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Safety and dynamic factors for determining the military load capacity of road bridges

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For efficient military transport, the load capacity of bridges must be classified. This can be done in several ways. A quick and sufficiently accurate method of classification is to compare loads (moments). The procedure requires finalising the values of the safety and dynamic factors for different concurrency cases. This document reviews the conditions and circumstances under which these factors can be determined.

KEYWORDS: overload transport, STANAG 2021, AEP-3.12.1.5, road bridges, heavy equipment transport, load capacity

A közúti hidak katonai teherbírásának meghatározásához tartozó biztonsági és dinamikus tényezők

A hatékony katonai közlekedéshez a hidak teherbírását be kell sorolni. Ez többféle módszerrel végezhető. Gyors és kellően pontos besorolási módszer az igénybevételek összehasonlítása. Az eljáráshoz véglegesíteni kell a biztonsági és dinamikus tényezők értékét, a különböző egyidejűségi esetekre. Jelen tanulmány áttekinti a tényezők meghatározásának feltételeit és körülményeit.

KULCSSZAVAK: túlsúlyos szállítás, STANAG 2021, AEP-3.12.1.5, közúti híd, nehéz katonai szállítás, híd teherbírás

Introduction

Most military road transport uses civilian road infrastructure typically. Military vehicles sometimes may have different loads and dimensions to civilian vehicles. The frequency and several characteristics of the two types of traffic (civil and military) are different. For planning and conducting military road transport a military load classification of road bridges and military vehicles has to be carried out.

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The Allied Engineering Publication 3.12.1.5 (AEP) Military load classification of bridges, ferries, rafts and vehicles issued by NATO Standardization Agreement 2021 (STANAG 2021 establishes a uniform procedure for the load classification of military vehicles and road bridges for the NATO operations in the territory of member countries. (Hereafter, I will refer to the Agreement together with the underlying standard as STANAG 2021. The text of the AEP standard refers to itself as STANAG 2021.) The standard includes 16 classes of tracked vehicles and 16 classes of wheeled vehicles. Bridges are to be classified in these classes. A particularly sensitive point in the static calculation is the magnitude of the safety factors and dynamic factors, for which no values are given in STANAG 2021, as these are to be determined under national competence.

The magnitude of the safety factors and dynamic factors depends on the standard used for the design of the bridge, the simultaneity considered, and the calculation procedures used. No previous studies or publications have been carried out on the use of STANAG 2021 in Hungary, which would have addressed these factors. In this paper, I will review the theoretical considerations on the factors, the recommendations in the standard international publications, and give a proposal for the definition of Hungarian factors.[1]

What is safety?

All static calculations involve taking a risk. There is no risk-free scaling, but the risk can be very small.[2] The risk assumed is dependent on the total loss in the event of a breakdown. This is a complex search for an optimum.

The static calculation of structures is based on a semi-probabilistic approach. Some of the effects can be modelled with probability distributions, some are not. Such a procedure is used both in the Hungarian civil bridge design code and in the Eurocode.

In the design process, the load capacity of a structure, the technical requirements and the design margin or safety must be determined. The amount of safety depends on the risk to be taken.

The risk is given by mathematical methods as a function of the design working life. The design working life can be short term, temporary, semi-permanent, permanent, and monumental. It is unnecessary to demonstrate that the approach to determining the design working life is different for civil and military calculations. From a military point of view, the design working life can be as short as one week.

Knowing the probability of occurrence and design working life, the expected return time can be determined. The characteristic value commonly used in civil bridge design for road vehicle loads is a return period of 1,000 years (for a design working life of 50 years with a 5% probability of non-passage, the exact value of the return period is 975 years, rounded to 1,000 years).[3]

1 Sia 2021.

2 Mistéth 2001, 29.

3 Mistéth 2001, 33.

If the design working lifetime is much shorter, e.g. 1.5 years instead of 50 years, the same 5% probability implies a return period of 30 years (instead of 975 years, i.e. 1/32.5).

Bridges are built to carry the payload of the structures that pass over them. The mix of civil traffic is very varied. It is not known how many heavy trucks and how many light small cars will be on a bridge at any one time. It is possible that only heavy trucks will be on a bridge at any one time although the probability of this is small but not impossible. The probability is a function of traffic volume, traffic jam, etc. There is uncertainty that the actual weight of civilian trucks also depends on whether the carrier is following the rules.

Military traffic is characterised by discipline and punctuality. The weight of military vehicles can be determined more accurately and used in the calculation with a more precise value than for civilian trucks. Military convoy movement is much more regular and uniform than civilian traffic. For example, the following distance in civilian traffic depends on the individual decision of each driver (and on the traffic rules of the country). The following distance in military traffic depends on the movement orders given. The same applies to speed and other traffic parameters.

An important difference between civil and military traffic is that in civil traffic the probability of occurrence of the heaviest vehicle can be given by normal distribution (e.g. one time per month for the first 10 years of its life). In military traffic the measured heaviest vehicle is actually in the convoy, so its movement is a quasi-certain event, with a small relative variance.

The components of safety

In the design of structures such as bridges, safety is considered in terms of both action and resistance. The reliability of a bridge, i.e. the overall safety, is the sum of the individual safety measures.

On the action side, safety is provided by the characteristic value of the loads, which is typically higher than the value actually expected. This difference is larger for civil loads and smaller for military loads. The Military Load Classification (MLC) of military vehicles should be carried out in such a way that the load of the ideal vehicle pursuant to STANAG 2021 is always less favourable than the vehicle actually in motion.[4]

On the action side, the safety factors comprise the most significant part of the safety. in accordance with the current Hungarian bridge design code, the safety factor for dead load is 1.15 and the safety factor for live load is 1.35.[5] The Hungarian civil bridge design standard is currently changing; the new standard adopts the Eurocode values, so the safety factor for both dead and live load will be 1.35.[6]

Safety of action side is also reflected in the inclusion of the dynamic factor. In the current Hungarian bridge design specification, the dynamic factor is a function of

4 STANAG 2021, 5.1.

5 e-UT 07.01.12, 18–19.

6 MSZ EN 1990:2011.

the span, for example 1.25 for a span of 20 m. According to Eurocode and the new Hungarian specification that is under development, there is no separate dynamic factor, but the live load value includes the dynamic effect. For an overload vehicle, if the speed is low (< 5 km/h), there is no dynamic effect, however, at normal speed (around 70 km/h) the dynamic effect varies linearly between 1.4 and 1.0 as a function of the bridge span between supports, e.g. 1.36 for a 20 m distance between supports. However, Oliva's study[7] shows that below 15 km/h the dynamic factor can be omitted.

Safety also appears on the resistance side. This can be observed, for example, when determining the strength of materials.

Typically, on the action side, the factors are increased for safety, and on the resistance side, the factors are decreased.

Recommendations for the safety factor of STANAG 2021

The referenced engineering publication issued by NATO STANAG 2021 aims to ensure that all military vehicles and bridges concerned have an MLC. If the vehicle's classification is less than that of the bridge, the vehicle can pass safely.

In accordance with Annex A of STANAG 2021, there are 16 crawler- and 16 tire-ideal load conditions, there are four types of concurrency cases (situations), there are five levels of expertise, and there are nine types of classification procedures (assessment levels[8]).

The concurrency cases specify how military vehicles should be placed on the bridge and whether or not there is concurrent civilian traffic on the bridge. I have added a fifth case to the four cases[9] under STANAG 2021. In the concurrency case, called Axis, there is no concurrent civilian traffic, the bridge has a military convoy in single file on the axis of the bridge (Axis) and there is no speed limit.

This fifth concurrency case (Axis) the best serves the traffic of heavily loaded military vehicles and heavy equipment transport. If there is no civilian traffic, then the bridge load capacity does not need to be shared between military and civilian. If the convoy is in the middle of the bridge, the bridge load capacity is much more favourable. If there is no speed limit, the journey time is as short as possible.

I have developed a symbol system for providing a uniform designation for bridge load rating in limne with STANAG 2021, as shown in *Figure 1*. (Annex J of the referenced STANAG 2021 gives the standard of signs on bridges and rafts giving all of the information of classification about a given bridge to help the drivers or the convoy commanders make a decision whether to go or not to go across the bridge. The marking proposed here is for official use only. They should not be used on bridges.) The concurrency cases are illustrated in *Figure 2.*

7 Oliva 2012, 35.

8 STANAG 2021, K-30.

9 STANAG 2021, 6.1.2.

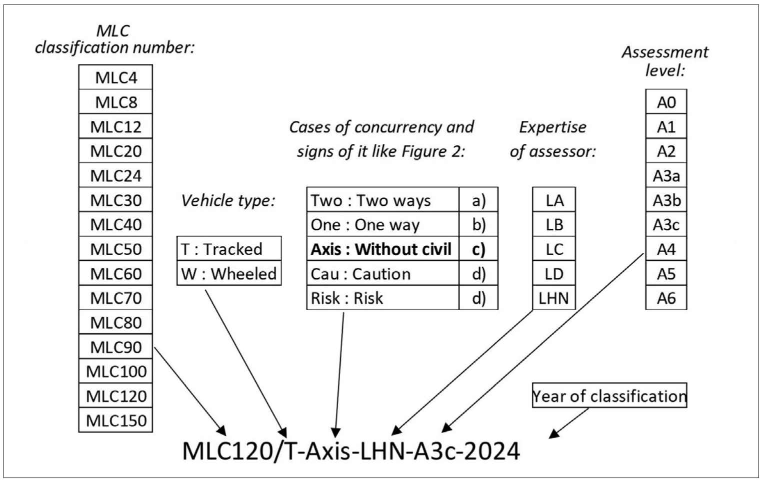

Figure 1.
Proposal for a standardised marking of the MLC for road bridges
(Edited by the Author)

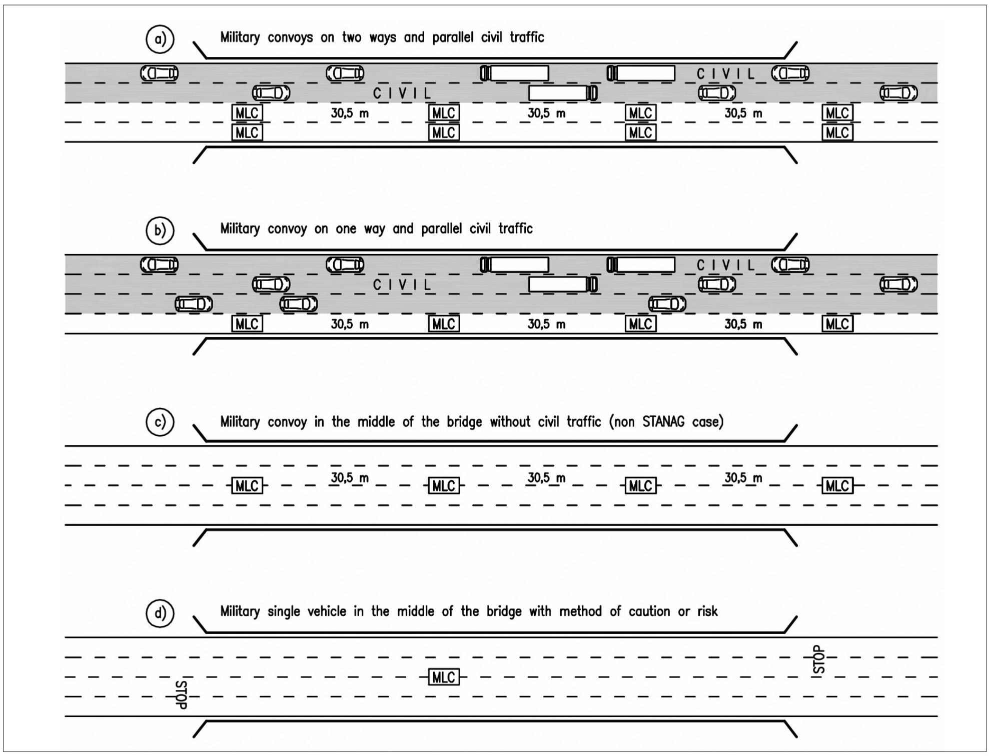

Figure 2.
Vehicle coincidence cases for military load classes (Drawing by the Author)

In accordance with STANAG 2021, the inclusion of the safety factor and the dynamic factor is a national competence.[10] The annexes to STANAG 2021 provide recommendations. For the cases of a cautious and risk concurrency, the standard states that no dynamic effect should be taken into account[11]

The working part of the Paper of Work (PoW 5) working group "Concept for Safety factors for Analytical Assessment of Existing Bridges for Military Use according to Civil Codes by Qualified Personnel" in Annex K[12] of the standard contains the following:

Safety factors (their modification) should only be considered for detailed calculation based procedures (Assessment levels 5-6-7) and only for qualified personnel (Level of Expertise C, D, HN). In accordance with STANAG 2021, no modification of safety factors is required for the bending moment comparison method.[13]

After detailed theoretical considerations[14] based on a reliability index, STANAG 2021 gives lower safety factors (*Table 1*).

Table 1.
Proposal to reduce the safety factor
(Based on STANAG 2021, edited by the Author)

	Dead load		MLC		MLC-corrigated	
Original	1,35		1,50		1,35	
Normal, with low dynamic	1,19	-46%	1,33	-34%	1,23	-34%
Normal, with medium dynamic	1,19	-46%	1,40	-20%	1,28	-20%
Caution	1,19	-46%	1,22	-56%	1,15	-56%
Risk, for 1 week	1,18	-49%	1,19	-62%	1,13	-62%
Risk, for 4 weeks	1,16	-54%	1,16	-68%	1,11	-68%
Risk, for 1 year	1,16	-54%	1,16	-68%	1,11	-68%

The factors for dead load and MLC in Table 1 are based on the Eurocode as defined by Roman Lenner in his PhD thesis.[15] Lenner's research results have been adopted in STANAG 2021. The base case factor of safety for the payload is taken as 1.5, which is only true for high structures, as for bridges it is 1.35.[16] If the base case factor of safety is taken as 1.35, the values in Table 1 should be corrected accordingly. The correction can be approximated by the percentage reductions given. This will give smaller values for the MLC partial factors shown in the table (e.g. 1.23 instead of 1.33).

There is no independent dynamic factor in Eurocode. The payload includes the dynamic effect. In Table 1 there is no dynamic factor for the cautious and risk case.

10 STANAG 2021, 6.1.5.-6.1.6.
11 STANAG 2021, H-2.
12 STANAG 2021, K-35 – K-51.
13 STANAG 2021, K-35.
14 Lenner et al 2014.
15 Lenner 2014.
16 Hajós 2024.

The safety factors given are lower than the original factor because the safety and dynamic effects have been reduced. The total reduction is given as a percentage in the table. The ratio of the normal to the cautious factors gives the dynamic factor for the normal cases, which is included in the factor above. For low dynamic effect (1.33/1.22 =) 1.09, for medium dynamic effect (1.40/1.22 =) 1.15. For cautious and risky 1.00, i.e. no dynamic excess.

Dynamic factor

The interaction between a moving road vehicle and a bridge causes an additional load compared to the static load, which can be taken into account by a dynamic factor. The dynamic effect is influenced by many factors. The dynamic effect depends on the suspension of the axis of vehicle, its damping, the number of wheels, the speed of the vehicle, the total mass of the vehicle, the span of the bridge, the first natural frequency of the bridge, the damping of the bridge, the defects of the carriageway.

In bridge design specifications, the dynamic effect is simplified. In many design specifications, the dynamic factor is a function of the span, with a larger span having a smaller dynamic factor. Other factors affecting the dynamic effect are not taken into account.

Eurocode has combined the dynamic effect and the base value of the payload. The payload of the vehicle includes the dynamic effect, so that in Eurocode the dynamic effect is independent of the spans.

A special case in the Eurocode is the analysis of overweight vehicles, because an overweight vehicle load does not include a dynamic effect. The Eurocode therefore only gives a dynamic factor for overweight vehicles (*Figure 3*).

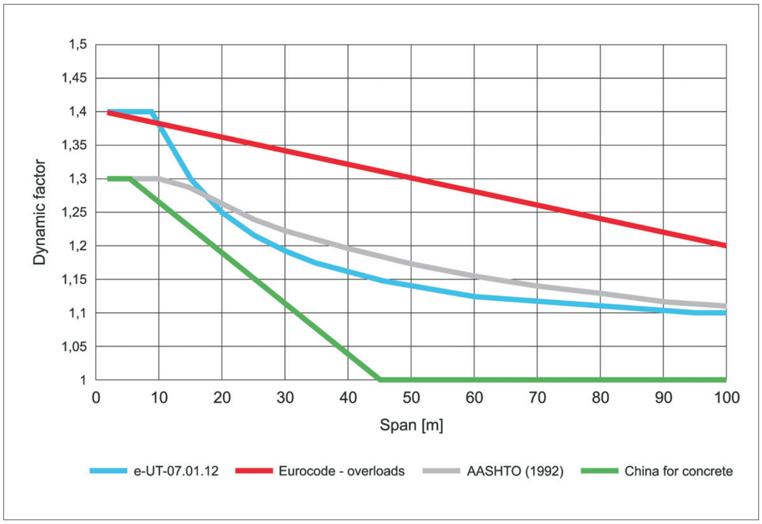

Figure 3.
Dynamic coefficient up to 100 m span
(Edited by the Author)

In Figure 3, I have also given the US specification: the dynamic factor is similar to the Hungarian specification, but the maximum value is 1.3 instead of 1.4, and for larger openings it is 1-3% higher.[17]

Some countries have separate factors for steel and reinforced concrete bridges. An example is the Chinese bridge design standard. In China, the dynamic factor for steel bridges is essentially the same as in the US, but the dynamic factor for reinforced concrete bridges (Figure 3) is much lower, with no dynamic effect above 45 m.[18]

In Canada, the dynamic coefficient is determined as a function of the natural frequency of the bridge's first flexural frequency between 1.2 and 1.4.[19]

The higher the mass of the vehicle, the higher the nominal value of the dynamic surplus effect, so it is worth considering this issue in more detail. The dynamic effect is difficult to model. When the palm of the hand strikes the surface of the water, the resistance of the water is greater than when the load is applied slowly. The same phenomenon can be observed in dynamic tests of bridges. For dynamic loading, Hook's law does not apply, the structure behaves in a non-linear elastic way.

The dynamic effect is significantly influenced by the suspension of the axels of vehicles. An excellent example is an agricultural tractor (e.g. MTZ-80, total weight 3,600 kg/8,000 pounds). A single light agricultural tractor can generate waves in a steel bridge with a 100 m span. This is because the MTZ-80 effectively excites the steel bridge under test.

We can also observe differences due to the type of suspension of the vehicle. Conventional trucks have air suspension. Multi-axle vehicles designed for heavy transport have a special suspension. The axles of a Heavy-Duty Modules trailer are suspended by oil-hydraulic circuits. The hydraulic circuits ensure that the axles in one circle are equally loaded. The behaviour of the suspension of these axles is quite different from that of air-sprung axles.

The greater the total mass of a vehicle, the more axles it has. For example, if the total weight of a vehicle is 250 tonnes, it typically has 22 axles. Such a vehicle is also long, for example 30 m. It can be seen that the interaction between such a vehicle and the bridge is completely different from that of a light agricultural tractor with two axles. The suspension of the many axles partially balances each other. It can be said that the greater the total mass of a vehicle, the smaller the dynamic effect will be.[20]

We can model the suspension and damping of the vehicle, also examining the behaviour in 3D. A simple model of a vehicle with three axles and two wheels on each axle is shown in Figure 4. It is easy to see that if the overweight vehicle has many axles, then the quasi-rigid trailer is supported at many points, and that the axles of overweight vehicles typically have four independent suspension wheels, so the model is more complex transversely.

At any one moment in time, the suspension and damping of the many independent suspension wheels are in different phases, so they cannot aggregate,

17 AASHTO 1992.
18 Everitt 2019, 16.
19 OHBDC 1983.
20 Lenner 2014, 79.

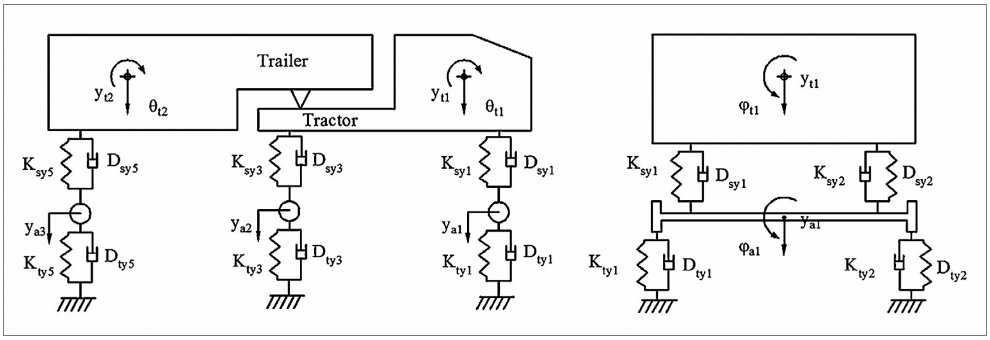

Figure 4.
Vehicle model (length and cross-section)[21]
(Edited by the Autor)

effectively counteracting to each other. For this reason, the dynamic effect will be smaller.

So far, I have only looked at wheeled vehicles. However, a significant proportion of military vehicles are not wheeled but tracked. Let us look at the dynamic effects of a tracked vehicle.

No bridge design code deals with the dynamic effect of tracked vehicles.[22] The subject of Antonty Everitt's thesis was an experimental measurement-based study. He compared the dynamic effects of four military vehicles on the same bridge structure. The experiment was carried out in Canada on a road bridge with a 29.6+32.9 m span. Three different wheeled vehicles (a five-axle heavy equipment transporter with a gross weight of 50.4 tonnes, a four-axle military vehicle with a gross weight of 27.5 tonnes, a three-axle military vehicle with a gross weight of 26.1 tonnes) and a Leopard 2 tank with a gross weight of 63.2 tonnes were used for the measurements.[23] Without specific testing, a dynamic coefficient of 1.15 is recommended for military vehicles in the United States and Canada.[24]

Everitt modelled the possible unevenness and damage of the road surface by placing wooden obstacles on the road. A total of 90 different passage cases with the four vehicles were measured. These included a measurement with an undamaged road surface and a measurement with a damaged road surface modelled with wooden barriers. The measurements were taken at different speeds (10, 20, 30, 40 and 50 km/h).

The results show that the dynamic impact of wheeled vehicles was one and a half times[25] that of tracked vehicles on a faultless road surface and five times[26] that of tracked vehicles on a damaged road surface with obstacles.

21 Deng et al 2015.
22 Everitt 2019.
23 Everitt 2019, 33–34.
24 Everitt 2019, 11.
25 Everitt 2019, 50.
26 Everitt 2019, 75.

For military vehicles a dynamic coefficient of 1.15 is proposed as a standard for the military load rating of bridges in a 2005 German-English-American study.[27]

In his doctoral thesis, Lenner examines the dynamic coefficient of tracked vehicles in detail.[28] He cites the recommendations of Homberg, who carried out his research in 1970. He maximised the dynamic coefficient for tracked vehicles at 1.1.[29]

Proposal for normal case crossings

The proposals presented give a reduction of the safety factor. The published proposals are the results of a probabilistic procedure based on the analysis of confidence levels. The mathematical methods used for this purpose are applied to the design of military operations and to the evaluation of the military load capacity of bridges. There is a detailed literature on this procedure.[30]

The aim of my research is to determine the factors that can be used for an approximate method of classifying bridges. Only mathematically based proposals for modifying the safety factors are available in the literature for detailed structural analysis. These values are subject to detailed calculation. What can be done for an approximate procedure?

The safety factors given for a detailed calculation can also be used for calculations using the load or bending moment comparison method. In such a case, it is sufficient to compare the effects of the vertical load of the payload of the original bridge standard vehicle and the vertical load of the military vehicle (including, where appropriate, the simultaneous civilian traffic). A simple comparison gives a simple and reliable result.

In the case of a comparative method, the ratio of dead weight to payload can only be estimated. Therefore, for the higher level of safety, it is proposed to leave the safety factor for dead loads unchanged in a comparative method and to apply the lower safety factor only to the live load. In all cases, the standard payloads should be calculated with the safety factor of the original standard. Therefore, to use the comparative method, it is also necessary to be familiar with the old bridge standards.

It is worth mentioning that the load transfer of tracked vehicles is assumed to be uniformly distributed over the deck, although we know that this is not always true in reality.[31] Since the length of the track shoe is typically short (e.g. 5 m), the global effect of the unevenness within the track is not significant and is therefore negligible. The only significant impact would be for bridges with small openings, but then the solo axis would be the dominant load.

I suggest that the dynamic factor should be refined based on further research and measurements. The literature suggests that the dynamic factor for tracked vehicles should be maximised at 1.1. After the necessary, more detailed analysis of

27 Hornbeck et al 2005, 18.
28 Lenner 2014, 80–81.
29 Homberg 1970.
30 MacDonald et al 2016.
31 MacDonald et al 2017, 140.

the vehicle-bridge interaction, I propose to maximize the dynamic coefficient[32] for wheeled vehicles above 800 kN with a value of 1.1, considering the many independent suspension axles.

For the calculation of the normal case, it is still necessary to fix the ideal load for simultaneous civil traffic. The base value of the congested freight traffic load, with upper estimate, is 23,125 kN/rm per lane. The same for passenger cars 2,86 kN/rm.[33]

The road traffic load combined with military traffic has a major impact on the MLC of the bridge. Further research and technical discussions are needed to finalise the lane load representing civilian traffic. I propose to set it per lane and in dependence on the number of lanes used by civil traffic. A specific rule should be developed for the case of a divided carriageway over a bridge and a common superstructure loaded by two-way traffic lanes. Fortunately, there are only a few bridges of this type in Hungary, so they can be classified separately after a more detailed analysis.

Proposal for axis and caution cases

In the Axis case and caution and risk cases of STANAG 2021, the military vehicle is on the axis of the bridge and there is no concurrent civilian traffic.

In these cases, it is possible to take advantage of the bridge cross-distribution. When designing a bridge, a heavy vehicle should be placed at the edge of the bridge, which is less favourable than a heavy vehicle traveling in the middle of the bridge. This advantage can be easily quantified.

A method should be developed. The procedure should be specified separately for each bridge structure type. In this context, it is possible to limit the width of the simultaneous distributed load considered on the standard side.

Proposal for risk case

The most detailed investigation and analysis is required for the risky case. In addition to the mathematics-based factors, a comparative method may also take into account the allowable damage.

How does a bridge structure fail? A bridge structure can fail by fracture or loss of stability.

The overall safety for total bridge failure depends on the material and the structure. For reinforced concrete bridges, this can be up to 3.8 times the design load.[34] Few bridge loads to failure have been carried out. Safety associated with bridge failure is typically high when there is no stability risk. The passage with risk case allows little damage to the bridge. What might be small damage?

As minor damage, I recommend conditions related to frequent or operational loads (e.g. fatigue, cracking of reinforced concrete). Small damage could be the

32 MacDonald et al 2020.

33 Hajós 2023.

34 Zhang et al 2009.

formation of a ductile hinge over an intermediate pier in a multi-span reinforced concrete bridge (two-span model instead of multi-span).

The allowable damage shall be specified separately for reinforced concrete bridges, steel bridges and vaults.[35]

The majority of the Hungarian bridges is prefabricated reinforced concrete girder bridges. Since the introduction of the 1986 Bridge Code, it has been analysed to limit cracks in prestressed reinforced concrete. The design of such bridges is based on the service load. It is easy to see that if some small defect (cracking) is allowed, the load capacity of the bridge can be increased by about 20-40%. The calculation can be done with a modifying factor for the bridge type. The modification factor can be determined by further testing.

Summary

The classification of the load capacity of bridges can be carried out using the load and bending moment comparison method. This procedure is fast and sufficiently accurate. The procedure requires the determination of the safety factors, the dynamic factors, and the load replacing the simultaneous civil traffic.

I have shown that the factors recommended in STANAG 2021 can be used with this method, and that more favourable factors for safety and dynamic factors can be considered. The procedure requires finalisation and validation of the factors. Further studies and research are proposed for this purpose.

With the successful implementation of the comparative method, the inexpensive and fast classification of many bridges will be possible.

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35 Zizi et al 2024.

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