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Journal:	*2010 Joint IABSE-fib Conference*
Manuscript ID:	IABSE-0282-2010.R1
Theme:	Additions to Future Codes
Keywords:	Existing Structures

UPDATING OF TRAFFIC LOADS ON EXISTING BRIDGES

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Keywords: Existing structures, updating, traffic loads, dynamic amplification factor, codes for existing structures, examination.

Abstract: *In the examination (often referred to as "assessment") of existing bridges, a modern approach consists in updating traffic loads based on traffic data and structural properties of the bridge to be investigated. The future Swiss Code SIA 269/1 on "Actions on existing structures" will introduce such updated traffic loads. These have been determined from traffic measurement data considering structural behaviour and static traffic load and actual dynamic amplification effects on existing bridges. The principle idea of the suggested approach is to define specific load models depending on the character of the traffic line or to determine so-called updating factors that are multiplied with the characteristic values of the traffic load models as defined in the code valid for new structures. In addition, dynamic amplification effects are deduced from both elastic and non-elastic structural behaviour of bridge elements at limit states. This approach is applied for the deterministic verification of structural safety, serviceability and fatigue safety of existing bridges.*

This rational approach will provide the basic tool to demonstrate that many existing bridges fulfil the requirements of structural and fatigue safety as well as serviceability of current and future traffic loading.

1. INTRODUCTION

For the examination (often referred to as "assessment") of existing bridges, most structural engineers apply the codes and in particular load models valid for the design of new bridges. This is a problematic approach since the codes for design and construction of new structures, called "design codes" thereafter, are in principle not or only analogously applicable to existing structures.

The professional approach to existing structures is based on an inherent methodology that essentially includes collecting actual information since the structure exists. Actual road and rail traffic data may be obtained and the action effect of traffic loading on structural elements may depend on the type of structure.

It may be shown that load models used in design codes in Europe (and Switzerland) largely cover actual and future traffic loading. These heavy load models are justified for new construction with the argument to provide significant load carrying reserves for the case of much higher traffic loads in the long term future since strengthening of existing bridges usually is a costly operation. Load models in design codes may thus be seen as a reference describing an upper bound enveloping traffic loading covering the long term of more than 80 years.

For the same reason, i.e., to avoid strengthening unnecessary for the current and future (up to 30 years) traffic loading, updated load models considering actual site specific data have to be used for the examination of existing bridges.

The objective of the examination of existing bridges is to show that the requirements are fulfilled regarding:

- the Ultimate Limit State ULS through verification of the structural safety,
- the Serviceability Limit State SLS through the verification of the serviceability,
- the Fatigue Limit State FLS through the verification of the fatigue safety.

Updated traffic models are thus needed for all three kinds of verification. This paper presents a rational approach to define updated traffic load models.

2. BASIC APPROACH

The basic approach of updating traffic action effects consists in considering (static) loads Q and q (axle and line loads respectively) as well as forces due to dynamic traffic effects. The updated action effect $E_{updated}$ of traffic loads may be expressed in two ways :

- the characteristic traffic load values from the design code, i.e. $Q_k(designcode)$, are multiplied with an updating factor α_i to consider actual and future traffic loads as well as specific existing bridge type. Dynamic traffic effects are already integrated in $Q_k(designcode)$:

  $$E_{updated} = E[\alpha_i \cdot Q_k(designcode)] \qquad (1)$$

  In the present article, this approach is used for updating *road* traffic loads, Section 3.
- Static traffic loads are updated considering actual and future traffic on a given traffic line. The resulting updated characteristic value $Q_{k,updated}$ usually is – for convenience – the same irrespective of the limit state to be verified. Forces occurring in the bridge

structure due to dynamic traffic action are expressed by a dynamic amplification factor φ_i which depends on the limit state considered, e.g. ULS, SLS or FLS, (Section 5):

$$E_{updated} = E(\varphi_i \cdot Q_{k,updated}) \tag{2}$$

In the present article, this approach is used for updating *rail* traffic loads, Section 4.

3. UPDATED *ROAD* TRAFFIC MODELS

The Swiss road network is equipped with several weigh-in-motion installations which provide permanently traffic data. Based on this data, a load model for road traffic in Switzerland limited by a legal truck weight of 40 tons, has been recently developed [1] to verify existing roadway bridges regarding structural safety and serviceability. This model has been established according to the following approach:

- the first stage consisted in analysing the weigh-in-motion measurement results in order to define a traffic model which approximates as closely as possible the real traffic. Using software developed on purpose, traffic from the measuring stations could be modelled and compared.
- A traffic simulation program was then developed to virtually pass the various modelled traffic cases on several types of bridges. Various cross sections (box, twin-beam, multi-beam and slab), static systems and spans were analysed for various configurations and traffic situations. For all investigated cases, the program provided the distribution of the maximum internal forces in the bridge structure, recorded for a defined period of simulation (considering implicitly a dynamic amplification factor, according to Fig. 2a.
- Finally, the results of the simulations were compared with internal force values calculated using the load model of the SIA 261 design code [2] (Fig. 1). It was noted that the values obtained from the simulation on the basis of traffic measured in 2003 were about 50% lower overall than those calculated with the SIA 261 load model. The SIA 261 code for the design of new bridges thus includes a significant reserve compared to the current traffic.

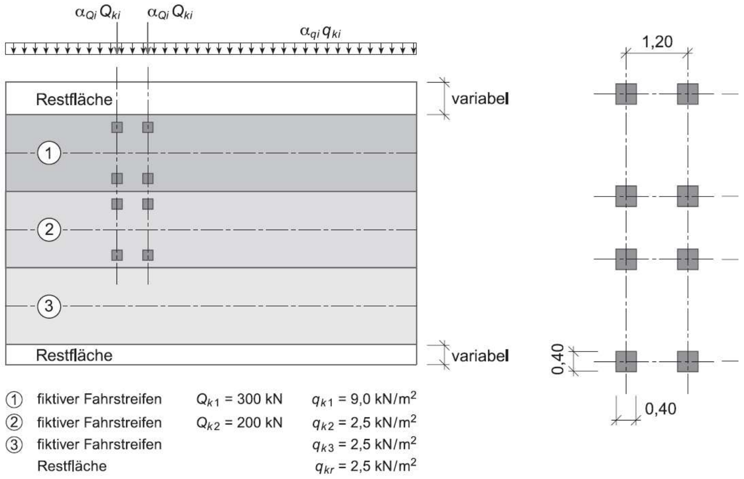
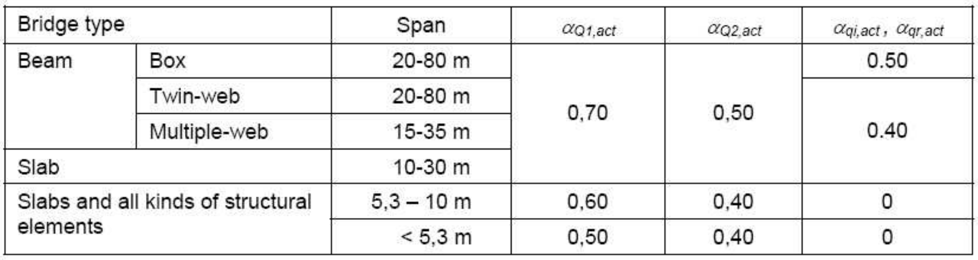


Figure 1: Road traffic model as defined in the Swiss design code (dimensions in m) [2].

Assumptions were made to consider the future evolution of the traffic over a time span up to 20 years. Parametric studies were carried out which made it possible to define a correction to be applied to the results of the simulations to consider these forecasts in the updated model.

The proposed updated model involves the approach according to equation (1), i.e., application of the SIA 261 design load model with updating factors α. These coefficients were established by dividing the simulated internal forces with those calculated according to the design code. The various quotients obtained were relatively constant and they were round up to the first decimal. In this way, it was possible to provide a simple updated model, i.e. the updating factors α are in fact independent of the span, the type of internal force and the road type; only the effect of the bridge type was differentiated (Table 1).

Table 1: Updating factors for road traffic on road bridges with two lanes (bidirectional traffic) and highway bridges with two lanes (unidirectional traffic) [3].



Bridge type		Span	$\alpha_{Q1,act}$	$\alpha_{Q2,act}$	$\alpha_{qi,act}$, $\alpha_{qr,act}$
Beam	Box	20-80 m	0,70	0,50	0.50
	Twin-web	20-80 m			0.40
	Multiple-web	15-35 m			
Slab		10-30 m			
Slabs and all kinds of structural elements		5,3 – 10 m	0,60	0,40	0
		< 5,3 m	0,50	0,40	0

This study shows that the use of the design code for the evaluation of existing road and highway bridges is in fact very conservative for the traffic expected in the next 20 years. Then, data from traffic load monitoring will be analysed and it will be decided whether the updating factors α need to be modified.

In addition, for bridges carrying roadways with a width up to 6m, the updating factors may be further reduced to the following values : $\alpha_{Q1,act}$ = 0,50, $\alpha_{Q2,act}$ = 0,40 und $\alpha_{qi,act}$ = 0,40. If the roadway is smaller than 5.4m a single lane is considered only.

In the case of signalised load limitations, traffic load models are updated considering nominal axle loads and geometric properties of the allowed road traffic, in case supplementary safety measures (such as vehicle weight control) guaranties observation of the imposed load limit.

4. UPDATED *RAIL* TRAFFIC MODELS

Railway infrastructure operators in Europe categorize their lines into international line classes according to UIC code 700-O [4]; a reference carriage with axle geometry and axle loads is defined as a load model for each line class (Table 2). Trains of an unlimited number of reference carriages create an effect that covers the effect of all allowed carriages on the given railway line class.

Dynamic action effects are taken into account by the dynamic amplification factor φ_i according to Section 5 which is multiplied with the updated axle load. The updated rail load model follows thus the approach according to equation 2.

Table 2: Reference carriages for line classes C3, D4, E4 and E5 (P: axle load) [3].

Line class	Updated axle load $Q_{k,updated}$ [kN]	Spacing of updated axle loads in [m] for 1 reference carriage 2 x $Q_{k,updated}$ 2 x $Q_{k,updated}$
C3	200	1,5 ↓ 1,8 ↓ 4,50 ↓ 1,8 ↓ 1,5 11,10
C4	200	1,5 ↓ 1,8 ↓ 3,40 ↓ 1,8 ↓ 1,5 10,00
D3	225	1,5 ↓ 1,8 ↓ 5,90 ↓ 1,8 ↓ 1,5 12,50
D4	225	1,5 ↓ 1,8 ↓ 4,65 ↓ 1,8 ↓ 1,5 11,25
E4	250	1,5 ↓ 1,8 ↓ 5,90 ↓ 1,8 ↓ 1,5 12,50
E5	250	1,5 ↓ 1,8 ↓ **4,75** ↓ 1,8 ↓ 1,5 **L = 11,35**

The updated axle loads multiplied with updated dynamic amplification factors represent about 30 to 50 % smaller loading than the SIA 261 design load consisting of 4 axle loads of 325kN and axle spacing of 1.6m as well as a line load of 104kN/m', both loads being multiplied with a dynamic amplification factor.

It is interesting to note that measurements of actual rail traffic loading indicate that axle loads higher than the ones covered by the load models occur occasionally. For example, [5] reports for the determinant case of a railway line with frequent and heavy freight traffic that 0.2% of all measured axle loads were up to a maximum of 10% higher than the allowed axle load. Partial safety factor for load effect takes account for overloaded axles. Since overloaded axles occur as single events unfavourable effects of overloaded axles are however limited to short spans, i.e. ranging from 2 to about maximum 10m.

5. CONSIDERATION OF DYNAMIC TRAFFIC EFFECTS

In order to obtain realistic dynamic amplification factors, the corresponding structural behaviour at the various limit states (i.e. ULS, SLS, FLS) has to be considered [6-8]. While at SLS and FLS the structural bridge behaviour is elastic, structural safety verification at ULS is usually performed considering plastic behaviour of cross sections and structural elements. As a consequence, dynamic amplification factors are derived in the following for plastic and elastic structural behaviour respectively.

5.1. Plastic structural behaviour at ULS with significant deformation capacity

At ultimate limit state ULS, structural elements in reinforced and prestressed concrete and in steel provide significant plastic deformation due to yielding of the steel. In statically undetermined systems, the plastic deformation capacity of the structural elements is usually not fully consumed by internal redistribution of cross sectional forces. In this case, deformation induced by dynamic forces may also be dissipated by the structural element.

However, in contrast to earthquake engineering, the so-called “gravity effect” consumes a considerable part of the available total dissipation capacity of the structure, i.e., both the forces due to traffic loads and gravity forces due to permanent loads act in the same direction, both leading to (external) work (energy) that the structural elements has to dissipate by plastic deformation.

Ludescher [7] and Herwig [8] showed by means of simple dynamic models how the external work (energy) due to dynamic action effects (i.e. impact-like events, excitation by surface irregularities) is easily dissipated in common structural elements before the element fully fails (fractures). Theses studies show among others that:

- the most unfavourable scenario for bridge elements is the impact-like excitation of passing vehicles by singular irregularities.
- bridge elements will most probably always fail in bending after significant plastic deformation if subjected to excessive dynamic traffic action effects. More brittle failure mechanisms like predominant shear failures are less likely to occur.
- the required dissipation capacity increases with the intensity of the excitation and the stiffness of the vehicle, and decreases with the stiffness of the structure.
- marked strain hardening in the structural response increases significantly the dissipation potential.
- resonance oscillation energy may also be dissipated by plastic deformations of the structural element.

The calculations indicate that only a small partition of the remaining dissipation capacity (after taking into account energy dissipation due to the gravity effect and internal redistribution) is needed to dissipate the energy due to dynamic rail traffic action effects. In reality, even less dissipation energy is necessary as the bridge structure changes its dynamic properties in terms of fundamental frequency after yielding and early plastic deformations, which leads to high damping before the virtual elastic stationary state is reached.

From these investigations follows that in the case of plastic structural behaviour at ULS the maximum static action effect due to train loads does not need to be amplified by a factor for considering dynamic rail traffic action effects, or $\varphi_{ULS} = 1.0$.

5.2. Structural behaviour at ULS with small deformation capacity

For failure modes showing small deformation, i.e. punching of slabs or other shear-type failure modes, it is prudent to assume some amplification factor that implies the following items:

- Only extremely high single vehicle loads cause ULS relevant scenarios. This means that the amplification factor depends on the determinant length L_φ, i.e. the longer L_φ the smaller the amplification factor φ_{ULS}.
- In addition, many investigations show (f.ex. also in (Ludescher 2004) and (Herwig 2006)) that dynamic amplification is smaller with higher acting load.

As a consequence, some amplification factor for failure modes showing small deformation at ULS is suggested based on the forgoing considerations (Fig. 2a).

5.2 Elastic structural behaviour at SLS and FLS

Formulas for dynamic amplification factors are given in design codes, f.ex. in EN 1991-2 [9]. These formulas have been derived in the past to deliver “envelope curves” from measurements of elastic bridge behaviour considering also average or light weight vehicles which often provide the highest dynamic amplification effects. However, in the present case, the dynamic effect of high vehicle weight is of interest since the dynamic amplification factor is multiplied with the highest (static) traffic load.

In the case of elastic structural behaviour, dynamic effects are predominantly due to (1) vehicle velocity and (2) road/track surface irregularities:

- Significant dynamic effects due to excitation from vehicle velocity only occur with regular axle spacing in narrow velocity domains of several vehicles which is very unlikely in the case of road traffic and rather seldom in the case of rail traffic.
- Dynamic amplification effects for high traffic loads are distinctly lower than for vehicles with lighter loads as has been shown by many investigations. In particular, wheel force amplification and corresponding action effects (forces) in a bridge element due to surface irregularities decrease with increasing vehicle weight.
- Dynamic amplifications due to both vehicle velocity and surface irregularities should not just be superposed to obtain the total dynamic amplification factor, as it is rather unlikely that the maximum dynamic effect of both effects occurs at the same time for the occasional case of a heavy vehicle.

From these considerations follows that formulas in design codes often provide unrealistically high dynamic amplification factors.

As a consequence and since the static load considered in the SLS and FLS verifications is extreme (high), following dynamic amplification factors are suggested (Fig. 2b):

- At *serviceability limit state SLS*, it must be taken into account that *occasional* values of dynamic action effects need to be considered since insufficient serviceability of the roadway deck or rail track could lead to a safety problem. A φ_{SLS} -value ranging from 1.3 to 1.15 is suggested for structural elements with up to 20m influence length; no dynamic effects need to be considered for influence lengths longer than 40m.
- At *fatigue limit state FLS*, *frequent* values of dynamic action effects are considered to represent service conditions. A φ_{FLS} -value ranging from 1.15 to 1.05 is suggested for structural elements with up to 20m influence length; no dynamic effects need to be considered for influence lengths longer than 40m.

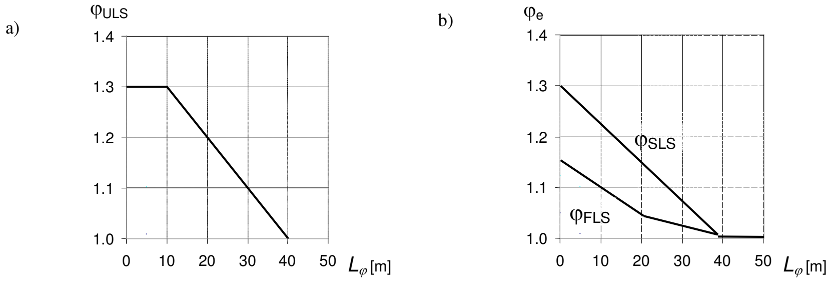


Figure 2: Dynamic amplification factor : a) at ULS for failure modes with *small* deformation, and b) at SLS and FLS for elastic structural behaviour.

6. CONCLUSIONS

Updated traffic load models are derived for the deterministic verification of structural safety, serviceability and fatigue safety of existing road and railway bridges. Realistic dynamic amplification factors are deduced considering both elastic and plastic structural behaviour of bridge elements at limit states.

The present rational approach is simple and reasonably conservative. It most likely provides the basic tool to demonstrate that most existing road and railway bridges in Switzerland fulfil the requirements of structural and fatigue safety as well as serviceability for both present and future traffic loading.

The present approach is applicable for most bridges. In special cases, site specific traffic measurements could be performed to determine specific load models and dynamic amplification effects.

The present approach has been integrated into the Swiss Codes of the series SIA 269 on existing structures [10], in particular SIA 269/1 on “Actions on existing structures” [3].

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