

DYNAMIC LOAD ALLOWANCE FOR REINFORCED CONCRETE BRIDGES

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Abstract. *A dynamic load allowance (DLA) is a quantitative measure of dynamic effects exerted in addition to static loads by moving vehicles on highway bridges. The American Association of State Highway and Transportation Officials (AASHTO) recommends using 33% as a maximum value of DLA [1]. The paper presents results of extensive investigation of DLA, which was carried out for the Florida Department of Transportation (FDOT) for a broad class of prestressed reinforced concrete bridges. FDOT manages over 6400 such bridges and precise information about their performance, due to heavy (so called: permit) vehicles, is critical for its Maintenance Office. Two parallel tracks: experimental and analytical, were designed and implemented as integral parts of this research. Each track resulted in data which was used to calculate DLA. Comparison of these results showed a good correlation between experiments and analyses, and was used to verify and validate finite element (FE) models developed.*

All experimental tests were carried out on a selected, typical, prestressed, reinforced concrete bridge #500133 on US 90 in north eastern Florida. It was a newer bridge, built in 1999 with three simply supported spans and AASHTO type III girders. A selected span of the bridge was instrumented with: (a) two linear variable displacement transformers (LVDT), (b) 38 strain gauges and (c) 14 accelerometers installed at the top of the bridge deck. 35 static and dynamic tests were carried out with the speed of 48 km/hr and 80 km/hr. Three representative permit vehicles were used for the tests. Data acquisition from experimental testing allowed for calculation of DLA.

The second research track consisted of FE model development and computational analysis using LS-DYNA computer code. In addition to the bridge #500133, two other local, prestressed, reinforced concrete bridges were selected for analytical studies of DLA. Their superstructure consisted of AASHTO type II and IV prestressed reinforced concrete girders. The FE model of the bridge #500133 was validated and verified using experimental data. DLA factors were calculated for all bridges as functions of vehicle types and their velocities. They were determined based on maximum displacements and strains. Several factors were identified as triggering significant DLA. They included: surface imperfections (as joint abutments and bridge approach depression), loosely attached cargo producing so called hammering effect, and characteristics of the vehicle suspension. This paper presents the latest results of the project, for which some earlier data was reported in [2] through [4].

1. INTRODUCTION

The Florida Department of Transportation (FDOT) has set a mission to rehabilitate the state transportation system, including roads highways and highway bridges. This research project responds to the call from the FDOT to improve the transportation system and to meet the needs for providing safer transportation. The state will need a huge investment over the next years to improve the transportation system. To decrease the total investment needed, the FDOT needs to significantly improve the operation and make sure that the proper maintenance of highway bridges is performed. In order to achieve this, more knowledge about certain effects resulting from dynamic loading of bridges is imperative. The information not only will help the FDOT make decisions on heavy vehicle permitting but also to establish permissible weight limits for bridges.

Traditional methods used for analysis of dynamic live loads on bridges use simplifications. This results in dynamic loads tending to be very conservative if not ignored. Ignoring the dynamic nature of live loads is not very convenient, and may result in premature damage of the bridge structure or a decrease in the bridge lifespan.

Dynamic live loads are taken into account by using dynamic load allowances (DLA), which is a factor to scale up the magnitude of the static load. By using a DLA engineers usually ignore vibrations and other damaging effects induced by heavy vehicles into bridges.

Reinforced concrete bridges usually have a behavior that is hard to explain, and applying advanced structural analysis to this type of structure is not simple. With advances in computational power and methods in computational mechanics, newer methods to analyze complex structures like bridges are coming to light. This advances in computer technology and computational capabilities, followed by development of commercial finite element (FE) software have made 3-D dynamic analysis of bridge structures more effective.

Further development of FE software in material models, and different applications of constraint and damping allows the software to more accurately represent the actual behavior of the bridge structure. The vast variety of element and material types allow for a better representation of vehicle components like the suspension system, which is critical in the interaction between vehicle and bridge. All these advancements in FE model software provide a powerful tool for the assessment of complex structural and mechanical phenomena such as a wheel rolling on the pavement. Most important for this type of analysis is the dependence of moving live loads varying with time caused by dynamic interaction of masses for the vehicle and the bridge components.

Experimental testing of bridges in the field is expensive and can only provide a limited amount of data. This project seeks to conduct comprehensive research on transient analysis of the dynamic interaction between heavy vehicles and prestressed concrete bridges using computational mechanics. Such approach offers less expensive and more accurate ways to conduct this research on dynamic load allowance factors.

Verification and validation of numerical models is a process that builds the credibility of the model. It is usually done by comparing a numerical model of a phenomena to the data obtained from the actual physical tests. Validated FE models can provide accurate information about the behaviour of the structure which are expensive and difficult if only experiments are used. This paper focuses on the use of validated FE models for the assessment of DLA of reinforced concrete bridges.

Three heavy permit vehicles were selected for analysis and their FE models were developed. The vehicles were selected based on their span length, number of axles, weight

distribution, and suspension characteristics. The vehicle FE models were verified and validated through experimental testing of the vehicles crossing over a speed bump.

Three reinforced concrete bridges were also selected from the northern part of Florida and their FE models were also developed. The selected bridges varied in span length, width, and girder type. The FE models of the bridges included road surface irregularities to assess the influence of the road surface imperfections on the bridge response. The FE models of the bridges were verified and validated through experimental tests conducted on one of the bridges.

The analyses performed in the project were based on explicit, dynamic, non-linear finite element computational mechanics using LS-DYNA computer code [8].

2. FE MODELS OF PERMIT VEHICLES

The FE models of the vehicles were simple but still reliable, with a good geometrical and physical representation of the actual trucks. The simplicity of the model reduced the necessary calculation time needed for numerical simulations and increased the performance and stability of the simulations.

Three vehicles were selected for analysis and FE models of them were developed. The vehicles selected were: a CH613 truck tractor with a single drop lowboy trailer, a Terex T-340 Crane, and a FDOT truck.

The FE models of the selected vehicles were developed using direct measurement and constant inspection of the vehicle, as blueprints or files with the data for the selected vehicles were not available. Extended efforts were made on the development of the vehicle's components which have a significant influence in the interaction with the road. Some of these components include: the vehicle's elastic tires, wheels, suspension system, single and tandem axles, and the chassis.

The first vehicle, the tractor-trailer, was selected because of its well designed suspension system, its length, and uniform weight distribution. The FE model of the tractor-trailer was developed using 2-D 3- and 4-node shell elements, and 3-D 6- and 8- node fully integrated solid elements for most of the vehicle component. The suspension system was modelled using 1-D discrete beam elements, with discrete spring and damper material models. Constitutive material models included elastic material for the truck frame, and fabric and rubber material for the wheels. Other components of the vehicle which were modelled as rigid parts include the driver cab, hood, and engine. The FE model of the tractor-trailer is summarized in Table 1 and is presented in Figure 1.

Specification		Specification	
Number of parts	204	Number of elements	26,194
Number of nodes	19,941	- solid elements	1128
Number of material models	38	- shell elements	24,790
		- beam elements	248
		- discrete elements	22
		- mass elements	6

Table 1: Summary of complete FE model of tractor-trailer [5].

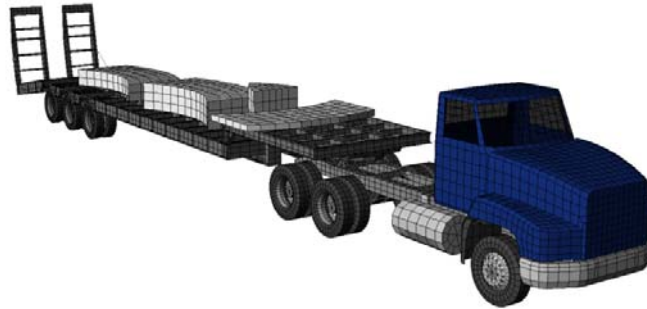


Figure 1: An FE model of the tractor-trailer.

The second vehicle, the Terex crane, was selected because of its short length, and heavy load. The distribution of the heavy load over a short span created a compact setup which was very different from that of the tractor-trailer. The FE model of the Terex crane was developed using the same technique as for the tractor-trailer with the same material models with slight variation on the properties of steel. This FE model was the simplest one with most of its components being rigid. More detailed information about the development of the FE model of the Terex crane is available in [5]. The FE model of the Terex crane is summarized in Table 2 and is presented in Figure 2.

Specification		Specification	
Number of parts	153	Number of elements	20,837
Number of nodes	17,401	- solid elements	1,338
Number of material models	29	- shell elements	19,323
		- beam elements	142
		- discrete elements	28
		- mass elements	6

Table 2: Summary of complete FE model of Terex crane [5].

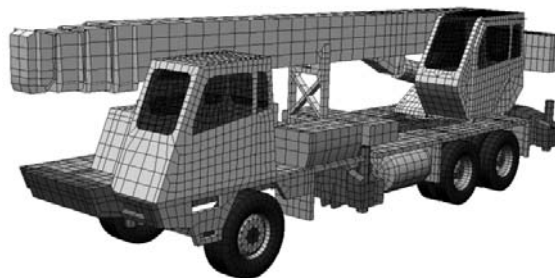


Figure 2: An FE model of the Terex crane.

The third vehicle, the FDOT truck, was chosen because of its purposely designed stiff suspension. The FDOT truck was custom-built for the FDOT to conduct dynamic tests on bridge structures and so was designed with the worst possible suspension characteristics to test the worst case dynamic loadings. The truck consists of a very simple suspension system

with two tandem axles which were easy to model. The FE model of the FDOT truck was developed using the same technique as the other two vehicles, with the same material models and element types. The FE model of the FDOT truck is summarized in Table 3 and is presented in Figure 3.

Specification		Specification	
Number of parts	181	Number of elements	18,569
Number of nodes	13,031	- solid elements	926
Number of material models	25	- shell elements	17,137
		- beam elements	440
		- discrete elements	58
		- mass elements	8

Table 3: Summary of complete FE model of FDOT truck [5].

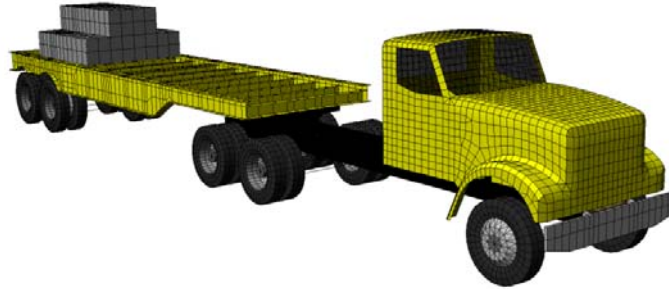


Figure 3: An FE model of the FDOT truck.

3. VERIFICATION AND VALIDATION OF VEHICLE FE MODELS

Verification and validation of the vehicle's FE model was obtained through comparison with data obtained from experimental testing on the actual vehicles. For the purpose of validation of the vehicle mass, each vehicle axle loads were measured using scales. Each axle of the FE models was then dropped into planar rigid walls for which LS-DYNA [8] allows an easy measurement of the load. The final measurements of the experiment and the virtual trucks are summarized in Table 4.

A test was designed and conducted in Broadmoor Estate in Tallahassee for validation of the suspension system of the vehicles. The vehicles were equipped with displacement gauges and accelerometers, and then driven over a speed bump at speeds varying from 8 to 32 km/h. Lower velocities were used to ensure the driver's safety and preserve the testing equipment, which is a common practice found in the literature. The test measured the acceleration of a point in the frame and the change in distance between a point in the frame and the axle. The test was then replicated virtually with the vehicles driven over the same speed bump at the same speeds. To ensure the numerical analysis matched the actual test, the asphalt speed bump was modelled using the exact geometry of the bump which was obtained from an Optech's Intelligent Laser Ranging and Imaging System (ILRIS) scanner. More detailed information about the development of the speed bump FE model is available in [5]. Experimental and virtual results of the tractor-trailer are compared in Figure 4.

Axle No.	Axle type	Axle load (kN)		Relative error (%)
		Measurements	FE model	
1	Front steer axle	42.184	42.291	0.25
2	Forward tandem drive axle	89.440	89.439	0.00
3	Rear tandem drive axle	94.957	95.008	0.05
4	First trailer axle	94.601	93.946	-0.69
5	Second trailer axle	98.517	97.908	-0.62
6	Third trailer axle	100.831	101.754	0.92
TOTAL		520.530	520.346	-0.04

Table 4: Axle loads for the tractor trailer in experiment and FE analysis [5].

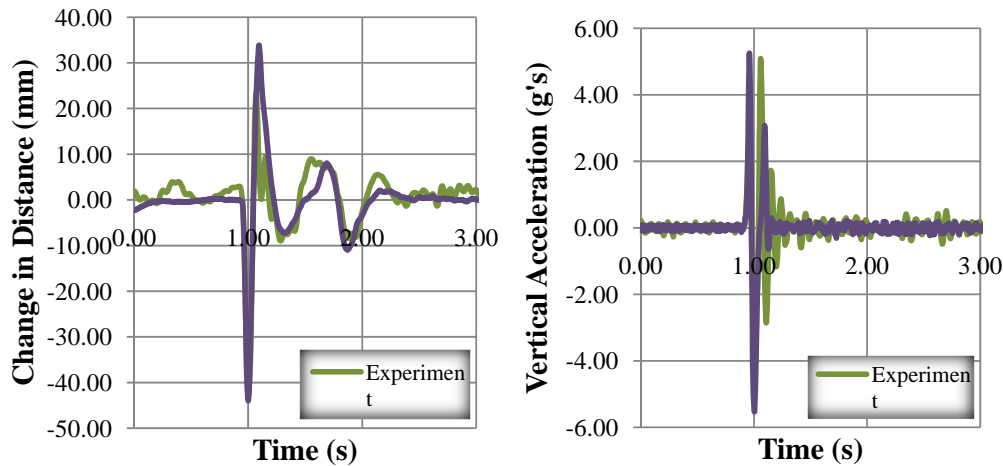


Figure 4: Time histories from experiment and FE analysis of the tractor trailer at 24 km/h.

The load measurements of the truck and its FE model were matched quantitatively; this was obtained by adding discrete mass points in the FE model and making changes in material densities.

The spring and damper coefficients for the FE models were initially obtained from the manufacturer's websites. The results of the test were matched with the numerical analysis quantitatively by modifying the spring stiffness until there was conformity between the two. The process was done carefully to keep the proper distribution of sprung and unsprung mass, as well as to maintain the proper length of the springs in its static configuration. This process was applied to all the FE models of the permit vehicles used in this study. The vehicles were then considered to be validated.

4. FE MODELS OF REINFORCED CONCRETE BRIDGES

FE modelling of 3-D bridges became more common over the past decade [3], [4], [5], [6]. The models are becoming more sophisticated due to the increased efficiency and capability of computer software.

Three highway bridges near Tallahassee were selected for analysis of DLA factors. These bridges were selected because they consisted of prestressed reinforced concrete girders according to the American Association of State Highway and Transportation Officials

(AASHTO) [1]. Data for one span of each of the three bridges selected for analysis is summarized in Table 5.

Bridge Name	Bridge No.	AASHTO Girder Type	Span Length (m)	Width (m)
No Name Creek	#540074	II	12.1	11.6
Chattahoochee	#500133	III	21.0	13.1
St. Mark's	#590056	IV	29.3	12.6

Table 5: Summary of selected bridges for analysis.

An FE model of one span of each bridge was developed. The bridge model included six different components such as: bearing pads, concrete girders, diaphragm, concrete deck, bridge barriers, and bridge approach surface. The components were modelled according to geometric data obtained from one of the bridge's blueprints provided by the FDOT. The other two bridges were modelled using measurements obtained in situ.

Unreinforced neoprene bearing pads were used to support the FE model of the girders at each end. The bearing pads were modelled using 3-D 8-node fully integrated solid elements with a viscoelastic material model selected for analysis. The material properties of the neoprene pads were inspected and assessed in [7].

The FE model of the concrete girders was developed using 3-D 8- and 6-node fully integrated solid elements. An elastic material model was used for analysis with properties for concrete obtained from cylinder testing of the girders by the FDOT Structures Research Laboratory.

Reinforcement of the girders included reinforcing bars and prestressing strands, which were modelled using 1-D beam and rod elements respectively.

Each AASHTO girder included two No. 9 strands at the top and 24 No. 13 strands at the bottom. One equivalent strand at the top and eleven equivalent strands at the bottom were modeled due to the discrete location of the nodes in the FE model cross section. Selected strands were grouped and their properties were lumped together as presented in Figure 5. The process was done to make sure that the FE model accurately behaved like the real beam.

A special material model (MAT_CABLE_DISCRETE_BEAM) was applied to the strands which allowed an introduction of prestressing forces, and allowed the cables to carry tensile loads without any stiffness for compression [8].

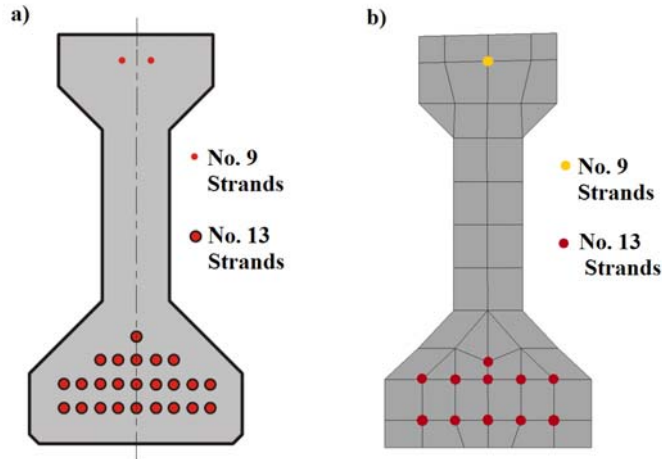


Figure 5: Prestressing strands: a) actual location in girder, b) equivalent location in FE model.

The FE model of the diaphragm, concrete deck, and bridge barriers were modelled using 3-D fully integrated solid elements. The elastic material model was selected for analysis, with their actual properties for concrete as tested. Reinforcement of these components was modelled using 1-D beam elements for the reinforcing bars. Elastic material models with specific properties for steel were used for the reinforcements according to the blueprint information.

The bridge approach surfaces of all three bridges were inspected and the surface with the worst deterioration of the three was selected. The surface of bridge #500133 exhibit an area characterized by two distinct ruts made in the asphalt by passing vehicles, with the adjacent stronger concrete deck not showing such wear and tear damage. As a result there was a difference in elevation between the asphalt and the concrete which was found to be around 15 to 20 mm. The approach surface was found to have a pronounced effect in the dynamic response of the bridge; therefore the same approach surface was used on all three bridges to make use of the worst conditions available. The bridge approach surface was modelled as is, with the exact geometry obtained using Optech's ILRIS scanner. More detailed information on the development of the bridge approach surface model is available in [5].

The final FE model of the bridge consisted of 145,604 finite elements. A similar process was used for the development of the other two bridges. The final FE model of one of the bridges is presented in Figure 6.



Figure 6: An FE model of bridge #500133.

5. VALIDATION AND VERIFICATION OF FE BRIDGE MODELS

Validation of the concrete bridges was obtained by experimental testing of one of the selected bridges. All experimental tests were carried out on bridge #500133 on US 90 in north eastern Florida. This newer bridge was built in 1999 with three simply supported spans and with six AASHTO type III girders in each span. The bridge was tested twice, first in 2003 with an FDOT truck, and then in 2008, including two additional vehicles: the tractor trailer and the Terex crane. One span of the bridge was instrumented with two linear variable displacement transformers (LVDT), 38 strain gauges, and 14 accelerometers installed at the top of the bridge deck. Over 35 static and dynamic tests were carried out at speeds ranging from 48 to 80 km/h. Data obtained from the experimental testing allowed for calculation of DLA, and comparison to results from the numerical model. Detailed description of the tests carried out on the bridge and the results are available in [5].

The tests were virtually replicated, with strains and displacements obtained from the same points as in the experiment. Figure 7 shows result of the experiment and numerical analysis for one case, in which the tractor trailer crosses the bridge in the center of the westbound lane at a speed of 80 km/h.

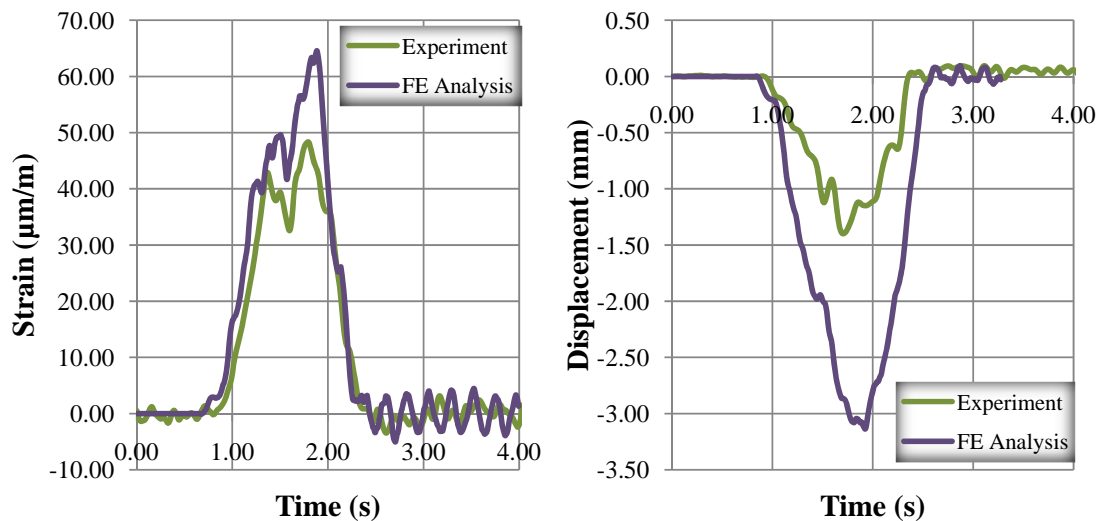


Figure 7: Time histories from experiment and FE analysis at 80 km/h over bridge #500133.

It is observed that the strain values are between ranges of measurement error. Results for displacements show a largest discrepancy which is attributed to the lack of zeroing of the displacement meters before each test. Still with some of the error observed, the values are accepted as qualitatively rather than quantitatively. The complete results of the tests are available in [5]. The same process was carried out with all three vehicles, and the FE model of the bridge was considered to be validated.

6. ANALYSIS OF DYNAMIC LOAD ALLOWANCE

DLA factors were calculated for all three bridges loaded with all three vehicles. DLAs were determined based on maximum displacement and strains in the bottom of the girder in the middle of the bridge span. DLA factors based on maximum strains proved to be more reliable, and closer to the experimental data, as well as recommended values by AASHTO [1]. The largest strains and displacements were recorded in girders no. 4 and 5 located

directly underneath the path of the vehicle during the tests. Over ninety different tests with the numerical models were conducted to study the effect of the velocity on the DLA factor. As an illustration, DLA variation due to the vehicle speed is presented for one of the cases in Figure 8.

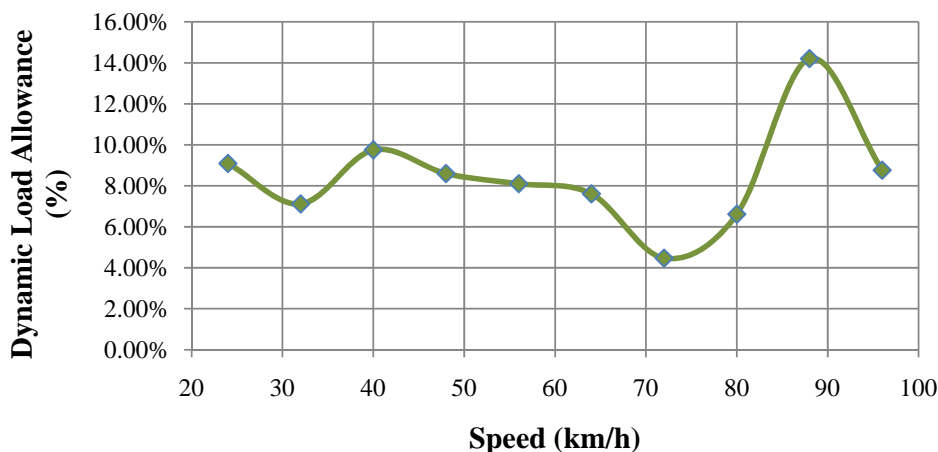


Figure 8: DLA factor vs. speed for the tractor trailer on bridge #500133.

Figure 8 illustrates the fact that DLA factors do not necessarily monotonically increase as vehicle speed increases. For this case of the tractor-trailer crossing over the bridge, the maximum DLA factor observed was at speed of about 88 km/h with a value of about 14%. DLA factors were calculated for every case with the same observation in all the cases.

The suspension system of the vehicles was one of the most influential characteristics that affected the dynamic response of the bridge. Results of DLA factors for the three vehicles crossing over bridge #500133 at a specified speed are presented in Table 6.

Vehicle	Speed (km/h)	DLA (%)
Tractor-trailer	80	6.6
Terex crane	80	32.7
FDOT truck	80	35.4

Table 6: Analysis of vehicles traveling over bridge #500133.

Another feature identified as triggering an increased DLA is a loosely attached cargo that is able to bounce on top of the trailer, producing a so called hammering effect. The tractor trailer model was modified to allow the bouncing of the cargo on top of the trailer. The cargo was detached from the trailer and seatbelt elements were introduced to act as tying chains. Final results of the testing of the tractor-trailer on bridge #500133 are presented in Figure 9.

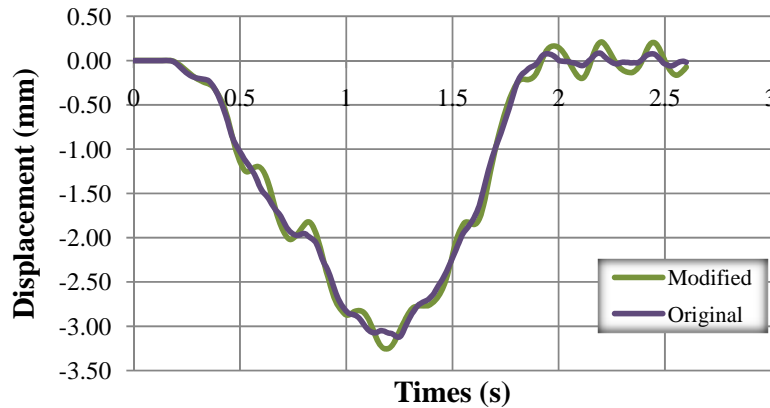


Figure 9: Deflection of the bridge girder #4 from FE analyses at 80 km/h.

It can be seen from Figure 9 that with the modifications made to the tractor-trailer model, the bridge was subjected to a larger displacement, which was caused by an additional pounding of the bouncing load on the bridge. Qualitatively both time histories look the same, but there is an additional frequency observed in the modified model of about $f = 4.8$ Hz. This pounding frequency was consistent with those observed earlier during the experimental testing of bridge #500133.

The quality of the bridge approach depression was also found to have a significant impact on the DLA factors calculated. The bridge approach depression of the FE model of bridge #500133 was replaced by a perfectly flat approach surface. The virtual experiment used the Terex crane travelling at a speed of 80 km/h. Strain measurements from the virtual tests are presented in Figure 10. The strain for the case in which the vehicle travels over the flat approach shows a decrease in magnitude.

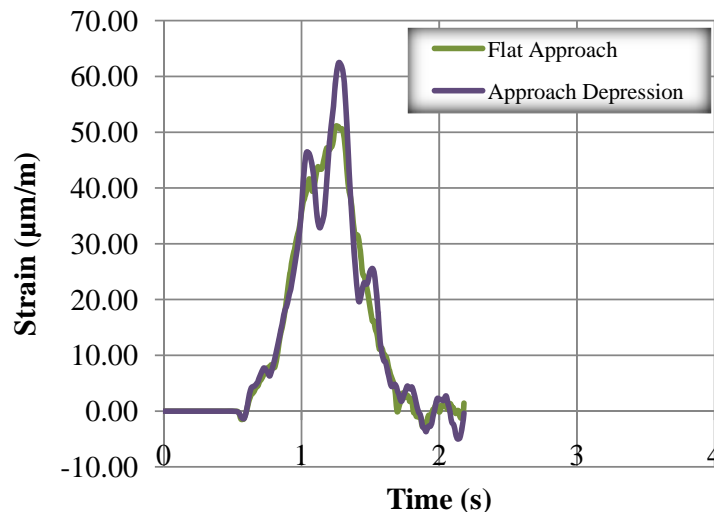


Figure 10: Longitudinal strains from FE analyses for girder #4 at 80 km/h.

7. CONCLUSIONS

This paper presented a comprehensive analysis of vehicle-bridge dynamic systems. The complete analysis consisted of computational mechanics and experimental parts. Three FE models of highway bridges and three FE models of heavy vehicles were used. Analysis of DLA factors was conducted for all bridges depending on vehicle speed and type. Efforts were made to develop realistic vehicle models for they account as much as 20% of the total mass of the vehicle-bridge system. Representing them as concentrated loads would not provide accurate data on the real system.

Considering the analysis was of dynamic nature, the vehicles springs and dampers were accounted for through a careful modelling process of the suspension systems. Rotating wheels and tires were also modelled carefully due to their influence on the vehicle-bridge dynamic system. The accuracy of the results obtained is credited to the development of the innovative finite element models and is supported with data from experimental tests. From the analysis several factors were found to have a significant influence on the DLA such as:

1. Vehicle suspension system: the very stiff suspension from FDOT resulted in the worst DLA factors in most of the cases.
2. Road surface condition: faults in the abutment joint and surface imperfections such as cracks and ruts; when compared to a flat surface result in a much higher DLA factor.
3. Loosely attached cargo which is able to bounce on top of the trailer: an additional pounding frequency is observed with a higher dynamic response on the bridge.

These were the factors that had the most influence on the magnitude of the DLA factors. From the variety of tests conducted in computational analysis, some other observations were also made, such as:

1. AASHTO recommendation value of DLA = 33% appeared to be a reasonable approximation with only five cases surpassing it, but at relatively high speeds as presented in Figure 11.

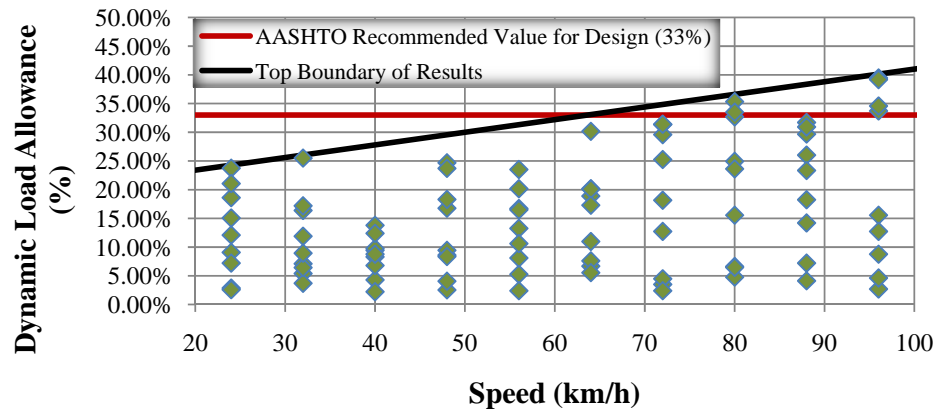


Figure 11: Summary of FE analyses of all the vehicle-bridge interactions.

2. The DLA factor does not monotonically increase as the vehicle speed increases; a lower vehicle speed in certain cases resulted in a higher DLA factor.
3. The bridge dynamic response is dependent on a combination of span length, width, and girder type which specifies the structure natural frequency.
4. The DLA factors also depend on the bridge natural frequency, and vibrations transferred in the interaction with the heavy vehicle.

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