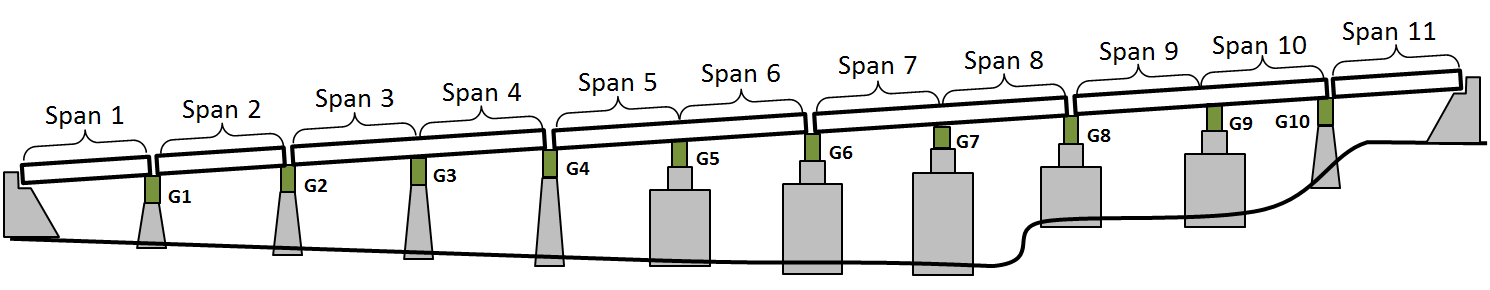
# Appendix

## Case Study Bridge Description



#### Superstructure

The structural type is steel multi-girder. Eight girders run longitudinally, resting on steel box girders that span transversely and are supported by the concrete piers. A reinforced concrete composite deck was cast in place, with a “raked” finish and no overlay. There is no skew. The bridge has eleven spans. The maximum span length is 140’-0”. The out-to-out width is 76’-6”. Three spans are simply supported, while the remaining eight are two-span continuous. Each span has five interior rows of X-framed diaphragms and chevron diaphragms over the piers.



#### Substructure and Bearings

The concrete piers and abutments were constructed in 1952 and are all that remains of the original structure. They are supported by driven piles. Elastomeric bearing pads are installed on top of the piers and support the transverse box girders. Rocker bearings or pedestals are installed between the box girders and longitudinal girders at those locations which are in the center of continuous spans. Elastomeric bearings are installed between the box girder and the longitudinal girders at the remaining locations.



### Condition

Visually, the deck appears to be in good condition, with no major cracking visible. Minor damage was observed in some regions of the center concrete barrier. The girders appeared in excellent condition. No major rusting was observed, and the girders appeared well maintained. The access hatches on many of the box girders had been left open. Any ill effects from this could not be immediately observed. The piers exhibited very little efflorescence and virtually no spalling. Repairs had been performed on several piers, where an embedded drainage pipe had rusted and caused a portion of concrete to spall off.

NBI Details

| NBI Structure Number | 000000000027280 |
| --- | --- |
| Year Reconstructed | 1986 |
| Owner | PennDOT |
| Skew | 0 degrees |
| Deck Width | 76’-6” |
| Maximum Span Length | 140’-0” |
| ADT | 57410 (2013) |
| Deck Condition | 6 (Satisfactory Condition) |
| Superstructure Condition | 7 (Good Condition) |
| Substructure Condition | 5 (Fair Condition) |
| Sufficiency Rating | 70 |

## Case Study: Phase 1 Testing

### Longitudinal Acceleration Time History

|  |  |  |
| --- | --- | --- |
| Acceleration (g) |  | Pier 2 |
|  | Pier 3 |
|  | Pier 5 |
|  | Pier 7 |
|  | Time (sec) ◼-West; ◼-East |  |

### Vertical Acceleration Time History

|  |  |  |
| --- | --- | --- |
| Acceleration (g) |  | Pier 2 |
|  | Pier 3 |
|  | Pier 5 |
|  | Pier 7 |
|  | Time (sec) |  |

### Phase 2 Testing

#### Mode shapes

## FE Model Creation

### 3D Element-based model

This model type employs

### Plate Eccentric-Beam (PEB) model

## FE Model Validation

### Phase 2

### Phase 3

|  |  |
| --- | --- |
| FE Modes | Experimental Modes |
| 2.03 Hz | 2.0 Hz |
| 2.07 Hz | 2.1 Hz |
| 2.49 Hz | 2.44 Hz |
| 2.50 Hz | 2.54 Hz |
| 2.82 Hz | 2.83 Hz |
| 3.14 Hz | 3.2 Hz |
| 3.63 Hz | 3.56 Hz |
| 3.63 Hz | 3.56 Hz |

## State-Space Model Validation

Validation of the 2-DOF state-space models was performed by comparing responses to those predicted by 2D FE models of the beams. The following lists the beam parameters as assigned in the state-space model.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Bridge/Beam Parameters | | | Vehicle/Sprung Mass Parameters | | |
| Length | 1200 | in | Mass | 100 | slinch |
| EI | 7.50E+12 | lb-in2 | Spring K | 6.32E+04 | lb/in |
| Total Mass | 460000 | lb | Damping Coefficient | 502.65 | lb-s/in |
| Length | 1200 | in |  |  |  |

The FE models were constructed with 2D Kirchhoff beam elements which are parabolically curved thin beam elements in which shear deformations are excluded. The beams were discretized with a mesh length of 6 inches. The elements were assigned the following attributes.

Table 1: FEM Beam Attributes

|  |  |  |
| --- | --- | --- |
| Moment of Inertia (I) | 1500 | in^4 |
| Cross sectional area (A) | 10 | in^2 |
| Modulus of Elasticity (E) | 5.00E+09 | psi |
| Material Density | 0.099286 | slinch/in^3 |

The sprung-mass in the FE model was assigned the same attributes as listed for the state-space model.

The profile was constructed using ISO 8608 standards whereby two parameters describe the frequency content of the profile. For these simulations a profile was constructed with a roughness coefficient (C10) of 300 and a waviness (*w*) of -2. A profile with these parameters would be categorized as average according to ISO 8608. The profile was located such that the beam began at the profile’s distance of 100 feet.

The sprung mass was assigned a velocity of 720 in/sec. Its path began 100 feet before the beam at the beginning of the profile. The state-space model evaluated each state in increments of 1 inch thus resulting in a time-step of 0.0014 sec. The FE simulations were performed with a time-step of 0.0015 sec.

### Comparison of state-space to FEM for single-span

Figure 1: Comparison of midspan displacement

Figure 2: Comparison of force at vehicle contact point

### Comparison of state-space to FEM for two-span continuous

Figure 3: Comparison of midspan (span 1) displacement

Figure 4: Comparison of force at vehicle contact point

## Construction of Artificial Profiles

## Simulation of VBI with Traffic

Table : Vehicles and their corresponding sprung-mass properties

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Vehicle # | Axle # | Name | Distance from rear axle (ft) | Weight (kip) | Mass (slinch) | Spring Stiffness (kip/in) | Damping Coefficient (lb-s/in) | Damping Ratio | Natural Frequency |
| 1 | 1 | HS20-32\_1 | 0 | 32 | 82.882 | 20 | 257.529 | 0.1 | 2.472 |
| 1 | HS20-32\_1 | 14 | 32 | 82.882 | 20 | 257.529 | 0.1 | 2.472 |
| 2 | HS20-8\_1 | 28 | 8 | 20.721 | 15 | 111.513 | 0.1 | 4.282 |
| 2 | 3 | HS20-32\_2 | 0 | 32 | 82.882 | 16 | 460.682 | 0.2 | 2.211 |
| 3 | HS20-32\_2 | 30 | 32 | 82.882 | 16 | 460.682 | 0.2 | 2.211 |
| 4 | HS20-8\_2 | 44 | 8 | 20.721 | 8 | 407.189 | 0.5 | 3.127 |
| 3 | 5 | HS20-32\_3 | 0 | 32 | 82.882 | 13 | 415.253 | 0.2 | 1.993 |
| 5 | HS20-32\_3 | 22 | 32 | 82.882 | 13 | 415.253 | 0.2 | 1.993 |
| 6 | HS20-8\_3 | 36 | 8 | 20.721 | 10 | 455.251 | 0.5 | 3.496 |
| 4 | 7 | tst-tand | 0 | 17 | 44.031 | 15 | 162.557 | 0.1 | 2.937 |
| 7 | tst-tand | 6 | 17 | 44.031 | 15 | 162.557 | 0.1 | 2.937 |
| 8 | tst-drive | 29 | 17 | 44.031 | 15 | 162.557 | 0.1 | 2.937 |
| 8 | tst-drive | 35 | 17 | 44.031 | 15 | 162.557 | 0.1 | 2.937 |
| 9 | tst-front | 51 | 12 | 31.081 | 2.2 | 261.522 | 0.5 | 1.339 |
| 5 | 10 | dump-rear | 0 | 25 | 64.752 | 12 | 176.318 | 0.1 | 2.166 |
| 10 | dump-rear | 5 | 25 | 64.752 | 12 | 176.318 | 0.1 | 2.166 |
| 11 | dump-front | 20 | 20 | 51.801 | 12 | 315.407 | 0.2 | 2.422 |
| 6 | 12 | car1 | 0 | 1.5 | 3.885 | 0.2 | 27.878 | 0.5 | 1.142 |
| 12 | car1 | 8 | 1.5 | 3.885 | 0.2 | 27.878 | 0.5 | 1.142 |
| 7 | 13 | car2 | 0 | 2 | 5.180 | 0.4 | 45.525 | 0.5 | 1.398 |
| 13 | car2 | 10 | 2 | 5.180 | 0.4 | 45.525 | 0.5 | 1.398 |
| 8 | 14 | car3 | 0 | 3 | 7.770 | 2 | 124.676 | 0.5 | 2.553 |
| 14 | car3 | 14 | 3 | 7.770 | 2 | 124.676 | 0.5 | 2.553 |

Table : Traffic Pattern Parameters

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

Table : Spring-mass configuration for traffic patterns

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
| Location (in) | Axle # | Location (in) | Axle # | Location (in) | Axle # | Location (in) | Axle # | Location (in) | Axle # | Location (in) | Axle # |
| 0 | 6 | 0 | 2 | 0 | 9 | 0 | 9 | 0 | 4 | 0 | 4 |
| -168 | 5 | -168 | 1 | -192 | 8 | -192 | 8 | -168 | 3 | -168 | 3 |
| -432 | 5 | -336 | 1 | -264 | 8 | -264 | 8 | -528 | 3 | -528 | 3 |
| -1260 | 2 | -2028 | 6 | -540 | 7 | -540 | 7 | -2676 | 2 | -17220 | 12 |
| -1428 | 1 | -2196 | 5 | -612 | 7 | -612 | 7 | -2844 | 1 | -17316 | 12 |
| -1596 | 1 | -2460 | 5 | -3096 | 2 | -2496 | 14 | -3012 | 1 | -21672 | 12 |
| -1860 | 6 | -4260 | 14 | -3264 | 1 | -2664 | 14 | -6816 | 9 | -21768 | 12 |
| -2028 | 5 | -4428 | 14 | -3432 | 1 | -4584 | 11 | -7008 | 8 | -35880 | 9 |
| -2292 | 5 | -5568 | 12 | -5208 | 6 | -4764 | 10 | -7080 | 8 | -36072 | 8 |
| -2880 | 9 | -5664 | 12 | -5376 | 5 | -4824 | 10 | -7356 | 7 | -36144 | 8 |
| -3072 | 8 | -6828 | 2 | -5640 | 5 | -9192 | 12 | -7428 | 7 | -36420 | 7 |
| -3144 | 8 | -6996 | 1 | -7752 | 13 | -9288 | 12 | -10320 | 13 | -36492 | 7 |
| -3420 | 7 | -7164 | 1 | -7872 | 13 | -11100 | 6 | -10440 | 13 | -43068 | 14 |
| -3492 | 7 | -8772 | 13 | -9396 | 6 | -11268 | 5 | -12408 | 14 | -43236 | 14 |
| -4632 | 12 | -8892 | 13 | -9564 | 5 | -11532 | 5 | -12576 | 14 | -47508 | 2 |
| -4728 | 12 | -10860 | 12 | -9828 | 5 | -13092 | 13 | -16788 | 4 | -47676 | 1 |
| -5640 | 14 | -10956 | 12 | -11520 | 11 | -13212 | 13 | -16956 | 3 | -47844 | 1 |
| -5808 | 14 | -11760 | 6 | -11700 | 10 | -15780 | 12 | -17316 | 3 | -56724 | 14 |
| -6960 | 12 | -11928 | 5 | -11760 | 10 | -15876 | 12 | -22140 | 9 | -56892 | 14 |
| -7056 | 12 | -12192 | 5 | -12672 | 11 | -18036 | 14 | -22332 | 8 | -61128 | 6 |
| -8064 | 11 | -14148 | 4 | -12852 | 10 | -18204 | 14 | -22404 | 8 | -61296 | 5 |
| -8244 | 10 | -14316 | 3 | -12912 | 10 | -21132 | 4 | -22680 | 7 | -61560 | 5 |
| -8304 | 10 | -14676 | 3 | -15180 | 4 | -21300 | 3 | -22752 | 7 | -75024 | 11 |
| -8904 | 12 | -16632 | 2 | -15348 | 3 | -21660 | 3 | -26928 | 9 | -75204 | 10 |
| -9000 | 12 | -16800 | 1 | -15708 | 3 | -25524 | 13 | -27120 | 8 | -75264 | 10 |
| -10092 | 11 | -16968 | 1 | -17316 | 12 | -25644 | 13 | -27192 | 8 | -84300 | 11 |
| -10272 | 10 | -18336 | 4 | -17412 | 12 | -28644 | 14 | -27468 | 7 | -84480 | 10 |
| -10332 | 10 | -18504 | 3 | -19740 | 11 | -28812 | 14 | -27540 | 7 | -84540 | 10 |
| -10680 | 9 | -18864 | 3 | -19920 | 10 | -30504 | 9 | -29844 | 2 | -98004 | 12 |
| -10872 | 8 | -19824 | 14 | -19980 | 10 | -30696 | 8 | -30012 | 1 | -98100 | 12 |
| -10944 | 8 | -19992 | 14 | -23040 | 13 | -30768 | 8 | -30180 | 1 | -102528 | 2 |
| -11220 | 7 | -21540 | 2 | -23160 | 13 | -31044 | 7 | -33036 | 6 | -102696 | 1 |
| -11292 | 7 | -21708 | 1 | -24312 | 12 | -31116 | 7 | -33204 | 5 | -102864 | 1 |
| -12204 | 6 | -21876 | 1 | -24408 | 12 | -35664 | 11 | -33468 | 5 | -109392 | 14 |
| -12372 | 5 | -23760 | 6 | -25596 | 11 | -35844 | 10 | -39420 | 6 | -109560 | 14 |
| -12636 | 5 | -23928 | 5 | -25776 | 10 | -35904 | 10 | -39588 | 5 | -122256 | 2 |
| -13584 | 12 | -24192 | 5 | -25836 | 10 | -37584 | 12 | -39852 | 5 | -122424 | 1 |
| -13680 | 12 | -25716 | 9 | -28620 | 6 | -37680 | 12 | -44664 | 13 | -122592 | 1 |
| -14460 | 14 | -25908 | 8 | -28788 | 5 | -39312 | 14 | -44784 | 13 | -139116 | 13 |
| -14628 | 14 | -25980 | 8 | -29052 | 5 | -39480 | 14 | -46188 | 6 | -139236 | 13 |
| -15456 | 13 | -26256 | 7 | -30588 | 6 | -43752 | 12 | -46356 | 5 | -146268 | 12 |
| -15576 | 13 | -26328 | 7 | -30756 | 5 | -43848 | 12 | -46620 | 5 | -146364 | 12 |
| -16368 | 13 | -27276 | 11 | -31020 | 5 | -45696 | 13 | -51708 | 6 | -156360 | 2 |
| -16488 | 13 | -27456 | 10 | -33636 | 11 | -45816 | 13 | -51876 | 5 | -156528 | 1 |
| -17280 | 9 | -27516 | 10 | -33816 | 10 | -49164 | 9 | -52140 | 5 | -156696 | 1 |
| -17472 | 8 | -28356 | 12 | -33876 | 10 | -49356 | 8 | -54936 | 9 | -162732 | 2 |
| -17544 | 8 | -28452 | 12 | -35028 | 13 | -49428 | 8 | -55128 | 8 | -162900 | 1 |
| -17820 | 7 | -30072 | 11 | -35148 | 13 | -49704 | 7 | -55200 | 8 | -163068 | 1 |
| -17892 | 7 | -30252 | 10 | -36588 | 13 | -49776 | 7 | -55476 | 7 | -171156 | 6 |
| -18348 | 13 | -30312 | 10 | -36708 | 13 | -50904 | 4 | -55548 | 7 | -171324 | 5 |
| -18468 | 13 | -32340 | 12 | -39492 | 12 | -51072 | 3 | -57480 | 11 | -171588 | 5 |
| -19236 | 11 | -32436 | 12 | -39588 | 12 | -51432 | 3 | -57660 | 10 | -175704 | 4 |
| -19416 | 10 | -34416 | 4 | -41280 | 11 | -55764 | 11 | -57720 | 10 | -175872 | 3 |
| -19476 | 10 | -34584 | 3 | -41460 | 10 | -55944 | 10 | -61608 | 12 | -176232 | 3 |
| -20052 | 2 | -34944 | 3 | -41520 | 10 | -56004 | 10 | -61704 | 12 | -183612 | 14 |
| -20220 | 1 | -37224 | 13 | -42312 | 4 | -57408 | 12 | -63660 | 2 | -183780 | 14 |
| -20388 | 1 | -37344 | 13 | -42480 | 3 | -57504 | 12 | -63828 | 1 | -198480 | 4 |
| -21372 | 11 | -38256 | 12 | -42840 | 3 | -61176 | 2 | -63996 | 1 | -198648 | 3 |
| -21552 | 10 | -38352 | 12 | -45336 | 6 | -61344 | 1 | -66264 | 9 | -199008 | 3 |
| -21612 | 10 | -39456 | 14 | -45504 | 5 | -61512 | 1 | -66456 | 8 | -213192 | 4 |
| -22716 | 12 | -39624 | 14 | -45768 | 5 | -63360 | 2 | -66528 | 8 | -213360 | 3 |
| -22812 | 12 | -41688 | 11 | -47256 | 4 | -63528 | 1 | -66804 | 7 | -213720 | 3 |
| -23244 | 12 | -41868 | 10 | -47424 | 3 | -63696 | 1 | -66876 | 7 | -225048 | 14 |
| -23340 | 12 | -41928 | 10 | -47784 | 3 | -66756 | 9 | -72240 | 2 | -225216 | 14 |
| -24504 | 11 | -44004 | 6 | -50268 | 13 | -66948 | 8 | -72408 | 1 | -239328 | 12 |
| -24684 | 10 | -44172 | 5 | -50388 | 13 | -67020 | 8 | -72576 | 1 | -239424 | 12 |
| -24744 | 10 | -44436 | 5 | -53832 | 6 | -67296 | 7 | -77412 | 12 | -243732 | 9 |
| -25068 | 11 | -46416 | 12 | -54000 | 5 | -67368 | 7 | -77508 | 12 | -243924 | 8 |
| -25248 | 10 | -46512 | 12 | -54264 | 5 | -71616 | 2 | -81696 | 6 | -243996 | 8 |
| -25308 | 10 | -47664 | 12 | -56676 | 4 | -71784 | 1 | -81864 | 5 | -244272 | 7 |
| -26232 | 14 | -47760 | 12 | -56844 | 3 | -71952 | 1 | -82128 | 5 | -244344 | 7 |
| -26400 | 14 | -48684 | 12 | -57204 | 3 | -73116 | 4 | -85752 | 11 | -252432 | 9 |
| -27096 | 12 | -48780 | 12 | -60420 | 2 | -73284 | 3 | -85932 | 10 | -252624 | 8 |
| -27192 | 12 | -50520 | 12 | -60588 | 1 | -73644 | 3 | -85992 | 10 | -252696 | 8 |
| -27696 | 9 | -50616 | 12 | -60756 | 1 | -75912 | 9 | -91596 | 13 | -252972 | 7 |
| -27888 | 8 | -51444 | 12 | -61584 | 11 | -76104 | 8 | -91716 | 13 | -253044 | 7 |
| -27960 | 8 | -51540 | 12 | -61764 | 10 | -76176 | 8 | -95220 | 6 | -261276 | 2 |
| -28236 | 7 | -52248 | 14 | -61824 | 10 | -76452 | 7 | -95388 | 5 | -261444 | 1 |
| -28308 | 7 | -52416 | 14 | -63888 | 6 | -76524 | 7 | -95652 | 5 | -261612 | 1 |
| -28896 | 6 | -53988 | 12 | -64056 | 5 | -79344 | 6 | -98028 | 4 | -266820 | 14 |
| -29064 | 5 | -54084 | 12 | -64320 | 5 | -79512 | 5 | -98196 | 3 | -266988 | 14 |
| -29328 | 5 | -55884 | 13 | -66372 | 2 | -79776 | 5 | -98556 | 3 | -278844 | 2 |
| -30132 | 6 | -56004 | 13 | -66540 | 1 | -81156 | 9 | -102936 | 4 | -279012 | 1 |
| -30300 | 5 | -56856 | 12 | -66708 | 1 | -81348 | 8 | -103104 | 3 | -279180 | 1 |
| -30564 | 5 | -56952 | 12 | -68292 | 9 | -81420 | 8 | -103464 | 3 | -291204 | 12 |
| -30804 | 2 | -59124 | 9 | -68484 | 8 | -81696 | 7 | -109104 | 11 | -291300 | 12 |
| -30972 | 1 | -59316 | 8 | -68556 | 8 | -81768 | 7 | -109284 | 10 | -305184 | 6 |
| -31140 | 1 | -59388 | 8 | -68832 | 7 | -85044 | 9 | -109344 | 10 | -305352 | 5 |
| -31776 | 2 | -59664 | 7 | -68904 | 7 | -85236 | 8 | -112152 | 14 | -305616 | 5 |
| -31944 | 1 | -59736 | 7 | -70512 | 9 | -85308 | 8 | -112320 | 14 | -319728 | 2 |
| -32112 | 1 | -60216 | 11 | -70704 | 8 | -85584 | 7 | -116232 | 6 | -319896 | 1 |
| -32712 | 6 | -60396 | 10 | -70776 | 8 | -85656 | 7 | -116400 | 5 | -320064 | 1 |
| -32880 | 5 | -60456 | 10 | -71052 | 7 | -88620 | 11 | -116664 | 5 | -336072 | 6 |
| -33144 | 5 |  |  | -71124 | 7 | -88800 | 10 | -121332 | 11 | -336240 | 5 |
| -34056 | 6 |  |  | -72708 | 14 | -88860 | 10 | -121512 | 10 | -336504 | 5 |
| -34224 | 5 |  |  | -72876 | 14 | -90132 | 9 | -121572 | 10 | -348972 | 6 |
| -34488 | 5 |  |  | -74076 | 6 | -90324 | 8 | -125028 | 12 | -349140 | 5 |
| -35616 | 6 |  |  | -74244 | 5 | -90396 | 8 | -125124 | 12 | -349404 | 5 |
| -35784 | 5 |  |  | -74508 | 5 | -90672 | 7 | -130368 | 13 | -352764 | 11 |
| -36048 | 5 |  |  | -77904 | 6 | -90744 | 7 | -130488 | 13 | -352944 | 10 |
| -36288 | 11 |  |  | -78072 | 5 | -94620 | 12 | -135372 | 2 | -353004 | 10 |
| -36468 | 10 |  |  | -78336 | 5 | -94716 | 12 | -135540 | 1 |  |  |
| -36528 | 10 |  |  | -79056 | 11 | -98316 | 11 | -135708 | 1 |  |  |
|  |  |  |  | -79236 | 10 | -98496 | 10 | -137640 | 11 |  |  |
|  |  |  |  | -79296 | 10 | -98556 | 10 | -137820 | 10 |  |  |
|  |  |  |  |  |  | -103164 | 11 | -137880 | 10 |  |  |
|  |  |  |  |  |  | -103344 | 10 | -139080 | 11 |  |  |
|  |  |  |  |  |  | -103404 | 10 | -139260 | 10 |  |  |
|  |  |  |  |  |  | -104364 | 11 | -139320 | 10 |  |  |
|  |  |  |  |  |  | -104544 | 10 |  |  |  |  |
|  |  |  |  |  |  | -104604 | 10 |  |  |  |  |

Table : Simulation Decisions

|  |  |  |
| --- | --- | --- |
| Decision | Selection | Units |
| Number of modes to solve for/include | 15 |  |
| Incremental distance along load-path | 6 | inches |
| Time integration scheme | Hilber Hughes Taylor (HHT) |  |
| Profile interpolation method | Linear |  |
| Structural damping | 1% |  |
| Traffic speed | 960, 5 | in/sec |
| Solution time-step | 0.0015, 0.5 | sec |