**Overview:**

This document aims to investigate the dynamic response of unsprung and sprung mass of a vehicle model with and without an engine, and the effect of changing boundary conditions on the APPVMD algorithm. In the first study, the equations of motion for a vehicle with an engine are derived, where they are transformed to the frequency domain by applying the Laplace transform. Afterward, the magnitude of the system’s transfer function is taken to investigate its gain based on input forces. In the second study, three boundary conditions are simulated; namely, pinned-pinned (default study), fixed-pinned, and fixed-fixed. These simulations are carried out for all four vehicle classes to gain an understanding of these effects of almost all vehicle classes. It is worth mentioning that the default boundary condition us rerun, where negligible differences are observed due to the variability of the surface roughness definition for each vehicle pass. The following tables are generated to investigate the effects of boundary conditions on the APPVMD accuracies.

**Transfer Function of Vehicle Model with Engine:**

The figure below shows the five degrees-of-freedom (DOF) vehicle model with an engine mounted on its front. Its equations of motions can be found in the bottom of the figure.

Mb, Jz

MR

KRS

CRS

KRT

MF

KFS

CFS

KFT

ME

KM

CM

b

a

zb

zR

zF

zE

ϕb

PE

Equation of motion of 5 DOF vehicle model (with engine):

1. Body bounce:
2. Body pitch:
3. Front wheel bounce:
4. Rear wheel bounce:
5. Engine bounce:

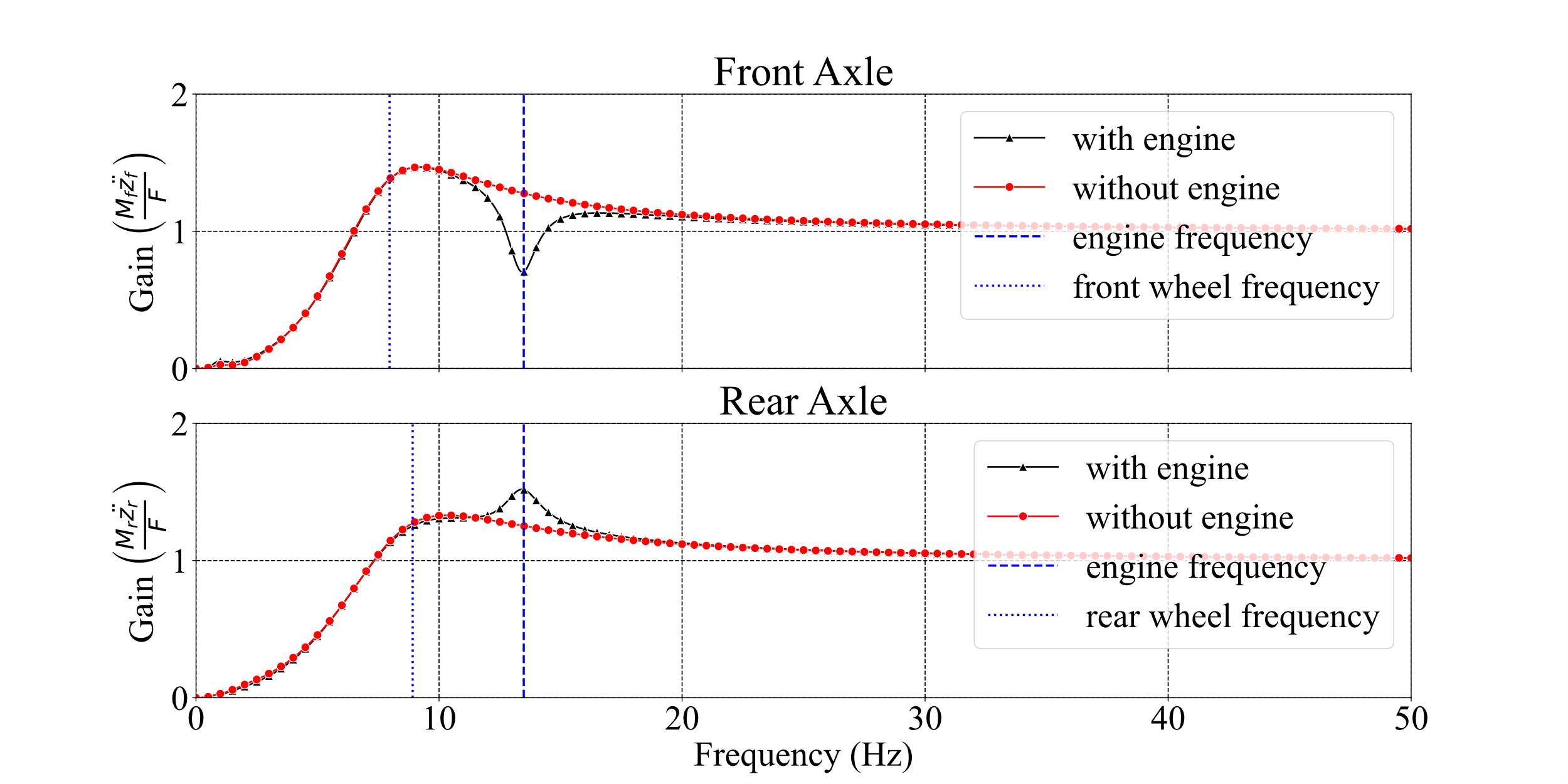
Assemble [K], [C], and [M] matrices:

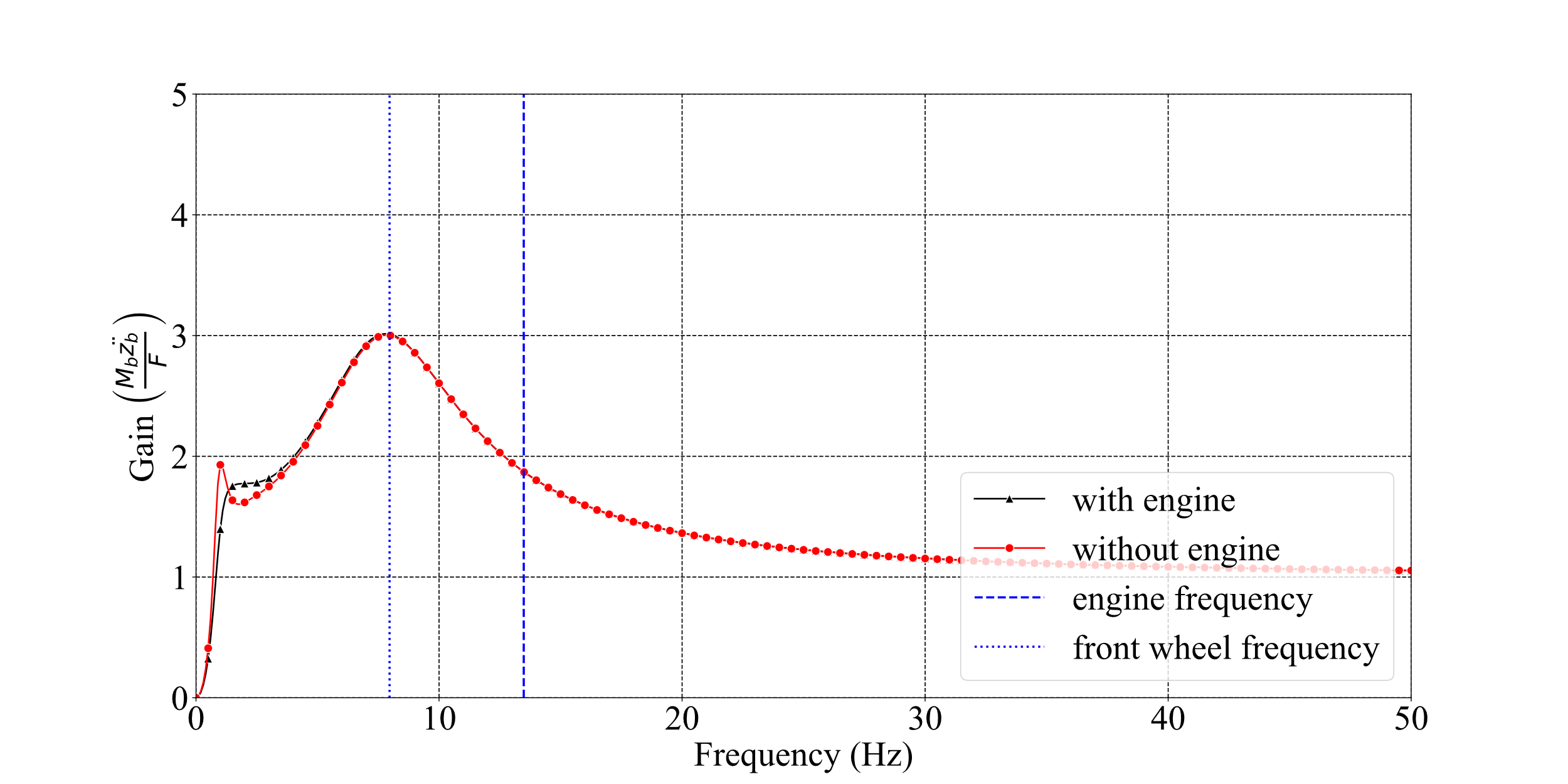
Transform equation of motion to S-domain using the Laplace transform:

Where G(s) is the transfer function of the dynamic system.

**Frequency Response Plots:**

Both figures show that the curves between the vehicle with and without engine effects are roughly similar. In addition, the front and rear axles attenuate the vehicle body’s natural frequencies. However, in the first figure, we observed that both axles, in both vehicle models, align well with each other except at the engine’s natural frequency, where both the front and rear axles attenuate and amplify engine harmonics, respectively. Therefore, engine harmonics will be present in one of the axles, while being attenuated in the other. In one of the steps within the APPVMD algorithm, the difference in peak frequencies between the front and rear axles are disregarded; indicating that even if engine harmonics are present in the response of a single axle, they would more likely be removed. In the second figure, the authors noticed significantly higher amplification in vehicle response for the harmonics in the body, engine, and axles; indicating that placing the sensor in the body would more likely disturb the algorithm’s ability to identify the natural frequency of the bridge. Therefore, the placement of sensors in the un-sprung mass is the most optimum technique to minimizing external harmonics.





**Results of Boundary Condition Study:**

Table 1: Pinned-pinned condition.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Vehicle Class | Not Detected | Low CFR | Med CFR | High CFR | % detected |
| Hatchback | 9 | 20 | 8 | 2 | 76.9% |
| Sedan | 1 | 12 | 17 | 9 | 97.4% |
| SUV | 2 | 8 | 16 | 13 | 94.8% |
| Truck | 7 | 7 | 9 | 16 | 82.1% |

Table 2: Fixed-pinned condition.

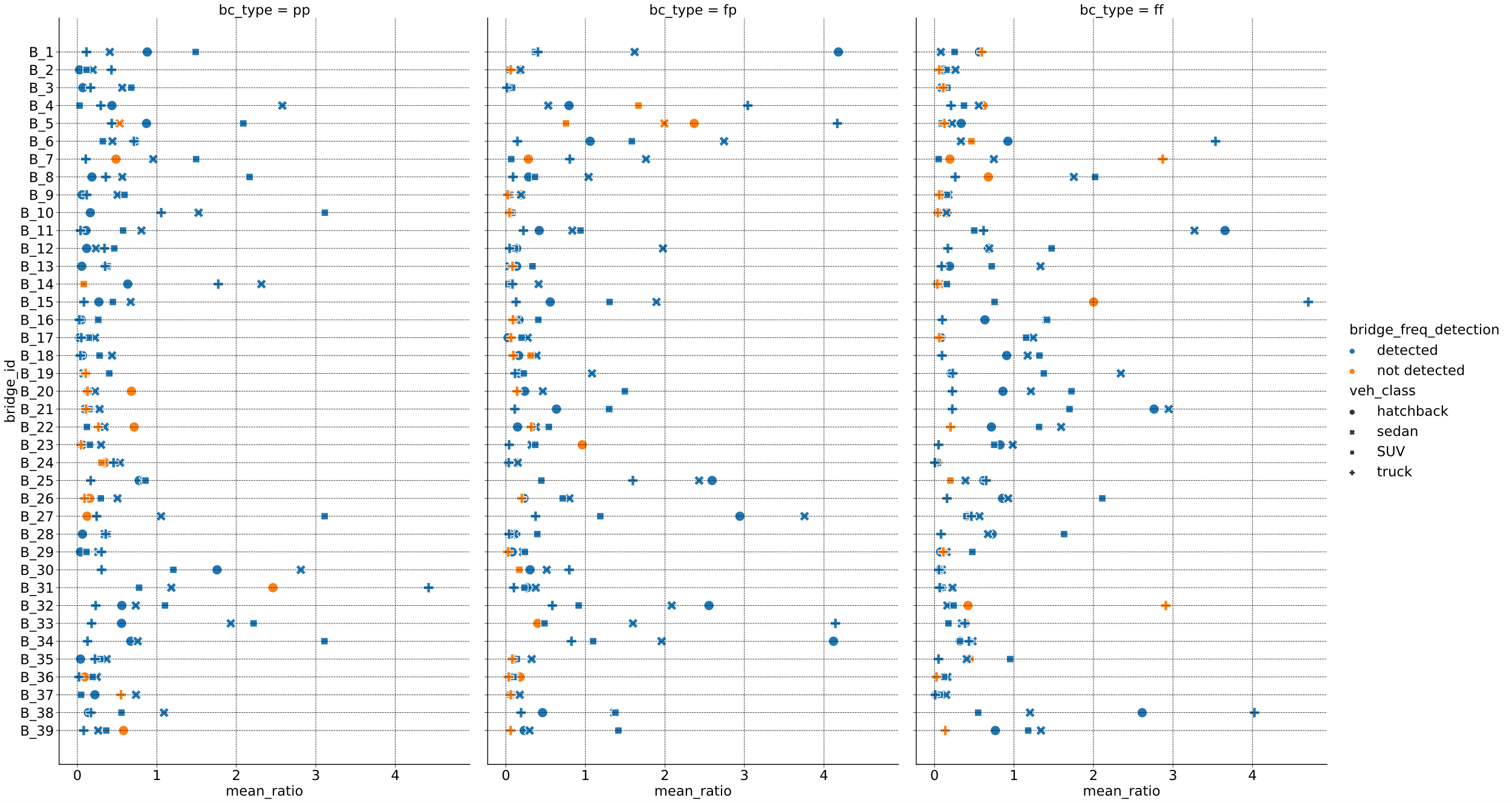
|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Vehicle Class | Not Detected | Low CFR | Med CFR | High CFR | % detected |
| Hatchback | 10 | 19 | 10 | 0 | 74.4% |
| Sedan | 1 | 26 | 11 | 1 | 97.4% |
| SUV | 4 | 22 | 11 | 2 | 89.7% |
| Truck | 15 | 18 | 6 | 0 | 61.5% |

Table 3: Fixed-fixed condition.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Vehicle Class | Not Detected | Low CFR | Med CFR | High CFR | % detected |
| Hatchback | 14 | 14 | 10 | 1 | 64.1% |
| Sedan | 2 | 27 | 10 | 0 | 94.8% |
| SUV | 2 | 25 | 10 | 2 | 94.8% |
| Truck | 14 | 15 | 10 | 0 | 64.1% |

**Discussion:**

We also inspected the ratio of the bridge psd amplitude to the vehicle natural frequency and made a brief relational plot, as shown below. Each column represents a boundary condition type (bc\_type) where pp, fp, and ff correspond to pinned-pinned, fixed-pinned, and fixed-fixed, respectively. The x and y axes are the ratio and bridge IDs, respectively, and the points are distinguished based on color and type. The color classifies based on whether the vehicle was able to capture the frequency and the type corresponds to the vehicle class.



Afterwards, we arbitrarily decided to select the points that are above 0.10 ratio, since the specified height range to pick peaks is at 10% of the maximum amplitude. These points are then classified into tables based on the boundary condition type and vehicle class, as shown below.

Table 4: Number of successful detection that demonstrate a PSD ratio greater than 0.10.

|  |  |  |  |
| --- | --- | --- | --- |
| Vehicle Class | Count for PP | Count for FP | Count for FF |
| Hatchback | 11 | 14 | 17 |
| Sedan | 32 | 27 | 25 |
| SUV | 27 | 20 | 23 |
| Truck | 14 | 10 | 9 |