# A Framework Specialized for Large-scale Vehicle-bridge Interaction Simulation

Kyoto University Student Member ○ Zhuoran HAN
Kyoto University Regular Member Chul-Woo KIM
Kyoto University Regular Member Kai-Chun CHANG

## 1. INTRODUCTION

The coupled motion of bridges and moving vehicles, also known as Vehicle-Bridge Interaction (VBI), is critical to bridge design, monitoring, and vehicle safety and comfort. It involves two coupled subsystems whose kinematic relation makes it nonlinear and time-dependent. Therefore, most VBI studies rely on simulations with general-purpose finite element (FE) software. They typically include aspects such as vehicle and bridge models, road surface profile, and wheel-deck contact.

VBI systems can be classified into four scales based on bridge length and the number of vehicles, as shown in **Table 1**. The larger the scale, the more complex the bridge shape, seismic excitation, traffic patterns, and dynamic problems, and the more difficult to solve. However, most current studies still focus on the microscale, leaving several issues such as Asynchronous Seismic Excitation (ASE), deck shape such as curves and slopes, Variable Vehicle Velocity (VVV), and vehicle driving behavior unaddressed. One of the reasons is that the tools they use are not specialized for simple but time-varying systems like VBI, resulting in increased computation time and difficulties in handling large bridge models, diverse vehicle models, and vehicle entry and exit. This study aims to propose a framework for large-scale VBI simulation that is accurate, efficient, and versatile. Among all programming platforms, MATLAB was chosen because of its powerful matrix operations and a variety of built-in functions.

## 2. METHODOLOGY

The framework consists of four modules: bridge, deck, vehicle, and traffic. It considers real but often neglected phenomena, it is fast and easy to use, and all functions are carefully designed to facilitate secondary development.

The bridge module includes the basic FE method with 3D Euler-Bernoulli beam elements. All kinds of connectors are supported in arbitrary directions with extended transformation matrices. An interface matrix method (IMM) is proposed to handle the ASE effect and solve for an exact and absolute result.

The deck module maps the sloped and curved deck to a flat and straight one, unifying the bridge, deck, and vehicle coordinate systems and eliminating the need for coordinate transformations, as shown in **Figure 1**. A deck profile is generated to assist and compensate for the mapping, including a positioning function to handle vehicle entry and exit, and a shape function for quadrilateral grids to facilitate force and reaction transmission. The roughness is generated by random PSD based on the ISO standard but with optimization for bridges.

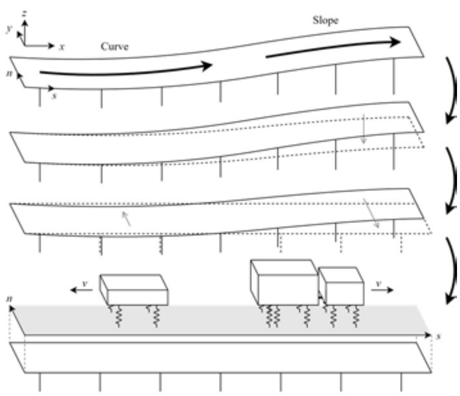


**Figure 1**. Deck mapping

The vehicle module unifies all road vehicles with a general criterion so that researchers do not have to develop separate models for each vehicle type in each paper. Vehicles are decomposed into units and axle sets, each having up to three DOFs, i.e., bounce, roll, and pitch, as shown in **Figure 2**. The vehicle matrices can be assembled based on this decomposition. The inertial forces of a vehicle traveling on slopes, curves, or changes in velocity are replaced by external forces and moments acting on both the vehicle components and the deck.

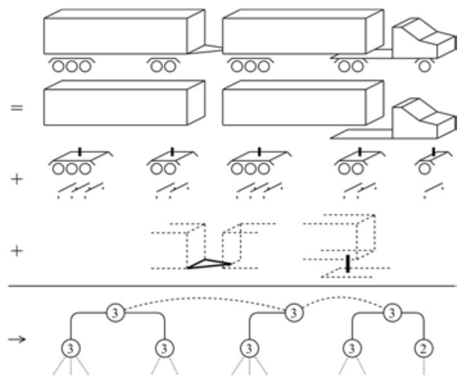

**Figure 2**. Vehicle library

The traffic module characterizes the vehicle kinematics with a car-following model to reproduce common scenarios such as free flow and congestion. An event trigger is introduced to account for changes in road conditions, such as accidents. The framework uses the decoupled approach with iterations, through which the coupling is established.

**Table 1**. VBI system scales.

| Scale* | Bridge | Vehicle | Problems to solve |
|---|---|---|---|
| Microscale | ~ 100 m | ~ 10 | Most current VBI studies |
| Mesoscale | ~ 1,000 m | ~ 100 | Asynchronous seismic excitation, variable vehicle velocity |
| Macroscale | ~ 10 km | ~ 1,000 | Deck slopes and curves, vehicle driving behavior |
| Meta-scale | ~ 100 km | ~ 10,000 | Junctions, overpasses, tunnels |

* The scales are only roughly defined, but all discussions based on them do not lose their generality.

Keywords: Computation efficiency; In-house experiment; Vehicle-bridge interaction; VBI platform
Contact address: 〒615-8540, Kyotodaigaku Katsura, Nishikyo-ku, Kyoto, Email: kim.chulwoo.5u@kyoto-u.ac.jp

## 3. VERIFICATION VIA IN-HOUSE EXPERIMENT

The framework is verified with a laboratory experiment on a 5.6-meter steel model bridge with a 277.6 N vehicle running through it. The bridge and the vehicle numerical models are verified with high consistency to the real ones. Measured track roughness is adopted, and the simulation results are compared with the experiment, as shown in **Figure 3**.

The vehicle took 7 s to pass through the bridge. The first plot is bridge center deflection, while the rests are bridge and vehicle accelerations and FFT. The solid line and shaded areas are simulation and experiment plus or minus 1~3 standard deviations from twenty runs. The dashed and dotted lines at the top are the influence line from static and closed-form solutions. The simulation matched well with the experimental results.

The simulation with 4 iterations took 2 s to finish. On the contrary, a similar model in Abaqus took 400 to 450 seconds. Thus, this framework can be hundreds of times faster than general-purpose FE software when dealing with VBI systems.

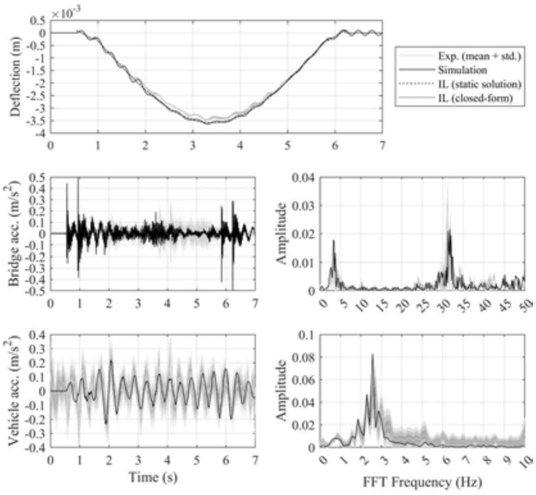


**Figure 3**. Simulation vs. experiment

## 4. SEISMIC EXCITATION VALIDATION

The seismic performance is validated by comparing it to an early paper by Kawatani et al. (2008). In this paper, we use only one of the two bridge models, i.e., model B, for seismic analysis. It is slightly modified by removing the offset beams attached to the girders to reduce the total DOFs, as plotted in **Figure 4**. The modified ground motions GI-0 and GII-0 are used, where the dominant excitation is in the transverse direction, and the vertical direction is complemented by the same wave with half amplitude. The results are summarized and compared in **Table 2**. The response of the superstructure is 1.5 to 2 times that of the base input, and both the amplitude and frequency of the simulation agree with the reference paper. Therefore, the framework is reliable for seismic excitations.

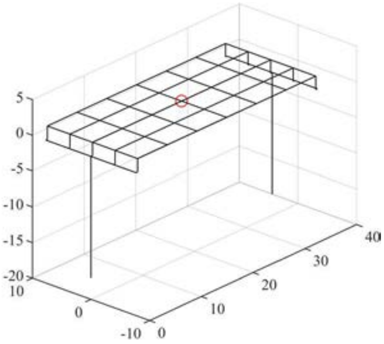

**Figure 4**. Bridge model

## 5. CONCLUSIONS

This paper proposes and verifies a framework specialized for large-scale VBI simulation in MATLAB. It proposes innovative features such as a vehicle library to unify all road vehicles and a deck profile to integrate bridge structure, deck shape, and vehicle paths. It also supports asynchronous seismic excitation, road surface profile, wheel detachment, and variable vehicle velocity. The framework includes extensive optimizations for computational efficiency and is hundreds of times faster than general-purpose FE software, enabling statistical analysis of complex models while maintaining rich functionality and compatibility with arbitrary inputs. Most functions, judgments, and operations within the framework are fully automated, allowing users to focus on results. With ongoing enhancements, it will greatly facilitate the study of VBI and improve our understanding of it.

Despite its usefulness, the current version of the framework has several limitations that hinder its applicability. For example, due to its linear nature, it cannot perform nonlinear analyses under strong earthquakes. In addition, its support for only quadrilateral grids, without the ability to handle multilayer or parallel spans and junctions, limits its suitability for certain structures, including overpasses and tunnels.

In the future, in addition to these aspects, a common vehicle library can be created and shared with researchers around the world. It can even provide real-time analysis such as structural health monitoring using vision-based sensors and smart vehicles and enable rapid simulation to estimate structural stability and traffic capacity before or after an earthquake, enhancing safety.

**Table 2**. Results compared with the reference paper.

| Earthquake | Term | Reference paper | Framework | Error |
|---|---|---|---|---|
| GI-0 | Peak acc (Gal) | 164 | 163 | 0.6% |
| | RMS acc (Gal) | 33.9* | 42.5 | 25.5% |
| | FFT peak (Hz) | 1.51 | 1.48 | -2.0% |
| GII-0 | Peak acc (Gal) | 236 | 226 | -4.2% |
| | RMS acc (Gal) | 77.7 | 80.7 | 3.9% |
| | FFT peak (Hz) | 1.64 | 1.63 | -0.4% |

* There might have been a typesetting mistake on this data since the plots seem identical, but the numbers are different.

## REFERENCES

川谷充郎, 金哲佑, 岩下謙司, 安井克典, 橋梁– 車両連成系を考慮した高架道路橋の地震応答解析. 土木学会論文集 A, Vol. 64, NO.4, pp. 678-691, 2008.