# Applications in Vehicle-Bridge Interaction

The simulation tools demonstrated in Part 1 and developed in Part 2 are leveraged in this part to address some of the challenges facing bridges associated with VBI.

Parts 1 and 2 both demonstrated the influence of roadway profile roughness of bridge response and dynamic amplification. In Part 2 it was shown that IRI has a strong (but inconsistent) correlation with dynamic amplification. Chapter 1 once again addresses profile roughness with examination of rolling straightedge criteria. Various straightedge requirements are used to modify a real (measured) profile and the effect of these modifications on dynamic amplification is quantified.

Chapter 2 extends vehicle-bridge interaction to include multiple vehicles. While a single vehicle (per lane) is often the load case analyzed for design and evaluation, real world structures are routinely subjected to traffic conditions in which the bridge experiences multiple vehicles. The additional response due to multiple vehicles is traditionally ignored in design and evaluation methodologies because of the inherent conservatism associated with the live-load model (i.e. it is unlikely that every lane will be simultaneously occupied with a HL-93 truck). However, the effect of multiple vehicles on bridge dynamics and dynamic amplification has not been addressed.

Therefore, chapter 2 seeks to identify the effect of multiple vehicles on dynamic amplification and provide guidance on how the effect of multiple vehicles should considered when it is impractical to perform VBI simulation (i.e. static analysis). This is accomplished by first examining the effects of a few traffic flows and then extended to truck platoons.

## Remediation and Smoothness Criteria

If a bridge is suspected to exhibit large dynamic amplification as a result of a rough roadway, the bridge owner may wish to grind the roadway smooth. Furthermore, to reduce dynamic amplification in new construction, deck profile specifications should provide smoothness targets. Currently, smoothness criteria are prescribed differently for different locations.

The IRI, which is widely used as a smoothness criterion by providing upper limits, has already been shown to influence dynamic amplification. The IRI is a measure of vehicle response and can therefore only be implemented as a performance metric. As such it provides no methods for specifying or monitoring of smoothness during construction or grinding and will not be presented in this section. However, if a deck profile is shown to have a high IRI, intervention should be considered.

Rolling straightedge requirements are widely used for specifying localized roughness criteria and are expressed in terms of deviation over a certain length. Parameters commonly range from 1/8 to ¼ inch deviation over a 10 to 16-foot distance. A computer algorithm was developed that effectively smooths the profile according the straightedge requirements.

This algorithm steps through the profile, incrementally advancing the reference point and assessing if any point, between the reference point and a point at a distance equal to the straightedge length, exceeds a straight-line fit between the two points by more than the specified deviation. If a point falls outside of the bounds specified by the deviation value, the elevation of the point is reduced such that the deviation equals the specified deviation. This is accomplished in the following steps.

* Linearly interpolate every point within the straightedge window based on the elevation of the first and last point (i.e. create a straight line between the first and last point).
* Compute the vertical deviation that results in a perpendicular (to the interpolated road surface) deviation equal to the specified deviation.
* Find indices of points that exceed the interpolated surface (line) plus the vertical deviation and set equal to the interpolated surface plus the vertical deviation.
* Find indices of points that are less than interpolated surface minus the vertical deviation and set equal to the interpolated surface minus the vertical deviation.

The effect of this smoothing is illustrated in the following plot whereby a measured profile (measured during Part 1, Phase 3 testing) is compared to the same profile smoothed such that no point deviates more than 1/8th inch over 10ft.



Figure .: Effect of Smoothing (1/8" over 10ft.) on Real Profile

The ability of straightedge criteria to limit dynamic amplification is assessed by simulating vehicle-bridge interaction with a problematic profile, and again with the profile smoothed according to specified criteria. The FE model of a single 140 ft. span with the 2.5 Hz vehicle model as described in Part 2 was utilized for this study. Simulation parameters are summarized in the following table.

Table .: Simulation Parameters for Smoothing Studies

|  |  |  |
| --- | --- | --- |
| Number of modes included | 15 |  |
| Incremental distance along load-path | 6 | inches |
| Structural damping | 1% |  |
| Vehicle speed | 720 | in/sec |
| Solution time-step | 0.0015 | sec |

The following plot compares bridge midspan displacement amplification for the two profiles. Amplification was computed according to equation **XX**, for which the static displacement was taken as the maximum quasi-static (i.e. 5 in/sec) displacement.

Figure .: Comparison of Bridge Dynamic Amplification with Rough Profile and with Smoothed Profile

The above plot clearly shows the 1/8th inch over 10 feet criterion is ineffective at limiting dynamic amplification.

The straightedge requirements target features with lengths less than the straightedge length. At normal traffic speeds profile features with lengths of 5-50 feet result in forcing frequencies within the range of natural frequencies commonly exhibited by bridges. Therefore, the straightedge length should be specified long enough to avoid/remove features in this range. A variety of straightedge criterion were assessed with the 2-DOF state-space model of the 140ft single-span bridge (as described in Part 2, Chapter 4). Straightedge smoothing of the same profile was performed with maximum specified deviation ranging from 1/8th inch to ½ inch and straightedge length ranging from 10 to 24 feet. The results are plotted below.

Figure .: Effect of Smoothing Parameters on Dynamic Amplification

The preceding plot demonstrates the ability of straightedge requirements to limit dynamic amplification. Criteria that specify deviation limits greater than ¼” are wholly inadequate at limiting amplification. Even criteria with ¼” deviation limits were only successful at reducing the amplification to 1.33 when the straightedge length was 24 feet. Based on these findings it is recommended that straightedge criteria specify a maximum deviation of 1/8th inch over at least 16 feet.

### Conclusions

Rolling straightedge criteria with common limits (i.e. 1/8 to ¼ inch deviation over 10 to 16 feet) are not effective at reducing dynamic amplification. This is because (1) deviations even as small as ¼ of an inch () can significantly influence bridge response, and (2) short straightedge lengths fail to remove features with large wavelengths that still have appreciable effect on bridge response. The shorter the straightedge length, the more stringent the deviation limit must be. Based on these simulations, if this criterion is to continue being used, the straightedge length should be no less than 16 feet and the specified deviation limit should be no greater than 1/8th inch.

## Multiple Vehicles

The many simulations that have thus far been reported, have considered a single vehicle traversing a bridge. In reality, bridges experience a large variety of different live-load configurations and many times are subjected to multiple vehicles at the same time.

### Traffic

The scenario of multiple-vehicle loading is accounted for in most design methodologies through the use of multi-presence factors. These factors serve to reduce the load presented by vehicles in adjacent lanes based on the assumption that vehicles with legal-limit weights are unlikely to occupy adjacent lanes at the same time. While this assumption may be valid for bridge response to static loads, other vehicles, including light vehicles (e.g. small passenger vehicles) may contribute to the dynamic response. The effect of other vehicles (traffic) on a bridge’s dynamic response and the dynamic amplification of a major load event are investigated.

#### Methods

Several traffic patterns were created with randomly distributed vehicles and varying density (i.e. vehicle spacing). Each pattern sampled 8 different vehicles that included HS20 trucks, a dump truck, a tractor-trailer, and small passenger vehicles. The vehicles and their axle configurations are provided below.

Table .: Vehicle Parameters for Traffic Simulations

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Vehicle # | Axle # | Name | Distance from rear axle (ft) | Weight (kip) | Spring Stiffness (kip/in) | Damping Coefficient (lb-s/in) | Damping Ratio | Natural Frequency |
| 1 | 1 | HS20-32\_1 | 0 | 32 | 20 | 257.529 | 0.1 | 2.472 |
| 1 | HS20-32\_1 | 14 | 32 | 20 | 257.529 | 0.1 | 2.472 |
| 2 | HS20-8\_1 | 28 | 8 | 15 | 111.513 | 0.1 | 4.282 |
| 2 | 3 | HS20-32\_2 | 0 | 32 | 16 | 460.682 | 0.2 | 2.211 |
| 3 | HS20-32\_2 | 30 | 32 | 16 | 460.682 | 0.2 | 2.211 |
| 4 | HS20-8\_2 | 44 | 8 | 8 | 407.189 | 0.5 | 3.127 |
| 3 | 5 | HS20-32\_3 | 0 | 32 | 13 | 415.253 | 0.2 | 1.993 |
| 5 | HS20-32\_3 | 22 | 32 | 13 | 415.253 | 0.2 | 1.993 |
| 6 | HS20-8\_3 | 36 | 8 | 10 | 455.251 | 0.5 | 3.496 |
| 4 | 7 | tst-tand | 0 | 17 | 15 | 162.557 | 0.1 | 2.937 |
| 7 | tst-tand | 6 | 17 | 15 | 162.557 | 0.1 | 2.937 |
| 8 | tst-drive | 29 | 17 | 15 | 162.557 | 0.1 | 2.937 |
| 8 | tst-drive | 35 | 17 | 15 | 162.557 | 0.1 | 2.937 |
| 9 | tst-front | 51 | 12 | 2.2 | 261.522 | 0.5 | 1.339 |
| 5 | 10 | dump-rear | 0 | 25 | 12 | 176.318 | 0.1 | 2.166 |
| 10 | dump-rear | 5 | 25 | 12 | 176.318 | 0.1 | 2.166 |
| 11 | dump-front | 20 | 20 | 12 | 315.407 | 0.2 | 2.422 |
| 6 | 12 | car1 | 0 | 1.5 | 0.2 | 27.878 | 0.5 | 1.142 |
| 12 | car1 | 8 | 1.5 | 0.2 | 27.878 | 0.5 | 1.142 |
| 7 | 13 | car2 | 0 | 2 | 0.4 | 45.525 | 0.5 | 1.398 |
| 13 | car2 | 10 | 2 | 0.4 | 45.525 | 0.5 | 1.398 |
| 8 | 14 | car3 | 0 | 3 | 2 | 124.676 | 0.5 | 2.553 |
| 14 | car3 | 14 | 3 | 2 | 124.676 | 0.5 | 2.553 |

Six traffic patterns were created with the following parameters. Each traffic pattern concluded with the dump truck (vehicle 5). Each vehicle in a traffic pattern was randomly selected from the vehicle list and the spacing was set from random (uniform) sampling between the bounds specified in the table.

Table .: Traffic Pattern Parameters

|  |  |  |  |
| --- | --- | --- | --- |
|  | Num. of Vehicles | Min. Spacing | Max. Spacing |
| 1 | 36 | 20 | 100 |
| 2 | 36 | 40 | 200 |
| 3 | 36 | 60 | 300 |
| 4 | 36 | 80 | 400 |
| 5 | 36 | 100 | 500 |
| 6 | 36 | 280 | 1400 |

The 3D FE model of the 2-span bridge with span lengths of 140 ft (Part 2, Chapter 4) was used for the simulations. Each traffic pattern was simulated at a speed of 960 in/sec (≈55 mph) as well as at 5 in/sec to provide the quasi-static response. The first 15 modes of vibration were included in the simulation. Simulation time-steps of 0.002 seconds and 0.5 seconds were used for the 960 in/sec and quasi-static simulations, respectively.

#### Results

The bridge responses acquired from the simulations of the traffic patterns are summarized in the following table.

Table .: Maximum Responses from Traffic Simulations

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Max. Static Disp. (in.) | | Max. Dynamic Disp. (in.) | | Max. Amplification | |
|  | Span 1 | Span 2 | Span 1 | Span 2 | Span 1 | Span 2 |
| Traffic1 | **-0.41113** | **-0.41906** | **-0.588347** | -0.48383 | 1.431056 | 1.154555 |
| Traffic2 | -0.32891 | -0.32505 | -0.369981 | **-0.54378** | 1.12486 | **1.672918** |
| Traffic3 | -0.26793 | -0.26538 | -0.407771 | -0.38494 | 1.521942 | 1.450507 |
| Traffic4 | -0.26009 | -0.25963 | -0.438268 | -0.40802 | **1.685082** | 1.571517 |
| Traffic5 | -0.26012 | -0.25962 | -0.380595 | -0.40768 | 1.463129 | 1.570283 |
| Traffic6 | -0.25986 | -0.25962 | -0.356183 | -0.37011 | 1.370688 | 1.425589 |

Except in a few cases, large dynamic amplifications were observed for the traffic patterns. The time history corresponding to the events that produced the largest dynamic response are plotted below along with the quasi-static response.

Figure .: Span-1 response to traffic pattern no. 1

Figure .: Span-2 response to traffic pattern no. 2

The vehicles that are inducing the response shown in the above plots are vehicle numbers 3 and 5 (HS-20 and dump truck), respectively. The responses that these vehicles alone produce are provided below for comparison.

Table .: Single Vehicle Responses for Vehicles 3 and 5

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Max. Static Disp. (in.) | | Max. Dynamic Disp. (in.) | | Max. Amplification | |
|  | Span 1 | Span 2 | Span 1 | Span 2 | Span 1 | Span 2 |
| Vehicle3 | -0.251 | -0.252 | -0.304 | -0.320 | 1.21 | 1.27 |
| Vehicle5 | -0.245 | -0.245 | -0.336 | -0.337 | 1.37 | 1.38 |

All but two of the amplifications induced by the traffic patterns presented in table **XX** meet or exceed the amplification produced by a single vehicle. It can therefore be concluded that multiple vehicle loading serves to not only increase the static bridge response but may also result in dynamic amplification even greater than that which would be observed for a single vehicle.

The response of span 1 to the final vehicle (dump truck) is compared in the following plot and serves to illustrate the effect that initial conditions (preexisting motion) has on bridge response to a vehicle crossing.

The (dynamic) bridge response over the duration for which the last vehicle was on the bridge was a maximum for the first span under traffic pattern number 1 for which the final vehicle was preceded by an HS-20 (vehicle 3) with a headway of 20 ft. That for span 2 was a maximum under traffic pattern number 2, for which the final vehicle was preceded by a tractor-trailer (vehicle 4) with a headway of 40 ft. Those responses are plotted below.

Figure .: Span-1 Response to final vehicle (#5) in traffic pattern 1

Figure .: Span-2 Response to final vehicle (#5) in traffic pattern 2

The remaining traffic patterns failed to produce greater responses than if the final vehicle had no preceding vehicles. Incidentally, for all these remaining traffic patterns, the final vehicle was preceded by either a dump truck (vehicle 5) or HS-20 (vehicle 3) and at a distance not less than 60ft. The maximum responses for this final loading event for all traffic patterns are summarized in the following table.

Table .: Maximum Responses for Final Vehicle Loading Event

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Max. Dynamic Disp. (in.) | | Dynamic Amplification | | Preceding Vehicle | Distance (ft.) |
|  | Span 1 | Span 2 | Span 1 | Span 2 |
| Traffic1 | -0.438 | -0.484 | 1.31 | 1.15 | 3 | 20 |
| Traffic2 | -0.370 | -0.544 | 1.12 | 1.67 | 4 | 40 |
| Traffic3 | -0.348 | -0.350 | 1.30 | 1.32 | 3 | 60 |
| Traffic4 | -0.341 | -0.301 | 1.39 | 1.23 | 5 | 80 |
| Traffic5 | -0.360 | -0.326 | **1.77** | 1.33 | 5 | 100 |
| Traffic6 | -0.351 | -0.344 | **1.43** | 1.41 | 3 | 280 |
| Vehicle5 | -0.336 | -0.337 | 1.37 | 1.38 | - | - |

The results provided in the previous table further demonstrate that traffic serves to increase structural response due to both increased static effects as well as increased dynamic amplification. However, small passenger vehicles have insufficient mass to appreciably excite the structure and thus will not have significant impact on bridge response to truck loads. Therefore, it is repeated truck loading that results in the greatest bridge response. The following section explores this further.

### Platooning

Platooning is when several trucks follow closely with reduced headway supported by control and communications technologies, resulting in a “train” of trucks. Therefore, a truck-train may be described by the following parameters:

1. Number of vehicles
2. Individual vehicle dynamics (mass and suspension properties)
3. Vehicle spacing
4. Speed

To reduce simulation computing requirements, the number of vehicles will first be investigated. We may first bound this parameter by considering that the upper limit for number of vehicles is controlled by the time it takes for bridge motion induced by past trucks to damp out. Therefore, this parameter is dependent on vehicle spacing and speed and bridge length. Vehicle spacing is conservatively bounded at 15 feet for the closest spacing, and vehicle speed is not likely to exceed 1200 in/sec (68 mph).

Therefore, the number of vehicles in a platoon was investigated while holding vehicle spacing to the conservative minimum of 15 feet and platoon speed to the conservative maximum of 1200 in/sec (68 mph), thereby maximizing the energy input to the bridge. Platoons were therefore composed of dump trucks (vehicle 5) spaced at 15 feet. The number of vehicles in each platoon was set according to: {1, 2, 4, 6, 8, 10}. Simulations were repeated for a vehicle headway spacing of 150 feet.

Simulations were performed using the 3D FE model of the 2-span bridge with span lengths of 140 ft (Part 2, Chapter 4) and a real profile (measured in Part 1). The first 15 modes of vibration were included in the simulation. A time-step of 0.002 seconds was used.

The following plot displays the effect the number of vehicles has on dynamic bridge response.

Figure .: Effect of Number of Sequential Vehicles on Bridge Response

As can be seen in the above plot, for both large and small vehicle spacing, the maximum response is captured with just 4 vehicles and any additional vehicles fail to increase the bridge response or appreciably change the nature of its motion.

The vehicle spacing was further investigated with the single-span 100-ft. model and with the single-span 140-ft. model; the same profile was used. Four dump trucks (vehicle 5) were arranged with a constant headway spacing. That spacing was varied from 15 feet to 100 feet for the 120 ft. model and from 15 feet to 75 feet for the 100 ft model. Platoons were assigned a speed of 1200 in/sec () . The results are summarized in the following plots which illustrate the effect of vehicle spacing on bridge response: amplification and displacement.

Figure .: Response summary for 140ft single-span model

Figure .: Response summary for 100ft single-span model.

Amplification in the above plots was computed by dividing the maximum dynamic displacement by the maximum static displacement, for which the static displacement was obtained from quasi-static simulation (5 in/sec) thereby accounting for the effect of multiple vehicles.

As vehicle spacing decreases, more vehicles are able to fit on the bridge, thus increasing the total load experienced by the bridge and increasing the bridge response (both static and dynamic). However, the dynamic amplification associated with this increased load tends to decrease as the vehicle spacing decreases (number of vehicles present on the bridge increases).

The dynamic amplification reaches the level corresponding to just a single vehicle when the spacing is greater than 75% of the bridge length. The dynamic amplification is a maximum when the vehicle spacing is roughly 60% of the bridge length and is greater than the dynamic amplification experienced for a single vehicle. If the bridge is designed for closer vehicle spacing (less than 35% of bridge length) and the additional load is considered in static analyses, the dynamic amplification factor computed for a single vehicle will suffice.

**2-span**

### Conclusions

Additional vehicles present additional loads to the bridge and ultimately increase bridge response. The response will exhibit dynamic amplification which may exceed that experienced for a single vehicle when a vehicle enters the bridge while it is still in motion from the previous vehicle crossing. But vehicles also present damping sources and will generally serve to reduce bridge vibration and thus dynamic amplification as they become more numerous on the bridge (simultaneously).

This is echoed by simulations of truck platoons, which suggest that platooned vehicles present no greater risk to increased bridge dynamics than posed by other traffic conditions because it only takes a single previous truck to induce the bridge conditions that result in maximum dynamic amplification.

Similarly, the amplification experienced when multiple lanes are occupied would be less than if only a single vehicle is present. Therefore, the conservatism introduced by considering loading in multiple lanes is further increased if dynamic amplification for a single vehicle is implemented.

It should be stressed that even though multiple vehicles, present on the bridge simultaneously, serve to reduce the level of dynamic amplification, it is still present and should be considered in analysis.

If the total response of the bridge is to be minimized, spacing between sequential trucks should be such that the bridge has had time to settle down. Thus, headway distance should be at least 75% of the bridge length (span length?). When performing analysis for platoons with very small headway spacing (e.g. less than 35% of the bridge length), the effect of the additional vehicles should be included in a static analysis with an amplification factor as predicted for a single vehicle.

Estimations of dynamic amplification for a single vehicle event should consider the possibility that the bridge may already have been excited by a previous vehicle. However, the additional amplification experienced by the bridge in this scenario is not likely to be more than 20% greater than that predicted for a single vehicle.

## Part 3 Conclusions and Future Work

### Conclusions

The simulation tools demonstrated in Part 1 and developed in Part 2 were used to investigate the efficacy of rolling-straightedge requirements on a real profile (measured in Part 1). From the results of these simulations the following conclusions can be made.

* Rolling straightedge criteria with common limits (i.e. 1/8 to ¼ inch deviation over 10 to 16 feet) are not effective at reducing dynamic amplification.
* It is recommended that, if this criterion is to continue being used, the straightedge length should be no less than 16 feet and the specified deviation limit should be no greater than 1/8th inch.

VBI simulations were performed for traffic and truck platoons. The number of vehicles simultaneously present and the spacing between vehicles was principally investigated. From these studies the following conclusions are drawn:

* Traffic and truck platoons can result in increased dynamic amplification because even a single previous truck can induce the bridge conditions (motion) that result in increased dynamic response (≈20%).
* As spacing between vehicles decreases and more vehicles are present on the bridge, the static load effect increases, but the dynamic amplification will likely be less than what would occur for a single vehicle.
* If the total response of the bridge is to be minimized, spacing between sequential trucks should be such that the bridge has had time to settle down (at least 75% of bridge length).
* When designing for truck platoons, the opportunity for multiple trucks to be present on the bridge simultaneously should be considered in static analysis, and the dynamic amplification factor for a single vehicle can provide conservative estimate of the dynamic response.
* Dynamic amplification for simultaneous loading of multiple lanes can be conservatively estimated as that for a single vehicle.

### Future Work

Effect of transient features: bump at the beginning of the bridge, ramped approaches up or down (sinking of abutments).

Dynamic amplification of shear

Studies with greater structural variation

Studies with other bridge types (i.e. other than multi-girder)

Improvement of simplified models, especially 2-span (include more modes)

Assessment of simplified models with more advanced vehicle models, especially for shorter bridges in which the spatial distribution of wheel loads will have more of an effect.

Other vehicles with different suspension parameters (based on vehicle population statistics).

Investigation of grinding practices and the effect of this smoothing on reducing dynamic amplification.

Identify how construction practices may result in harmonic profile content (i.e. bridge deck pouring machines result in regular discontinuities).

Develop improved smoothness criterion that are appropriate for actual remediation (smoothing) methods.