Heavy Vehicles on Minor Highway Bridges

calculation of dynamic impact factors from selected crossing scenarios

Kirkegaard, Poul Henning; Nielsen, Søren R. K.; Enevoldsen, I.

Publication date:
1997

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Kirkegaard, P. H., Nielsen, S. R. K., & Enevoldsen, I. (1997). *Heavy Vehicles on Minor Highway Bridges: calculation of dynamic impact factors from selected crossing scenarios*. Dept. of Building Technology and Structural Engineering. Structural Reliability Theory Vol. R9722 No. 172

INSTITUTTET FOR BYGNINGSTEKNIK

DEPT. OF BUILDING TECHNOLOGY AND STRUCTURAL ENGINEERING
AALBORG UNIVERSITET • AAU • AALBORG • DANMARK

STRUCTURAL RELIABILITY THEORY
PAPER NO. 172

P. H. KIRKEGAARD, S.R.K. NIELSEN, I. ENEVOLDSEN

HEAVY VEHICLES ON MINOR HIGHWAY BRIDGES - CALCULATION OF DYNAMIC IMPACT FACTORS FROM SELECTED CROSSING SCENARIOS

OCTOBER 1997 ISSN 1395-7953 R9722

Printed at Aalborg University

INSTITUTTET FOR BYGNINGSTEKNIK

DEPT. OF BUILDING TECHNOLOGY AND STRUCTURAL ENGINEERING
AALBORG UNIVERSITET • AAU • AALBORG • DANMARK

STRUCTURAL RELIABILITY THEORY
PAPER NO. 172

P. H. KIRKEGAARD, S.R.K. NIELSEN, I. ENEVOLDSEN

HEAVY VEHICLES ON MINOR HIGHWAY BRIDGES - CALCULATION OF DYNAMIC IMPACT FACTORS FROM SELECTED CROSSING SCENARIOS

OCTOBER 1997 ISSN 1395-7953 R9722

CONTENTS

1. INTRODUCTION

Vibration of a bridge structure under the passage of vehicles is an important consideration in the design of bridges. Further, a common problem in bridge engineering practice in these years is the upgrading of minor highway bridges (≈5-20 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.

For the minor highway bridges the critical design scenario occurs, at the simultaneous passage of two heavy vehicles. According to the present Danish regulations these two heavy vehicles are taken as a lighter 50 t and a heavier 100 - 150 t vehicle, respectively Vejdirektoratet (1996). For both these vehicles the dynamic amplification factor is taken simultaneously as 1.25, which is an expensive generalization for the strengthening projects, and underline the need for better estimation and more bridge specific determination of the dynamic amplification factor. This problem has initiated the research project which includes the present report including simulation results.

The principal aims of the present report are to present the results obtained using the numerical models given in details in Kirkegaard et al. (1997b). The models are established using a ordinary vehicle which consists of a 48 t Scania with a 3 axle tractor and a 3 axle trailer, jointed in a flexible hinge. Each axle is suspended on two elastic supports modelling the wheels. Further, support springs are supplied between the axle and the superstructure, modelling the suspension system of the vehicle. The heavyweight vehicle is taken as a 106t Goldhofer truck, with a 3 axle tractor and a 8 axle trailer, consisting of sub-vehicles jointed together in unflexible hinges. The dynamic response of the bridge is assumed rather insignificant for the present shortspan bridge. For this reason a truncated normal mode expansion is used, which preserves the basic quasi-static response of the bridge, and includes the dynamic response of the few lowest eigen modes. The numerical models are shortly presented in section 2. In section 3 a parameter study is performed in order to determine the most important parameters for the vehicle bridge interaction problem. Section 4 presents the results which can be used evaluate the dynamic amplification factors given in the Danish regulations. At last in sections 5, 6 and 7 conclusions, acknowledgment and references are given, respectively.

2. DESCRIPTION OF VEHICLES AND BRIDGE

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

2.1 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.

2.1.1 Description of the Scania Heavy Lorry

A Scania heavy lorry was chosen as the lightweight vehicle in the project. The Scania , see figure 2.1 consists of two modules, a truck-tractor and a trailer. The truck-tractor has three axles and the trailer 3 axles.

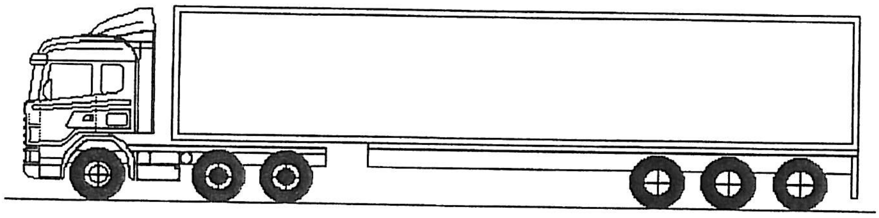


Figure 2.1 *A Scania heavy vehicle*

The Scania considered in the present study has the specifications given in table 2.1. (weight), table 2.2 (dimensions) and table 2.3 (axle load). These data are based on information from Ole M. Jørgensen, Scania Denmark.

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

Table 2.1 *Weight of the Scania vehicle.*

Width	Total Vehicle Length	Axle Spacing Tractor	Axle Spacing Trailer
m	m	m	m
2	16.5	2.35, 3.7	1.56

Table 2.2 *Dimension of the Scania vehicle.*

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

Table 2.3 *Axle load for the Scania vehicle.*

Based on the information from Scania the tractor has leaf springs in the front and air springs in the 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.

2.1.2 Description of the Goldhofer SKPH 8 Special Transportation

A 106 t Goldhofer SKPH 8 semi low loader vehicle is selected as the heavy special transportation vehicle. The Goldhofer SKPH 8, see figure 2.2 consists of two modules, a truck-tractor and a trailer. The truck-tractor has 3 axles and the trailer 8 axles.The heavyweight trailer consists of 8 sub-vehicles jointed together in unflexible hinges.

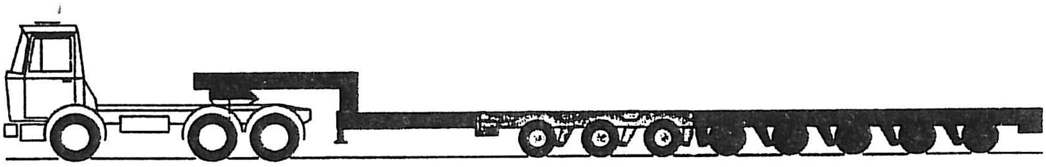


Figure 2.2 *A Goldhofer SKPH 8 .*

The Goldhofer SKPH 8 considered in the present study has the specifications given in table 2.4, (weight), table 2.5 (dimensions) and table 2.6 (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 2.30

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

Table 2.4 *Weight of the 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 2.5 *Dimension of the SKPH 8.*

Speed	Tractor Front	Tractor Rear	Axle Load	5th Wheel Load
km/h	*kg*	*kg*	*kg*	*kg*
62	5142	10429, 10429	8x10000	17500

Table 2.6 *Axle load for the SKPH 8.*

The Goldhofer SKPH 8 has a wide variety of standard equipment for steering and loading, such as:

- In conjunction with the hydraulic axle compensation unit the hydraulical lift- and lowerable *Goose-neck* allows lifting/lowering of the loading platform, i.e. a constant static loading of the tractor fifth wheel on uneven roads.

- A hydraulic axle compensation (± 150 mm) incorporating hydraulic cylinders with swivel bearings, ensures a minimum wear .

The SKPH 8 considered in this study is assumed to have axle compensation units at the bogies of the semi lowloader., i.e at all of the eight axles.

The axle compensation units at the bogies is effected by cylinders in vertical arrangement in the axle suspension units, connected with the bogie frame by means of a pivot bearing. The axle suspension units incorporate one spring unit, consisting of a dual gas pressure accumulator. The gas pressure accumulator consists of a pressure reservoir, a flexible diaphragm and a hydraulic body with a non-return valve. Upon deflection of the axle suspension units, the displaced oil from the axle compensation cylinder is supplied to the gas pressure accumulator. The diaphragm and the nitrogen of the gas-pressure accumulator damp the hydraulic oil flow, thus enabling the compression and rebound of the axle suspension units.

No information has been given for the tractor wherefore leaf springs in front and air springs in rear are assumed. 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 2.3, is a part of the road Åsvej in the municipality of Roskilde on the island Zealand in Denmark. The bridge is considered for the project since measurements of the road irregularities exist from the stationing 15.872 km (record no. 7722) to the stationing 15.672 km (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 figures 2.3 and 2.4. The bridge super structure is a continuous two spans deck over supporting columns. The supports for the deck are pinned, with rollers at all but not at the columns. From figures 2.3 and 2.4 it is seen that the total length of the bridge deck is 31.280 m, the width is 12.3 m and the deck thickness is 0.75 m. The columns are approximately 4.3 m long with cross sectional dimensions 1.0 *x* 0.6 m.

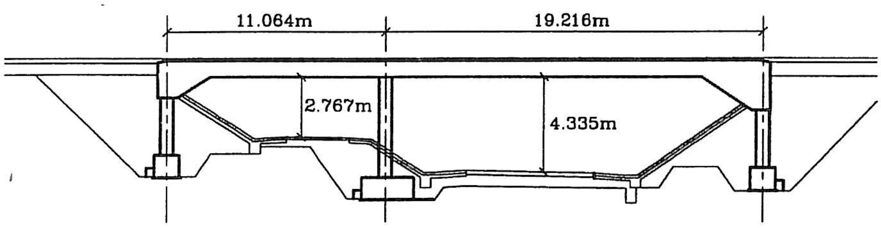


Figure 2.3 *Elevation details for the considered bridge*

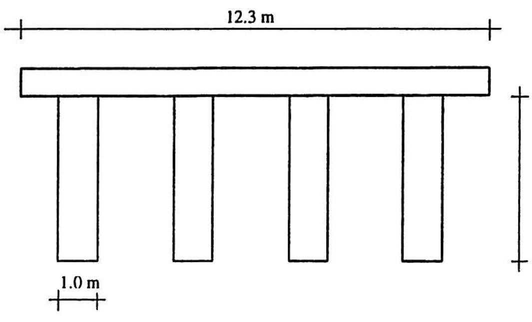


Figure 2.4 *Cross-section details for the considered bridge.*

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 wave length of the bumps, and the parameters of the vehicles can be varied. The program is based on a set of coupled first order differential equations. In order to solve the bridge response modal decomposition using quasi-static correction was implemented . 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 the 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. More details concerning the numerical models and implementation is given in Kirkegaard et al. (1997b).

3. PARAMETER STUDY

This section presents results where the dynamic amplification of the displacements in the longest span is investigated as a function of changes in parameters included in the simulation model. The dynamic amplification factor (DAF) of the displacement in the middle of the longest span, see figure 2.3, is usually defined as follows

$$R_{dyn} = R_{sta}(1+DA) = R_{sta}DAF \qquad (1)$$

where R_{dyn} and R_{sta} are the maximum dynamic and static responses, respectively. The term (1+DA) is called the dynamic amplification factor (DAF) and DA is the “dynamic amplification”, “dynamic increment” or “impact factor”. Many different terms have been used for this quantity in the technical literature, se Kirkegaard et al. (1997a). The dynamic response is taken at the time when the maximum dynamic response occurs. In the following sections the sensitivity of the DAF is investigated due to lane position of the vehicles, surface irregularities and the parameters of the vehicles.

3.1 The Effect of the Lane Position

Three different lane positions have been defined for the crossings of the vehicles as follows :

- Right lane : the right wheels of the vehicle are located 1.15 meter from the right edge of the bridge

• Mid-lane : the right wheels of the vehicle are located 5.25 meter from the right edge of the bridge

• Left lane : the right wheels of the vehicle are located 9.35 meter from the right edge of the bridge

Figures 3.1-3.3 show the displacements at three different locations (the transverse 1/3-points) for two different speeds (v = 15m/s, 30 m/s) when the Scania vehicle is crossing the bridge at the right lane, mid-lane or left lane, respectively. The same scenarios are considered in figure 3.4-3.6 for the Goldhofer vehicle. The abscissas in these figures are the distances measured from the left end of the bridge to the front axle of the vehicle. The vehicle is moving from left to right. The values in the figures are calculated using the parameters for the simulation model given in Kirkegaard et al. (1997b). The bump is modelled as a 0.5 m long half sine function with an amplitude at 0.03 m. From the figures the following observations can be made :

1)The DAF is greatly influenced by the wheel load distribution in the transverse direction of the bridge, i.e. the DAF is closely related to the wheel-load distribution. It is seen that the larger the load carried by a part of the bridge, the smaller the DAF will be.

2) The DAF at the lanes where the vehicle does not cross the bridge for a given scenario is larger than those at the lane where the vehicle is crossing.

3) The DAF decreases as the static load increases as the DAF is smaller for the Goldhofer vehicle than for the Scania vehicle.

3.2 The Effect of the Surface Irregularities

Figures 3.7- 3.8 show the variation of the DAF of the displacements in the mid-lane versus height and length of a bump when a Scania or a Goldhofer vehicle is crossing the bridge in the mid-lane. A bump is modelled as a half-sine function,see Kirkegaard et al. (1997b). At figures 3.9- 3.10 the DAF of the displacements in the mid-lane versus height of a bump and distance to the bump is shown when a Scania or a Goldhofer vehicle crossing the bridge in the mid-lane. The distance to the bump is the distance between the end of the bump and the entrance to the bridge. At last in figure 3.11 the DAF of the displacement in the mid-lane is shown versus height of a 0.5m long bump at the entrance to the bridge and speed of the vehicles. The values in the figures 3.7 - 3.11 are calculated with the same parameters as in section 3.1. From the figures 3.7 - 3.11 it can be seen that :

1) The DAF is very sensitive to changes in height and length of the bump, but not very sensitive to the distance between the bump and the entrance to the bridge.

2) The DAF is also very sensitive to the change in speed. However, it is seen that the DAF does not have a monotonous change due to change in vehicle speed.

3.3 The Effect of the Parameters of the Vehicles

At the figures 3.12 - 3.29 the effect on the DAF of the displacements in the mid-lane of varying parameters of the vehicles is shown. The values in the figures 3.12- 3.29 are calculated with the same parameters as in sections 3.1 and 3.2. The figures show :

- the DAF versus stiffness of suspension and stiffness of tires, figure 3.12, 3.16.

- the DAF versus damping of tires and stiffness of tires, figure 3.13, 3.17.

- the DAF versus damping of suspension and stiffness of suspension, figure 3.14, 3.18.

- the DAF versus damping of suspension and damping of tires, figure 3.15, 3.19.

- the DAF versus friction force in compression and pull, respectively, figure 3.20, 3.21.

- the DAF versus mass moment of inertia of rotation about the transverse axis for the trailer and mass moment of inertia of rotation about the transverse axis for the tractor, figure 3.22, 3.26.

- the DAF versus mass moment of inertia of rotation about the transverse axis for the trailer and mass moment of inertia of rotation about the longitudinal axis for the tractor, figure 3.23, 3.27.

- the DAF versus mass moment of inertia of rotation about the longitudinal axis for the trailer and mass moment of inertia of rotation about the transverse axis for the tractor, figure 3.24, 3.28.

- the DAF versus mass moment of inertia of rotation about the longitudinal axis for the trailer and mass moment of inertia of rotation about the longitudinal axis for the tractor, figure 3.25, 3.29.

Based on the figures 3.12 - 3.29 following conclusions can been made :

1) The DAF is very sensitive to changes in stiffness of the suspension and stiffness of the tires, but not sensitive to changes in damping parameters. Further, it is seen that relative small values of suspension stiffness implies small DAF values. Therefore, it could be recommend to have air - suspension (soft) on all vehicle in order to reduce the the dynamic response. However, it is worth mentioning at this point that a soft suspension, while desired for good ride quality and cargo safety, contradicts the handling and roll stability as well as the static suspension deflection requirements.

2) The DAF is not very sensitive to the friction forces in compression and pull.

3) The DAF is sensitive to mass moment of inertia of rotation about the transverse axis for the trailer and the tractor but not very sensitive to the mass moment of inertia of rotation about the longitudinal axis for the trailer and the tractor.

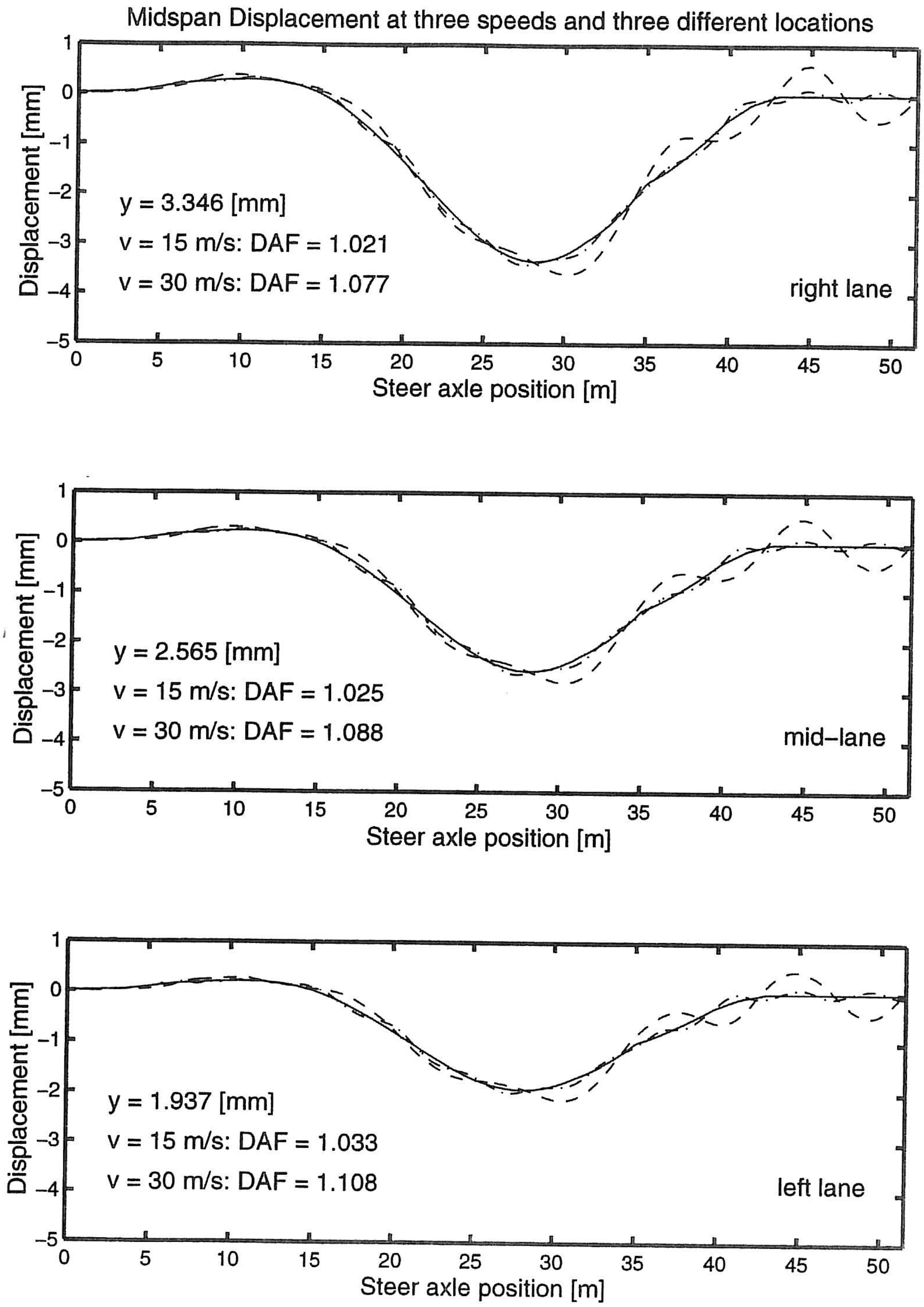


Figure3.1: *Variation of midspan displacement versus time for a Scania vehicle crossing the bridge in the right lane. (y is the static displacement).*

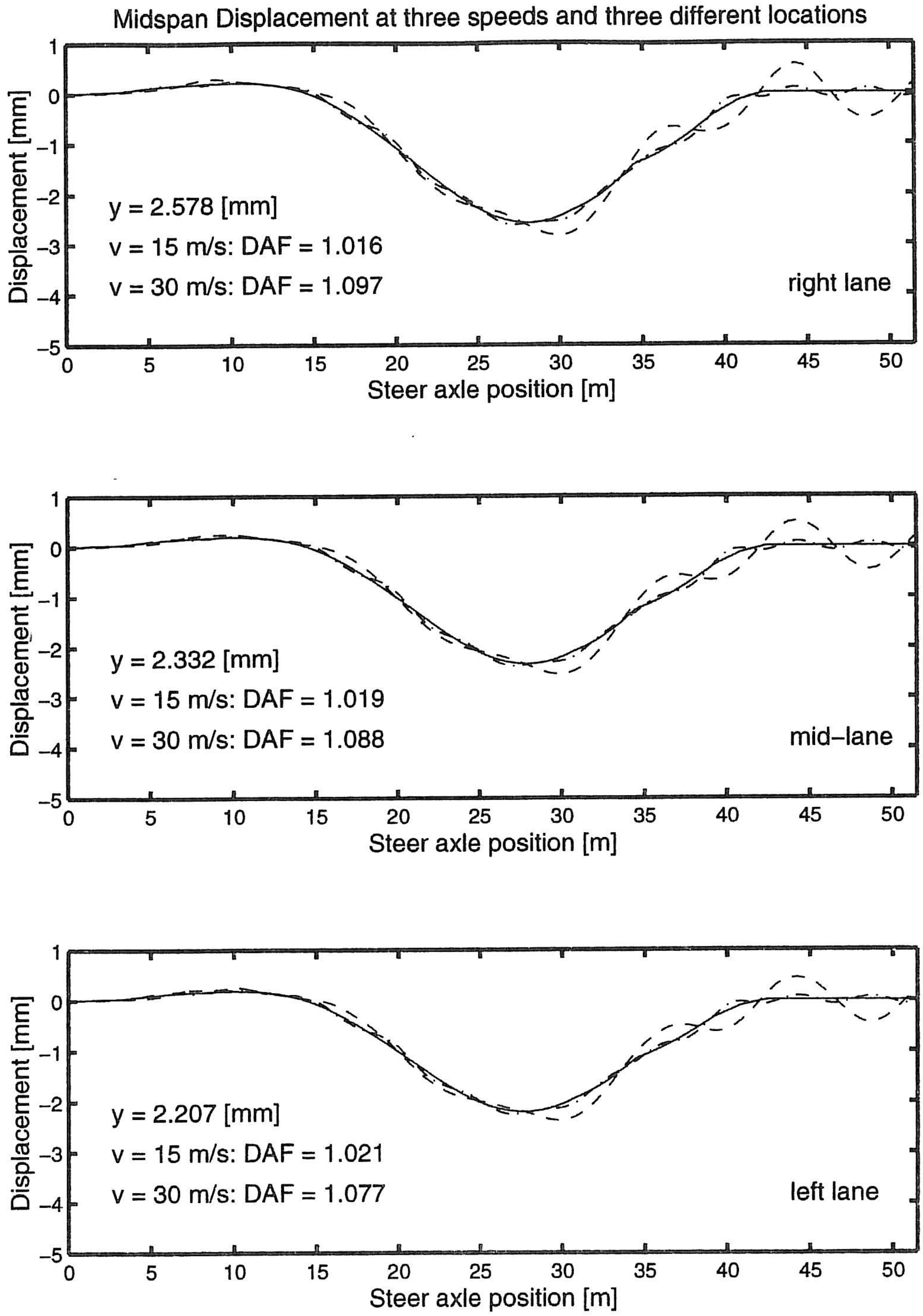


Figure 3.2 *Variation of midspan displacement versus time for a Scania vehicle crossing the bridge in the mid-lane. (y is the static displacement).*

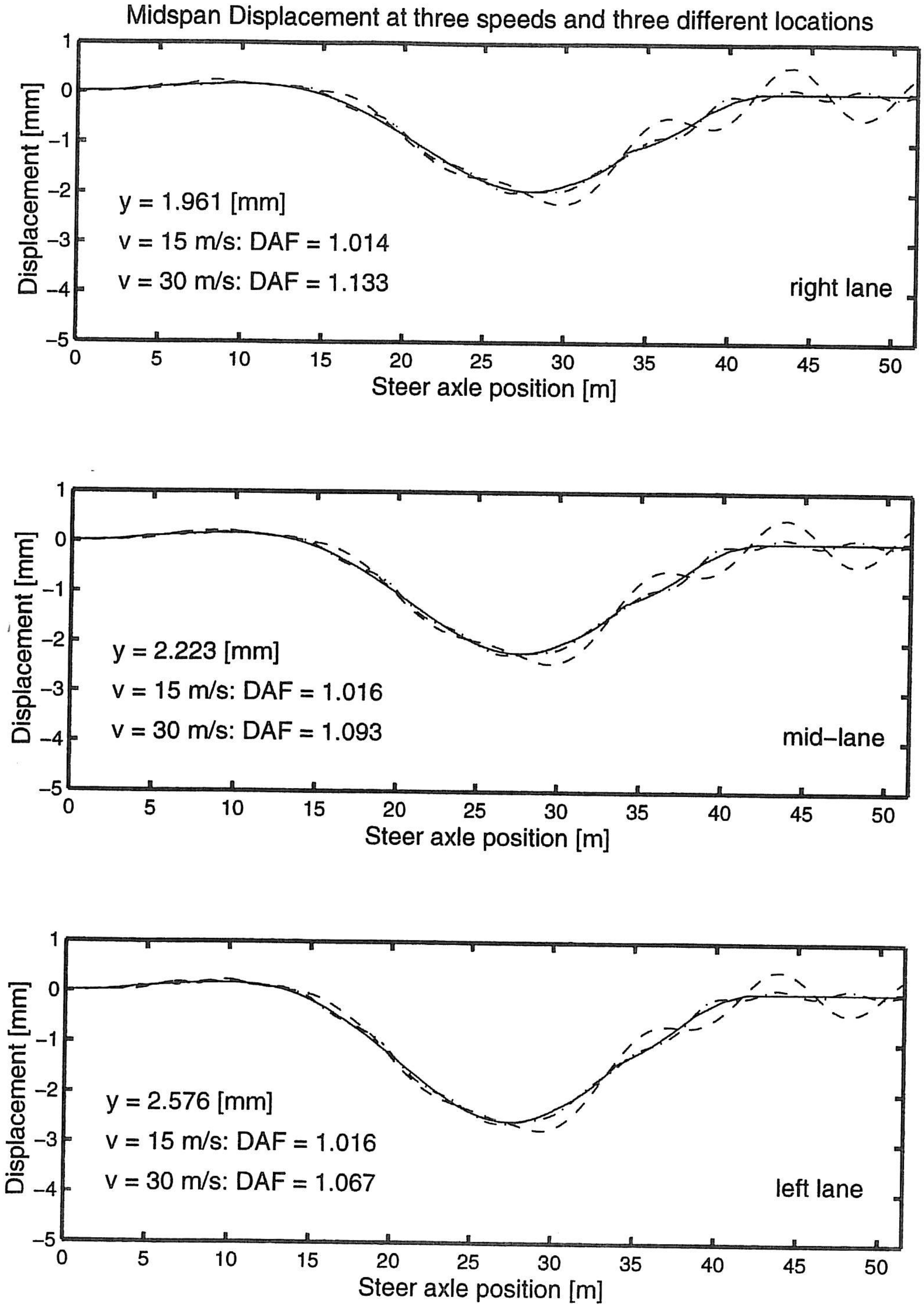


Figure 3.3 *Variation of midspan displacement versus time for a Scania vehicle crossing the bridge in the left lane. (y is the static displacement).*

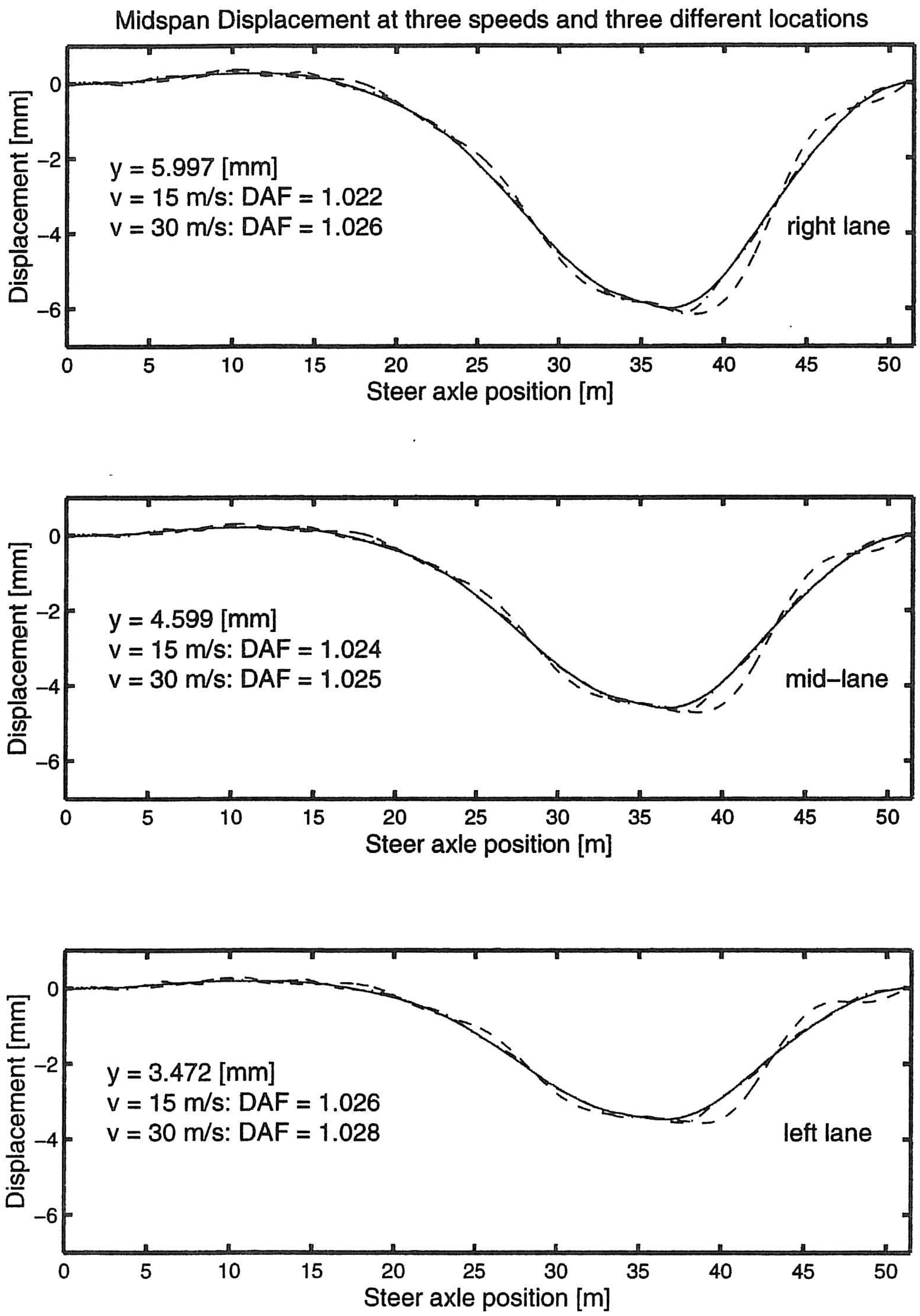


Figure 3.4 *Variation of midspan displacement versus time for a Goldhofer crossing the bridge in the right lane.* (*y is the static displacement*).

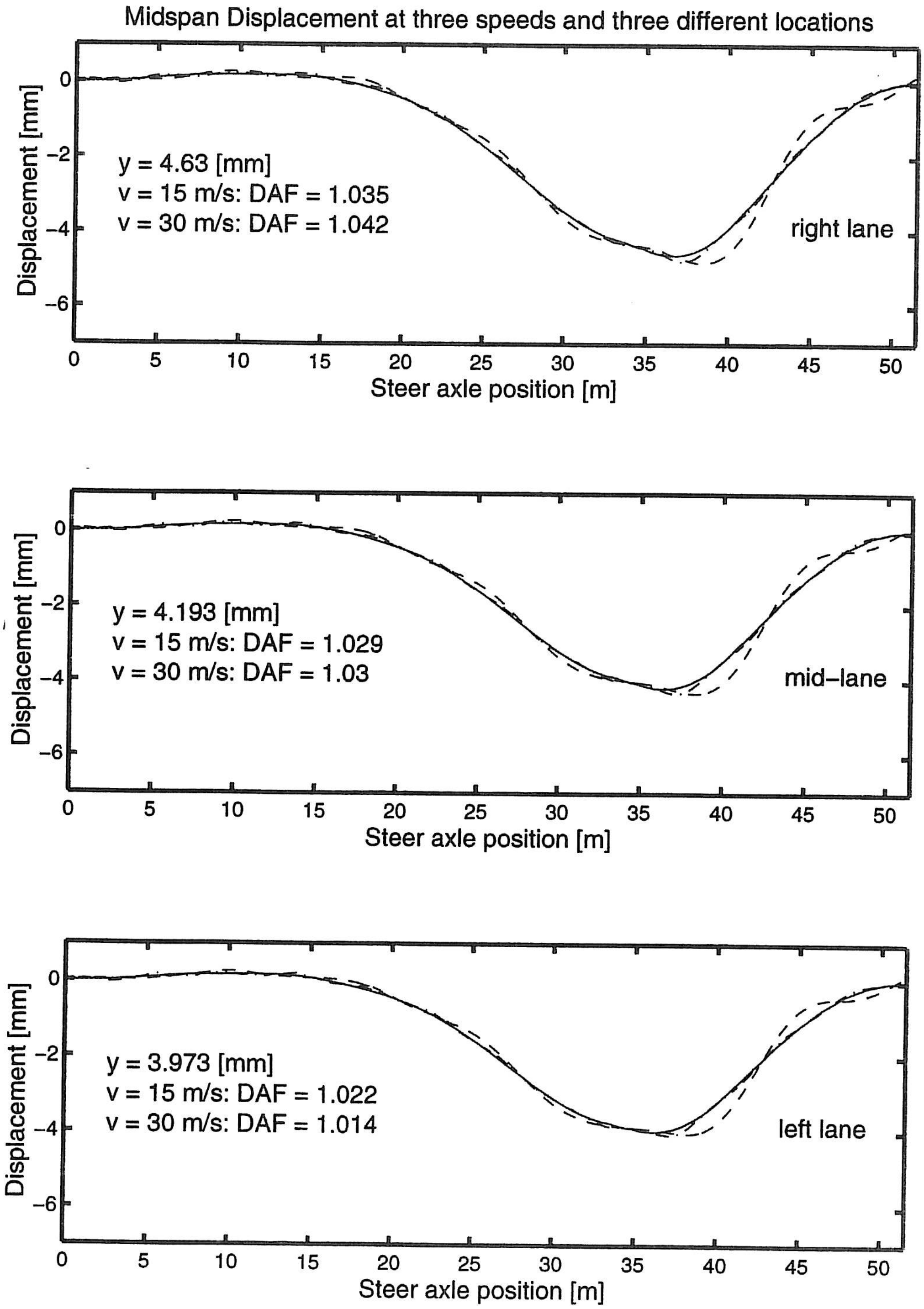


Figure 3.5 *Variation of midspan displacement versus time for a Goldhofer vehicle crossing the bridge in the mid-lane. (y is the static displacement).*

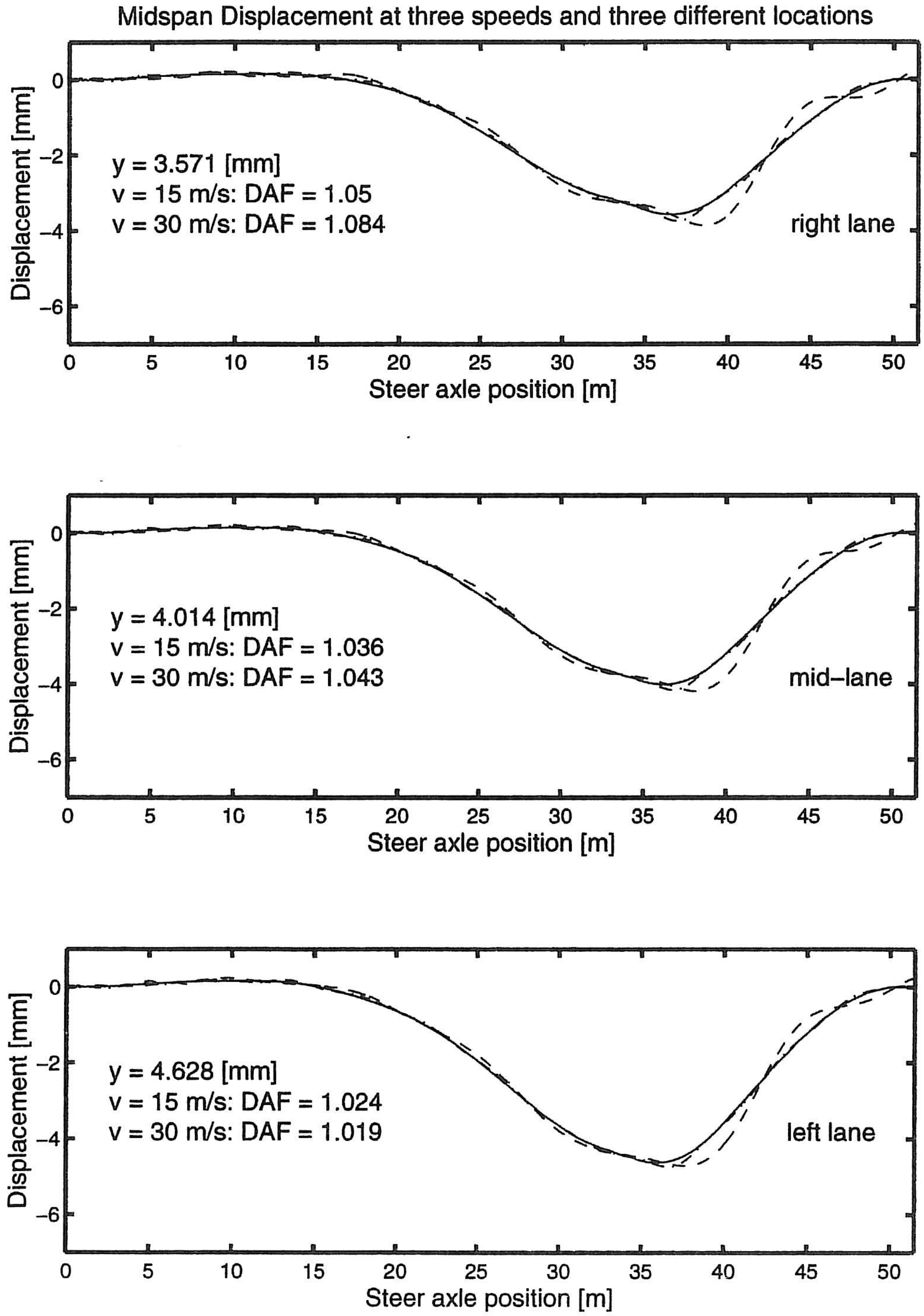
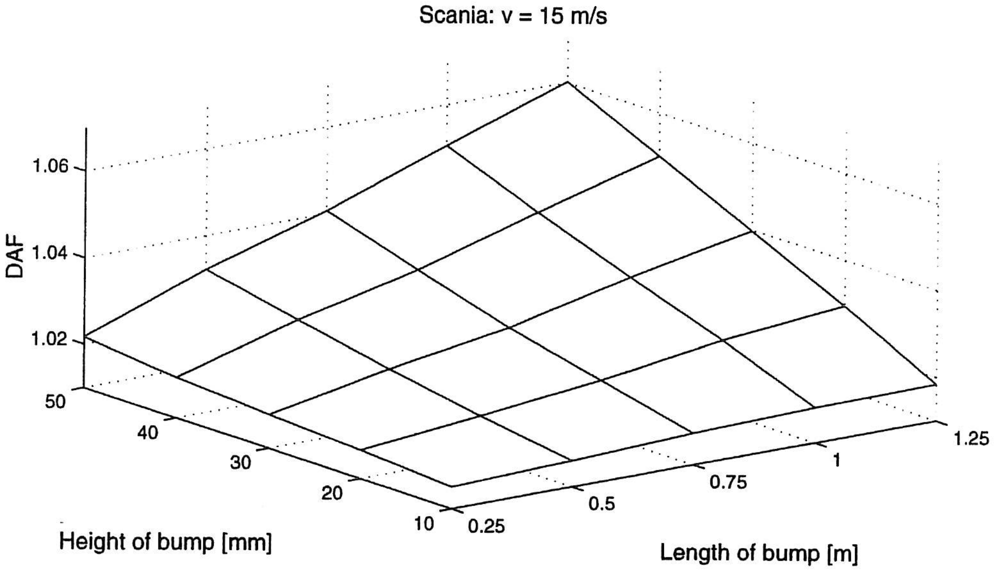


Figure 3.6 *Variation of midspan displacement versus time for a Goldhofer vehicle crossing the bridge in the left lane.* (*y is the static displacement*).



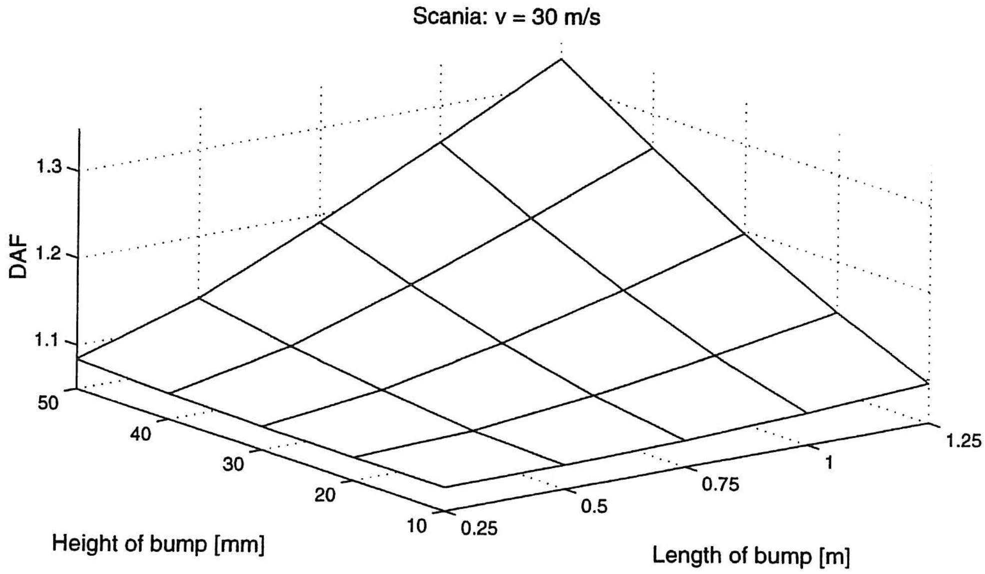
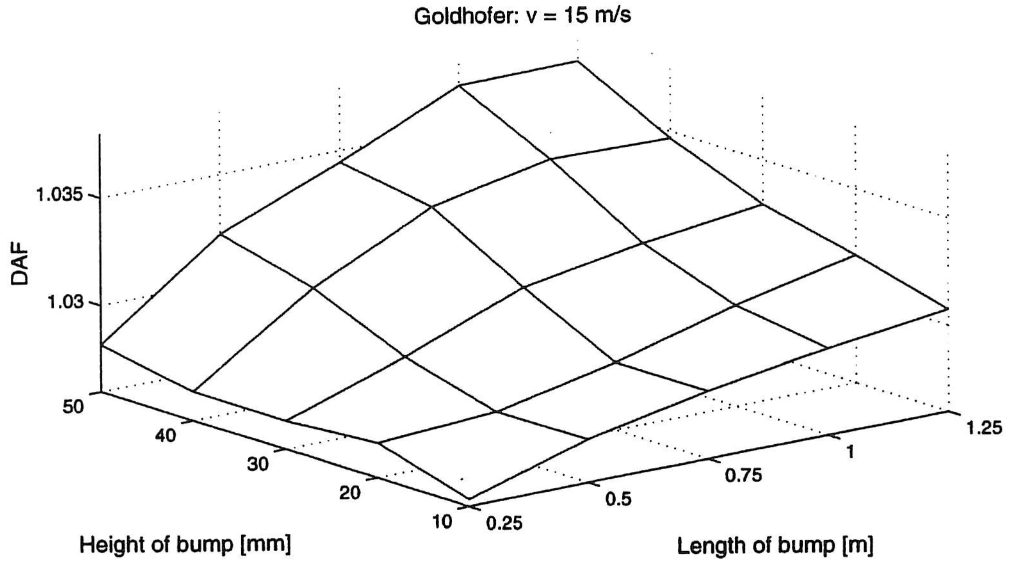


Figure 3.7 *Variation of the dynamic amplification of the displacements versus height and length of a bump for a Scania vehicle crossing the bridge in the mid-lane.*



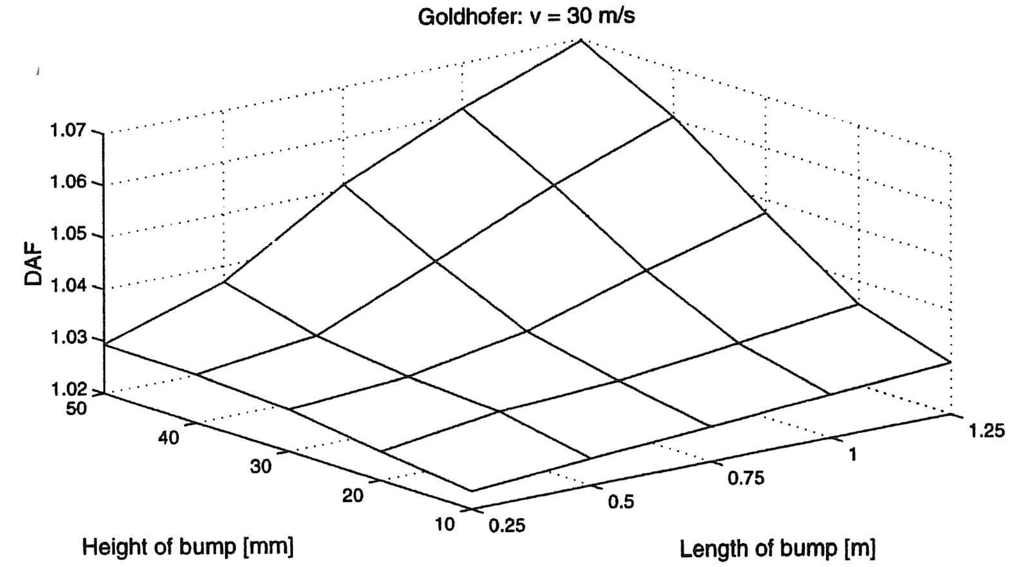


Figure 3.8 *Variation of the dynamic amplification of the displacements versus height and length of a bump for a Goldhofer vehicle crossing the bridge in the mid-lane.*

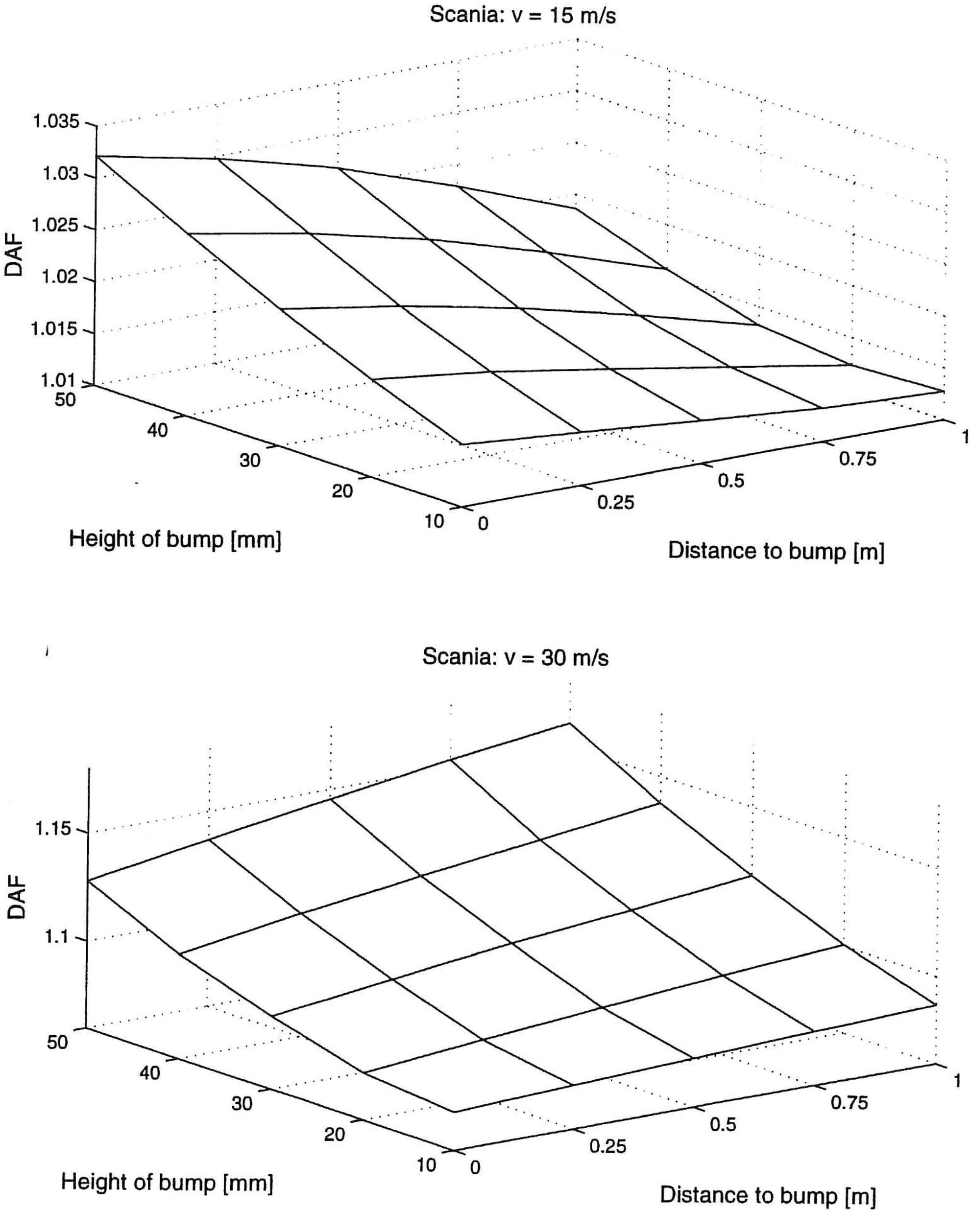
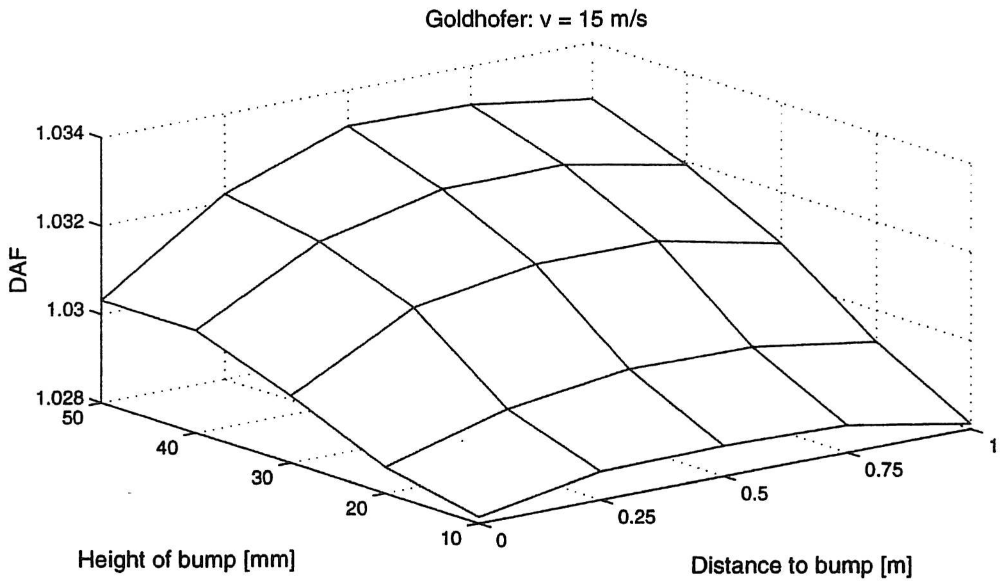


Figure 3.9 *Variation of the dynamic amplification of the displacements versus height of bump and distance to bump for a Scania vehicle crossing the bridge in the mid-lane. (length of bump is 0.5 m)*



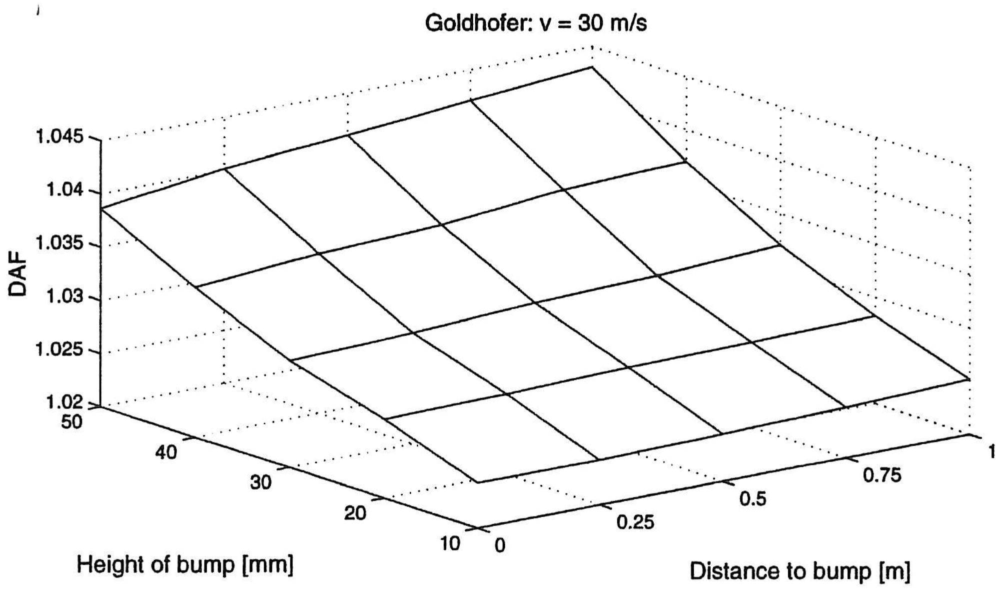


Figure 3.10 *Variation of the dynamic amplification of the displacements versus height of bump and distance to bump for a Goldhofer vehicle crossing the bridge in the mid-lane.*

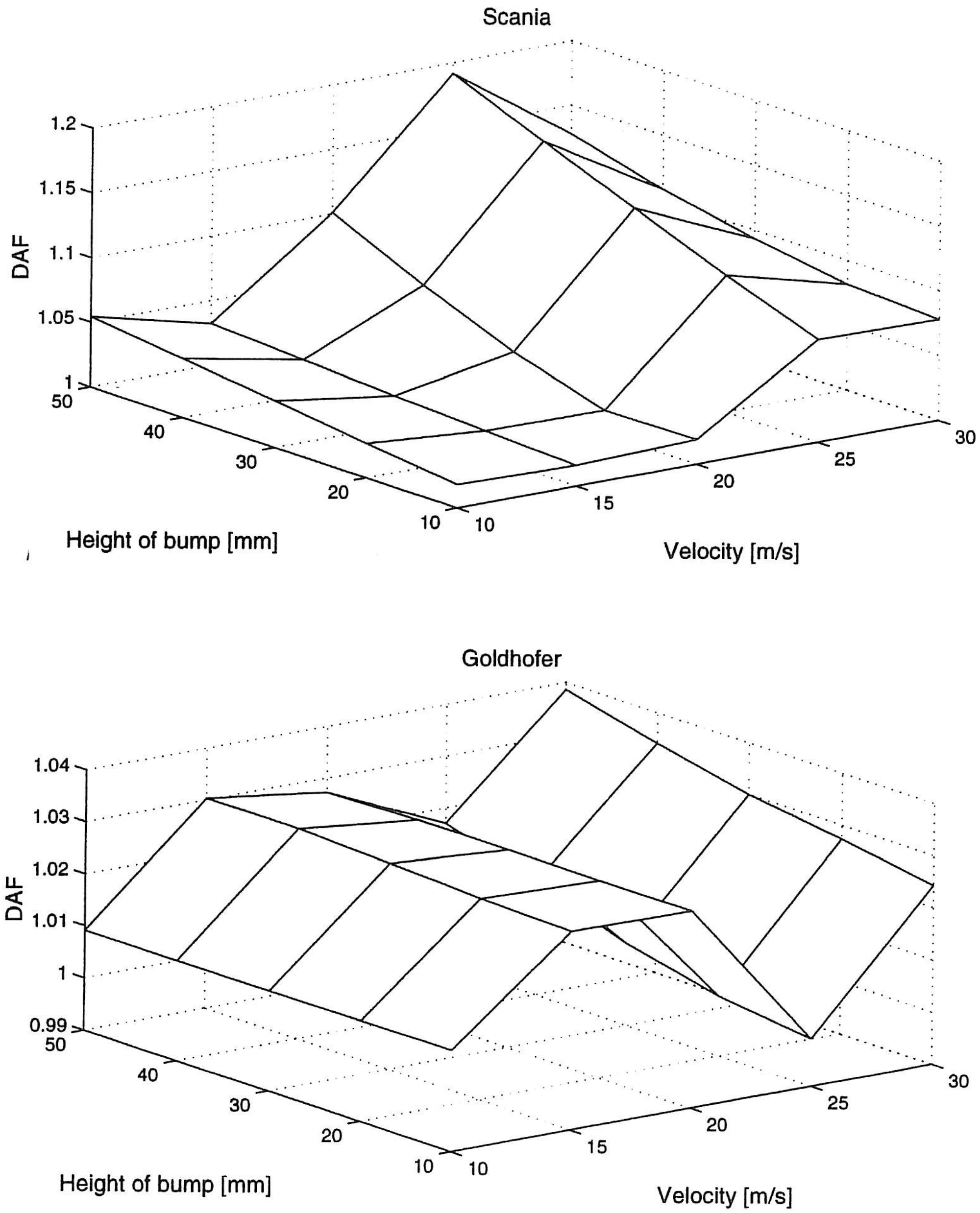
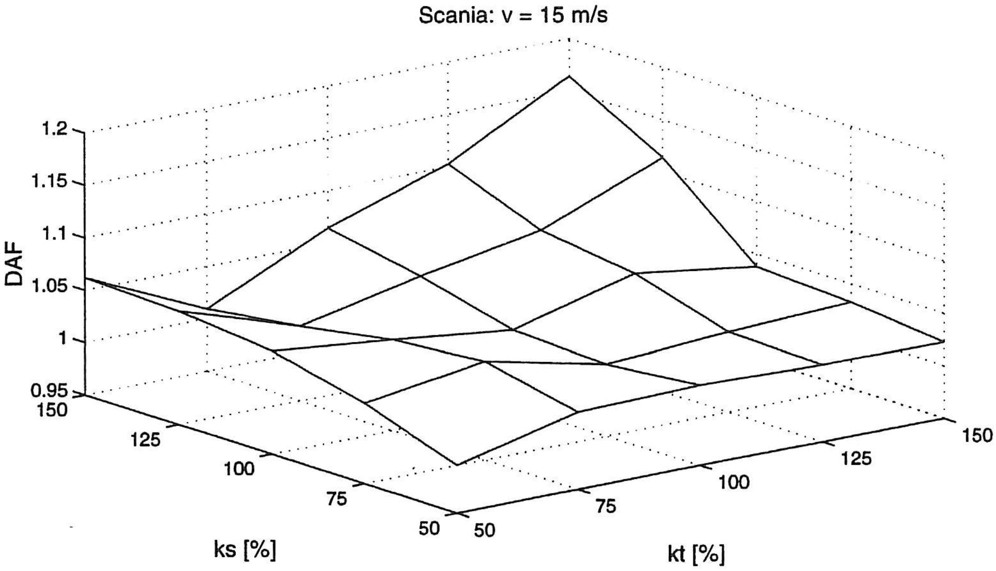


Figure 3.11 *Variation of the dynamic amplification of the displacements versus height of bump and speed of a Scania and a Goldhofer vehicle crossing the bridge in the mid-lane.*



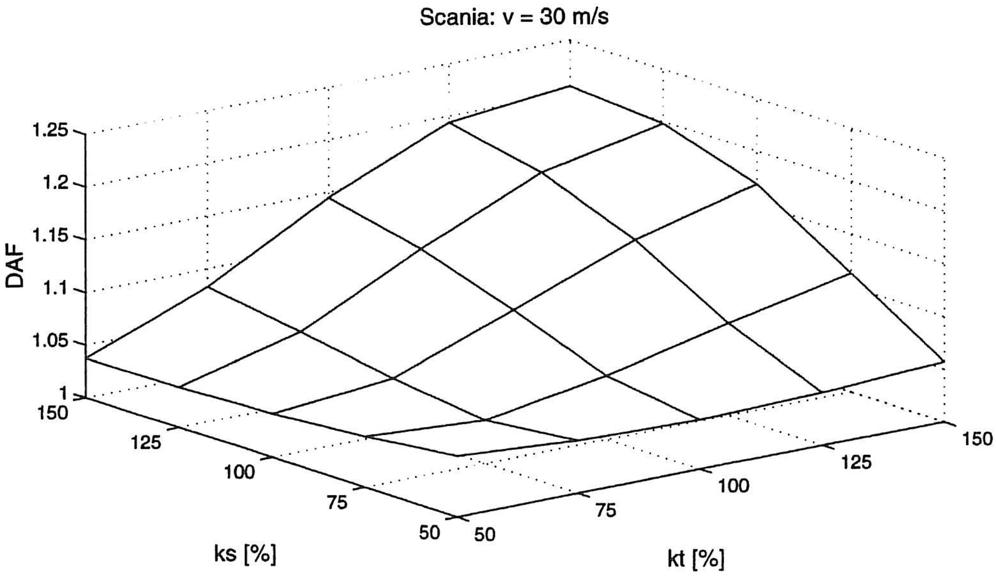
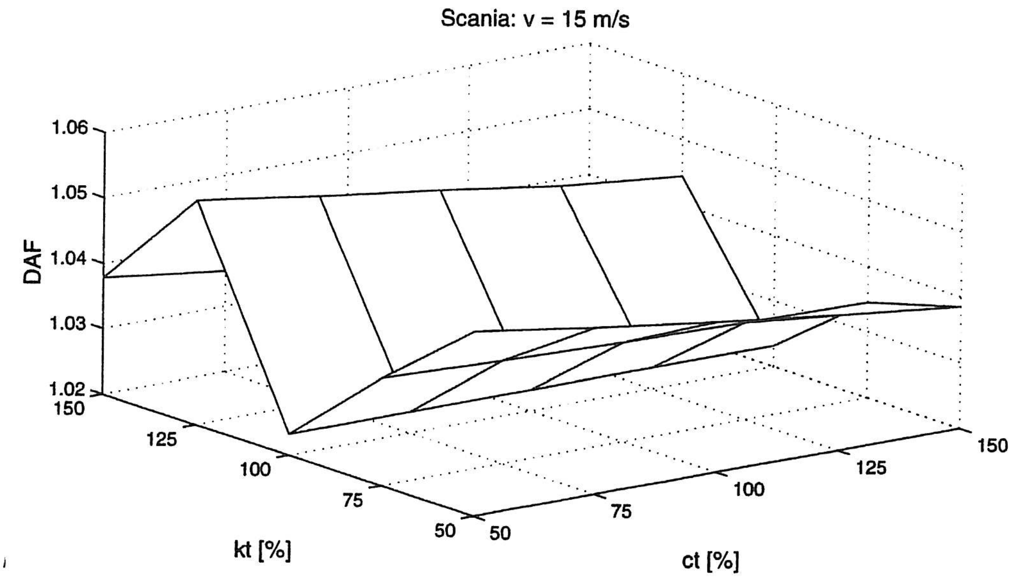


Figure 3.12 *Variation of the dynamic amplification of the displacements versus relative changes of stiffness of suspension and stiffness of tires for a Scania vehicle crossing the bridge in the mid-lane.*



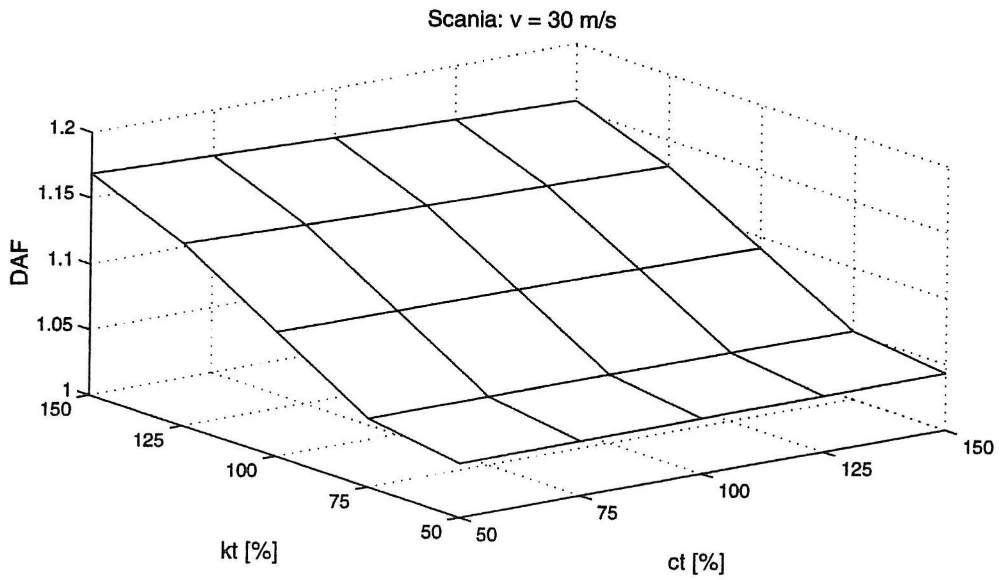
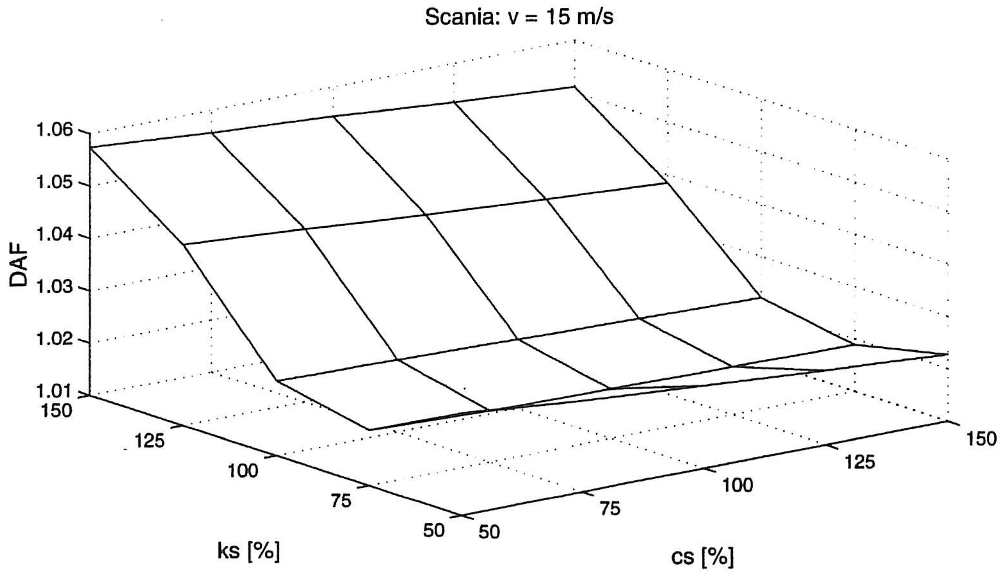


Figure 3.13 *Variation of the dynamic amplification of the displacements versus relative changes of damping of tires and stiffness of tires for a Scania vehicle crossing the bridge in the mid-lane.*



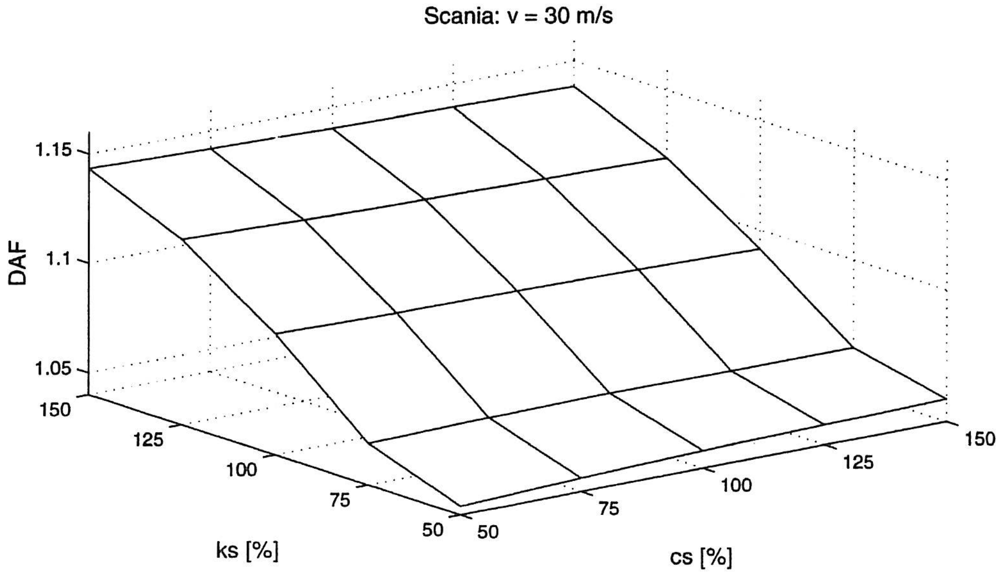
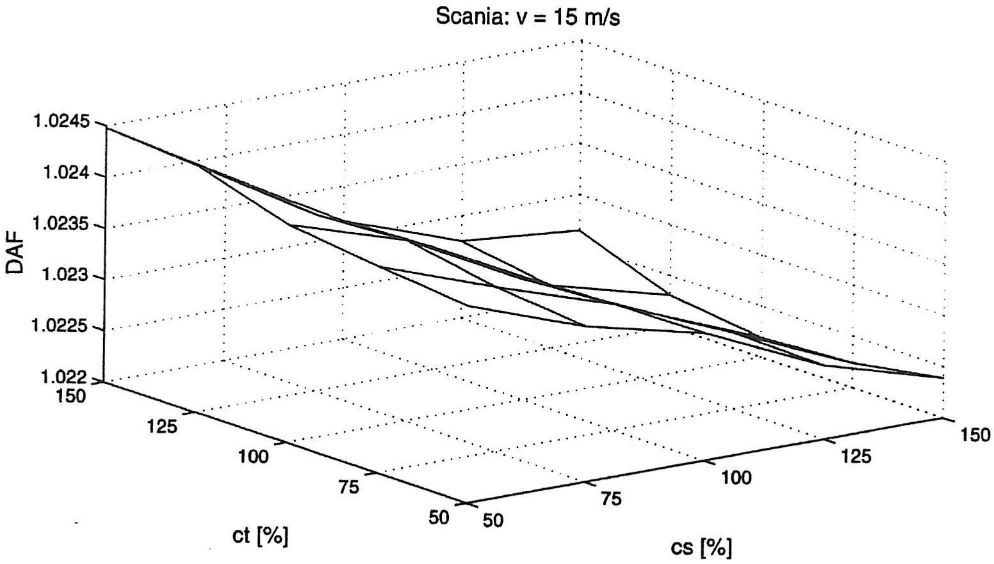


Figure 3.14 *Variation of the dynamic amplification of the displacements versus relative changes of damping of suspension and stiffness of suspension for a Scania vehicle crossing the bridge in the mid-lane.*



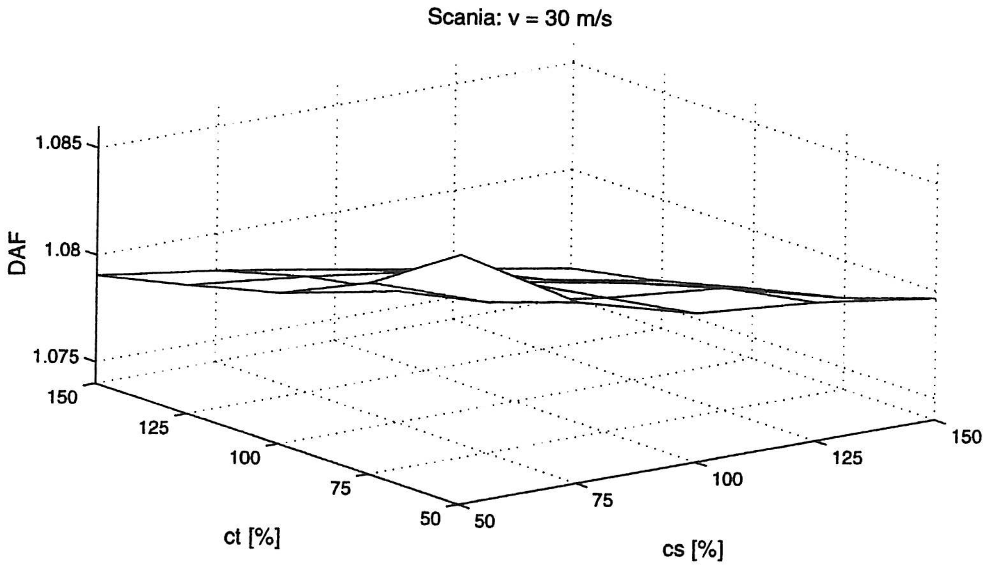
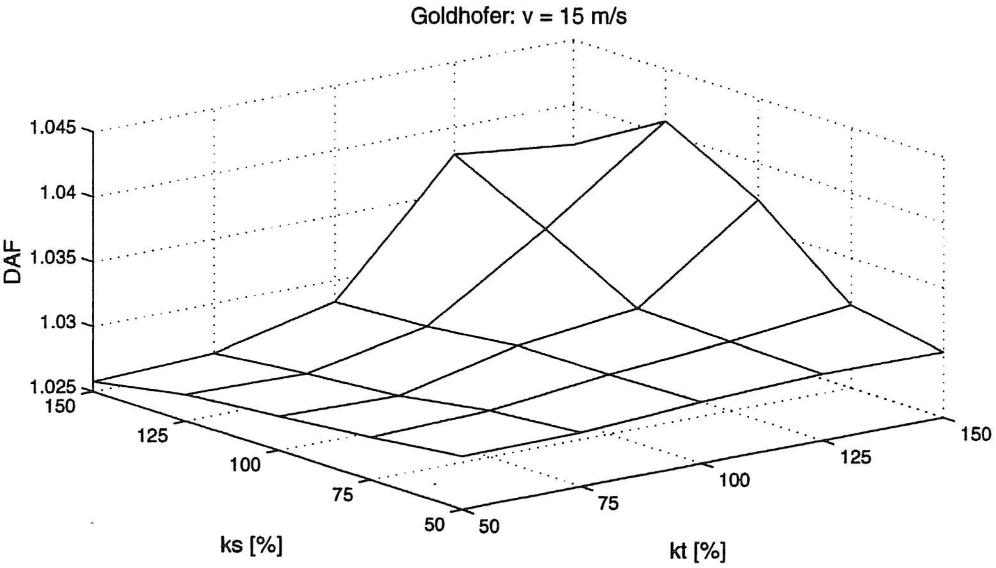


Figure 3.15 *Variation of the dynamic amplification of the displacements versus relative changes of damping of tires and damping of suspension for a Scania vehicle crossing the bridge in the mid-lane.*



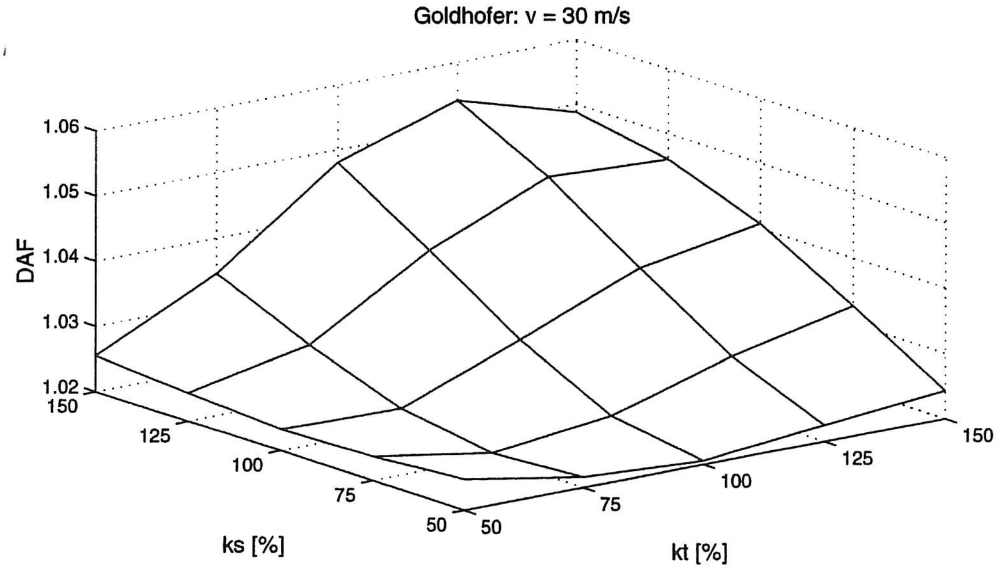
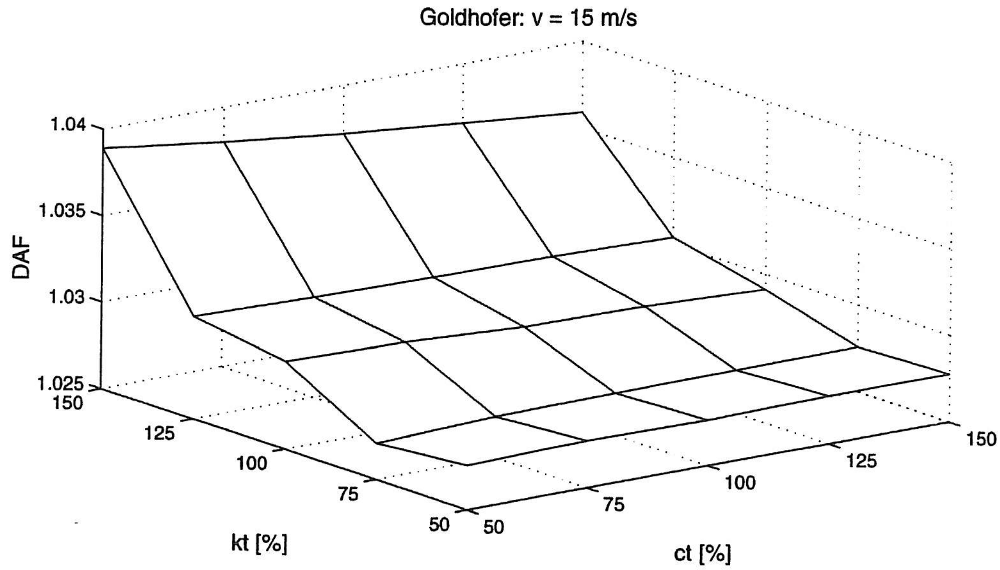


Figure 3.16 *Variation of the dynamic amplification of the displacements versus relative changes of stiffness of suspension and stiffness of tires for a Goldhofer vehicle crossing the bridge in the mid-lane.*



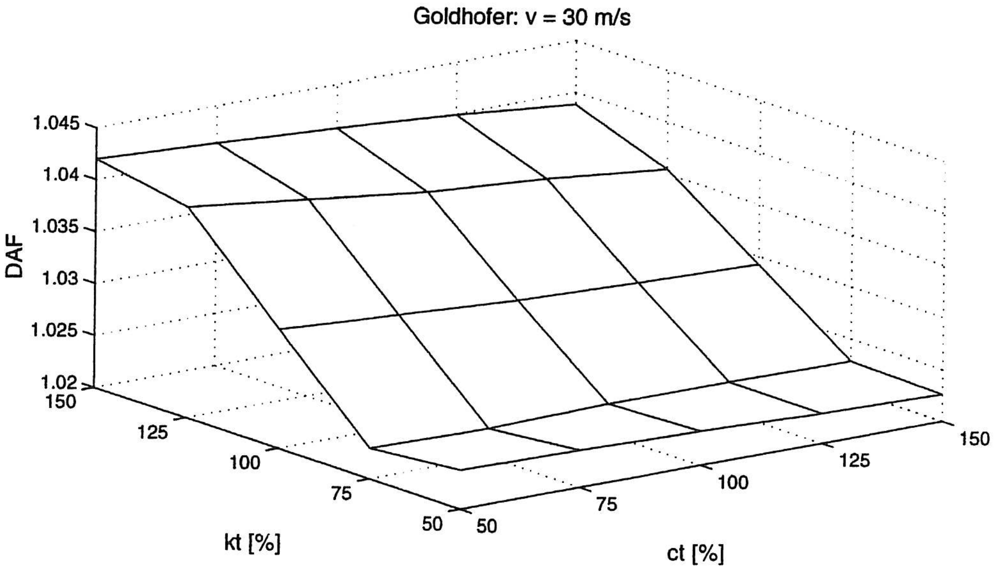


Figure 3.17 *Variation of the dynamic amplification of the displacements versus relative changes of damping of tires and stiffness of tires for a Goldhofer vehicle crossing the bridge in the mid-lane.*

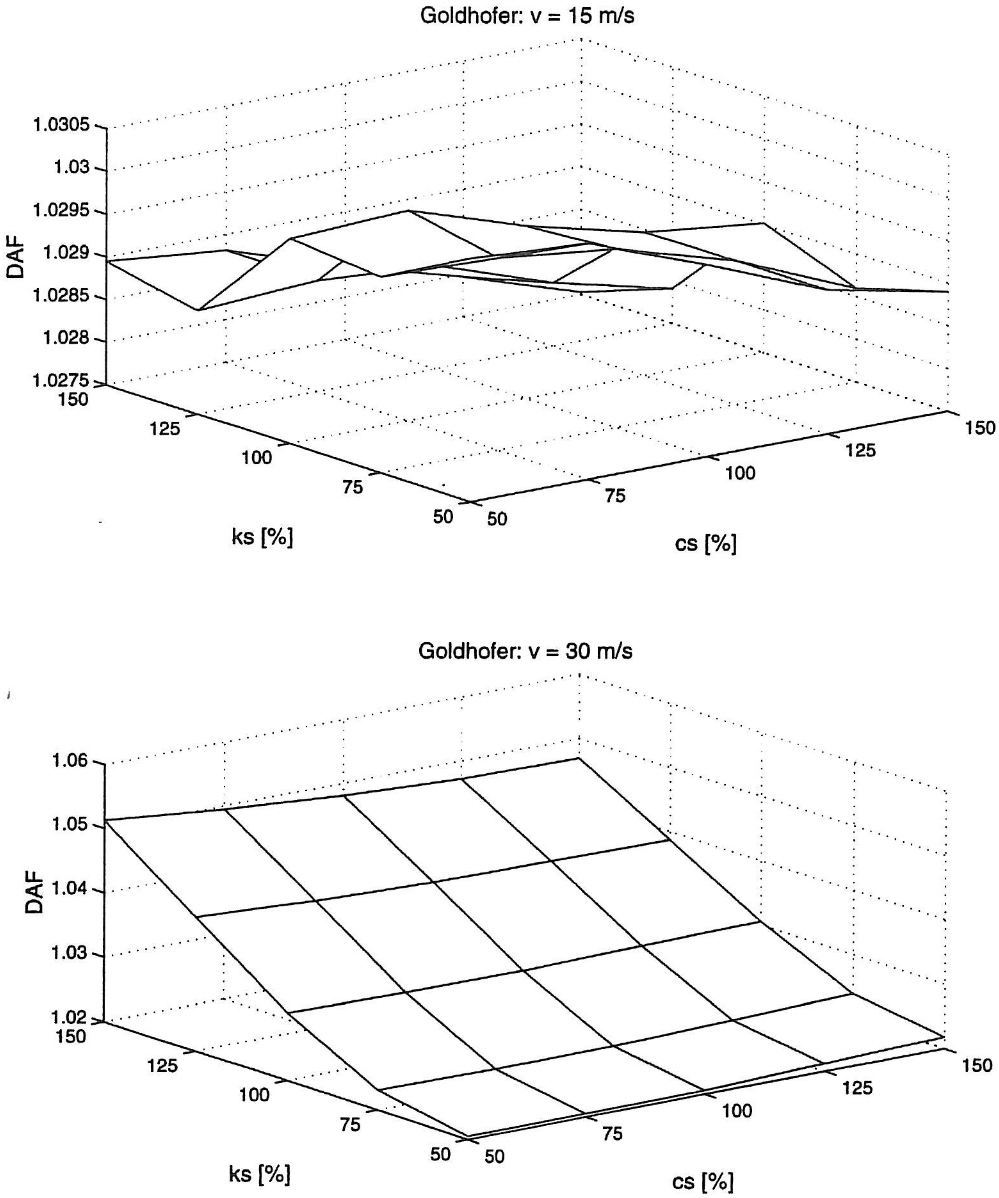
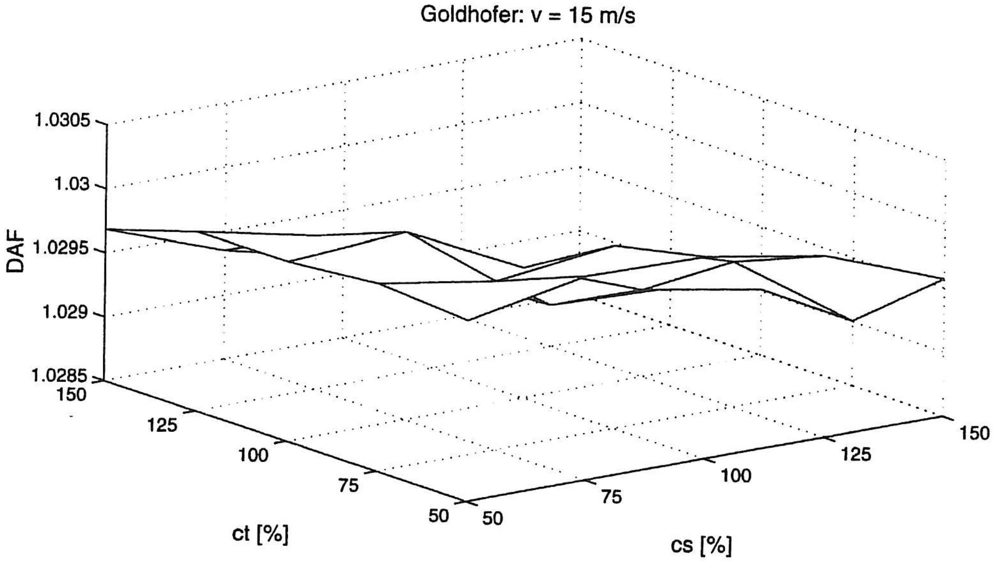


Figure 3.18 *Variation of the dynamic amplification of the displacements versus relative changes of damping of suspension and stiffness of suspension for a Goldhofer vehicle crossing the bridge in the mid-lane.*



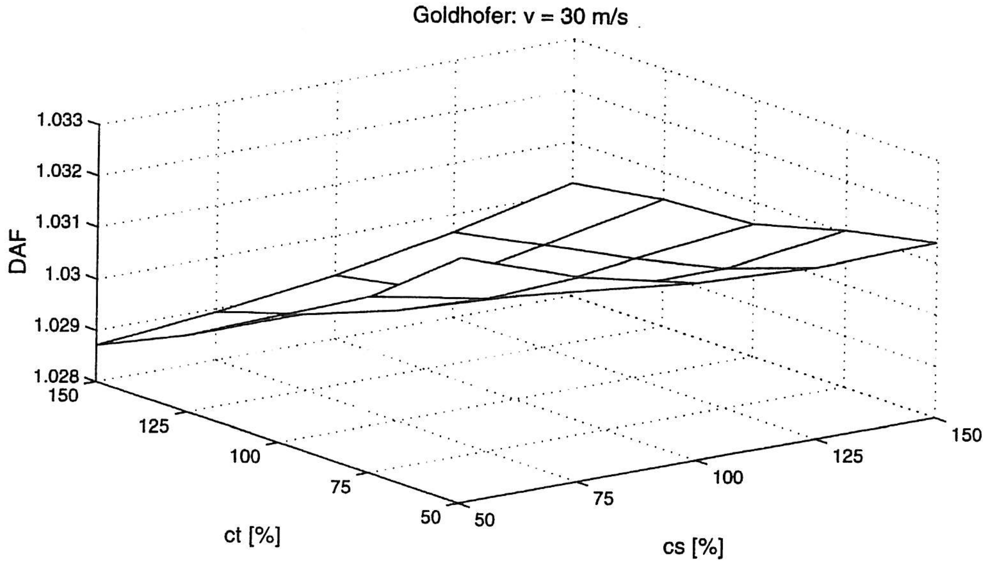
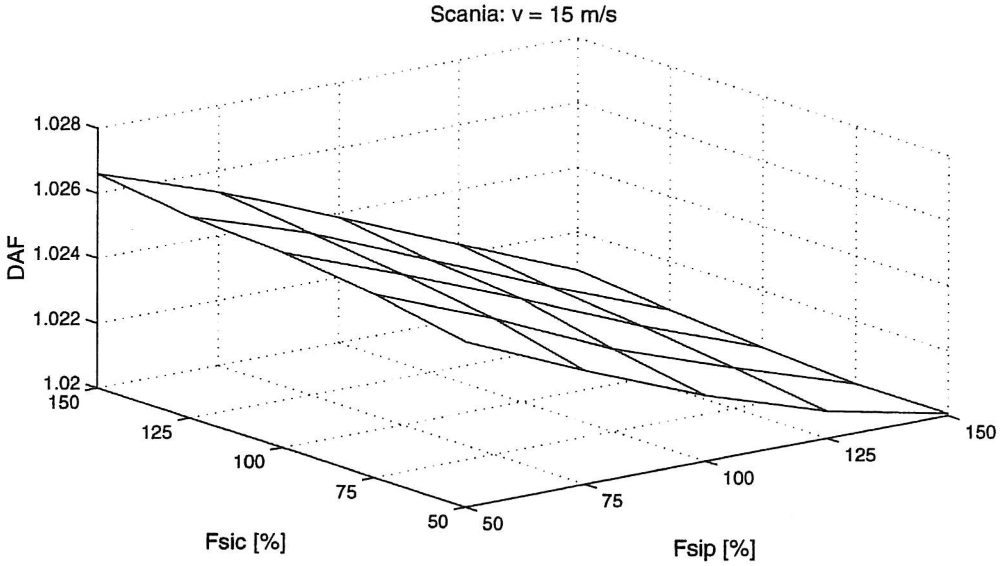


Figure 3.19 *Variation of the dynamic amplification of the displacements versus relative changes of damping of tires and damping of suspension for a Goldhofer vehicle crossing the bridge in the mid-lane.*



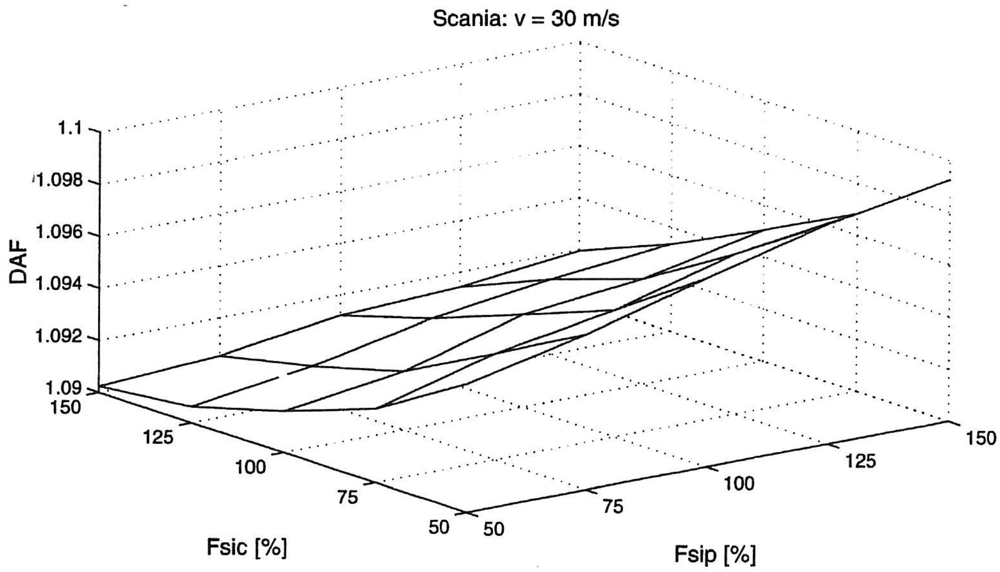


Figure 3.20 *Variation of the dynamic amplification of the displacements versus relative changes of friction force in compression and pull for a Scania vehicle crossing the bridge in the mid-lane.*

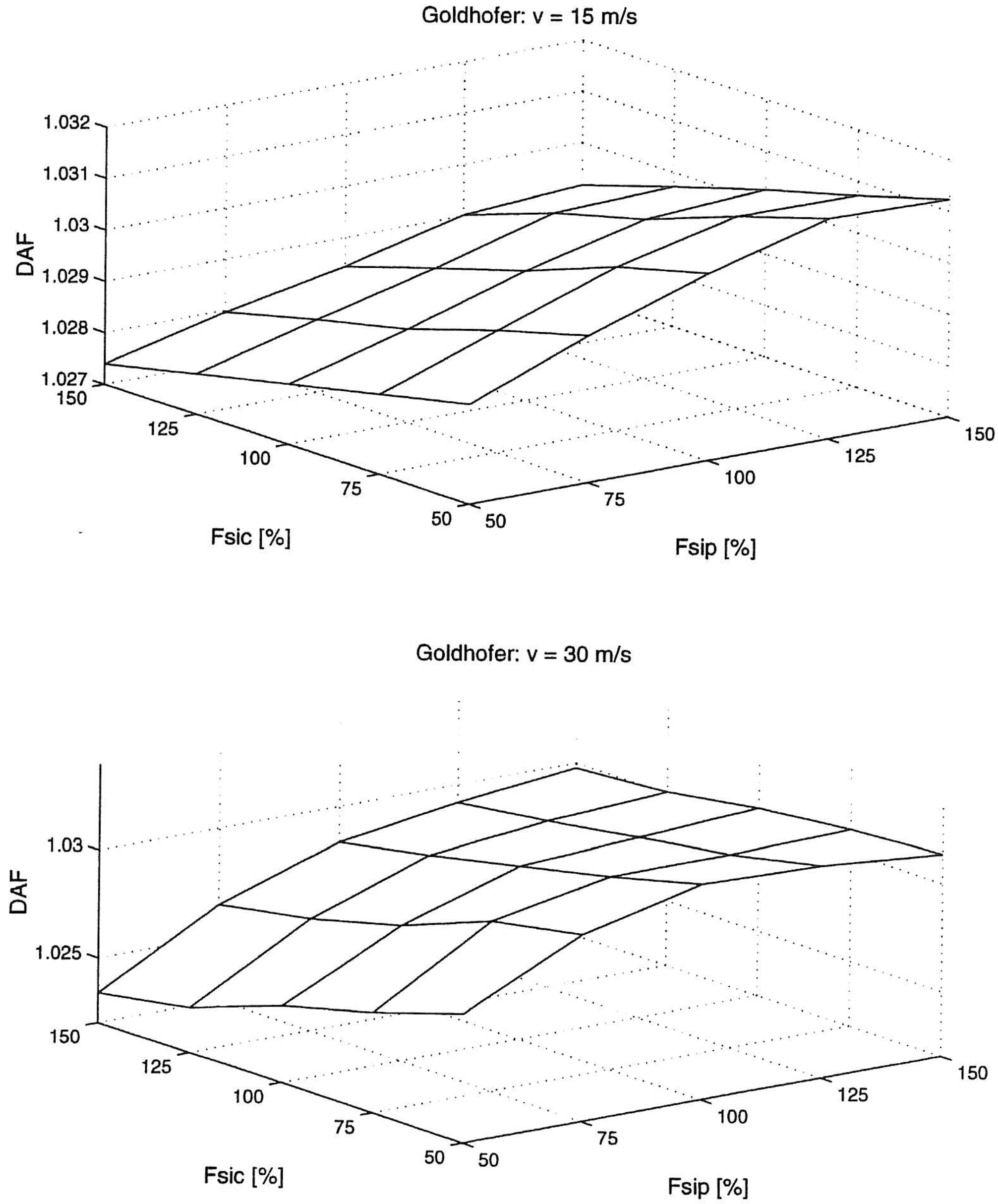
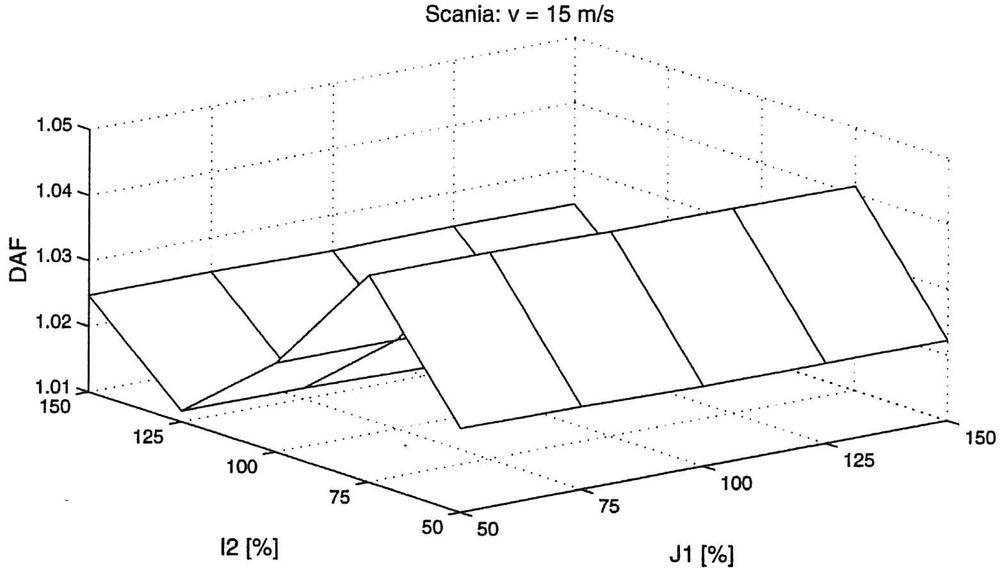


Figure 3.21 *Variation of the dynamic amplification of the displacements versus relative changes of friction force in compression and pull for a Goldhofer vehicle crossing the bridge in the mid-lane.*



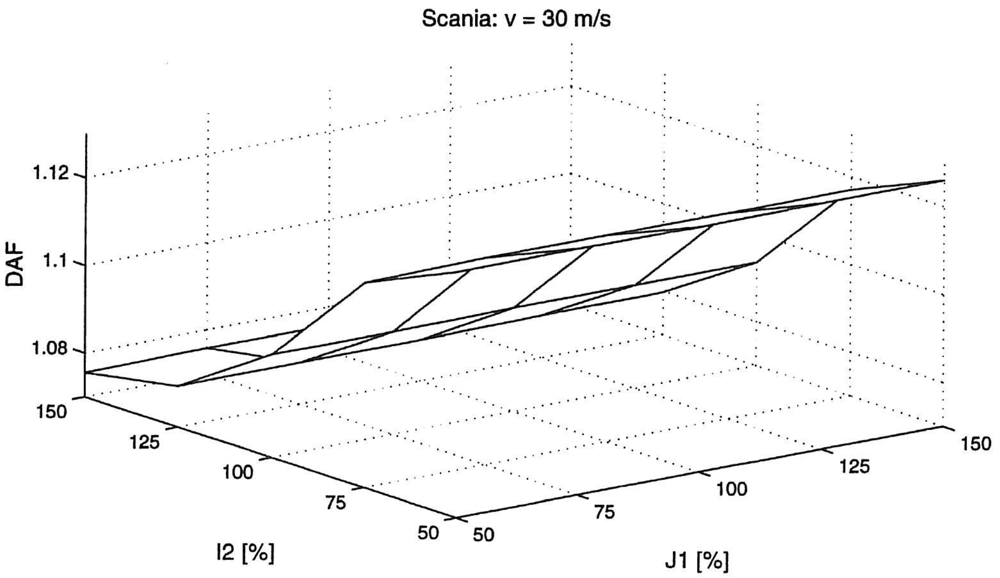
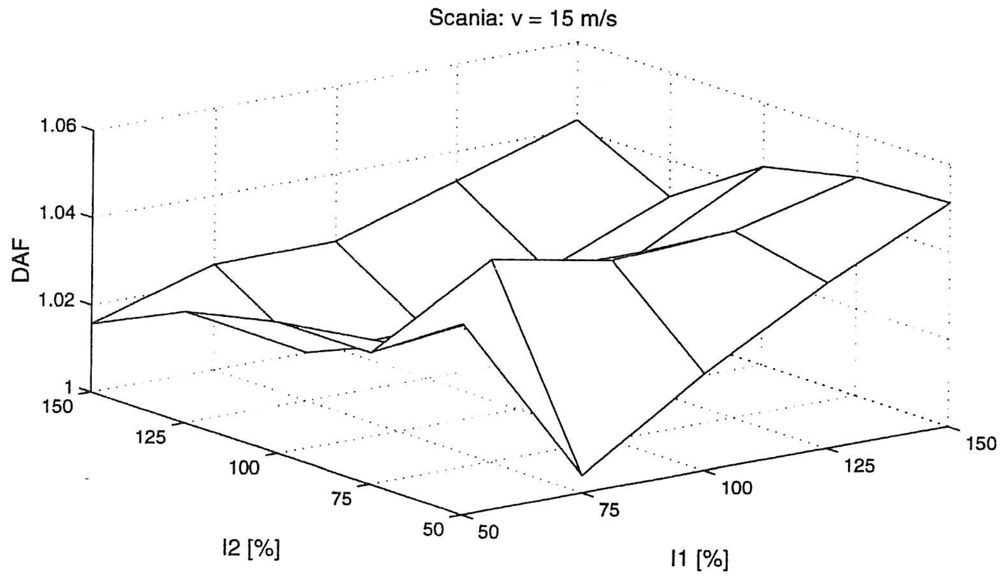


Figure 3.22 *Variation of the dynamic amplification of the displacements versus relative changes of mass moments of rotation about the transverse axis for Scania trailer and mass moments of rotation about the longitudinal axis for Scania tractor for a Scania vehicle crossing the bridge in the mid-lane.*



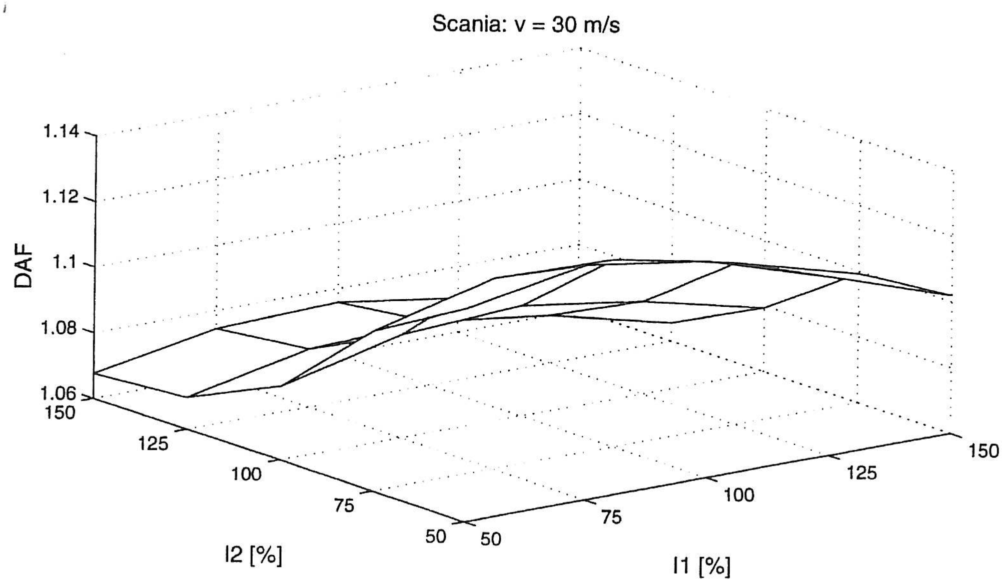


Figure 3.23 *Variation of the dynamic amplification of the displacements versus relative changes of mass moments of rotation about the transverse axis for Scania trailer and mass moments of rotation about the transverse axis for Scania tractor for a Scania vehicle crossing the bridge in the mid-lane.*

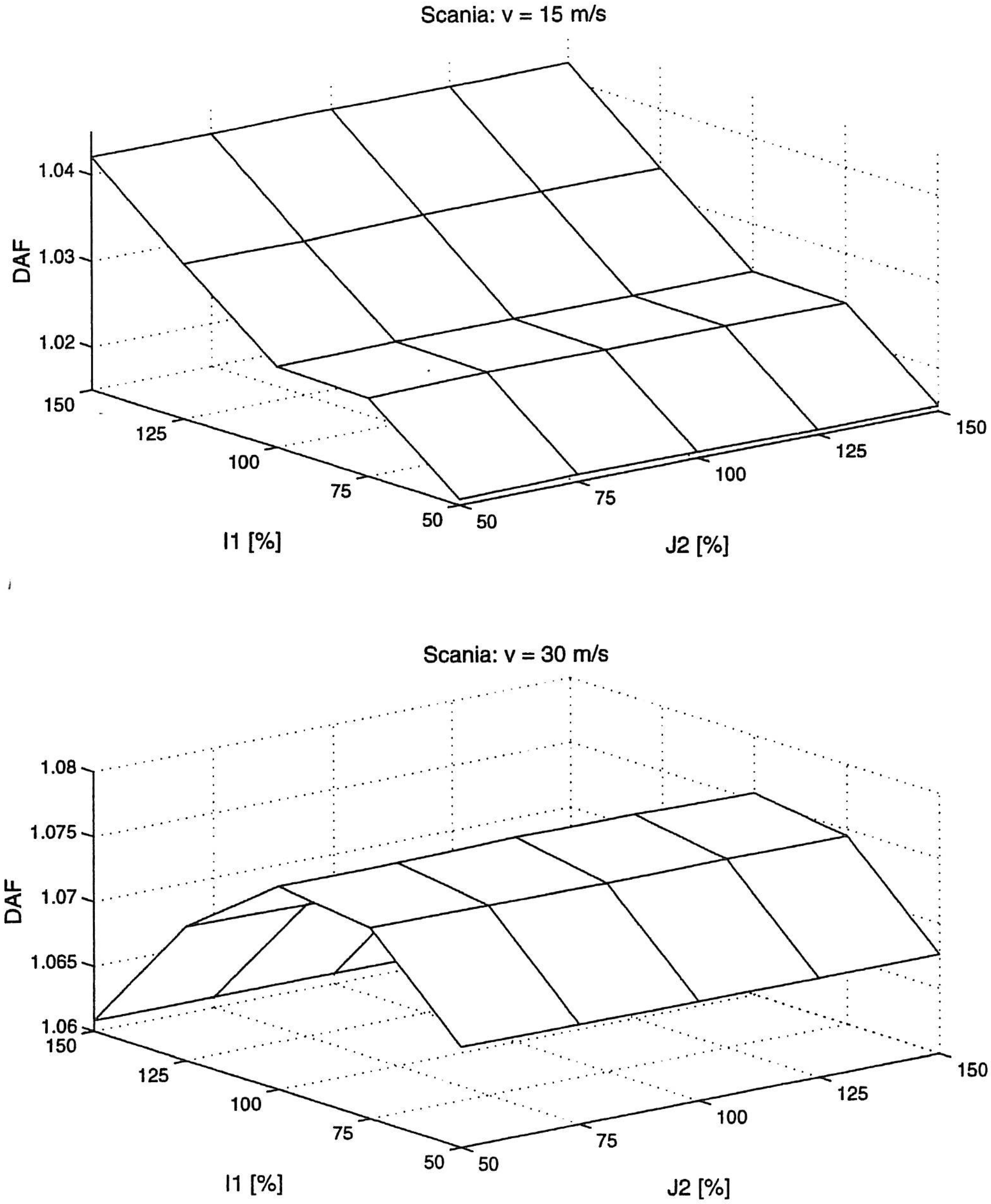
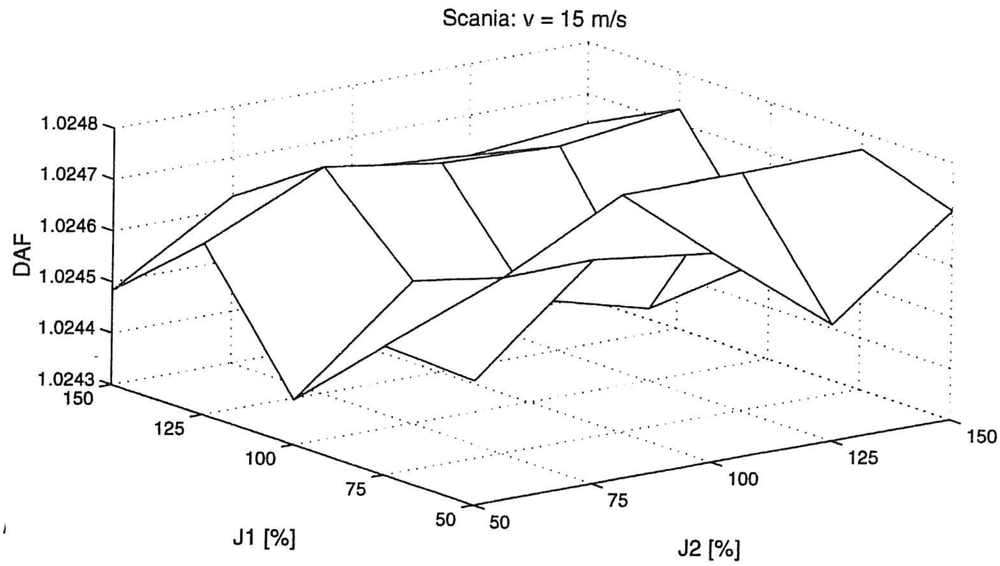


Figure 3.24 *Variation of the dynamic amplification of the displacements versus relative changes of mass moments of rotation about the longitudianl axis for Scania tractor and mass moments of rotation about the transverse axis for Scania trailer for a Scania vehicle crossing the bridge in the mid-lane.*



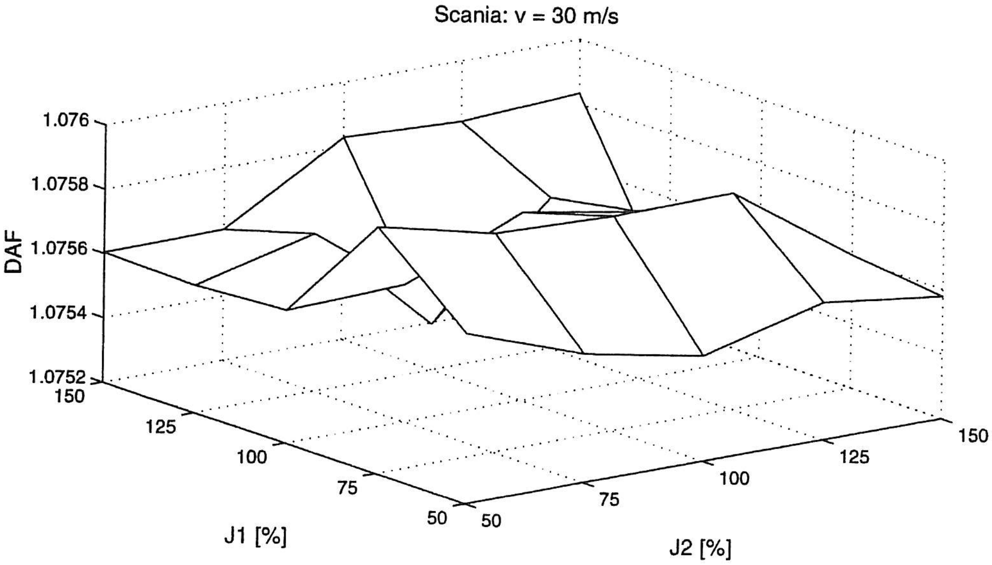
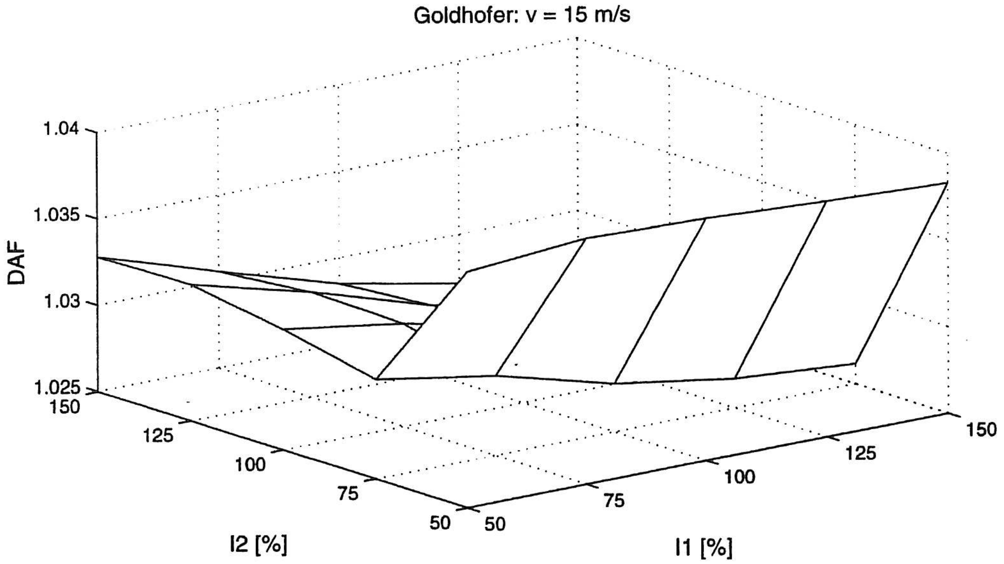


Figure 3.25 *Variation of the dynamic amplification of the displacements versus relative changes of mass moments of rotation about the longitudinal axis for Scania trailer and mass moments of rotation about the longitudinal axis for Scania tractor for a Scania vehicle crossing the bridge in the mid-lane*



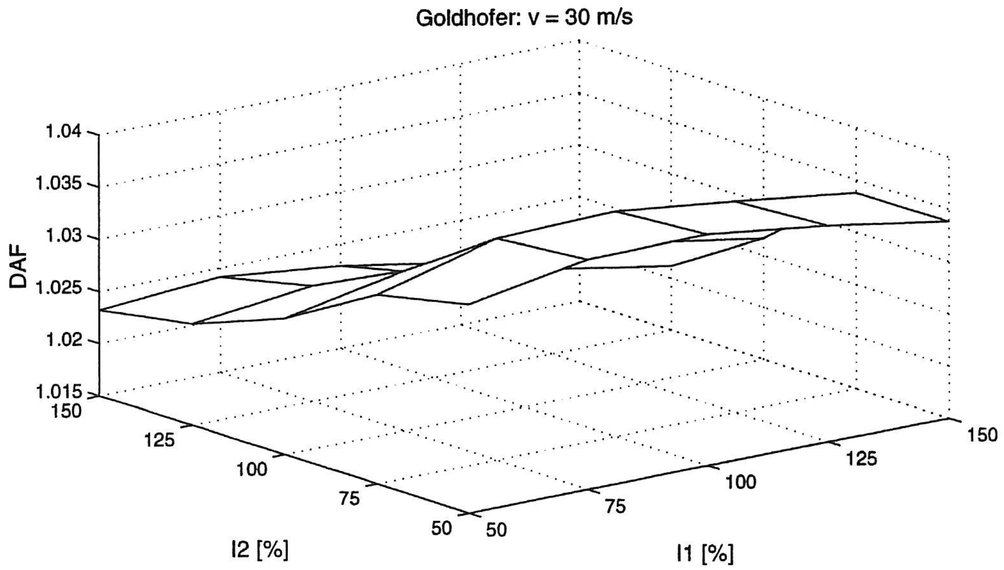


Figure 3.26 *Variation of the dynamic amplification of the displacements versus relative changes of mass moments of rotation about the transverse axis for Goldhofer trailer and mass moments of rotation about the transverse axis for Goldhofer tractor for a Goldhofer vehicle crossing the bridge in the mid-lane.*

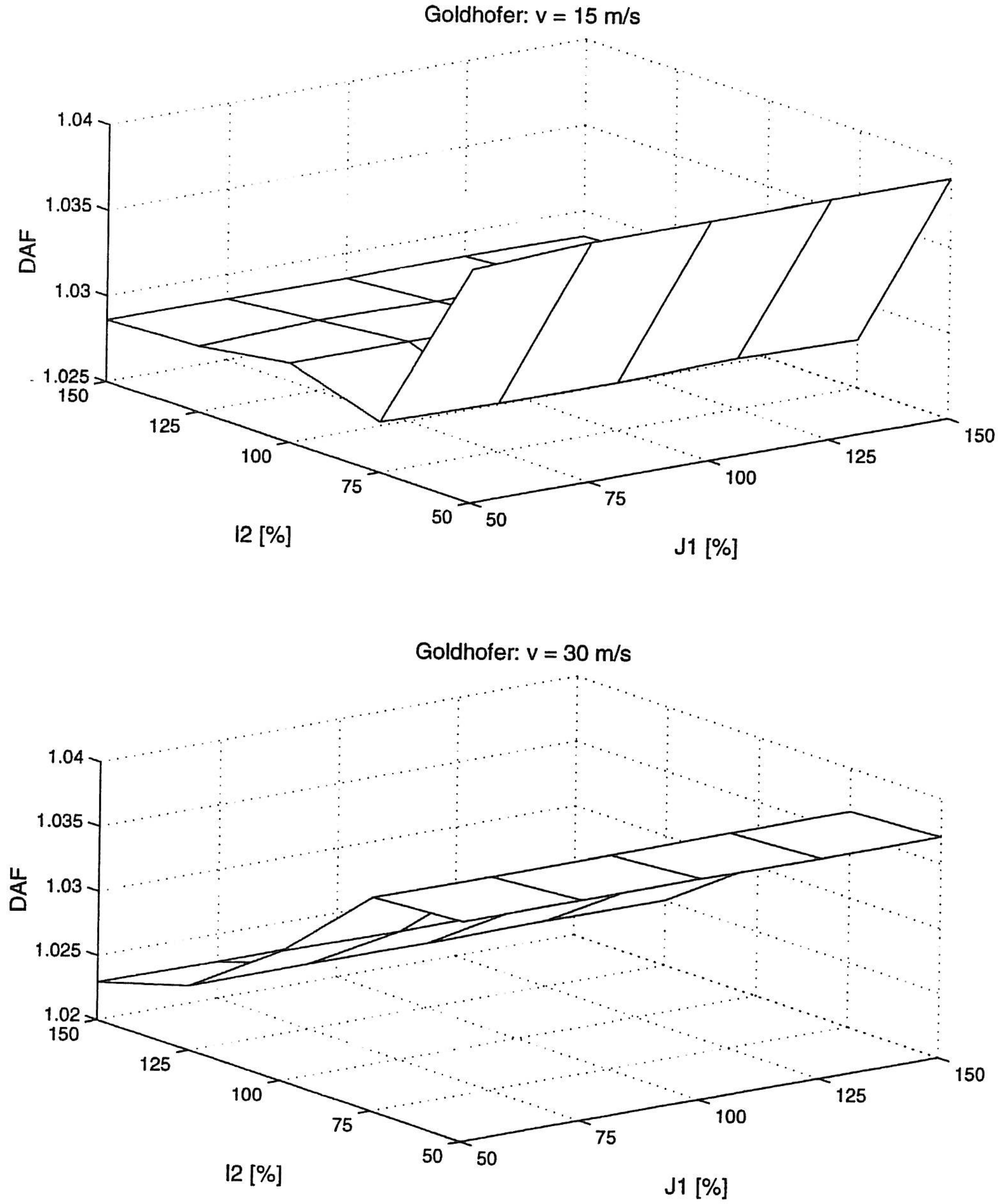
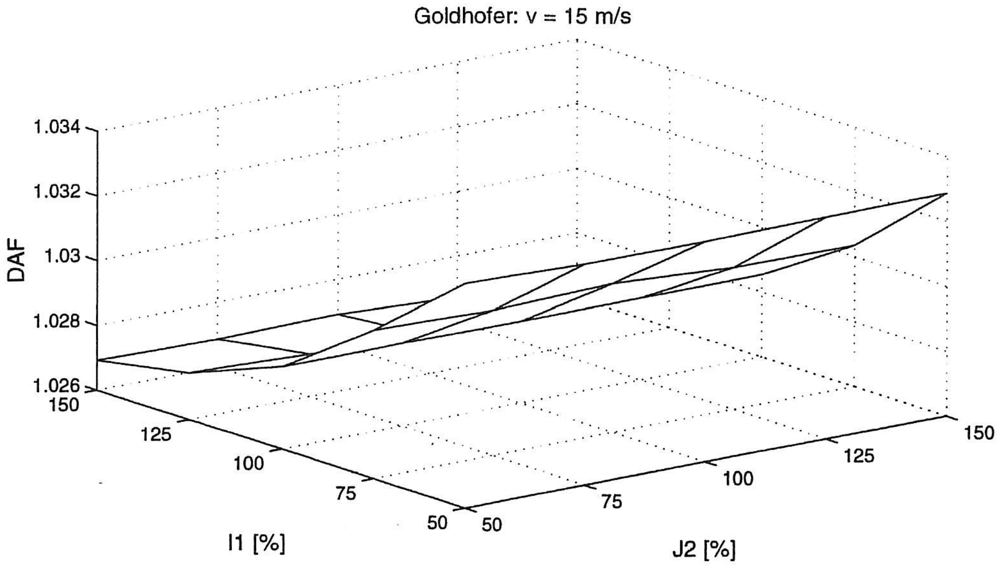


Figure 3.27 *Variation of the dynamic amplification of the displacements versus relative changes of mass moments of rotation about the transverse axis for Goldhofer trailer and mass moments of rotation about the longitudinal axis for Goldhofer tractor for a Goldhofer vehicle crossing the bridge in the mid-lane.*



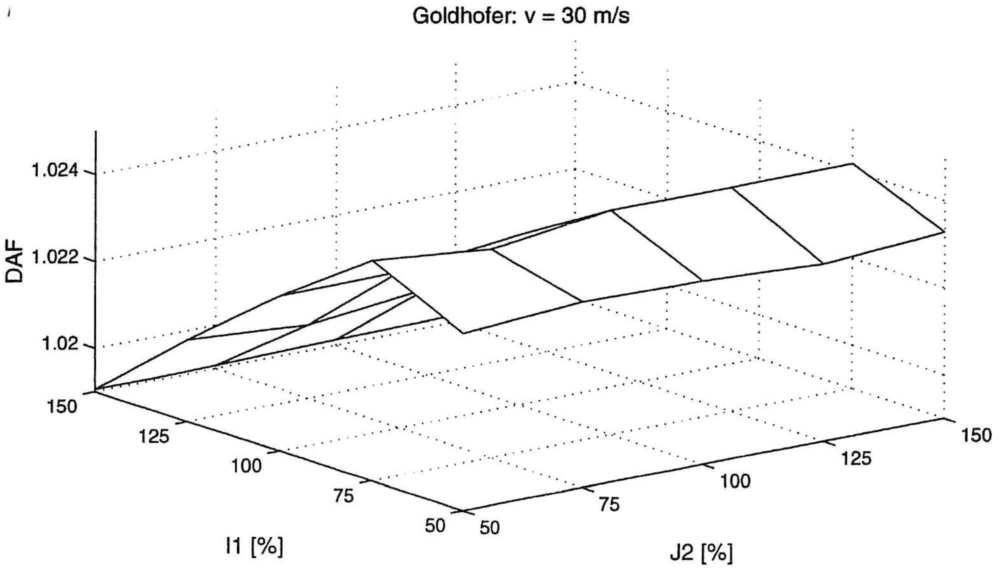
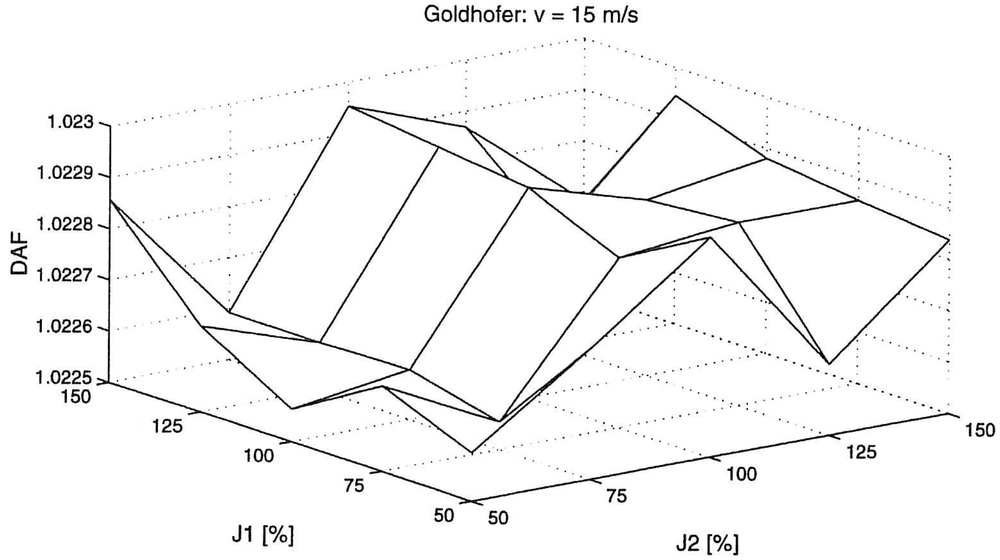


Figure 3.28 *Variation of the dynamic amplification of the displacements versus relative changes of mass moments of rotation about the transverse axis for Goldhofer tractor and mass moments of rotation about the transverse axis for Goldhofer trailer for a Goldhofer vehicle crossing the bridge in the mid-lane.*



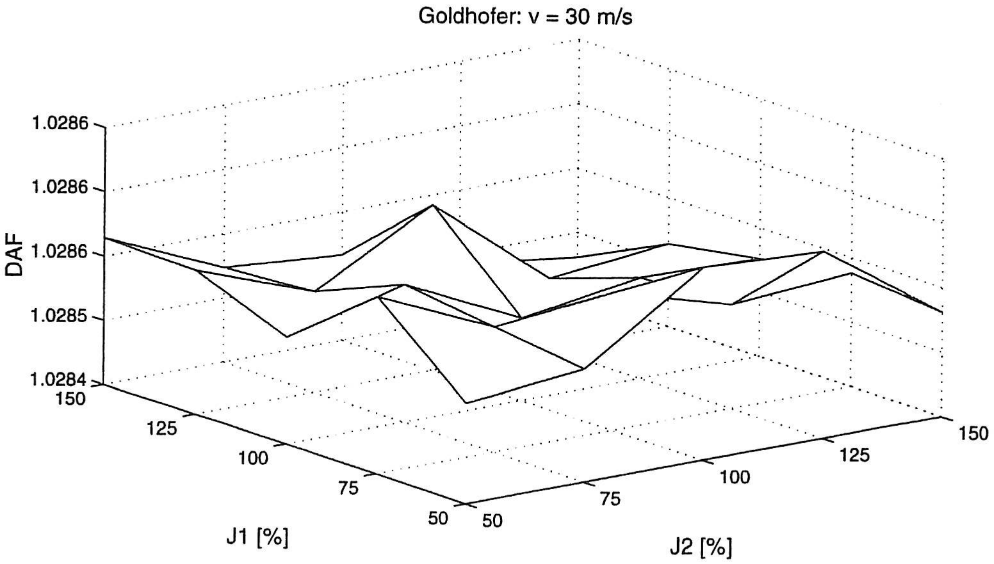


Figure 3.29 *Variation of the dynamic amplification of the displacements versus relative changes of mass moments of rotation about the longitudinal axis for Goldhofer trailer and mass moments of rotation about the longitudinal axis for Goldhofer tractor for a Goldhofer vehicle crossing the bridge in the mid-lane.*

4. EVALUATION OF THE DANISH REGULATIONS

As mentioned in the introduction the critical design scenario for minor highway bridges occurs, at the simultaneous passage of two heavy vehicles. According to the present Danish regulations these two heavy vehicles are taken as a lighter 50 t and a heavier 100 - 150 t vehicle, respectively Vejdirektoratet (1996). For both these vehicles the dynamic amplification factor is taken simultaneously as 1.25. The following sections will evaluate this quantity using the bridge vehicle simulation model presented in the preceding sections.

4.1 Simulation Scenarios

In the simulation study following simulation scenarios will be 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) entering the bridge from opposite directions and random meeting position at the bridge.

Based on the sensitivity study in chapter 3 the most important parameters in the simulation model have been 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 tires, respectively will be modelled as stochastic variables. All other parameters in the simulation model will be modelled as deterministic variables. However, for simulation scenario 3 the starting points for the two vehicles have also been modelled as stochastic variables in order to get different values for their mutual position at the opposite entrance at the bridge. Table 4.1 states the assumed statistical characteristics for the stochastic variables. The values for the deterministic parameters are given in Kirkegaard et al. (1997b).

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

Table 4.1 *Characteristics for stochastic variables used in the simulations. The statistical characteristics for the suspension and tire stiffness are given for normalized basic variables.*

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.

4.2 Simulation Results

This section presents the results from the simulations where the mean value 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 4.2, 4.3 and 4.4 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 4.4. Compared with the DAF given as 1.25 in the Danish regulations it can be concluded that this value seems to be rather conservative.

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 4.2 *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	1.005 (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 4.3 *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
80/60	1.020 (1.85 %)	1.017 (1.83 %)	1.008 (1.88 %)

Table 4.4 *Mean and COV results for simulation scenario 3.*

5. ACKNOWLEDGMENT

The present research was partially supported by The Danish Technical Research Council within the project: "Dynamics of Structures", and "Dynamic Amplification Factor of Vehicle Loads for Reinforcement Projects on Small Highway Bridges". Further, Ole M. Jørgensen and Tor Langhed from Scania Denmark and Scania Sweden, respectively, are acknowledged for kindly release of information concerning the Scania vehicle.

6. CONCLUSIONS

Dynamic amplification of vehicle load at minor highway bridges is investigated by a simulation study using selected crossing scenarios. Some of the parameters in the simulation model were selected to be stochastically modelled based on parameter study. The considered simulation 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.

7. REFERENCES

Hwang, E.-S. and Nowak, A.S. *Simulation of Dynamic Load for Bridges.* Journal of Structural Engineering, Vol. 119, No. 6, pp. 853-867, 1991.

Kirkegaard, P.H., Nielsen, S.R.K. & Enevoldsen, I. *Heavy Vehicles on Minor Highway Bridges - A Literature Review.* Structural Reliability Theory Paper, No. 169, 1997a.

Kirkegaard, P.H., Nielsen, S.R.K. & Enevoldsen, I. *Heavy Vehicles on Minor Highway Bridges -*

Dynamic Modelling of Vehicles and Bridge. Structural Reliability Theory Paper, No. 171, 1997b.

Nassif, H.H. and Nowak, A.S. *Dynamic Load for Girder Bridges under Normal Traffic*. Archives of Civil Engineering, XlII, 4, 1996.

Nielsen, S.R.K., Kirkegaard, P.H. & Enevoldsen, I. *Heavy Vehicles on Minor Highway Bridges - Stochastic Modelling of Surface Irregularities*. Structural Reliability Theory Paper, No. 170, 1997.

STAAD-111 - *Structural Analysis and Design Software*, Revision 21.0w, 1995.

Vejdirektoratet *Beregningsregler for eksisterende broers bæreevne* (The Danish Road Directorate: *Guideline/Code for assessment of the load carrying capacity of existing bridges*), April 1996.

STRUCTURAL RELIABILITY THEORY SERIES

PAPER NO. 144: S. Engelund: *Probabilistic Models and Computational Methods for Chloride Ingress in Concrete*. Ph.D.-Thesis. ISSN 1395-7953 R9707.

PAPER NO. 145: H. U. Köylüoğlu, S. R. K. Nielsen, Jamison Abbott & A. Ş. Çakmak: *Local and Modal Damage Indicators for Reinforced Concrete Shear Frames subject to Earthquakes*. ISSN 0902-7513 R9521

PAPER NO. 146: P. H. Kirkegaard, S. R. K. Nielsen, R. C. Micaletti & A. Ş. Çakmak: *Identification of a Maximum Softening Damage Indicator of RC-Structures using Time-Frequency Techniques*. ISSN 0902-7513 R9522.

PAPER NO. 147: R. C. Micaletti, A. Ş. Çakmak, S. R. K. Nielsen & P. H. Kirkegaard: *Construction of Time-Dependent Spectra using Wavelet Analysis for Determination of Global Damage*. ISSN 0902-7513 R9517.

PAPER NO. 148: H. U. Köylüoğlu, S. R. K. Nielsen & A. Ş. Çakmak: *Hysteretic MDOF Model to Quantify Damage for TC Shear Frames subject to Earthquakes*. ISSN 1395-7953 R9601.

PAPER NO. 149: P. S. Skjærbæk, S. R. K. Nielsen & A. Ş. Çakmak: *Damage Location of Severely Damaged RC-Structures based on Measured Eigenperiods from a Single Response*. ISSN 0902-7513 R9518.

PAPER NO. 150: S. R. K. Nielsen & H. U. Köylüoğlu: *Path Integration applied to Structural Systems with Uncertain Properties*. ISSN 1395-7953 R9602.

PAPER NO. 151: H. U. Köylüoğlu & S. R. K. Nielsen: *System Dynamics and Modified Cumulant Neglect Closure Schemes*. ISSN 1395-7953 R9603.

PAPER NO. 152: R. C. Micaletti, A. Ş. Çakmak, S. R. K. Nielsen, H. U. Köylüoğlu: *Approximate Analytical Solution for the 2nd-Order moments of a SDOF Hysteretic Oscillator with Low Yield Levels Excited by Stationary Gaussian White Noise*. ISSN 1395-7953 R9715.

PAPER NO. 153: R. C. Micaletti, A. Ş. Çakmak, S. R. K. Nielsen & H. U. Köylüoğlu: *A Solution Method for Linear and Geometrically Nonlinear MDOF Systems with Random Properties subject to Random Excitation*. ISSN 1395-7953 R9632.

PAPER NO. 154: J. D. Sørensen, M. H. Faber, I. B. Kroon: *Optimal Reliability-Based Planning of Experiments for POD Curves*. ISSN 1395-7953 R9542.

PAPER NO. 155: J. D. Sørensen, S. Engelund: *Stochastic Finite Elements in Reliability-Based Structural Optimization*. ISSN 1395-7953 R9543.

PAPER NO. 156: C. Pedersen, P. Thoft-Christensen: *Guidelines for Interactive Reliability-Based Structural Optimization using Quasi-Newton Algorithms*. ISSN 1395-7953 R9615.

PAPER NO. 157: P. Thoft-Christensen, F. M. Jensen, C. R. Middleton, A. Blackmore: *Assessment of the Reliability of Concrete Slab Bridges*. ISSN 1395-7953 R9616.

PAPER NO. 158: P. Thoft-Christensen: *Re-Assessment of Concrete Bridges*. ISSN 1395-7953 R9605.

STRUCTURAL RELIABILITY THEORY SERIES

PAPER NO. 159: H. I. Hansen, P. Thoft-Christensen: *Wind Tunnel Testing of Active Control System for Bridges.* ISSN 1395-7953 R9662.

PAPER NO 160: C. Pedersen: *Interactive Reliability-Based Optimization of Structural Systems.* Ph.D.-Thesis. ISSN 1395-7953 R9638.

PAPER NO. 161: S. Engelund, J. D. Sørensen: *Stochastic Models for Chloride-initiated Corrosion in Reinforced Concrete.*ISSN 1395-7953 R9608.

PAPER NO. 162: P. Thoft-Christensen, A. S. Nowak: *Principles of Bridge Reliability - Application to Design and Assessment Codes.* ISSN 1395-7953 R9751.

PAPER NO. 163: P. Thoft-Christensen, F.M. Jensen, C. Middleton, A. Blackmore: *Revised Rules for Concrete Bridges.* ISSN 1395-7953 R9752.

PAPER NO. 164: P. Thoft-Christensen: *Bridge Management Systems. Present and Future.* ISSN 1395-7953 R9711.

PAPER NO. 165: P. H. Kirkegaard, F. M. Jensen, P. Thoft-Christensen: *Modelling of Surface Ships using Artificial Neural Networks.* ISSN 1593-7953 R9625.

PAPER NO. 166: S. R. K. Nielsen, S. Krenk: *Stochastic Response of Energy Balanced Model for Wortex-Induced Vibration.* ISSN 1395-7953 R9710.

PAPER NO. 167: S.R.K. Nielsen, R. Iwankiewicz: *Dynamic systems Driven by Non-Poissonian Impulses: Markov Vector Approach.* ISSN 1395-7953 R9705.

PAPER NO. 168: P. Thoft-Christensen: *Lifetime Reliability Assessment of Concrete Slab Bridges.* ISSN 1395-7953 R9717.

PAPER NO. 169: P. H. Kirkegaard, S. R. K. Nielsen, I. Enevoldsen: *Heavy Vehicles on Minor Highway Bridges - A Literature Review.* ISSN 1395-7953 R9719.

PAPER NO. 170: S.R.K. Nielsen, P.H. Kirkegaard, I. Enevoldsen: *Heavy Vehicles on Minor Highway Bridges - Stochastic Modelling of Surface Irregularities.* ISSN 1395-7953 R9720.

PAPER NO. 171: P. H. Kirkegaard, S. R. K. Nielsen, I. Enevoldsen: *Heavy Vehicles on Minor Highway Bridges - Dynamic Modelling of Vehicles and Bridges.* ISSN 1395-7953 R9721.

PAPER NO. 172: P. H. Kirkegaard, S. R. K. Nielsen, I. Enevoldsen: *Heavy Vehicles on Minor Highway Bridges - Calculation of Dynamic Impact Factors from Selected Crossing Scenarios.* ISSN 1395-7953 R9722.

PAPER NO. 175: C. Frier, J.D. Sørensen: *Stochastic Properties of Plasticity Based Constitutive Law for Concrete.* ISSN 1395-7953 R9727.

PAPER NO. 177: P. Thoft-Christensen: *Review of Industrial Applications of Structural Reliability Theory.* ISSN 1395-7953 R9750.

Department of Building Technology and Structural Engineering
Aalborg University, Sohngaardsholmsvej 57, DK 9000 Aalborg
Telephone: +45 9635 8080 Telefax: +45 9814 8243