Dynamic Vehicle Impact for Safety Assessment of Bridges

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STRUCTURAL RELIABILITY THEORY
PAPER NO. 173

To be presented at the 2nd European Conference on Weigh-in-Motion of Road Vehicles, Lisbon, September 1998

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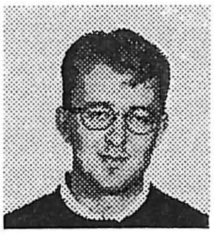

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Abstract
In this paper the dynamic amplification of vehicle load at minor highway bridges is considered for safety assessment of the load carrying capacity of bridges. The considered case is the most critical for the bridges, i.e. the simultaneous passage of two heavy trucks. A short description of the numerical modelling of the bridge and the two vehicles is given. The dynamic parameters of the vehicles and the modal parameters of the bridge are known. Only irregularities from imperfect expansion joints have been modelled as bumps at the entrance to the bridge. The results are obtained from a simulation study for different passage situations of the two heavy vehicles. Further, consequences for the safety assessment of the bridges are outlined. The results actually obtained show that the dynamic amplification factors used in the Danish and several other national regulations are too conservative.
Keywords: Dynamic amplification, heavy vehicles, dynamics of vehicles, bridge safety

Resumé
Cet article regarde le renforcement dynamique de la charge des véhicules sur petits ponts des autoroutes en vue de fixation de la sûreté de la résistance des ponts. La situation regardée est très critique pour les ponts, c.-à-d. le passage simultané de deux véhicules lourdes. Il y a une description courte du modelage numérique du pont et de deux véhicules. Les paramètres de la véhicule dynamique et les paramètres modaux du pont sont très connus. Les inégalités sur le pont modelées comme des secousses à l'entrée du pont. Les résultats sont obtenus de l'étude de la simulation pour les passage-situations différentes de deux véhicules lourdes. Encore les conséquences de la sûreté du pont son indiquées. Les résultats indiquent que les renforcement-facteurs dynamiques qui sont employés dans les normes danoises et beaucoup de normes étrangées sont trop conservateurs.
Mots-clés: Renforcement dynamique, véhicules lourdes, dynamique de véhicule, sûreté du pont.

Zusammenfassung
Dieser Artikel betrachtet dynamische Verstärkung von Last der Wagen auf kleinen Strassenbrücken in Hinblick auf Bestimmung der Sicherheit von der Tragfähigkeit der Brücken. Die betrachtete Situation ist die meist kritische Situation für Brücken, d.h. die gleichzeitige Passage von zwei schweren Wagen. Eine kurze Beschreibung der numerischen Modellierung von der Brücke und den zwei Wagen is gegeben. Die dynamischen Parameter der Wagen und die Modalparameter der Brücke sind bekannt. Die Oberflächenunregelmässigkeiten der Brücke sind am Eingang der Brücke als Rüttelschwellen modelliert. Die Ergebnissen sind von einem Simulationsstudium der verschiedenen Passage-situationen von den zwei schweren Wagen erreicht. Weiterhin sind die Konsequenzen der Siecherheit der Brücke angegeben. Die Ergebnisse zeigen, dass die dynamischen Faktoren der Verstärkung, die in dänischen und manchen ausländischen Normen gebraucht werden, zu konservativ sind.
Schlüsselwörter: Dynamischen Verstärkung, Schwere Wagen, Dynamik der Wagen, Sicherheit der Brücke.

1. Introduction

Dynamic load amplification due to vibration of a bridge structure under the passage of vehicles is an important problem in the design of bridges. Further, a common problem in bridge engineering practice in these years is the upgrading of minor highway bridges (span ≈5-35 m) to larger loadings partly due to a tendency of heavier trucks moving at larger speeds, and partly because the authorities want to permit transportation of special heavy goods at a larger part of the road net. These needs will in many cases cause that strengthening of the bridges becomes necessary. In order to keep the expenses of such strengthening projects at a minimum, it is necessary to perform accurate estimates of the dynamic amplification factor (defined as the dynamic load effect divided by the static load effect from the vehicles), so this quantity is neither over- nor underestimated.

It is very important to focus on the critical situations for the bridge safety due to vehicle load impact and not as many papers focus on cases which maybe from a academic point of view are interesting but not even with a large dynamic amplification factor are critical for the bridge safety. Further, it is important for the application of the results in a safety assessment of bridges that a statistical description of the results are obtained. A result described as the worst or the largest etc. cannot be related to other statistical modelling in the safety analysis and therefore is of minor use. For minor highway bridges the critical design scenario occurs, at the simultaneous passage of two heavy vehicles. According to the present Danish regulations in Vejdirektoratet (1996) these two heavy vehicles are taken as a lighter 50 t, corresponding to a heavy standard truck, and a heavier 100-200t vehicle, corresponding to a heavy special transport, respectively. For both vehicles the dynamic amplification factor is taken simultaneously as 1.25, which is an expensive generalization for the strengthening projects, and underlines the need for better estimation and more bridge specific determination of the dynamic amplification factor.

The present paper presents the results from a simulation study concerning dynamic amplification of minor Danish highways due to simultaneous passage of two heavy vehicles. The results are obtained using the simulation model described in Kirkegaard et al. (1997b). In sections 2 and 3 this simulation model is shortly described. Section 4 presents the simulation scenarios while section 5 gives the results from the simulations where the mean value and the coefficient of variation of the dynamic amplification of the maximum total moment in the longest span of the bridge, the total moment over the intermediate columns and the total shear force at the supports have been estimated for 50 crossings. At last conclusions are given in section 6 .

2. Simulation Model

The simulation model is based on passage of heavy vehicles on a typical Danish minor highway bridge. In the following the specifications of the vehicles and the bridge are given.

Description of the Vehicles

The heavy vehicles are a standard Scania heavy lorry (~ 48 t.) and a Goldhofer SKPH 8 special transportation (~106 t). These types of vehicles are chosen since they are some of the most common heavy vehicles in Denmark.

Description of the Scania Heavy Lorry
A Scania heavy lorry was chosen as the leightweight vehicle in the project. The Scania, see figure 1, consists of two modules, a truck-tractor and a trailer. The truck-tractor has three axles and the trailer three axles.

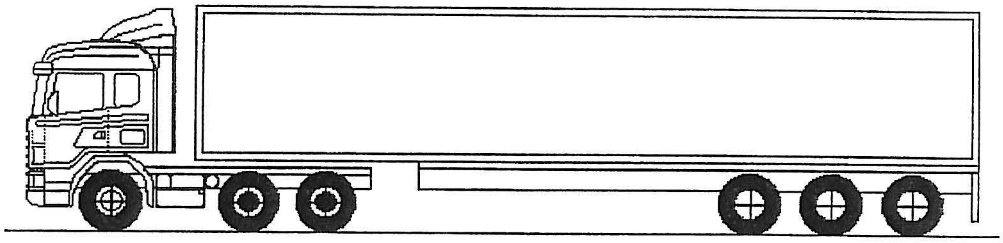

Figure 1-A Scania heavy vehicle

The Scania vehicle considered in the present study has the specifications given in table 1 (weight), table 2 (dimensions) and table 3 (axle load). These data are based on information from Ole M. Jørgensen, Scania, Denmark.

Table 1 Weight of the Scania vehicle.

Payload	Dead Weight	Gross Vehicle Load
kg	*kg*	*kg*
33839	14161	48000

Table 2 Dimension of Scania vehicle.

Width	Total Vehicle Length	Axle Spacing Tractor	Axle Spacing Trailer
m	m	m	m
2.0	16.5	2.35, 3.7	1.56

Table 3 Axle load for the Scania vehicle.

Tractor front	Tractor rear	5th Wheel Load	Trailer Axle Load
kg	*kg*	*kg*	*kg*
5249	9446, 9446	*17642*	*7953*

Based on the information from Scania the tractor has leaf springs in front and air springs in rear. No information about the trailer has been given wherefore the trailer is assumed to have leaf springs. All wheels of the vehicle are assumed to have 295/80R22.5 tyres.

Description of the Goldhofer SKPH 8 Special Transportation

A Coldhofer SKPH 8 semi lowloader vehicle is selected as the heavy special transportation vehicle at 106 t. The Coldhofer SKPH 8, see figure 2 consists of two modules, a truck-tractor and a trailer. The truck-tractor has three axles and the trailer eight axles. The heavyweight vehicle was taken as consists of eight sub-vehicles jointed together in inflexible hinges.

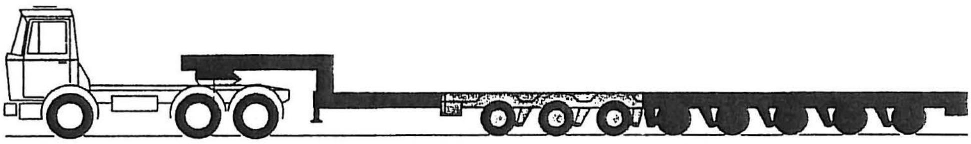

Figure 2 A Goldhofer SKPH 8

The Goldhofer SKPH 8 considered in the present study has the specifications given in table 4, (weight), table 5 (dimensions) and table 6 (axle load). These data are based on information from a Goldhofer brochure. However, the axle load for the tractor is estimated assuming a tractor with the same weight and load distribution as the Scania tractor in table 3

Table 4 Weight of the SKPH 8.

Speed	Payload	Dead Weight	Gross Weight	Gross Vehicle Load
km/h	*kg*	*kg*	*kg*	*kg*
62	70500	27000	97500	106000

Table 5 Dimension of SKPH 8.

Width	Total Vehicle Length	Loading Height	Axle Spacing Tractor	Axle Spacing Trailer
m	m	m	m	m
2.75	21.9	0.985±0.150	2.75, 4.1	1.36

Table 6 Axle load for the SKPH 8.

Speed	Tractor	Tractor	Axle Load	5th Wheel Load
km/h	*kg*	*kg*	*kg*	*kg*
62	5142	20859	8x10000	17500

No information has been given for the tractor wherefore it is assumed to have leaf springs in front and air springs in rear. All wheels of the trailer have 8.25R15PR18 tyres and the tractor wheels are assumed to have 295/80R22.5.

2.2 Description of the Bridge

The considered bridge see figure 3, is a part of the road Aasvej in the municipality of Roskilde on the island of Zealand. The bridge is considered for the project since measurements of the road irregularities exist from the stationing km 15.872 (record no. 7722) to stationing km 15.672 (record no. 9692) with 0.1 m between each record number., i.e. a road with a length of 200 m has been measured. In the present project these data have been analysed and a stochastic modelling of the surface irregularities is presented, see Nielsen et al. (1997). Elevation and cross-section details for the considered bridge are given in figure 3. The bridge super structure is a continuous deck over the two supporting columns. The supports for the deck are pinned, with rollers at all but not at the columns. From figure 3 it is seen that the total length of the bridge deck is 31.280 m. The width is 12.8 m and the deck thickness is 0.75 m. The columns are approximately 4.3 m long and have a cross section with the dimensions 1.0 x 0.6 m.

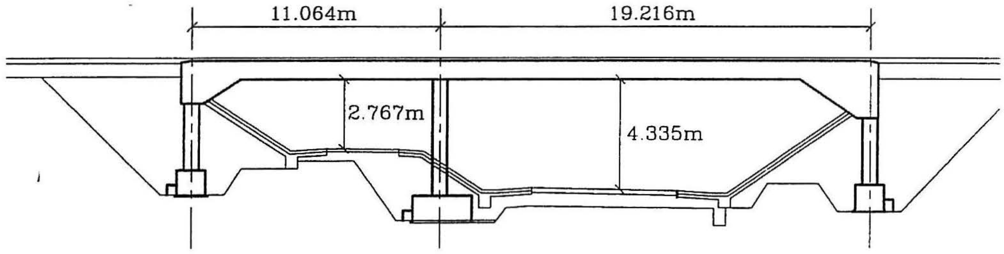

Figure 3-Elevation details for the considered bridge

2.3 Numerical Implementation

Based on the modelling of the vehicles and the bridge a PC-MATLAB 4.2 program has been developed. This program makes it possible to simulate the bridge response where the speed of the vehicles, their mutual position at opposite entrance at the bridge, the surface irregularities, the height and wavelength of the bumps, and the parameters of the vehicles can be varied.

From the dynamic analysis point of view, the vehicles are composed of the body, suspension system and tires. Each vehicle body is assumed to be represented by a distributed mass subjected to rigid-body motions. Vertical displacements, pitching and roll rotations were considered. The vehicles were modelled assuming that the two modules are linked together at a hinge, the so-called fifth wheel point, admitting rotations in all directions, i.e. only vertical forces are transmitted between the modules neglecting the roll stiffness of the fifth wheel. The modules are assumed to be infinitely stiff with the co-ordinate axes as principal axes of inertia. A local co-ordinate system is placed in the mass centre of gravity of the modules, with the three axes orientated in the vertical direction, the transversal and the longitudinal direction along the vehicle direction. The modules are free to move along the vertical direction and rotate about the two other axes. Hence, each module has three degrees-of-freedom, corresponding to the vertical displacements (heave), rotations about the transverse axis (pitch), and rotations about the longitudinal axis (roll). Each axle was modelled by two degrees-of-freedom, which were selected as the rotations about the local centre of gravity in the longitudinal direction and the translations in the vertical direction. Due to lack of information concerning the suspension system from the manufactures of the Scania and Goldhofer vehicles the spring forces and the reaction forces were modelled by the most common description of vehicle suspension hysteresis characteristics used in vehicle simulation, Kirkegaard et al. (1997c). The model for the spring forces consists of a linear spring with a spring constant in parallel with a linear viscous damping element with a damping constant and a constant Coulomb friction force. The model for the reaction forces modelling the tires consists of a linear spring with a spring constant in parallel with a linear viscous damping element with a damping constant. Based on the modelling a set of coupled first order differential equations were obtained. In order to solve the bridge response modal decomposition implemented using quasi-static correction was used. This implies that only a limited number of modes for the full problem shall be determined, and the effect of the remaining - undetermined - modes are included by an approximated static analysis. In order to model bumps at the entrance to the bridge a half sine function was used. The mode shape information used as input to the MATLAB program was obtained by modelling the bridge using the finite-element program STAAD-111, STAAD-111 (1995), assuming that the bridge can be modelled as a linear model based on a finite number of modes.

3. Simulation Scenarios with Two Vehicles

In the simulation study following simulation scenarios have been considered:

1) Goldhofer vehicle acting alone on the bridge (speed = 10, 40 and 60 km/h).

2) Scania vehicle acting alone on the bridge (speed = 10, 50 and 90 km/h).

3) Goldhofer vehicle (speed = 60 km/h) and Scania vehicle (speed = 80 km/h) entrance at the bridge from opposite directions and meets at a random position at the bridge.

Table 7 - Characteristics for stochastic variables used in the simulations. The statistical characteristics for the suspension and tyre stiffness are given for nomalized basic variables.

Basic Variable (X)	Distribution	mean (X)	std (X)
Bump height	Rayleigh	-	0.01 m
Bump wave lenght	Rayleigh	-	0.5 m
Suspension stiffness	Normal	1	0.5
Tyre stiffness	Normal	1	0.1
Starting point	Rayleigh	-	10 m

Based on a sensitivity study in Kirkegaard et al. (1997c) the most important parameters in the simulation model were chosen and modelled as stochastic variables in the simulation. This implied that for each simulation in scenarios 1 and 2, the wave length and height of the bumps at the entrance to the bridge, the stiffness of the suspension systems and the stiffness of the tyres, respectively were modelled as stochastic variables. All other parameters in the simulation model were modelled as deterministic variables. However, for simulation scenario 3 the starting points for the two vehicles were also modelled as stochastic variables in order to get different values for their mutual position at the opposite entrance at the bridge. Table 7 states the assumed statistical characteristics for the stochastic variables. The values for the deterministic parameters are given in Kirkegaard et al. (1997b).

For each simulation the dynamic amplification of the maximum total moment in the longest span of the bridge, the total moment over the intermediate columns and the total maximum shear force at the supports have been estimated. The dynamic amplification factor (DAF) is taken as the ratio of the maximum total response and the static response.

Section 4. Simulation Results

This section presents the results from the simulations where the mean value (μ) and the coefficient of variation (COV) of the DAF of the different response quantities have been estimated for 50 crossings. Unfortunately, there was not time to run enough simulations within the present project so the probability density functions for the dynamic amplification factors could be obtained with reasonable accuracy. Tables 8, 9 and 10 show the results for the three different scenarios. It is seen that the obtained DAFs are relatively small. However, the mean value of the DAFs compares very well with the results from the literature, see e.g. Kirkegaard et al. (1997a), Hwang and Nowak (1991) and Nassif and Nowak (1996). In Hwang and Nowak (1991) the DAFs of the response of prestressed concrete bridges are estimated from simulations. It is found that the mean value of the DAFs is 1.09 and 1.12 for bridges with 18m and 24m spans, respectively when one heavy vehicle (290 kN) with a speed at 97 km/h crosses the bridge. In Nassif and Nowak (1996) is was found from the field test that the actual DAF is even smaller and it does not exceed 1.1. Further, it was shown that the DAFs decrease for heavier vehicles. In both papers it was also found that the DAFs for two side-by-side vehicles were lower than for one vehicle. This result is also observed from table 10. Compared with the DAF given as 1.25 in the Danish regulations it can be concluded that this value seems to be rather conservative.

Table 8 Mean and COV results for simulation scenario 1.

Speed (km/h)	DAF of moment at mid-span	DAF of moment at intermediate support	DAF of shear force at end support
10	1.006 (0.03 %)	1.001 (0.03 %)	1.006 (0.03 %)
40	1.015 (0.12 %)	1.016 (0.10 %)	1.012 (0.10 %)
60	1.024 (0.15 %)	1.034 (0.12 %)	1.053 (0.13 %)

Table 9 Mean and COV results for simulation scenario 2.

Speed (km/h)	DAF of moment at mid-span	DAF of moment at intermediate support	DAF of shear force at end support
10	1.005 (0.09 %)	1.001 (0.05 %)	1.001 (0.11 %)
50	1.016 (1.94 %)	1.019 (1.86 %)	1.030 (2.06 %)
90	1.091 (3.19 %)	1.083 (3.33 %)	1.069 (3.18 %)

Table 10 Mean and COV results for simulation scenario 3.

Speed (km/h)	DAF of moment at mid-span	DAF of moment at intermediate support	DAF of shear force at end support
80/60	1.020 (1.85 %)	1.017 (1.83 %)	1.008 (1.88 %)

5. Conclusions

Dynamic amplification of vehicle load at minor highway bridges is investigated by a simulation study. The considered case is the most critical for the bridges, i.e. the simultaneous passage of two heavy trucks. The results from three different simulation scenarios show that the dynamic amplification factors used in the Danish and several other national regulations are too conservative. However, it is clear that before a final conclusion can be made more simulations have to be performed considering different bridges and other simulation scenarios including various types of trucks. The main conclusion which already can be drawn is that a better probabilistic and dynamic modelling of the dynamic amplification means that strengthening projects can be avoided and larger special heavy transports can be permitted without compromising the overall level of bridge safety. Hereby, considerable direct and indirect costs can be saved.

6. Acknowledgements

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