/220 kN
Tillståndsklas	TKx

Dispensfordon

Test

Antal axlar:	2	[st.]	
Lastbredd:	3	[m]	
Axelvidd:	2	[m]	
Fordonshastighet:	10	[km/h]	
Dynamisk faktor:	1.082		
Lastlängd:	5.0	[m]	
Fordonstyngd:	500	[kN]	50 [ton]

P [kN]	Avstånd* [m]
250.0	5.00
250.0	

*Avstånd till nästa last

Resultat:

Snittkrafter	Utnyttjandegrad	Konstruktionsdel	
Böjmoment	93%	Linje 10	OK!
Tvärkraft	99%	Linje 1	OK!

Postadress:
Tyrens AB
205 19 MALMÖ

Telefon:
010-452 20 00
0701-77 80 87

E-post:
tungtransport@tyrens.se

TYRÉNS

Figure C.2: Example of output from Brokontrollen for multiple bridges being passed by a five-meter two-axle test-truck with a total load of 500 kN Note the dynamic factor and the different degrees of utilization (output page 1 out of 2).

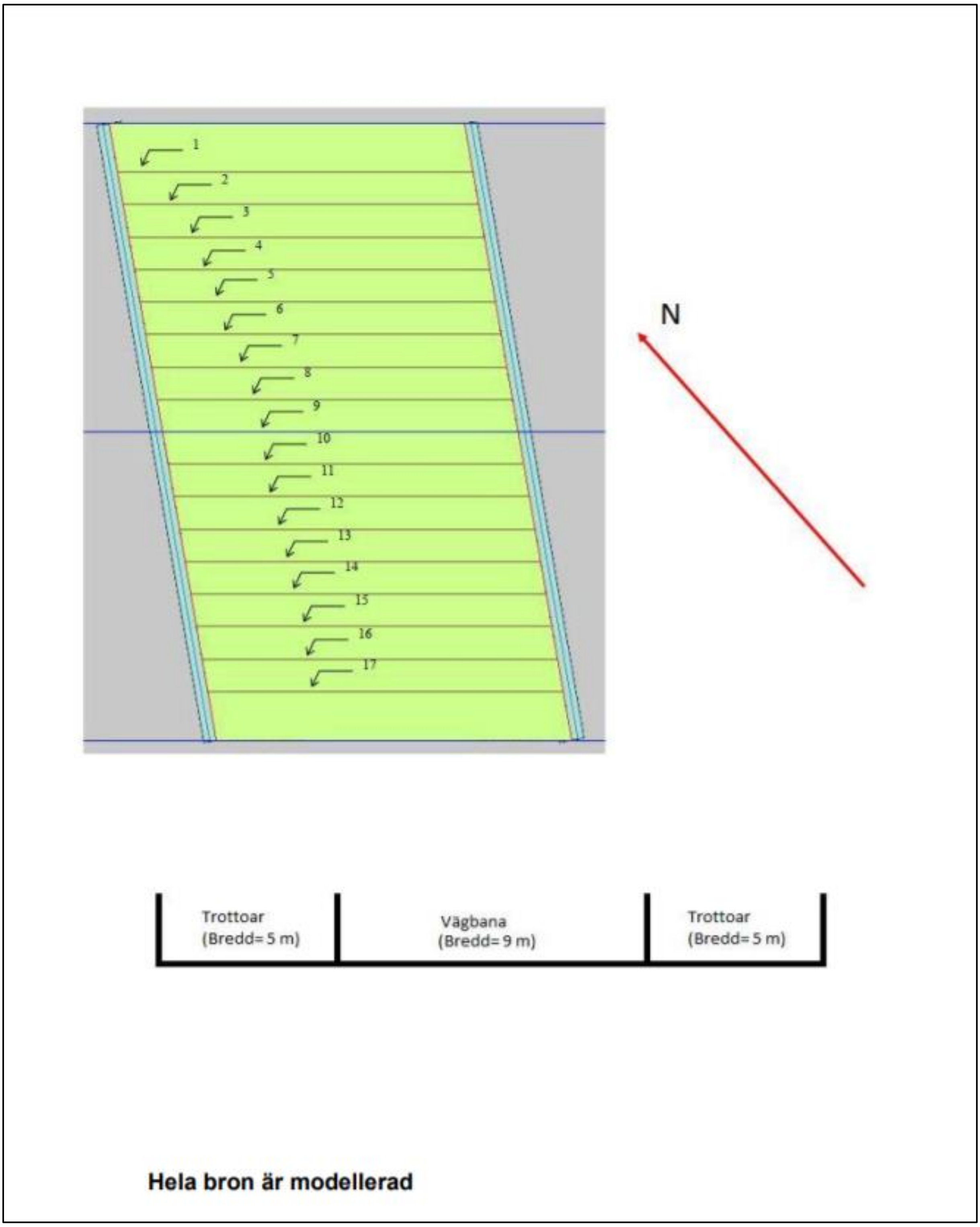


Figure C.3: Example of output from Brokontrollen for multiple bridges being passed by a five-meter two-axle test-truck with a total load of 500 kN (output page 2 out of 2).

Annex D: Summarized layout of processes in methods

D.1. TungTransport

When an analysis is requested a catalogue is copied to a temporary folder (Tyréns AB, 2016). The catalogue contains

- the Brigade model (Brigade/Plus or Brigade/Standard) for the bridge;
- choice of result-lines and its components;
- a file containing information about the bridge analysis,
    - project name,
    - type of analysis,
    - bridge name,
    - bridge type,
    - build year,
    - load capacity in the form of classification loads,
    - standard or plus,
    - dispensation class (0-3),
    - theoretical length of bridge,
    - vehicle velocity,
    - possible traffic load lines,
    - and chosen traffic load lines;
- a result excel-file containing the results from the analysis,
- a pdf showing the positions of the result-lines,
- a pdf showing the positions of the traffic-lines,
- a file documenting the computation time from the last analysis used as a prediction for the user.

The result excel sheet contains a few sheets (Tyréns AB, 2016). The first sheet contains all output from the analysis organized into tables for each line. Every table contains information about maximum and minimum load effects due to the permit vehicle and the classification vehicle at certain nodes along the result-line. The second sheet shows the positioning of the result-lines with a picture. The third sheet shows the highest degree of utilization for each result-line as well as the total highest degree of utilization for each load effect. The next few sheets show the degrees of utilization for all nodes in each result-line for every relevant load effect. The next to last sheet shows load effect diagrams. The last sheet provides a full report regarding the dispensation of the vehicle in relation to the bridge.

D.2. The Theoretical Method

D.2.1. Bridge creator script

The bridge creator script is a simple script where, through a dialogue window, the following data is inputted:

- Name of the bridge file,
- length of the bridge,

- width of the normal traffic lane,
- support conditions,
- number of moment locations along the bridge,
- A/B-values,
- and which classification vehicles should be used.

The data is then saved in the bridge file name and can be loaded, when called upon, into the classification or dispensation script.

D.2.2. Classification script

Input

In this subscript the bridge file is chosen. This is done with a dialogue window. The dialogue requests the bridge file name; here a predefined bridge file should be inputted.

Support conditions

After the data has been inputted, this subscript loads the support conditions out of the bridge file and based on that, using if statements, loads the correct support conditions that are applied to the influence field.

Influence functions

The influence functions subscript creates the influence surfaces using equations (3.6) – (3.12) (X), where the relevant equation for the support conditions are applied based on the previous subscript.

Loading bridge data

This subscript loads the remaining data from the bridge file chosen in the Input subscript.

Creating vehicle

This subscript created the classification vehicles, to be used in the computation subscript, based on the A/B-values given by the bridge-file.

Computation

The Computation subscript loops over the moment positions, which in turn loops over vehicle positions along the bridges, which in turn loops over the left and right axle-wheels where moment values are computed with the influence surfaces. In the vehicle position loop, surface loads are also computed. If statements dictate which axles and surface loads are currently on the bridge and are therefore contributing to the load effects. This whole procedure is performed twice, once for mid-span moments and one for edge moments (if applicable).

Saving

After the computation of the classification vehicle moments (modelled capacity). The data is saved.

D.2.3. Dispensation script

Input

In this subscript the bridge file is chosen and the permit vehicle data is inputted. This is done with dialogue windows. The first dialogue requests the bridge file name; here a predefined bridge file should be inputted. The second dialogue requests the number of axles on the permit vehicle. If "3" is inputted, the third dialogue requests the axle loads for each axle in kN and the distance between axle distance for axles one – two and two – three.

Support conditions

After the data has been inputted, this subscript loads the support conditions out of the bridge file and based on that, using if statements, loads the correct support conditions that are applied to the influence field.

Influence functions

The influence functions subscript creates the influence surfaces using equations (3.6) – (3.12), where the relevant equation for the support conditions are applied based on the previous subscript.

Loading bridge data

This subscript loads the remaining data from the bridge file chosen in the Input subscript.

Vehicle description

This subscript assigns the vehicle input from the Input subscript.

Creating vehicle

With the assigned variables from the previous subscript, this subscript creates the permit vehicle to be used in the Computation subscript.

Computation

The Computation subscript loops over the moment positions, which in turn loops over vehicle positions along the bridges, which in turn loops over the left and right axle-wheels where moment values are computed with the influence surfaces. In the vehicle position loop, surface loads are also computed. If statements dictate which axles and surface loads are currently on the bridge and are therefore contributing to the load effects. This whole procedure is performed twice, once for mid-span moments and one for edge moments (if applicable).

Results

The moments from the Classification subscript are loaded. The moments from the Dispensation script for each moment location divided by the moments from the Classification subscript. These utilization ratios are then presented in a table in combination with an indication of whether to look at the minimum or maximum moments (of the classification vehicles). This is determined based on the comparison of absolute value of the minimum moment compared to the maximum moment. The moment with the highest absolute value is the relevant moment for that moment location. Usually towards the clamped supports, minimum moments are relevant and towards mid-span, maximum moments are relevant.

Annex E: Additional tables and figures with results

E.1. Main comparison between methods

Table E.1: Highest permissible load (P) for different integral slab bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]								(Brk – TT) / TT [%]			
	Brokontrollen				TungTransport							
Nr. of axles	2	3	4	5	2	3	4	5	2	3	4	5
Bridge 1	560	580	570	550	500	510	500	490	12	14	14	12
Bridge 2	560	570	560	550	560	550	520	500	0	4	8	10
Bridge 79	510	630	660	620	440	530	530	530	16	19	25	17
Bridge 128	520	650	660	630	370	440	440	430	41	48	50	47

Table E.2: Highest permissible load (P) for different integral slab bridges and test-trucks a total load length of 5, 4, 3, or 2 meters; each test-truck has two axles. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]								(Brk – TT) / TT [%]			
	Brokontrollen				TungTransport							
Axle dist. [m]	5	4	3	2	5	4	3	2	5	4	3	2
Bridge 1	560	460	460	410	500	460	420	380	12	0	10	8
Bridge 2	560	470	470	400	560	520	470	420	0	-10	0	-5
Bridge 79	510	470	470	410	440	440	400	350	16	7	18	17
Bridge 128	520	480	480	430	370	350	330	300	41	37	45	43

Table E.3: Highest permissible load (P) for different three span girder bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]								(Brk – TT) / TT [%]			
	Brokontrollen				TungTransport							
Nr. of axles	2	3	4	5	2	3	4	5	2	3	4	5
Bridge 12[1]	470	460	450	460	320	340	350	330	47	35	29	39
Bridge 404[2]	820	1120	1120	1090	800	930	920	890	3	20	22	22

[1] For B12 the highest permissible loads are regarding the "normal passage" due to TungTransport not having an implemented "mid road, alone on bridge" model for this bridge.
[2] For B404 3, 4, or 5 axles have the following requirement: Mid-road, alone on bridge.

Table E.4: Highest permissible load (P) for different multi-span girder bridges and test-trucks with 5, 4, 3, or 2 meters between two axles of the truck; each test-truck has only two axles. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]								(Brk – TT) / TT [%]			
	Brokontrollen				TungTransport							
Axle dist. [m]	5	4	3	2	5	4	3	2	5	4	3	2
Bridge 12[1]	460	440	420	390	320	300	260	240	-2	47	62	63
Bridge 404[2]	820	820	820	820	800	790	780	790	3	4	5	4

[1] For B12 the highest permissible loads are regarding the "normal passage" due to TungTransport not having an implemented "mid road, alone on bridge" model for this bridge.
[2] For B404 2, 3, and 4 meters have the following requirement: Mid-road, alone on bridge.

Table E.5: Highest permissible load (P) for various other bridges and test-trucks with 2 or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]				(Brk – TT) / TT [%]	
	Brokontrollen		TungTransport			
Nr. of axles	2	5	2	5	2	5
Bridge 273[1]	420	390	350	310	20	26
Bridge 361[1]	820	770	1120	990	-27	-22
Bridge 347[1]	660	850	730	690	-10	23
Bridge 270[1]	520	480	510	510	2	6
Bridge 28[1]	800	750	1010	930	-21	-20
Bridge 324[1]	740	640	650	970	14	-34

[1] The highest permissible loads are regarding the "normal passage" due to TungTransport not having an implemented "mid road, alone on bridge" model for this bridge.

Table E.6: Highest permissible load (P) for various other bridges and test-trucks with 5 or 2 meters between two axles of the truck; each test-truck has only two axles. Brk stands for Brokontrollen and TT for TungTransport.

	Highest permissible load (P) [kN]				(Brk – TT) / TT [%]	
	Brokontrollen		TungTransport			
Axle dist. [m]	5	2	5	2	5	2
Bridge 273[1]	420	340	350	260	20	31
Bridge 361[1]	820	720	1120	840	-27	-14
Bridge 347[1]	660	670	730	630	-10	6
Bridge 270[1]	520	400	510	420	2	-5
Bridge 28[1]	800	660	1010	890	-21	-26
Bridge 324[1]	740	540	650	650	14	-15

[1] The highest permissible loads are regarding the "normal passage" due to TungTransport not having an implemented "mid road, alone on bridge" model for this bridge.

E.2. Lower- and upper-bound analysis

Table E.7: Data from Table 5.6, as well as new data from the Theoretical Method with two lanes for test-trucks with a varying number of axles and a total load length of five meters. Values for shear critical cases are not computed). Brk stands for Brokontrollen and TM1 stands for Theoretical Method with one lane. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load for moment utilization < 1.0 [kN]								(Brk – TM1) / TM1 [%]			
	Brk				TM1							
Nr. of axles	2	3	4	5	2	3	4	5	2	3	4	5
Bridge 1	-	-	570	550	350	390	370	360	-	-	46	45
Bridge 2	-	550	560	550	400	390	370	360	-	41	51	53
Bridge 79	440	-	-	620	350	500	460	430	26	-	-	44
Bridge 128	-	-	660	630	310	430	430	410	-	-	53	54

Table E.8: Data from Table 5.6, as well as new data from the Theoretical Method with two lanes for test-trucks with a varying number of axles and a total load length of five meters. Values for shear critical cases are not computed). Brk stands for Brokontrollen and TM2 stands for Theoretical Method with two lanes. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load for moment utilization < 1.0 [kN]								(Brk – TM2) / TM2 [%]			
	Brk				TM2							
Nr. of axles	2	3	4	5	2	3	4	5	2	3	4	5
Bridge 1	-	-	570	550	640	720	690	660	-	-	-17	-17
Bridge 2	-	550	560	550	620	650	620	600	-	-15	-10	-8
Bridge 79	440	-	-	620	450	630	820	780	-2	-	-	-20
Bridge 128	-	-	660	630	460	700	790	750	-	-	-16	-16

Table E.9: Highest permissible load (P) that gives a moment utilization less than 1.0 for different integral slab bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TT stands for TungTransport and TM1 stands for Theoretical Method with one lane. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load for moment utilization < 1.0 [kN]								(Brk – TM1) / TM1 [%]			
	TT				TM1							
Nr. of axles	2	3	4	5	2	3	4	5	2	3	4	5
Bridge 1	570	570	540	530	350	390	370	360	63	46	46	47
Bridge 2	630	590	560	540	400	390	370	360	58	51	51	50
Bridge 79	470	630	540	570	350	500	460	430	34	26	17	33
Bridge 128	430	530	470	460	310	430	430	410	39	23	12	12

Table E.10: Highest permissible load (P) that gives a moment utilization less than 1.0 for different integral slab bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TT stands for TungTransport and TM2 stands for Theoretical Method with two lanes. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load for moment utilization < 1.0 [kN]								(TT – TM2) / TM2 [%]			
	TT				TM2							
Nr. of axles	2	3	4	5	2	3	4	5	2	3	4	5
Bridge 1	570	570	540	530	640	720	690	660	-11	-21	-22	-20
Bridge 2	630	590	560	540	620	650	620	600	2	-9	-10	-10
Bridge 79	470	630	540	570	450	630	820	780	4	0	-34	-27
Bridge 128	430	530	470	460	460	700	790	750	-7	-24	-40	-39

Table E.11: Highest permissible load (P) that gives a moment utilization less than 1.0 for different integral slab bridges and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TM1 stands for Theoretical Method with one lane and TM2 stands for Theoretical Method with two lanes. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load for moment utilization < 1.0 [kN]								(TM1 – TM2) / TM2 [%]			
	TM1				TM2							
Nr. of axles	2	3	4	5	2	3	4	5	2	3	4	5
Bridge 1	350	360	350	280	640	720	690	660	-45	-50	-49	-58
Bridge 2	400	380	340	280	620	650	620	600	-35	-42	-45	-53
Bridge 79	350	350	350	300	450	630	820	780	-22	-44	-57	-62
Bridge 128	310	290	300	280	460	700	790	750	-32	-59	-62	-63

Table E.12: Table E.13: Data from Table 5.7, as well as new data from the Theoretical Method with two lanes for test-trucks with a varying number of axles and a total load length of five meters. Values for shear critical cases are not computed). Brk stands for Brokontrollen and TM1 stands for Theoretical Method with one lane. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load for moment utilization < 1.0 [kN]								(Brk – TM1) / TM1 [%]			
	Brk				TM1							
Axle dist. [m]	5	4	3	2	5	4	3	2	5	4	3	2
Bridge 1	-	-	-	-	350	360	350	280	-	-	-	-
Bridge 2	-	470	470	400	400	380	340	280	-	24	38	43
Bridge 79	440	470	-	410	350	350	350	300	26	34	-	37
Bridge 128	-	-	-	-	310	290	300	280	-	-	-	-

Table E.14: Table E.15: Data from Table 5.7, as well as new data from the Theoretical Method with two lanes for test-trucks with a varying number of axles and a total load length of five meters. Values for shear critical cases are not computed). Brk stands for Brokontrollen and TM2 stands for Theoretical Method with two lanes. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load for moment utilization < 1.0 [kN]								(Brk – TM2) / TM2 [%]			
	Brk				TM2							
Axle dist. [m]	5	4	3	2	5	4	3	2	5	4	3	2
Bridge 1	-	-	-	-	640	640	560	490	-	-	-	-
Bridge 2	-	470	470	400	620	580	530	440	-	-19	-11	-9
Bridge 79	440	470	-	410	450	440	460	420	-2	7	-	-2
Bridge 128	-	-	-	-	460	470	480	470	-	-	-	-

Table E.16: Highest permissible load (P) for different integral slab bridges and test-trucks with a total load length of 5, 4, 3, or 2 meters; each test-truck has only two axles. TT stands for TungTransport and TM1 stands for the Theoretical Method with one lane. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load for moment utilization < 1.0 [kN]								(TT – TM1) / TM1 [%]			
	TT				TM1							
Axle dist. [m]	5	4	3	2	5	4	3	2	5	4	3	2
Bridge 1	570	560	480	440	350	360	350	280	63	56	37	57
Bridge 2	630	570	500	450	400	380	340	280	58	50	47	61
Bridge 79	470	470	470	390	350	350	350	300	34	34	34	30
Bridge 128	430	430	420	340	310	290	300	280	39	48	40	21

Table E.17: Highest permissible load (P) for different integral slab bridges and test-trucks with a total load length of 5, 4, 3, or 2 meters; each test-truck has only two axles. TT stands for TungTransport and TM2 stands for the Theoretical Method with two lanes. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load for moment utilization < 1.0 [kN]								(TT – TM2) / TM2 [%]			
	TT				TM2							
Axle dist. [m]	5	4	3	2	5	4	3	2	5	4	3	2
Bridge 1	570	560	480	440	640	640	560	490	-11	-13	-14	-10
Bridge 2	630	570	500	450	620	580	530	440	2	-2	-6	2
Bridge 79	470	470	470	390	450	440	460	420	4	7	2	-7
Bridge 128	430	430	420	340	460	470	480	470	-7	-9	-13	-28

Table E.18: Highest permissible load (P) for different integral slab bridges and test-trucks with a total load length of 5, 4, 3, or 2 meters; each test-truck has only two axles. TM1 stands for Theoretical Method with one lane and TM2 stands for Theoretical Method with two lanes. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load for moment utilization < 1.0 [kN]								(TM1 – TM2) / TM2 [%]			
	TM1				TM2							
Axle dist. [m]	5	4	3	2	5	4	3	2	5	4	3	2
Bridge 1	350	360	350	280	640	640	560	490	-45	-44	-38	-43
Bridge 2	400	380	340	280	620	580	530	440	-35	-34	-36	-36
Bridge 79	350	350	350	300	450	440	460	420	-22	-20	-24	-29
Bridge 128	310	290	300	280	460	470	480	470	-33	-38	-38	-40

E.3. Impact of mid-bridge models

Table E.19: Highest permissible load (P) for Bridge 79 computed with different mid-bridge alternatives and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data is without the influence of the dynamic factor.

Bridge 79		Highest total load (P) [kN]			
Nr. of axles		2	3	4	5
Brokontrollen		510	630	660	620
TungTransport	Alternative 1: Mid-bridge model Mid-bridge A/B-values Result-lines only mid-bridge	470	570	570	570
	Alternative 2: Normal model Mid-bridge A/B-values Result-lines only mid-bridge	440	550	540	630
	Alternative 3: Normal model Mid-bridge A/B-values Results-lines over the whole bridge	440	470	470	490

Table E.20: Highest permissible load (P) for Bridge 79 computed with different mid-bridge alternatives and test-trucks a total load length of 5, 4, 3, or 2 meters; each test-truck has two axles. TungTransport data is without the influence of the dynamic factor.

Bridge 79		Highest total load (P) [kN]			
Axle distance [m]		5	4	3	2
Brokontrollen		510	470	470	410
TungTransport	Alternative 1: Mid-bridge model Mid-bridge A/B-values Result-lines only mid-bridge	470	470	430	370
	Alternative 2: Normal model Mid-bridge A/B-values Result-lines only mid-bridge	440	430	400	360
	Alternative 3: Normal model Mid-bridge A/B-values Results-lines over the whole bridge	440	400	350	320

Table E.21: Highest permissible load (P) for Bridge 128 computed with different mid-bridge alternatives and test-trucks with 2, 3, 4, or 5 axles; each test-truck has a total load length of five meters and equal distances between axles. TungTransport data is without the influence of the dynamic factor.

Bridge 128		Highest total load (P) [kN]			
Nr. of axles		2	3	4	5
Brokontrollen		520	650	660	630
TungTransport	Alternative 1: Mid-bridge model Mid-bridge A/B-values Result-lines only mid-bridge	400	470	470	460
	Alternative 2: Normal model Mid-bridge A/B-values Result-lines only mid-bridge	630	610	660	680
	Alternative 3: Normal model Mid-bridge A/B-values Results-lines over the whole bridge	480	510	540	500

Table E.22: Highest permissible load (P) for Bridge 128 computed with different mid-bridge alternatives and test-trucks a total load length of 5, 4, 3, or 2 meters; each test-truck has two axles. TungTransport data is without the influence of the dynamic factor.

Bridge 128		Highest total load (P) [kN]			
Axle distance [m]		5	4	3	2
Brokontrollen		520	480	480	430
TungTransport	Alternative 1: Mid-bridge model Mid-bridge A/B-values Result-lines only mid-bridge	400	370	350	320
	Alternative 2: Normal model Mid-bridge A/B-values Result-lines only mid-bridge	630	470	450	420
	Alternative 3: Normal model Mid-bridge A/B-values Results-lines over the whole bridge	480	460	420	370

E.4. Impact of varying axle width

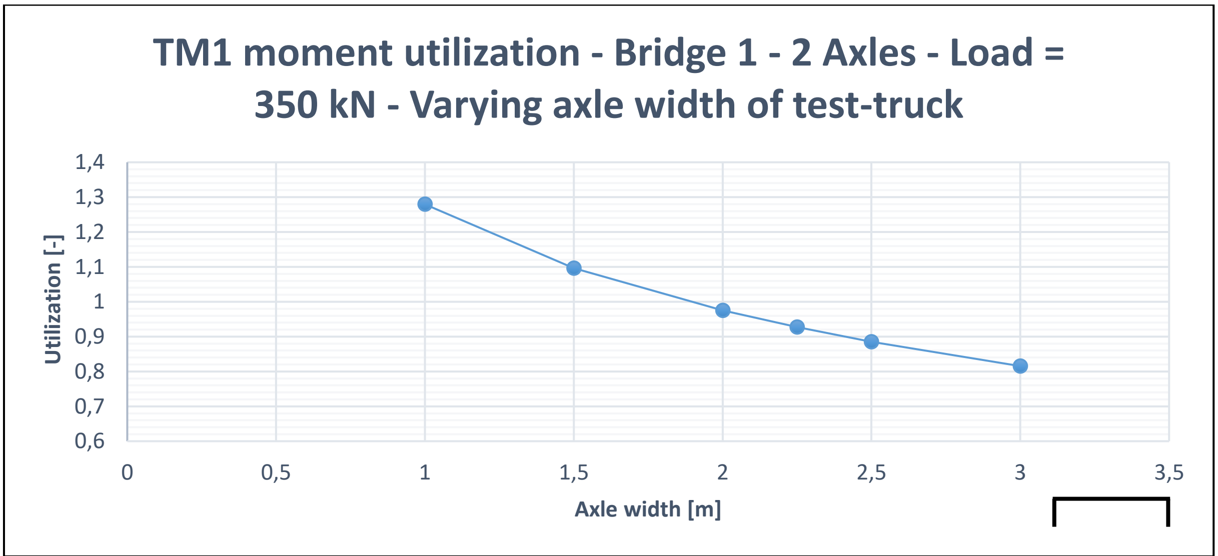


Figure E.1: Bridge 1 – one span integral slab bridge (plattrambro). Moment utilization from the Theoretical Method for varying axle widths of a test-truck with a 350 kN total load distributed over two axles with a total load length of five meters. TM stands for Theoretical Method. Furthermore, a small side-view sketch of the bridge is provided (bottom right, not to scale).

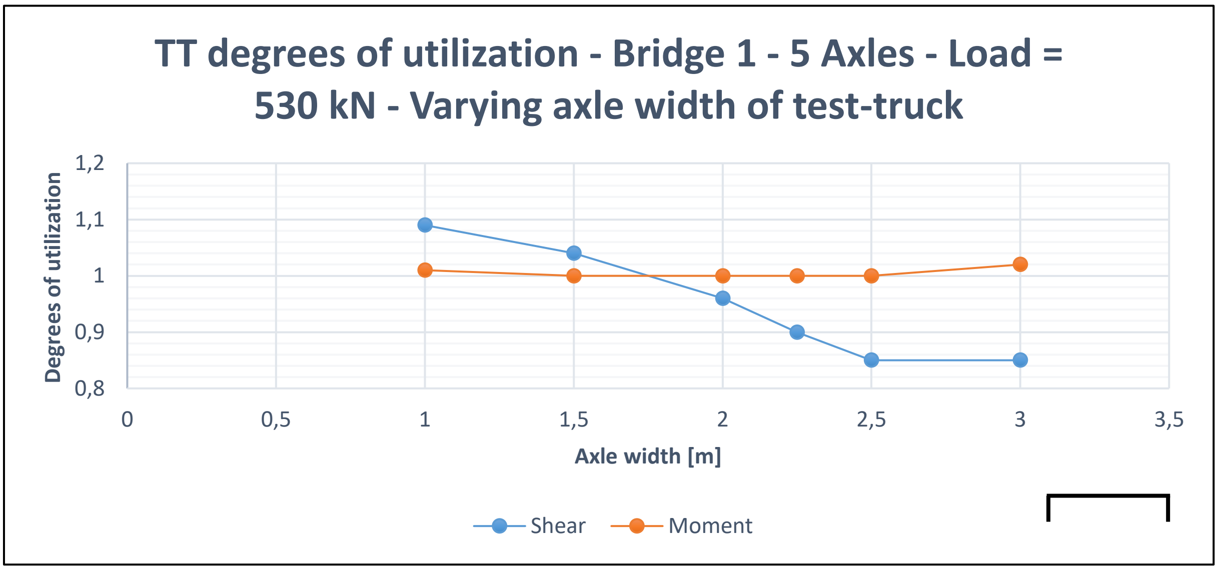


Figure E.2: Bridge 1 – one span integral slab bridge (plattrambro). Degrees of utilization from TungTransport for varying axle widths of a test-truck with a 530 kN total load distributed over five axles with a total load length of five meters. TT stands for TungTransport. Furthermore, a small side-view sketch of the bridge is provided (bottom right, not to scale).

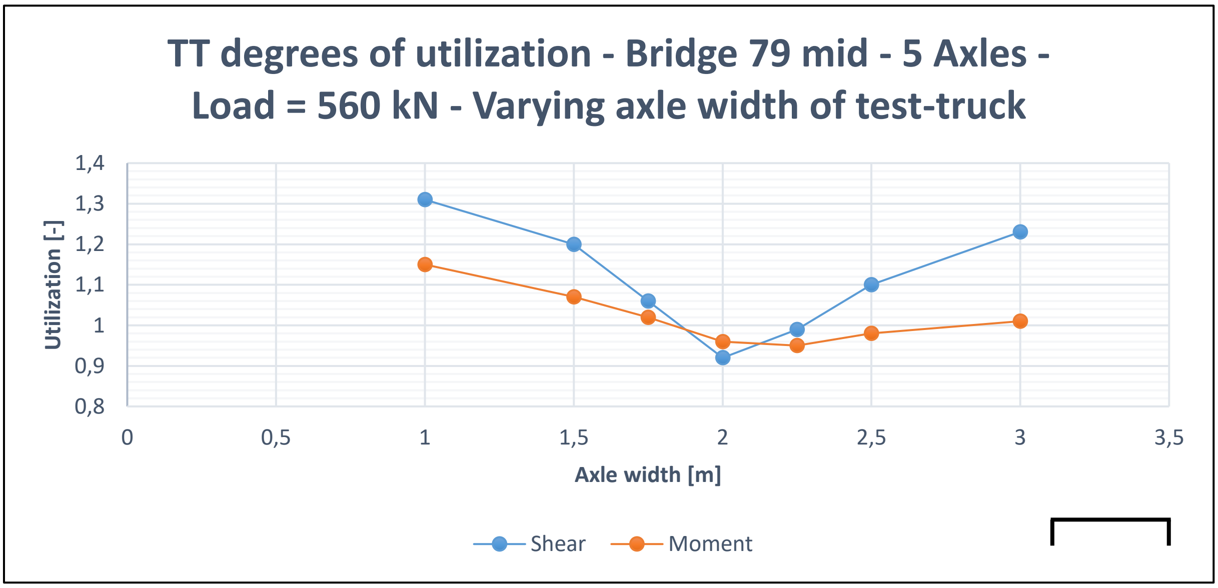


Figure E.3: Bridge 79 (evaluated mid bridge, alone on bridge) – one span integral slab bridge (plattrambro). Degrees of utilization from TungTransport for varying axle widths of a test-truck with a 560 kN total load distributed over five axles with a total load length of five meters. TT stands for TungTransport. Furthermore, a small side-view sketch of the bridge is provided (bottom right, not to scale).

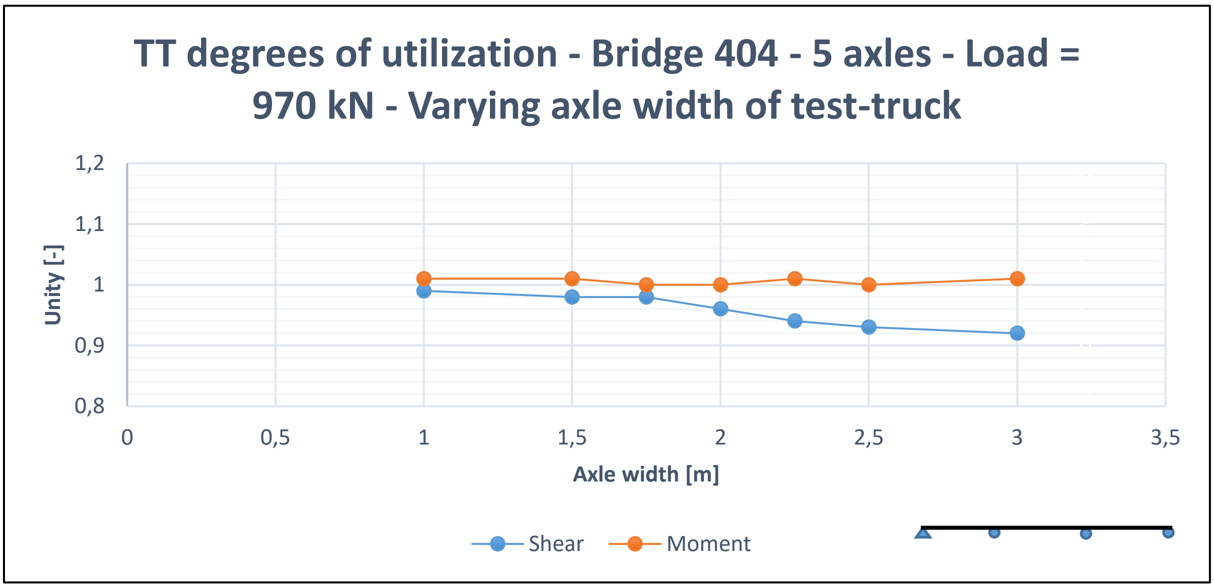


Figure E.4: Bridge 404 – three span girder bridge. Degrees of utilization from TungTransport for varying axle widths of a test-truck with a 970 kN total load distributed over five axles with a total load length of five meters. TT stands for TungTransport. Furthermore, a small side-view sketch of the bridge is provided (bottom right, not to scale).

E.5. Impact of failure modes

Table E.23: Highest total load with respect to failure modes for different bridges and test-trucks with 5, 4, 3, or 2 meters between two axles of the truck; each test-truck has only two axles. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load given by TungTransport [kN]							
	Moment utilization < 1.0				Shear utilization < 1.0			
Nr. of axles	2	3	4	5	2	3	4	5
Bridge 1	570	570	540	530	540	550	550	540
Bridge 2	630	590	560	540	600	600	590	570
Bridge 79	470	630	590	570	490	570	570	600
Bridge 128	430	530	470	460	440	470	480	480
Bridge 12	390	380	390	370	340	360	370	350
Bridge 404	860	1000	990	960	1080	1020	1020	990

Table E.24: Highest total load with respect to failure modes for different bridges and test-trucks with 5, 4, 3, or 2 meters between two axles of the truck; each test-truck has only two axles. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load given by TungTransport [kN]					
	Moment utilization < 1.0		Shear utilization < 1.0		Stress utilization < 1.0	
Nr. of axles	2	5	2	5	2	5
Bridge 273[1]	420	340	370	330	-	-
Bridge 361[1]	1210	1070	1260	1160	-	-
Bridge 347[1]	780	740	1030	950	-	-
Bridge 270[1]	800	660	550	550	730	610
Bridge 28[1]	1250	1300	1090	1000	1160	1210
Bridge 324[1]	1220	840	830	840	700	990

Table E.25: Highest total load with respect to different failure modes for different bridges and test-trucks a total load length of 5, 4, 3, or 2 meters; each test-truck has two axles. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load given by TungTransport [kN]							
	Moment utilization < 1.0				Shear utilization < 1.0			
Axle dist. [m]	5	4	3	2	5	4	3	2
Bridge 1	570	560	480	440	540	490	450	410
Bridge 2	630	570	500	450	600	560	500	450
Bridge 79	470	470	430	370	490	470	430	370
Bridge 128	430	430	420	340	400	370	350	320
Bridge 12	390	350	310	290	340	320	280	270
Bridge 404	860	850	840	850	1080	1050	960	900

Table E.26: Highest total load with respect to different failure modes for different bridges and test-trucks a total load length of 5, 4, 3, or 2 meters; each test-truck has two axles. TungTransport data has been adjusted to remove the dynamic factor.

	Highest total load given by TungTransport [kN]					
	Moment utilization < 1.0		Shear utilization < 1.0		Stress utilization < 1.0	
Axle dist. [m]	5	2	5	2	5	2
Bridge 273[1]	420	300	370	290	-	-
Bridge 361[1]	1210	900	1260	1010	-	-
Bridge 347[1]	780	680	1030	860	-	-
Bridge 270[1]	800	570	550	450	730	530
Bridge 28[1]	1250	960	1090	1220	1160	1120
Bridge 324[1]	1220	890	830	700	700	700

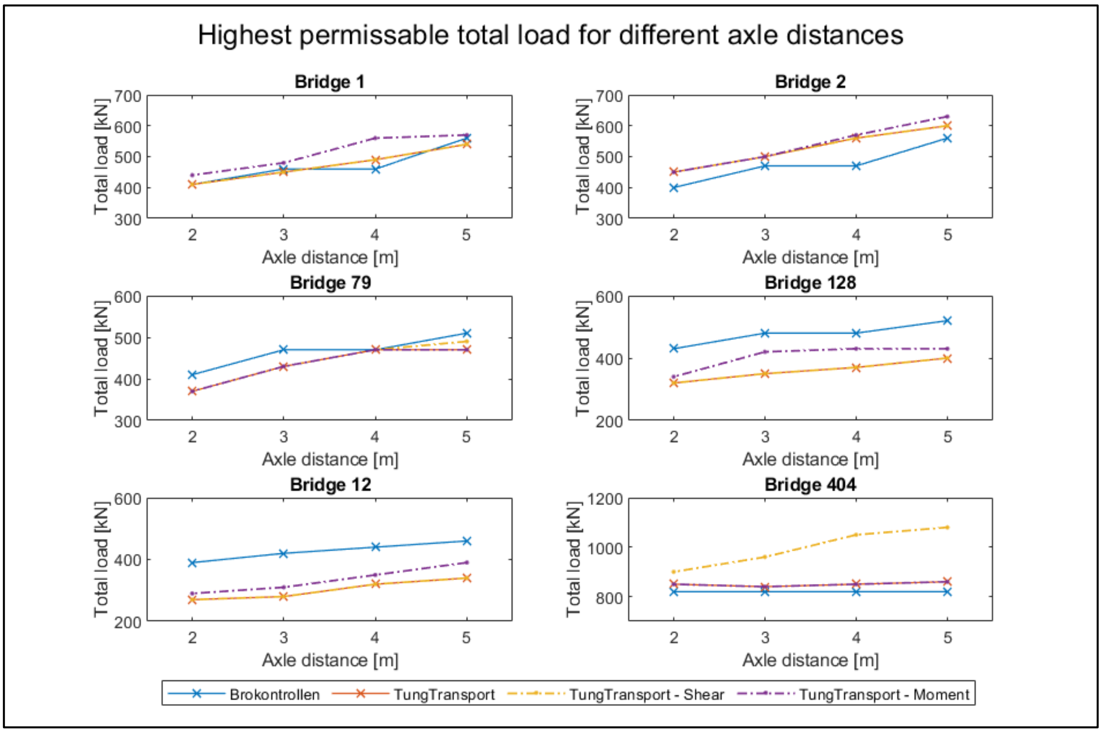


Figure E.5: Highest permissible load (P) that gives a shear or moment utilization less than 1.0 for different bridges and test-trucks with a total load length of 5, 4, 3, or 2 meters; each test-truck has only two axles. TungTransport data has been adjusted to remove the dynamic factor.

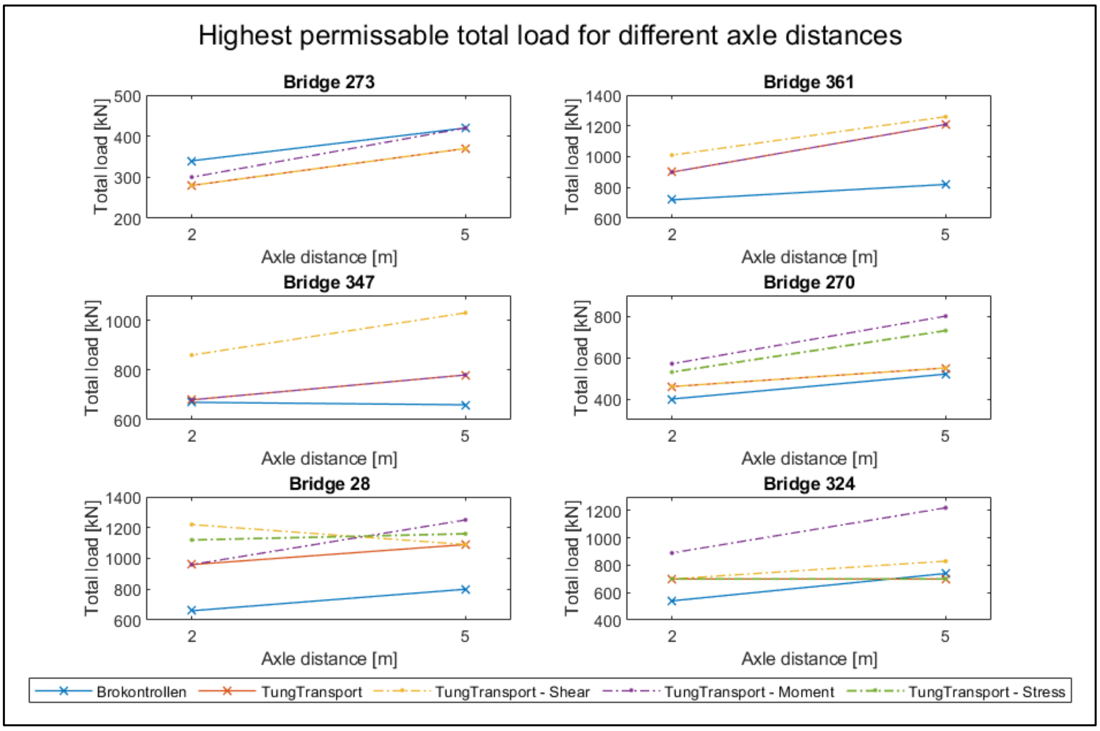


Figure E.6: Highest permissible load (P) that gives a shear or moment utilization less than 1.0 for different bridges and test-trucks with a total load length of five or two meters; each test-truck has only two axles. TungTransport data has been adjusted to remove the dynamic factor.