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SIMULATION OF ADVANCED 3D FINITE ELEMENT DYNAMIC VEHICLE BRIDGE INTERACTION USING SINGLE AND MULTI-VEHICLE SCENARIO FOR OBTAINING DYNAMIC AMPLIFICATION FACTOR

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ABSTRACT: This research paper focuses on simulation of vehicle bridge interaction using the spatial method of finite element modeling in order to obtain Dynamic Amplification Factor (DAF). The Simplified 3 Dimensional Finite Element Model (3D SFEM) of already verified vehicle bridge interaction was used for obtaining the DAF of US girder bridges. The effects of single and multiple heavy vehicles on the DAF of Prestressed Concrete I Girder Bridge was obtained using 3D SFEM heavy vehicle bridge interaction. Along with the number of vehicles, the effect of variable vehicle velocities and their positions on the DAF was studied. In addition to this, the combination of 3 Axle and 5 Axle vehicles over the bridge were used for obtaining DAF of the US Girder Bridges. The DAF was obtained for random vehicle scenarios where truck could travel over bridge without any synchronization. Using these variables, the true representative DAF of the bridge was obtained. From these multiple variable scenarios, an attempt was made to present the 3D SFEM as an alternative to 3D Finite Element Modeling (3D FEM) of US girder bridges, and multiple axle vehicles, so that the spatial method can be used to predict reliable responses using vehicle bridge interaction.

KEYWORDS: Simplified 3 Dimensional Finite Element Model (3D SFEM); Dynamic Amplification Factor (DAF); Spatial Method; 3D Finite Element Modeling (3D FEM).

1 INTRODUCTION

The Dynamic Amplification Factor (DAF) or Dynamic Impact Factor (DIF) is very crucial element which requires special attention when designing a bridge. The DAF is a ratio of dynamic strain to static strain of the bridge as given by equation 1.

$$\mathrm{DAF} = \frac{S_d}{S_s} = 1 + \mathrm{DIF} \tag{1}$$

Where: $S_{d,}$ is Dynamic strain at the center of sensor location
Ss is Static strain at the center of sensor location

The dynamic and static responses of any bridge depend on the types of bridges and the types and volume of vehicles moving on them [1]. The AASHTO LRFD Bridge design specification provides a factor of 1.33 for dynamic amplification of the load [2]. The static load is increased by 33% to account for dynamic forces induced by the vehicle movement. The AASHTO specifications provide a uniform value for all the bridges regardless of nature of traffic. The DAF provision in AASHTO attempts to allow for both increased load and the effect of vehicle induced dynamic forces. Since all the vehicles are made of types of complicated geometries, including suspension and damping systems, to obtain accurate data is a challenging issue and requires sophisticated data acquisition systems.

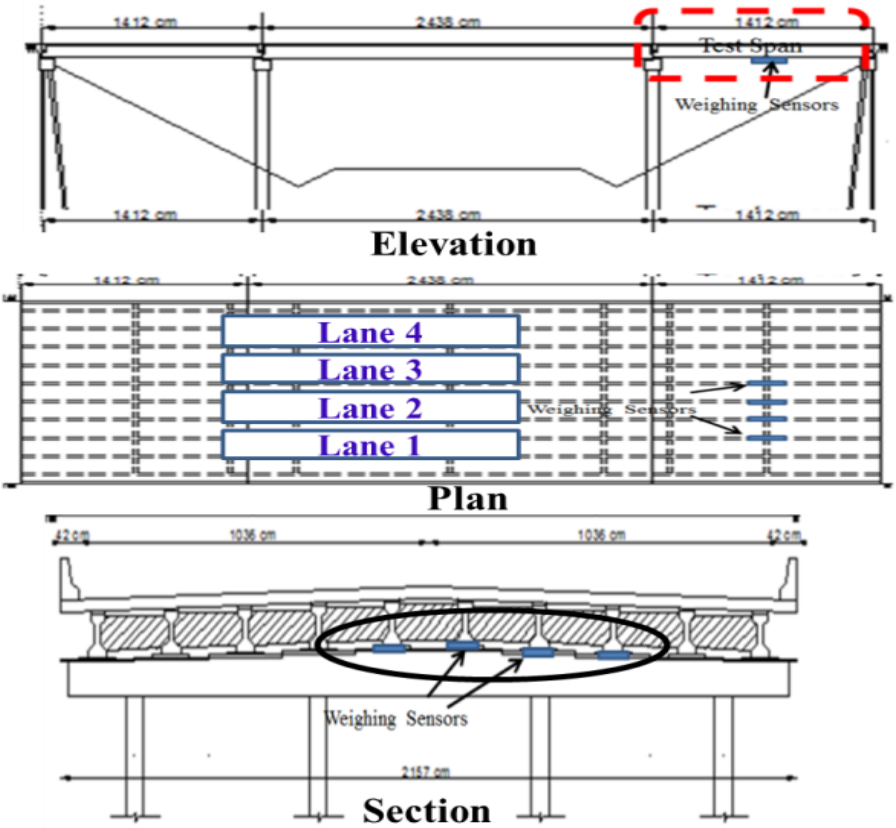


Figure 1. Detailed schematic of I 459 Bridge for B-WIM installation [6]

Previous researchers used Bridge Weigh in Motion (B-WIM) system for obtaining experimental vehicular data and responses of US girder bridges in terms of time strain histories [1]. The traditional B-WIM system uses Moses' algorithm where the static axle weights in the B-WIM system are calculated by minimizing the sum of the squares of differences between measured bridge responses and corresponding theoretical strain responses for the same bridge [3]. In terms of time strain histories, direct responses are obtained from experimental testing on real bridges using a calibration vehicle with premeasured axle weights. Therefore, based on the requirements of the B-WIM system for obtaining actual strain responses from the bridge, the experimental test was carried out on existing prestressed concrete I Girder Bridge located on I 459, designated as I 459 in this article [1, 4-5]. The schematic of I 459 bridge used for the experimental analysis is as shown in Figure 1 [6].

As shown in Figure 1, the I 459 is a Prestressed Concrete I Girder Bridge. This bridge is one of the most common types of bridges in US infrastructure. As shown in Figure 1 the end spans were selected for the installation of the sensors. The sensors were installed at the mid-span. Along with I 459, the ALDOT 5 Axle Truck, representing the most common type of truck on US highways, was selected as a heavy vehicle for experimental test as shown in Figure 2 [7].

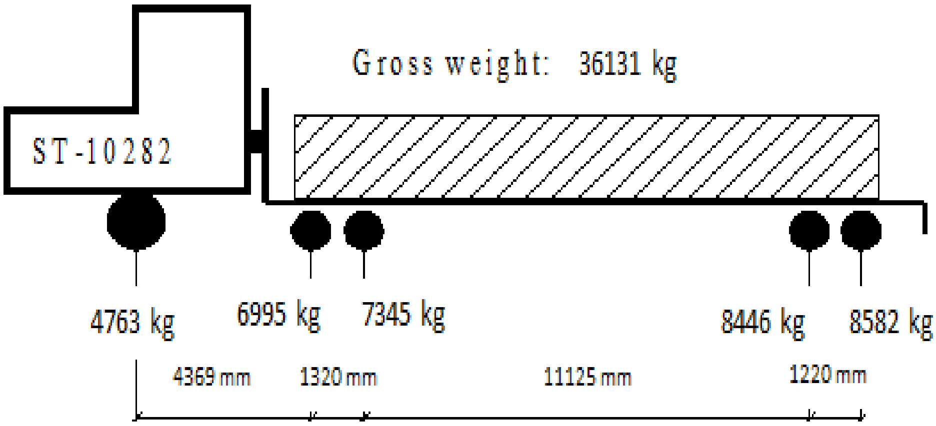


Figure 2. Schematic of ALDOT 5 axle fully loaded truck used as heavy vehicle [7]

As shown in Figure 2, the distance between axles of the truck as well the individual axle weights were measured at the test site. For the experimental test, the velocity of the truck was maintained at88 km per hour (55 mph). Time strain histories were measured on site while the vehicle is moving over the bridge using strain gauges installed under the girder at the mid-span. Using these strain responses, the DAF of the bridge was obtained using equation 1 [1]. However, the experimental test did not consider possible multiple presence of the vehicle over the bridge when obtaining strain data. Since the experimental test required a significant amount of time for installation, calibration, and data acquisition, it is therefore not possible to use the experimental test for data acquisition or for obtaining dynamic vehicle effect over the bridge, for various loading conditions. Hence, to predict accurate responses of the bridge for variable loading condition, previous researchers used an alternate approach of finite element model (FEM) of vehicle bridge interaction [1, 4].

The earlier version of the FEM for I 459 and heavy vehicle was developed using MATLAB. The measured and modeled responses using the FEM in previous studies yielded good result; however, the vehicle suspension effects and vibration induced by surface roughness of the bridge were neglected in the previous model. Due to the suspension of the truck and the surface roughness of the bridge, the bridge experiences large vibrations affecting the overall response of the bridge [8-9]. These responses should be considered in order to obtain an accurate DAF for the bridge. They can be attained using sophisticated 3 Dimensional Finite Element Modeling (3D FEM) of the vehicle bridge interaction. To provide accurate inputs, the 3D FEMs of vehicle bridge interaction were developed and verified using experimental strain responses [10]. The validation of the 3D FEM vehicle bridge interaction for the use of experimental test is as discussed in Section 2.

2 VALIDATION OF THE 3D FEM VEHICLE BRIDGE INTERACTION FOR DAF

The 3D FEM vehicle bridge interaction was developed and validated using strain responses obtained from experimental testing. The position of heavy vehicle over I 459, used for strain validation, is as shown in Figure 3 [10].

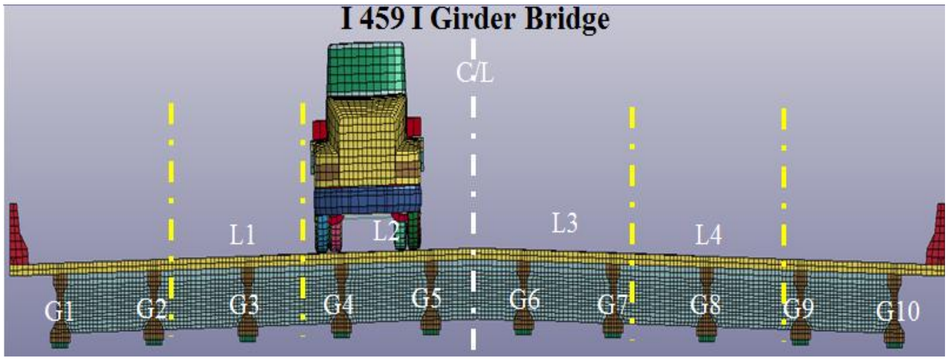
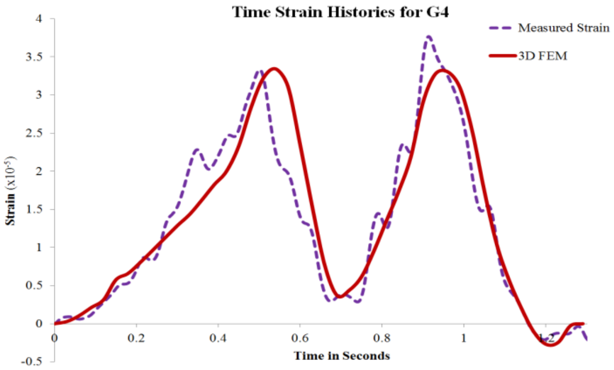
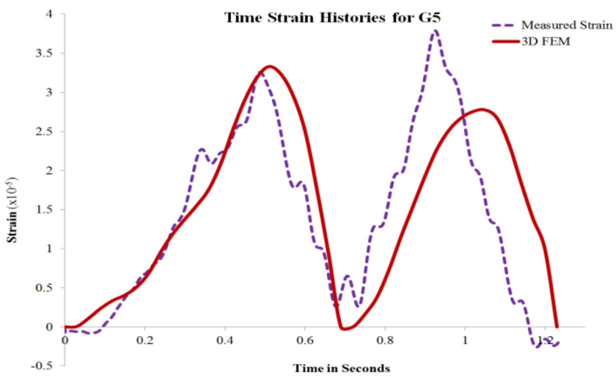


Figure 3. I 459 with vehicle position [10]

As shown in Figure 3, for I 459 the vehicle was positioned in lane 2 (L2). Using the arrangement of the heavy vehicle over I 459 as shown in Figure 3, the strain responses were measured for the girders under the vehicle (G4 and G5 for I 459). The comparison of strain responses, for the 3D FEM vehicle bridge interaction for I 459, with the experimental strain, is as shown in Figure 4 (a-b).



(a) Time Strain Histories for G4



(b) Time Strain Histories for G5

Figure 4. Time strain histories for I 459

As shown in Figure 4, for I 459 the first peak of strain responses is due to front three axles, and the second peak is due to rear two axles. The FE strain is 0.01% higher for G4and 2.40% lower for G5, than the measured strain. The 2nd peak responses showed inconsistent values for I 459. The inconsistency was observed due to the lack of actual suspension properties of the ALDOT 5 Axle truck used as heavy vehicle, where the nonlinear curve data provided by the manufacturers is adopted for the vehicle. This non-linear curve is for new vehicles and does not include the adjustments for the vehicles already been use. Since, the actual properties were not available for rear axle suspension, these responses due to rear axles were not used for further analysis. Based on acceptable dynamic strain responses, the static strains for the vehicle bridge interaction were obtained. The static strains were obtained by positioning the first three axles over the bridges such that the mid-span of the bridge experienced maximum load [10]. Using this vehicle position, static strains were obtained and compared with dynamic strain, as shown in Figure 5.

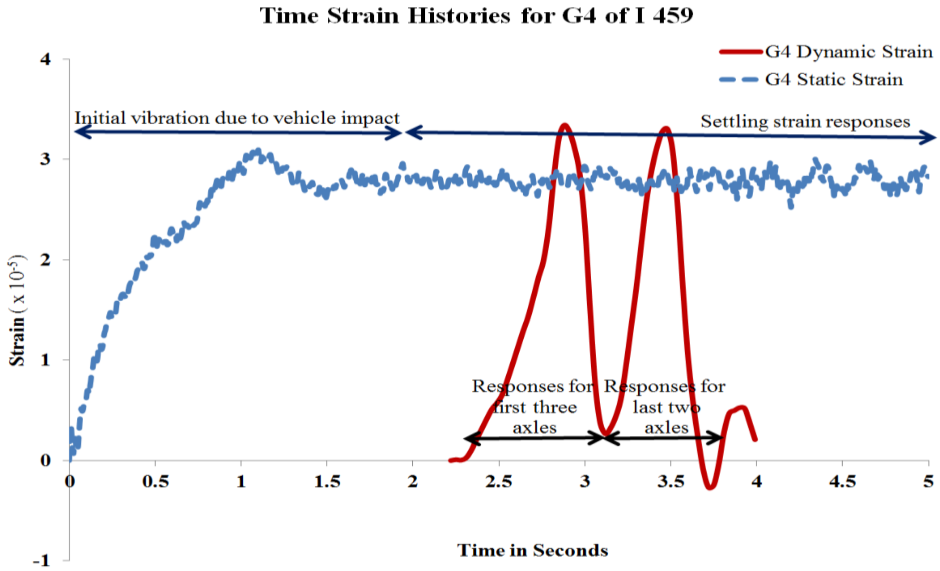


Figure 5. Static and dynamic responses for I 459 Bridge

From the static and dynamic strains as shown in Figure 5, the DAF was obtained using equation 1. The high vibrations were observed for the external girders of I 459, however, the magnitude of strain for external girders was less than the magnitude of strain for the girders under the vehicle. Therefore, only the girders under vehicle were used for DAF calculations. For I 459 and a single heavy vehicle, the DAF of 1.11 was obtained from the strain responses of G4. In I 459 with selected girders, the responses were marginally below the allowable values in AASHTO, showing that the AASHTO specifies conservative value of the DAF.

This DAF value in case of I 459, is obtained for single heavy vehicle over the bridge, whereas, the bridges are always subjected to multiple trucks at a time. Therefore, further simulations were needed on the DAF of I 459 for obtaining the effect of multiple vehicles. Moreover, although predicting accurate responses in dynamic vehicle bridge interaction for I 459, the 3D FEM is highly time inefficient and requires specialized tools such as parallel computing clusters to run the program. Hence the practical implementation of these results is not realistically possible where the demand for real time DAF calculations with reduced run time is required. To this end, an attempt was made to develop and validate vehicle bridge interaction using Simplified 3D FEM (3D SFEM) of I 459, along with heavy vehicles, in order to obtain the DAF in single and multiple vehicles situation as described in Section 3.

3 VERIFICATION OF THE 3D SFEM HEAVY VEHICLE BRIDGE INTERACTION

To obtain accurate behavior of bridge, the simplified 3D FEM (3D SFEM) of vehicle bridge interaction was developed using the spatial method, and verified using experimental strain responses [10]. The 3D SFEM of I 459, using a combination of beam, shell, and discrete elements is as shown in Figure 6 [10].

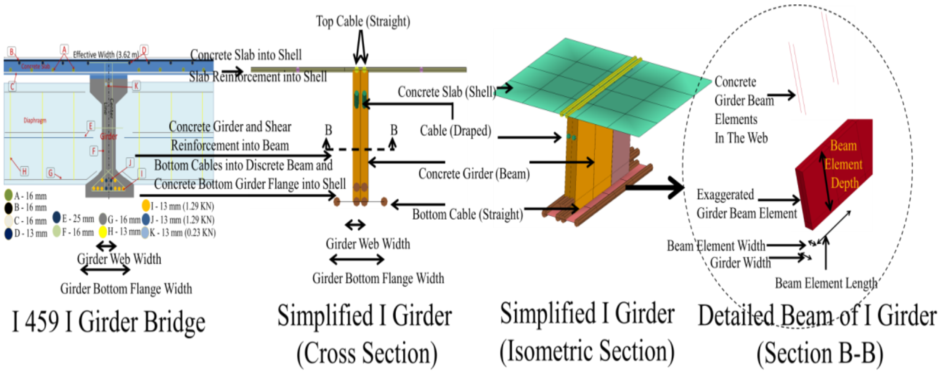


Figure 6. Detailed views of discretized I 459 used for 3D SFEM [11]

As shown in Figure 6, I 459 were discretized using different types of elements such as shell elements for slab and top and bottom flanges, beam elements for web and for the reinforcements [10]. The 3D SFEM of I 459 as shown in Figure 6 was verified using deflection and natural frequencies. Along with the 3D SFEM of I 459, the 3D SFEM of heavy vehicle was also discretized into beam elements, mass elements, and discrete elements in the spatial system, as shown in Figure 7 (a-b).

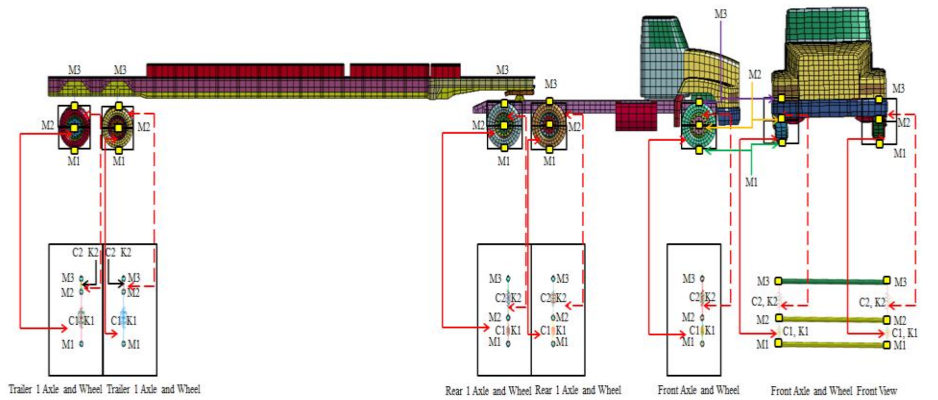


Figure 7(a). Discretization of heavy vehicle from 3D FEM to 3D SFEM [11]

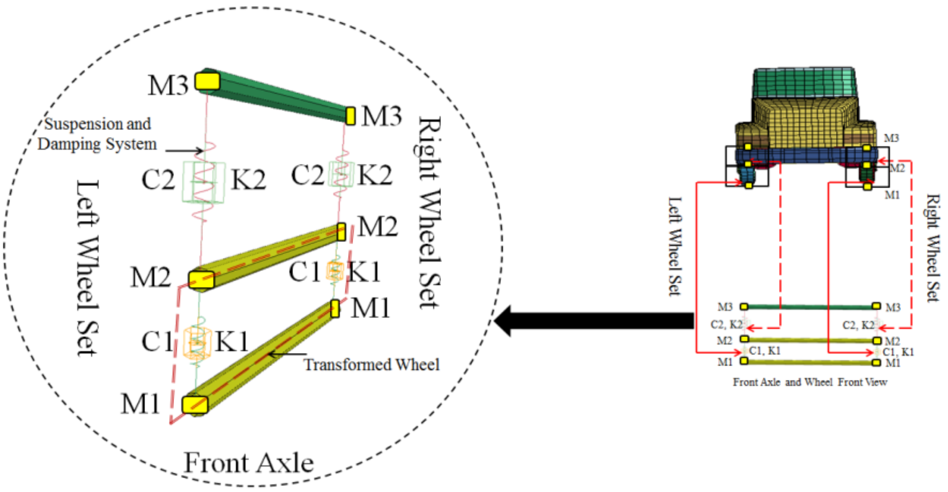


Figure 7(b). Detailed view of discretized front axle of heavy vehicle using 3D SFEM

As shown in Figure 7 (a-b), the 3D SFEM of the heavy vehicle was discretized using mass, beam, and discrete elements and verified for mass distribution over the axles [10]. With the verification of the 3D SFEM of I 459 and heavy vehicle in acceptable limits, the 3D SFEMs of heavy vehicle bridge interaction were developed and verified using strain responses [10]. The heavy vehicle was positioned on I 459 in the same manner in which it was positioned in the experimental test. The 3D SFEM of vehicle bridge interaction is as shown in Figure 8.

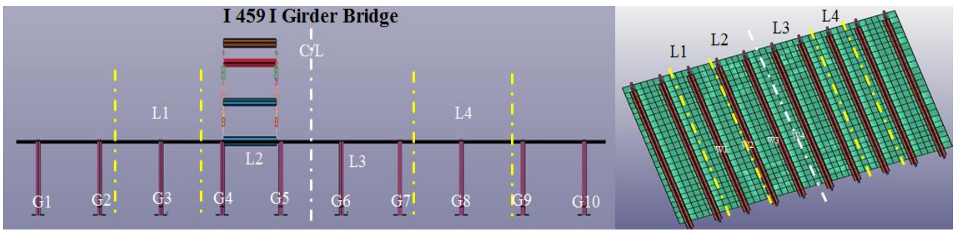
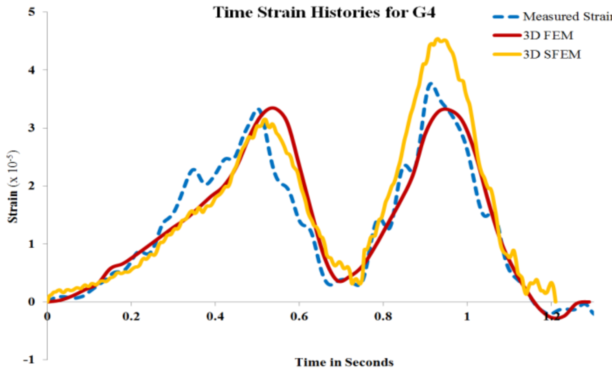
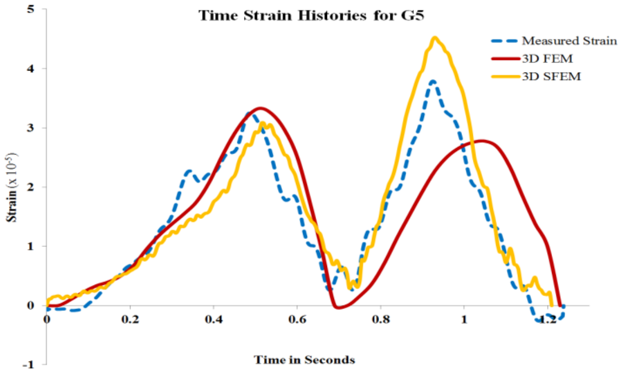


Figure 8. 3D SFEM Vehicle-Bridge interaction of I 459

As shown in Figure 8, the vehicle was positioned at L2 of I 459. The beam elements were modeled under the vehicle path in order to define contacts [10]. The RAIL TRACK types of contacts were used between bottom node at M1 and the beam elements over the bridge. Previous studies have highlighted the effect of surface roughness on the bridge responses using several roughness profiles [10]. However, the surface roughness measured at the site is a realistic surface roughness and therefore only measured surface roughness is adopted for current studies [10-11]. Using the information provided above, the 3D SFEM vehicle bridge interaction was carried out and the strain histories were obtained for I 459. The strain responses for G4 and G5 of I 459 were obtained and validated using experimental and 3D FEM strains, as shown in Figure 9 (a-b).



(a) Time Strain Histories for G4



(b) Time Strain Histories for G5

Figure 9(a-b). Comparison of time strain histories for I 459 using 3D SFEM, 3D FEM and experimental test

From Figure 9 (a-b), it can be observed that, for I 459, the 3D SFEM showed 5% lower strain compared to experimental strain and 6% lower strain compared to the 3D FEM for G4. For G5, the 3D SFEM showed 7% lower strain values than the experimental strain values, however, 8% higher strain values compared to the 3D FEM. Since the previous studies showed consistent responses only for 1st peak value, only 1st peak responses were considered for the analysis and 2nd peak values were neglected. Subsequently, the DAF was obtained for I 459. The DAF depends on dynamic and static responses of girders underneath the heavy vehicle. The DAF for a single heavy vehicle over I 459 using 3D SFEM, is as shown in Figure 10.

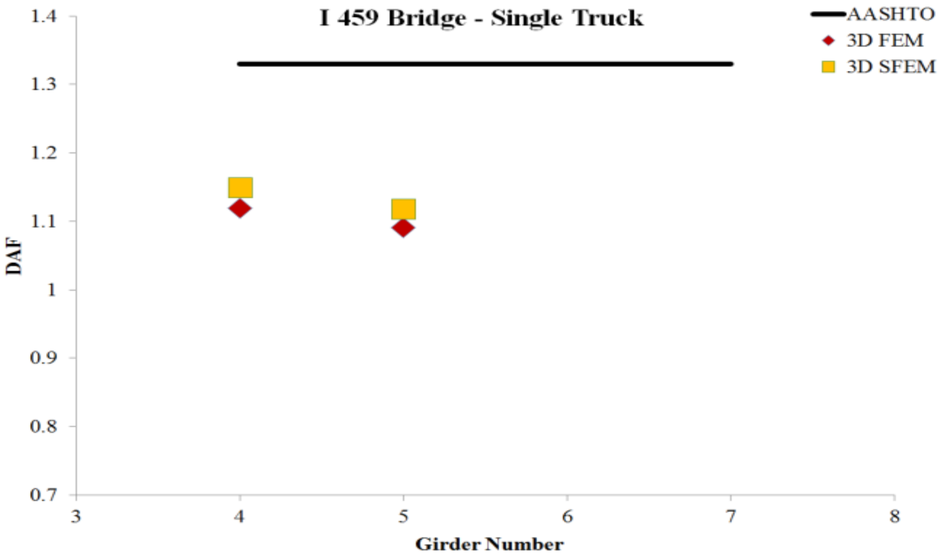


Figure 10. DAF of I 459 with single heavy vehicle

From Figure 10 it can be observed that, the DAF was presented only for G4 and G5 in case of I 459, since the vehicle is over these girders. These girders experience maximum dynamic and static strain due to the vehicle presence over them. In case of I 459, the DAF obtained from the 3D SFEM showed similar values - as it was obtained from 3D FEM - for single vehicle. Although reliable values are obtained, I459 often experiences higher loading as a response to multiple vehicles. Along with multiple vehicles, the bridge also experiences different types of vehicles passing over it with different velocities. Therefore, in order to obtain a realistic DAF in such cases, a wide-ranging parametric study needed to be carried out on I 459using the 3D SFEM, as discussed in Section 4.

4 PARAMETRIC ANALYSIS FOR OBTAINING DAF IN VARIABLE LOADING SITUATION

Although the vehicle bridge interaction, using the 3D SFEM of heavy vehicle with I 459 showed reliable strain responses and a DAF, it often subjected to multiple vehicles running over the bridge. The types of vehicles, their velocity, their position over the bridge, their combinations, etc. are the parameters that affect the responses of the bridge. Since the DAF requires multiple loading combinations, the previous studies were either dominated with a simplified vehicle bridge interaction FEM, using vehicle as a point load, or a sophisticated 3D FEM - only on a few I Girder bridges - with no multiple vehicles scenario. To this end, the current parametric study addresses numerous possible combinations of multi-vehicles, variable speeds, positions (vehicle running in parallel lanes, or vehicles following each other), vehicle types, and realistic simulations (random vehicle combination with random velocities). The goal of this parametric study is to predict a realistic DAF for most possible scenarios of vehicle loadings over I 459. Several cases were considered for analysis on I 459 (4 lane) bridge. Although I 459 is a 4 lane bridge, it can accommodate 6 lanes. Therefore the parametric analysis was also conducted for all 6 lanes loaded, in order to represent an extreme loading scenario. The possible scenarios for multi-vehicle positioning on I 459 are as shown in Figure 11.

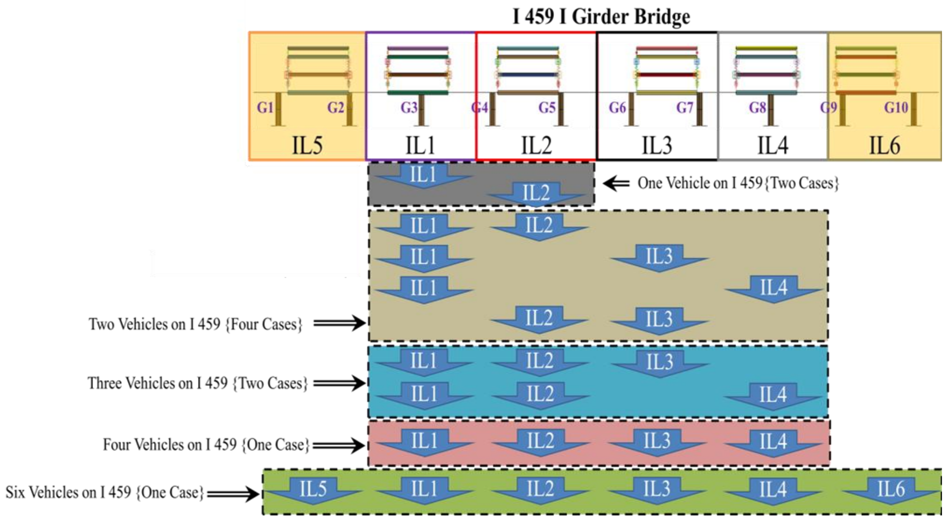
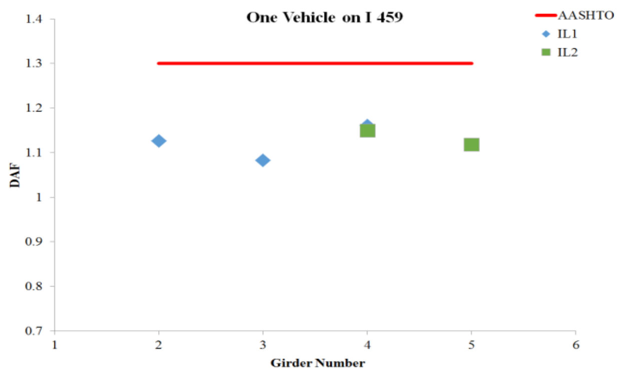
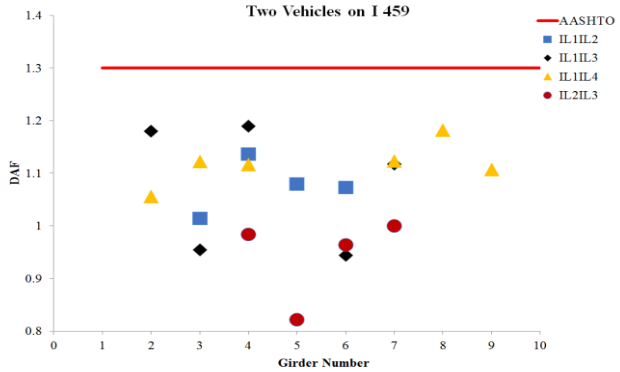


Figure 11. Multi-Vehicle positions on I 459 for DAF calculations

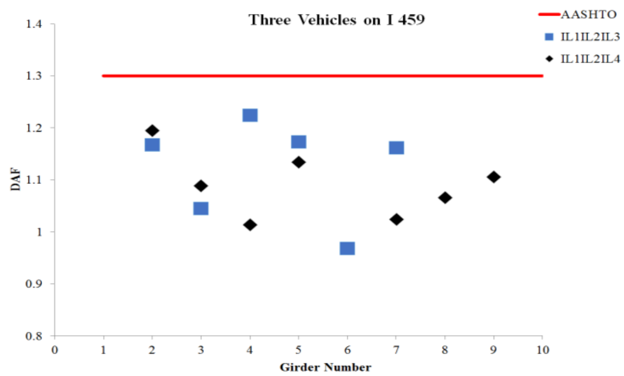
As shown in Figure 11, there were several combinations of vehicles used for I 459. The I 459 was simulated for one vehicle in lane 1 and 2 (IL1, IL2), two vehicles in two lanes (IL1IL2, IL1IL3, IL1IL4, IL2IL3), three vehicles in three different lanes (IL1IL2IL3, IL1IL2IL4), four vehicles in four lanes (IL1IL2IL3IL4), and six vehicles in six lanes (IL1IL2IL3IL4IL5IL6). As shown in Figure 10 in the case of I 459, the positions are designated by initial I. The DAF was obtained for each of these cases of multiple vehicles over I 459, with the constant velocity of 88 km per hour (55 mph). The girders under each vehicle for each position were used for DAF calculation. The DAF for I 459 is as shown in Figure 12 (a-d).



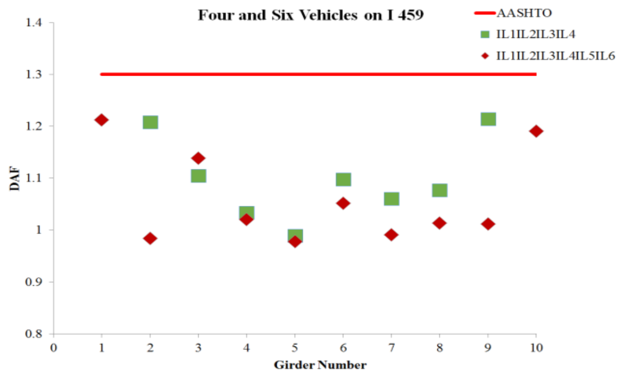
(a) DAF for I 459 with one vehicle



(b) DAF for I 459 with two vehicles



(c) DAF for I 459 with three vehicles



(d) DAF for I 459 with four and six vehicles

Figure 12(a-d). DAF for I 459 with multiple vehicle scenario

From Figure 12 (a-d), it can be observed that, with the single vehicle present over I 459, the DAF values are below 1.2. For two vehicles present over the bridge, the DAF was observed to be less than 1.2. When the trucks are in the center of the bridge (L2, L3), the DAF value decreases to 1.0 and as the trucks moved toward the edges (L1, L2 or L3, L4, the DAF values increased to 1.2.

With three vehicles over the bridge, the highest DAF of 1.21 was observed. For the case of four vehicles present over the bridge, the DAF value of 1.22 was observed for G9. Although the bridge has only four lanes, if there is an increase of lanes on each side (IL5 and IL6 as highlighted in Figure 11), the DAF was obtained for a worst possible scenario where all the lanes were loaded with extreme vehicular traffic. From the imaginary case of all six lanes loaded, the maximum DAF was observed to be 1.21. From all the possible multi-vehicle position scenarios, it was observed that the DAF, in all cases, was less than 1.33. From all the above cases, it was observed that the DAF increases as the number of vehicles increases over the bridge.

From Figure 12 (a-d) the highest DAF was observed for four vehicle scenario on I 459. With these results, further simulations were carried out on the effect of velocity on I 459 with 4 vehicles. The possible combinations of the velocities are as shown in Figure 13.

From Figure 13 it can be observed that, for I 459 with chosen vehicle combination, the vehicle velocities were gradually increased from 64 kph to 129 kph (40 mph to 80 mph). The DAF was obtained for respective velocity as shown in Figure 14.

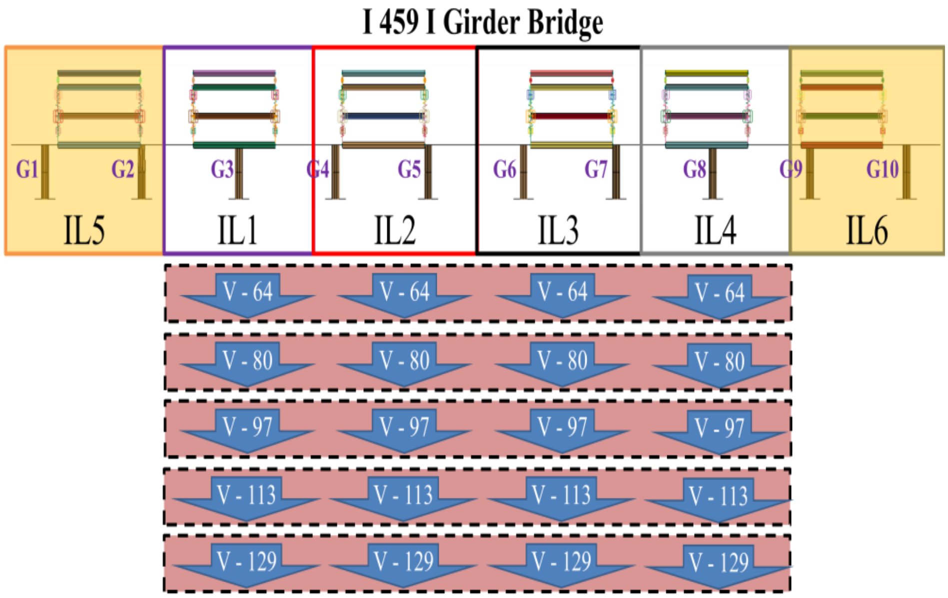


Figure 13. Variable vehicle velocities on I 459 for DAF calculation

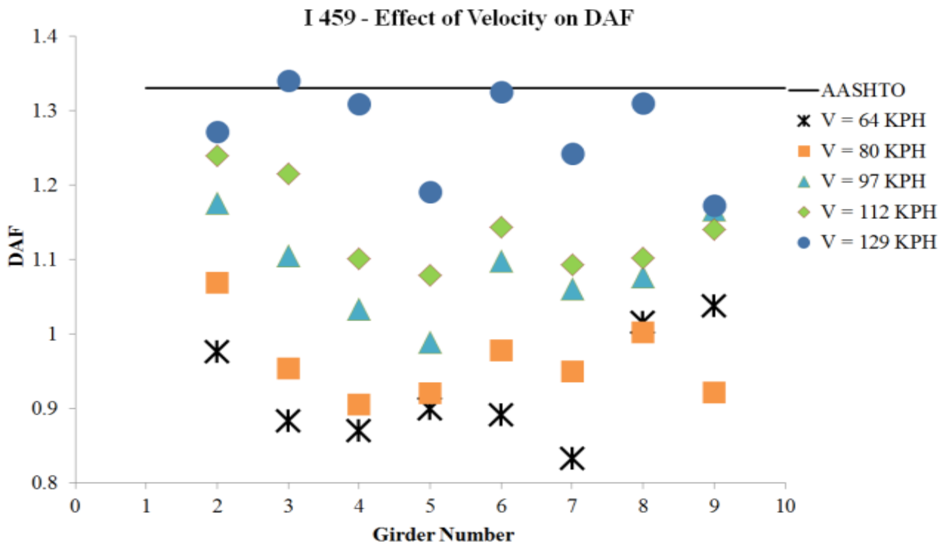


Figure 14. Effect of variable velocities on I 459 for DAF calculation

From Figure 14, it can be observed that, for I 459 the value of the DAF increased with an increase in velocity. When the velocity of the vehicle is lowest, there is less vibration on the bridge and as a result, the DAF is reduced. However, for G3 of I 459, with vehicle velocity at 129 kph, the DAF was found to be exceeding 1.3. This increase is due to the excessive vibration obtained during dynamic responses. Although the case of variable velocity holds true, all the vehicles considered for the study are entering and exiting the bridges at the same time. There are circumstances where the heavy vehicles form a train of loading over the bridge and the bridge is subjected to repeated loadings. To simulate the case of repeated loading, the trucks were placed on I 459 such that they would form a train of load on the bridge. The possible loading scenario of linear train positions are as shown in Figure 15.

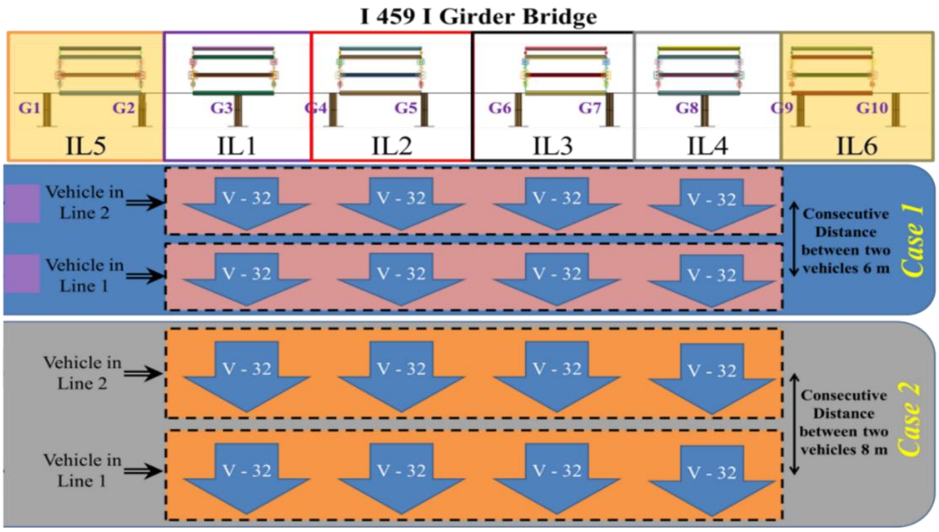


Figure 15. Variable vehicle positions on I 459 for train load effect on DAF

As shown in Figure 15, four heavy vehicles on I 459 were simulated for the effect of train load. In order to form the train of loading on I 459, a low velocity has to be maintained (in case of traffic jam). In this scenario, the velocity of heavy vehicles was maintained at 32 km per hour (20 mph). The consecutive distances between two vehicles following each other on the same lane were maintained at 6 meters (Case 1) and 8 meters (Case 2). With this arrangements, the bridge experiences maximum load at the center as the trailer axles of the vehicles in line 1 and the front axles of vehicles in line 2 (collective load of all the axles – 865580 N) are at the center of the bridge. Since this arrangement of vehicles over the bridge yields the highest load, the DAF was obtained using these loading scenarios for each girder. The DAF for I 459 under train loading effect is as shown in Figure 16.

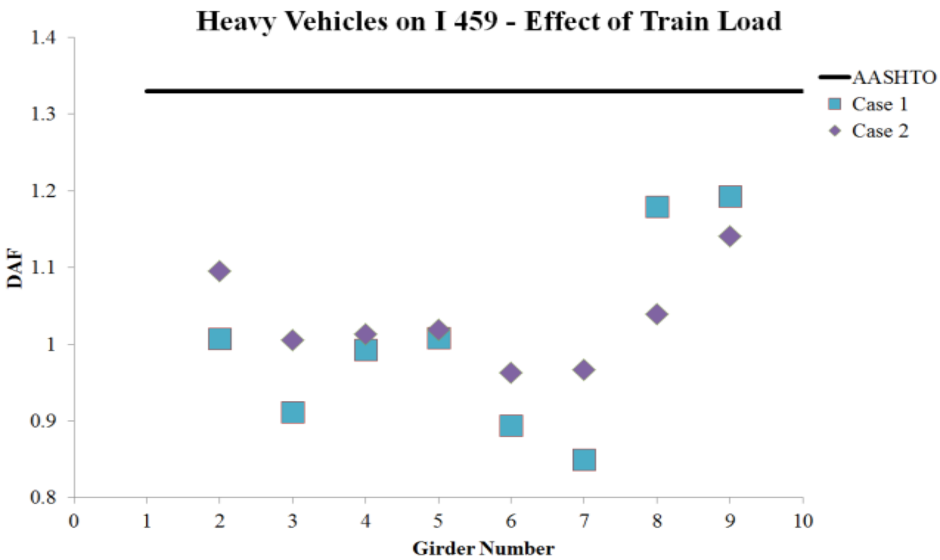


Figure 16. Effect of train load on DAF of I 459

From Figure 16 it can be observed that, for I 459 the DAF values were less than 1.2. When a heavy vehicle followed another vehicle at the velocity of 32 kph (20 mph) and there was 6 m of separation between them, the DAF obtained was less than for the same vehicles with separation of 8 m. Therefore, it can be concluded that, the increase in the distance between two vehicles in the same lane increases the DAF of the bridge. However, in this study only 5 Axle ALDOT trucks were used as the heavy vehicle, whereas, the bridge is always subjected to multiple vehicles with variable axle types (5 Axle and 3 Axle). Therefore, further studies were carried out on combinations of vehicles over I 459. In this case, an additional 3 axle heavy vehicle was selected for further analysis. Using the approaches as discussed in Section 3, the 3 axle heavy vehicle 3D SFEM was utilized and verified for the mass distribution as shown in Figure 17.

As shown in Figure 17, the 3 Axle truck used as a heavy vehicle was simulated using simplified approaches and using Class 8 specifications provided by the manufacturers. The properties such as mass elements (M3) were adjusted for final weight of the truck. The implicit static analysis was carried out and the final weight - using the 3D SFEM - is as shown in Figure 17. The weight shown in brackets is the weight measured at the site. Using the verified 3 Axle Truck along with 5 Axle ALDOT Truck, the trials for multiple vehicle were carried out in order to obtain the DAF for different types of truck over I 459. The trial combinations selected for effect of multiple types of trucks over I 459 are as shown in Figure 18.

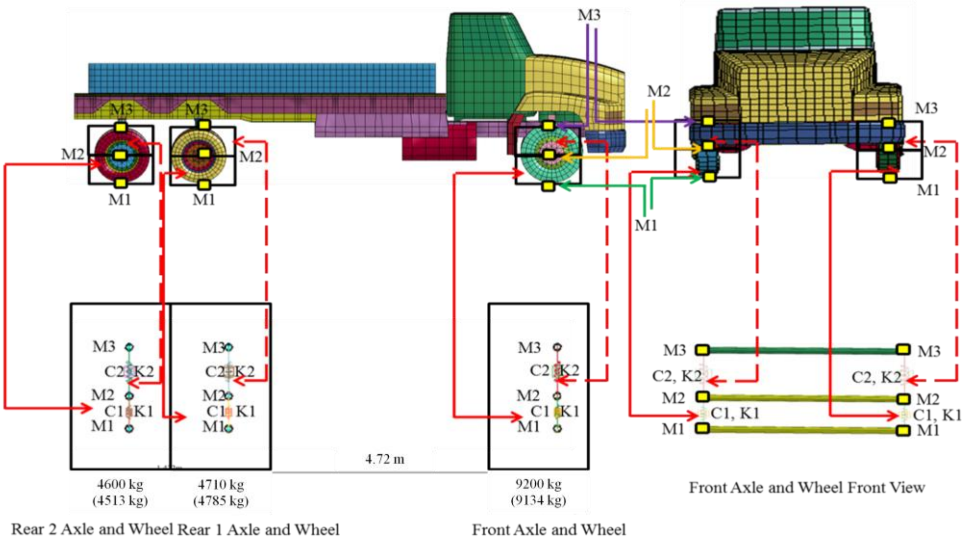


Figure 17. 3 Axle truck for vehicle bridge interaction

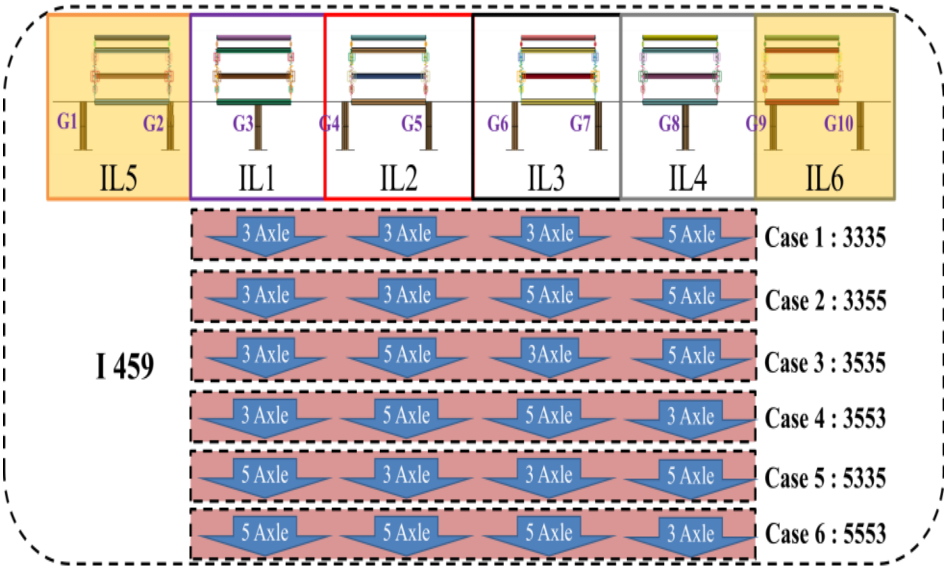


Figure 18. Combinations of vehicles for obtaining DAF on I 459

From Figure 18 it can be observed that, with I 459 (having four lanes), 6 vehicle combinations were simulated. Figure 19 shows the DAF for I 459 with the above vehicle combinations.

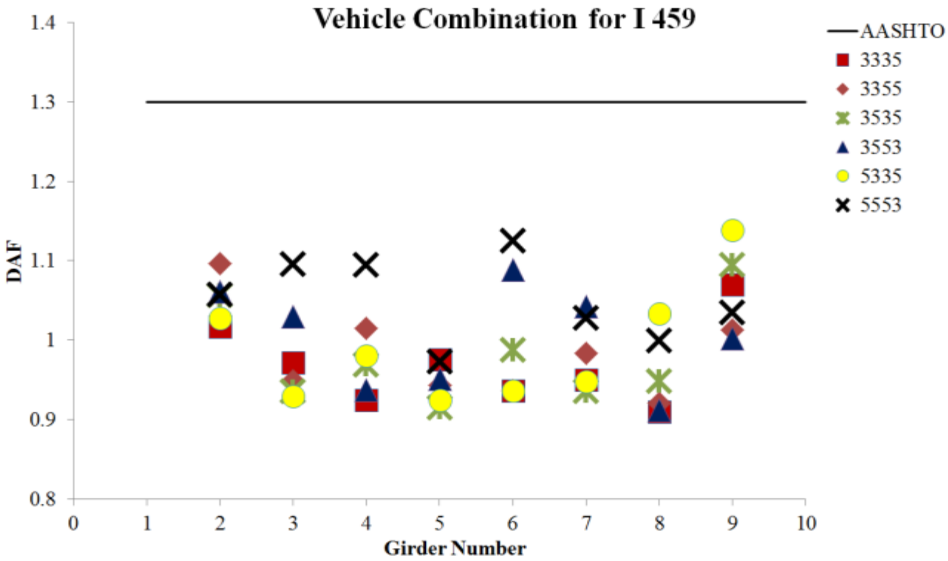


Figure 19. DAF of I 459 under variable vehicle combination

From Figure 19, it can be observed that, in case of I 459 where the girders under the 3 axle vehicle showed a lesser value for DAF compared with the girders under the 5 axle vehicle, regardless of the position of the vehicle. The maximum value of the DAF was observed to be for Case 6 (vehicle combination 5553). In all cases of vehicle combinations, the DAF values were observed to be less than 1.2. In the case of all vehicle combinations, all the vehicles are simulated with the same velocity (97 km per hour), however, in actual scenario, the vehicles travel with random velocities.

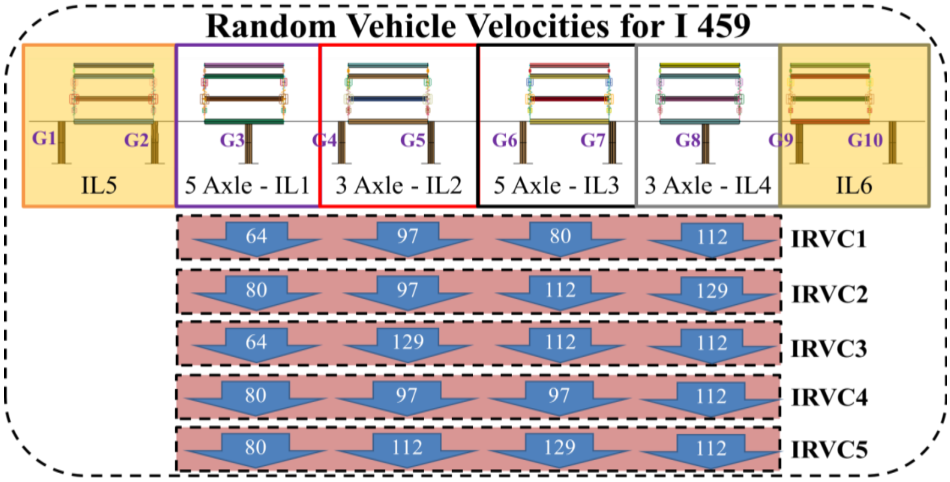


Figure 20. Random velocity cases for I 459 for obtaining DAF

In order to simulate the realistic cases of vehicle combinations with random velocities, the vehicle combination Case 3 (3535) of I 459 was selected for further analysis as shown in Figure 20.

From Figure 20, it can be observed that for I 459 there are five combinations with vehicle variable velocities (IRVC1 – IRVC5). Using these cases, the values of DAF were obtained for I 459 as shown in Figure 21.

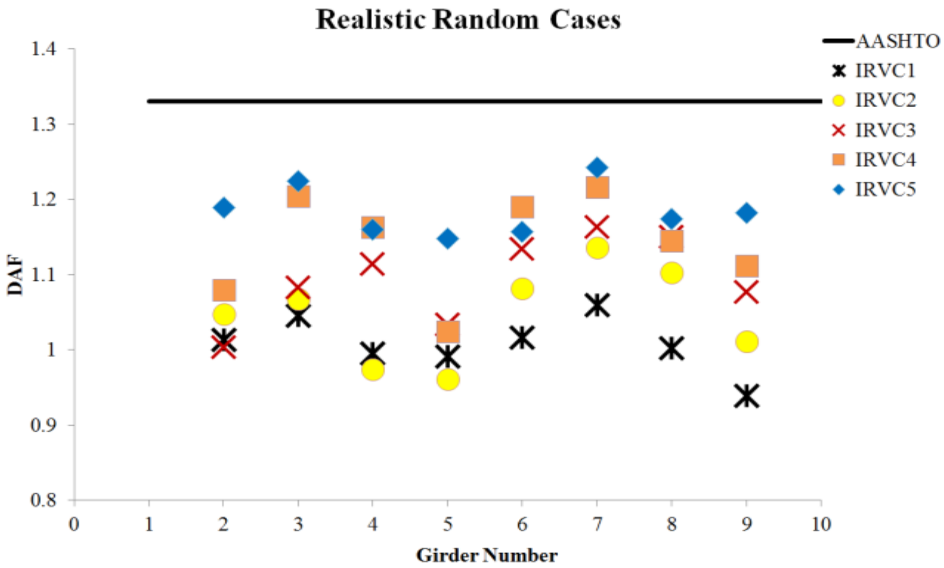


Figure 21. DAF for I 459 with random velocity cases

From Figure 21, it can be observed that for all the cases of random vehicles with random velocities, the maximum value of DAF obtained was 1.24 for I 459. In all scenarios, the average DAF falls in the range of 0.96 to 1.25. Therefore, based on these studies, it can be concluded that the DAF provided in the AASHTO specification does predict a conservative value and in realistic loading simulation the DAF is much smaller.

5 CONCLUSIONS

Based on the studies on I 459 for obtaining the DAF using the 3D SFEM, the following conclusions were drawn:

a) The spatial system of FEM showed comparable strain responses for vehicle bridge interaction with experimental strain and the strains obtained from 3D FEM. The spatial system showed the potential application of different combinations of vehicles over the bridge for obtaining a realistic DAF.
b) From the 3D SFEM for multiple vehicle scenarios, the DAF was observed to increase with an increase in the number of vehicles. However the value

of the DAF was still in acceptable limits. Even for the extreme loading case, where all the lanes of I 459 were occupied by vehicles, the DAF was found to be 8% less than specified by AASHTO.

c) From the variable velocity studies, using the 3D SFEM on I 459, the DAF was observed to be the lowest when vehicles travel with minimum velocity. The increase in velocity, thus, increases the DAF of bridges.
d) When the vehicles follow each other forming a train loading on the bridge, the DAF values depend on the distance between two consecutive vehicles. With the increase in the distance between said vehicles, the DAF also increased.
e) Using spatial method, different vehicle models can be generated with a lesser number of elements and in less time.
f) For various vehicle combinations over I 459, the girders under the lighter vehicle showed a lesser value of the DAF as compared with the girders under the heavier vehicle. In this scenario, the DAF obtained was less than the AASHTO specified DAF limit.
g) Using random vehicle velocity simulation, the maximum value of the DAF obtained was 1.23, which is 7.5% less than the allowable limit.

Using these simulation responses, it was observed and can be concluded that, in all possible combinations the DAF values were found to be less than AASHTO specified DAF values. This study provided a broader view of various simulation combinations otherwise is painstaking and time consuming work. From the responses, it was observed that the 3D SFEM, using spatial method predicted reliable strain responses, and DAFs and therefore it has the potential to replace the 3D FEM and can be utilized with experimental analysis.

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