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13. ABSTRACT (Maximum 200 words)
Transportation Technology Center, Inc. (TTCI) conducted a gapped foundation panel test and a full-scale three-rail crossing test from 2011 to 2012 at the Facility for Accelerated Service Testing (FAST) on the High Tonnage Loop (HTL) in the Transportation Technology Center (TTC), in Pueblo, CO, with instrumented freight car and load measuring instrumented wheelsets. Test results were used to investigate flangeway gap flexibility and foundation effects on dynamic wheel/rail (W/R) impact. Results from Phase I of the project were used during the field tests conducted in the Phase II report. The scope of this study includes field measurements with different flangeway gap structures and foundation variations, as well as a NUCARS® parametric study. The field measurements and modeling parametric study showed the following: (1) rail stiffness over a flangeway gap has the most significant effect on W/R impact among other factors; (2) carbody impact acceleration caused by the flangeway gap increases as the stiffness of the frog foundation increases, and (3) foundation stiffness and damping optimization depend on rail stiffness and track geometry (flangeway gap width, track differential settlement, etc.). This report recommends developing an optimized frog prototype design by introducing flangeway gap flexibility and by changing the foundation.

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Dynamic load environment, special trackwork frog foundations, wheel/rail impact, W/R, modeling, High Tonnage Loop, HTL, Facility for Accelerated Service Testing, FAST

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ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
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1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

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1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

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[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

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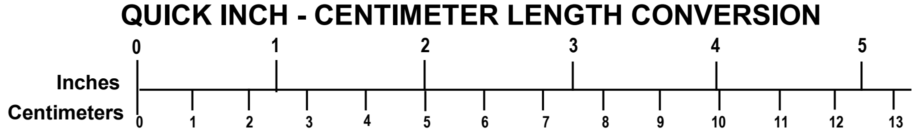

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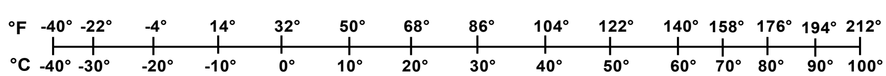

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Executive Summary

Transportation Technology Center, Inc. (TTCI) conducted this study under a research and development plan funded by the Federal Railroad Administration (FRA), and the work was performed from 2011 to 2012. The results from the Phase I modeling project were used during the field tests conducted during this study [1]. The scope of this study includes field measurements with different flangeway gap structures and foundation variations, as well as a NUCARS® parametric study.[1]

TTCI conducted a gapped foundation panel test and a full-scale three-rail crossing test at the Facility for Accelerated Service Testing (FAST) on the High Tonnage Loop (HTL), which is located at the Transportation Technology Center (TTC) in Pueblo, CO. These tests used the instrumented freight car (IFC) and load measuring instrumented wheelsets (IWS). The results of these tests were used to investigate flangeway gap flexibility and the foundation effect on dynamic wheel/rail (W/R) impacts. The following conclusions were drawn from the field measurements and the modeling parametric study:

- Out of all the factors investigated during tests, rail stiffness over flangeway gaps has the most significant effect on W/R impacts.
  - Three-rail diamond crossings generate less impact than casting crossings.
  - Carbody impact acceleration caused by flangeway gaps increase with frog foundation stiffness.
- The effect of flexible gap damping on W/R impact is small compared to the effects of the stiffness.
  - The W/R impact decreases with the increase of the flexible gap damping.
- Rail stiffness and track geometry (flangeway gap width, track differential settlement, etc.) influence foundation stiffness and the ability to optimize damping.

The following tasks were recommended and implemented for the Phase III project [3]:

- Evaluate frog structure and foundation materials, including artificial subgrades, which will minimize differential settlement.
- Develop optimized frog prototype design by introducing flangeway gap flexibility and changing foundation.
- Build and evaluate a frog prototype and/or a crossing diamond under controlled conditions.

[1] NUCARS® is a registered trademark of Transportation Technology Center, Inc.

1. Introduction

The objective of this Phase II project was to improve the performance of special trackwork by improving the performance of the foundations of frogs using the results provided in the Phase I project. In the past two decades, significant improvements in frog and switch performance have occurred due largely to changes in the superstructure of these components. The opportunity to make similar performance improvements is the goal of Transportation Technology Center, Inc.

1.1 Background

Special trackwork—particularly switches, turnout frogs, and crossing diamonds—are prone to rapid degradation. This is due to the combination of high dynamic loading (resulting from running surface discontinuities) and the use of conventional open track foundation designs. The rapid degradation of the foundation results in loss of track surface and ride quality, and increases maintenance demand. Accident statistics show that track surface defects have been one of the leading causes of track-caused accidents. Special trackwork foundations are designed using static or quasi-static design techniques. These procedures often ignore the dynamic stiffness and damping characteristics of the materials being used. Further, there are few published results of service environment measurements, such as typical stiffness and deflections for crossing diamonds (whole or components).

Phase I of this project consisted of a 1-year effort to (1) measure the service environment of a typical diamond crossing and (2) model the diamond to determine the scope of benefits to be gained by changes in design and materials [1]. The initial results suggested that optimizing foundation performance can generate significant benefits.

Phase II conducted during FY 2011 continued to explore the relationships between track foundation parameters and vehicle-track performance at frogs. Modeling and calibration with a limited range of field cases has shown some interesting results. For example, the effect of track stiffness is relatively important. Previous studies suggested that stiffness was unimportant over the likely range of values seen in the field, but this is true only when sufficient damping is present. Currently, damping is far less than optimal for track. The Phase I work showed that there might be an optimal stiffness level that minimizes W/R forces for frogs. Further, the field measurements have shown that the relative movement of components within the frog may contribute significantly to the performance of the frog in service.

Two types of diamond crossing structures are currently used in revenue service:

- The cast crossing with running rails and the flangeway casted in one piece with the cast crossing connected to the running rails through bolts, as Figure 1 shows, or through the leg rail and bolts as Figure 2 shows
- The three-rail crossing where the running rails in two lines are cut through and connected with leg rails, as Figure 3 shows

Figure 1. An Intermediate Angle Cast Crossing in Revenue Service


Figure 2. Cast Diamond Crossing Tested at FAST

Figure 3. Three-Rail Crossing in Revenue Service

Cast crossings are currently more popular than three-rail crossings in North American railroads because it is widely believed that a cast frog crossing provides the longest service life. The common wisdom asserts that a cast frog crossing is stronger than a three-rail frog crossing. More importantly, frogs cast with austenitic manganese steel (AMS) in the preferred rail-bound configuration, as shown in Figure 1 and Figure 2, are robust designs. The AMS castings have good impact resistance, resulting in relatively slow deterioration rates as compared to rail steel. It takes much longer for fatigue cracking to progress through the cross section of the frog before fracture occurs. Repairs to the casting, while not easy, generally can be done without disassembling the frog.

However, both testing at FAST and practice in revenue service showed that the cast flangeway wore faster than expected, and the crossing performance deteriorated quickly because of the impact. The high W/R impact broke not only the fastening components and the leg rail, but also the arm of the casting itself, as Figure 4 shows.

Figure 4. Components Failures in Cast Crossing

1.2 Objectives

The research is intended to improve safety by enhancing the dynamic performance of frogs in revenue service. Direct benefits include lower forces and reduced derailment risk at frogs while indirect benefits included lower vehicle component dynamic loading, which results in longer fatigue lives and fewer service failures for wheels, axles, and other truck components.

1.3 Overall Approach

The following project tasks included:

- Developing a detailed test plan that FRA and the John A. Volpe National Transportation Systems Center would participate in and review
- Reviewing relevant frog failure modes
- Measuring frog dynamic performance and vehicle response
- Computer modeling and analysis of frog structure
- Examining foundation parameters and their effects

The literature review results in Phase I helped to determine the essential features for the modeling effort and necessary field test plan parameters. The field test site was a material test bed at FAST with a high-angle diamond. The vehicle-track computer simulation model was built using the NUCARS® track model. NUCARS® has previously been used in special trackwork development efforts.

1.4 Scope

The scope of the work for the second phase of this project included a scaled gapped foundation panel test, a full-scale three-rail crossing test, and computer modeling. Effects of gap flexibility and foundation parameters on frog and freight car performances were investigated by testing and performing NUCARS® parametric studies.

1.5 Organization of the Report

This technical report was prepared as follows:

- Section 1 – Background of the Phase II study
- Section 2 – Dynamic Impact Test on a Gapped Panel with Track Structure and Foundation Variations
- Section 3 – Effects of Track Stiffness and Damping on Impact
- Section 4 – Vehicle Dynamic Response Over the Test Panel
- Section 5 – Model Validation and Parametric Study
- Section 6 – Conclusion from this study

2. Dynamic Impact Test on a Gapped Panel with Track Structure and Foundation Variations

A scaled panel with rail surface discontinuities (i.e., flangeways) was built at FAST to simulate the impact on frogs and crossings, as Figure 5 shows. Two types of rail discontinuity structures, simulating the flangeway gap of cast and three-rail crossings in revenue service, were implemented side by side in the test panel to investigate the effect of the rail structure and the foundation on W/R impact.

In Figure 5, there are two types of rails with flangeway gaps:

- *Rigid gap* – The rail with a flangeway gap that is milled in the head
- *Flexible gap* – The rail with a flangeway gap made of two rails and a set of joint bars

Figure 5. Scaled Test Panel with Two Different Types of Gaps (Lower Rail – Rigid Gap, Upper Rail – Flexible Gap)

Tests on load measuring instrumented wheelsets (IWS) were conducted at FAST from November 1–10, 2011. Two IWS were installed on the leading truck of a loaded hopper car with 39-ton axle loads. Table 1 lists nine test cases conducted on a scaled gapped foundation test panel and a full-scale three-rail crossing with various foundation conditions. Figure 6 shows the panel Test Case 1 configuration, which consisted of wood panels on ballast with steel rail seat plates. Figure 7 shows panel Test Case 4, a non-ballast foundation test configuration case, which used four 10-inch by 10-inch wood ties as foundation to replace ballast.

Table 1. Scaled Panel Foundation Test and Full-Scale Three-Rail Crossing Test at FAST Section 40, November 1–10, 2011

Test Date	Scaled Panel Foundation Test	Full-Scale Three-Rail Crossing Test
11/2/11	Test Case 1: Existing wood panels and ballast (as found); steel rail seat plates	Standard three-rail crossing, no rubber rail seat pads
11/3/11	Test Case 2: Existing wood panels and ballast; after tamping; steel rail seat plates	Rubber rail seat pads
	Test Case 3: Existing wood panels and ballast; rubber rail seat pads	Rubber rail seat pads, no other changes
11/4/11	Test Case 4: Rubber panels; 4-timber foundation; steel rail seat plates	Rubber rail seat pads, no other changes
11/7/11	Test Case 5: Rubber panels; 4-timber foundation; rubber rail seat pads (no vertical track modulus)	Rubber rail seat pads, no other changes
11/9/11	Test Case 6: Wood panels; 2-timber foundation; rubber rail seat pads (no vertical track modulus)	Rubber rail seat pads, loose inside rail crossing corner running rail bolts
	Test Case 7: Wood panels; 2-timber foundation; steel rail seat plates	Rubber rail seat pads, inside rail bolts retightened, loose outside rail crossing corner running rail bolts
11/10/11	Test Case 8: Wood panels; 4-timber foundation; steel rail seat plates.	Rubber rail seat pads, no other changes
	Test Case 9: Wood panels; 4-timber foundation; rubber rail seat pads	Rubber rail seat pads, no other changes

Figure 6. Panel Test Case 1 Configuration

Figure 7. Panel Test Case 4 Configuration

Figure 8 illustrates the measured maximum peak to minimum peak forces for Test Case 3 on the flexible and rigid gap for 40 mph operations. Figure 9 and Figure 10 show the measured maximum wheel vertical forces and peak-to-peak vertical forces.

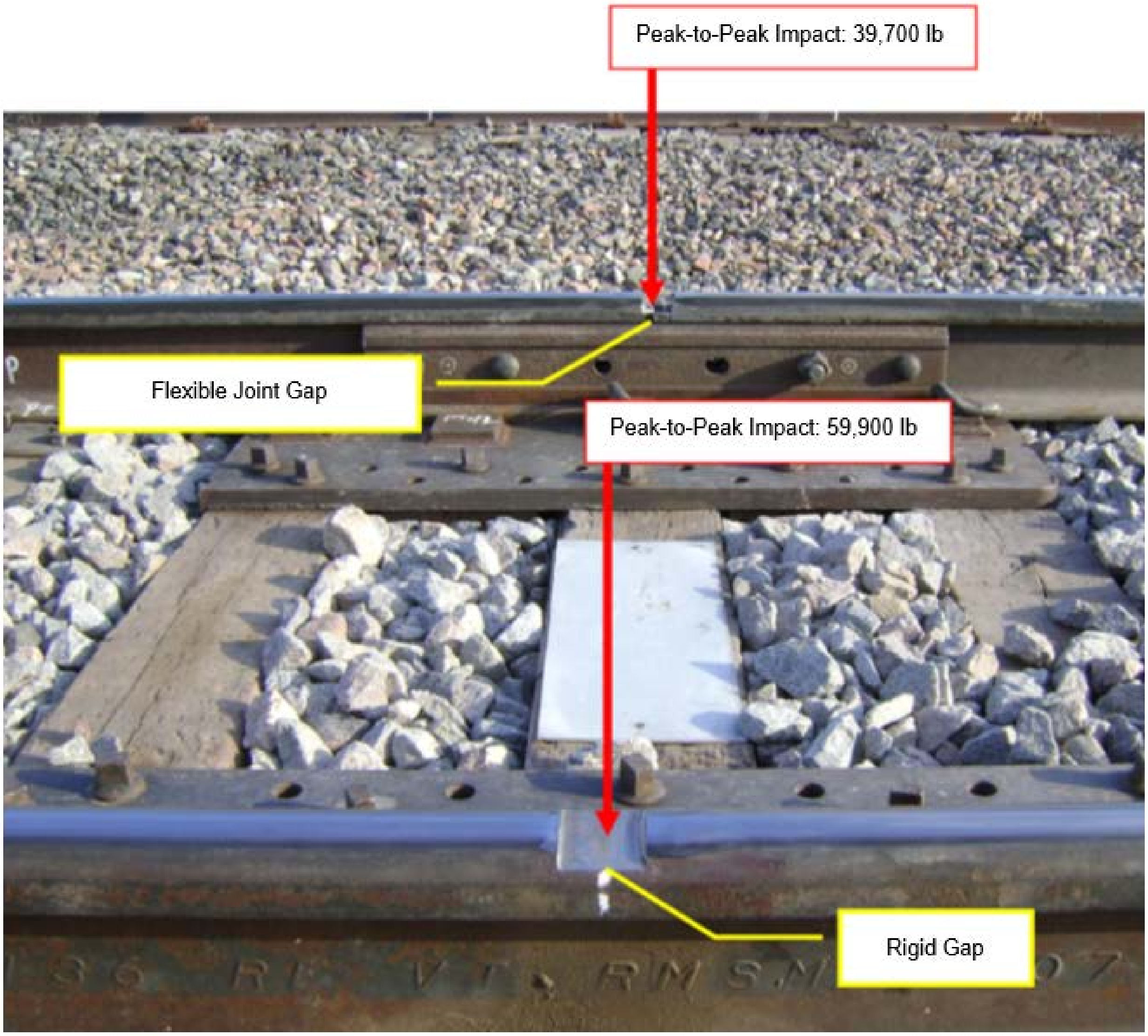


Figure 8. Peak-to-Peak Impact Comparison (Panel Test Case 3)

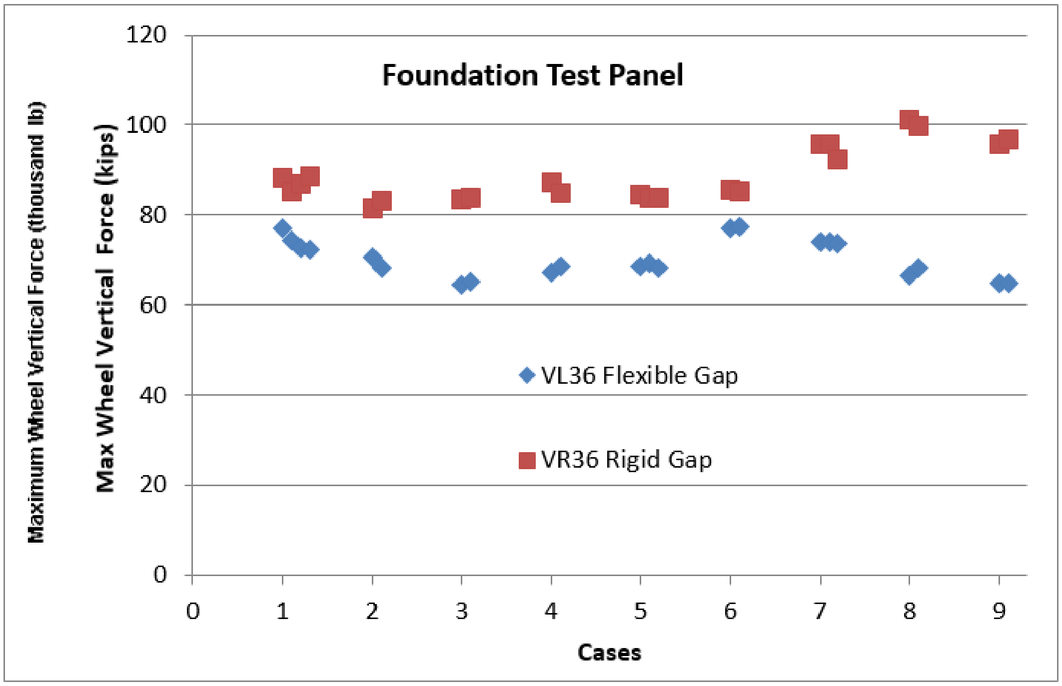


Figure 9. Maximum W/R Impact Forces on Scaled Panel (315, 000 lb. Car, 40 mph)

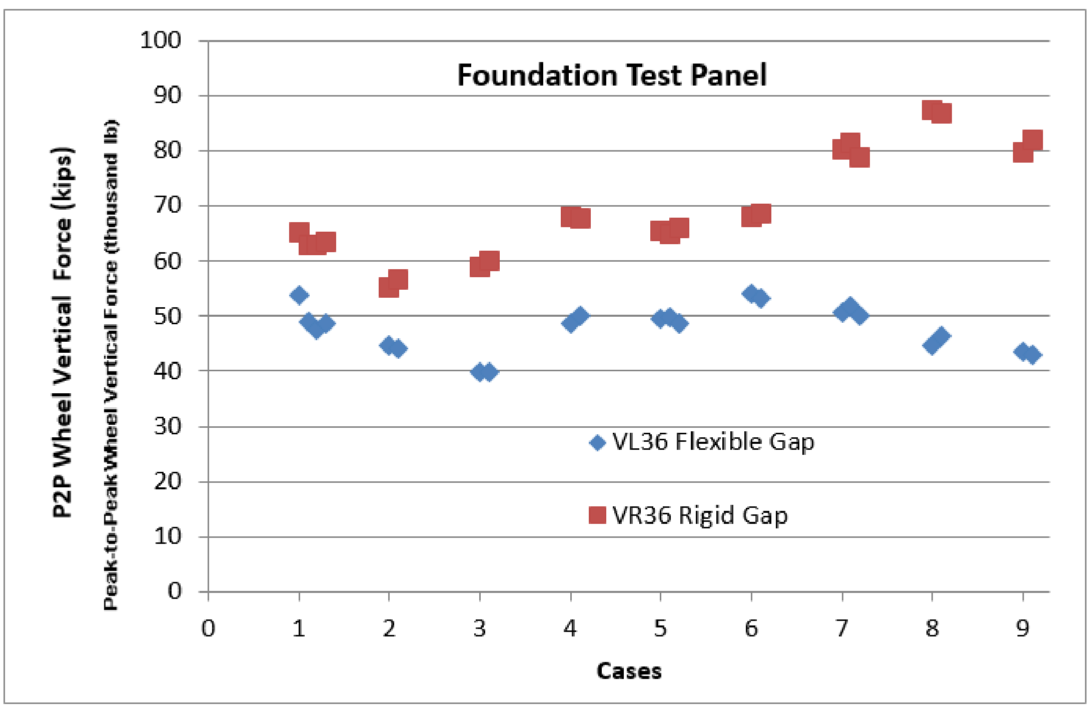


Figure 10. Peak-to-Peak W/R Impact Forces on Scaled Panel (315,000 lb. Car, 40 mph)

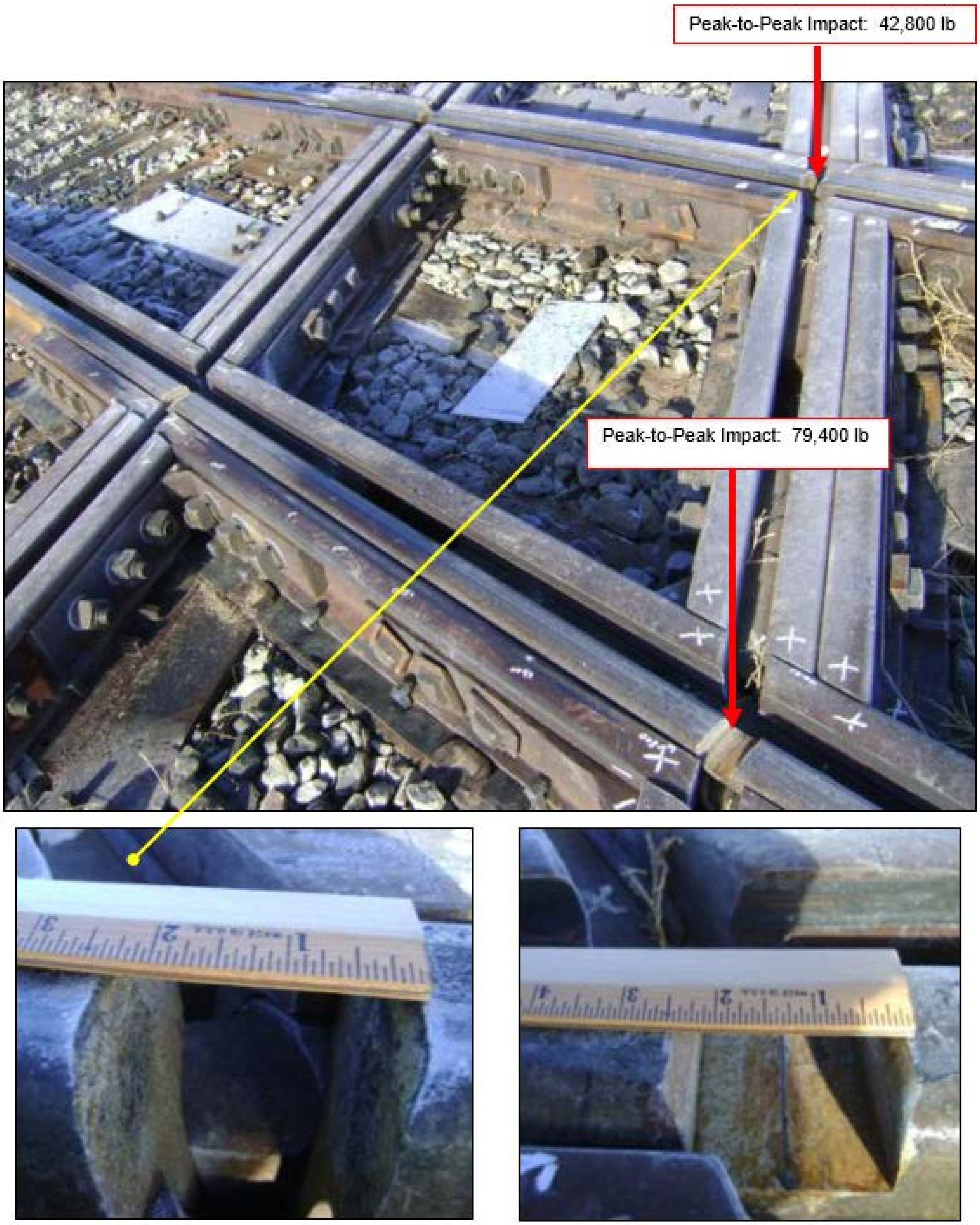
IWS test results showed that:

- Due to the flexibility generated from the joint connection, impacts on the flexible joint gap were significantly lower than those on the rigid gap for all scaled panel test cases.

- For the same foundation, the flexible gap can reduce impact by 17–49 percent compared to the rigid gap.
- Changing the foundation can reduce impact by up to 26 percent for flexible gap frogs.
- Changing the foundation can reduce impact by up to 37 percent for rigid gap frogs.

The track surface may affect the above results. Although the track was maintained to FRA Class 4, the many changes in foundations resulted in more rapid settlement for most cases. Track was not "steady state" in terms of settlement. Thus, there may have been more variations from train to train than one would see on settled track. These longitudinal rail surface elevation variations in the scaled panel may contribute to the impact variations.

A full size 70-degree three-rail crossing, which was modified in flangeway gaps, was implemented 200 feet away from the scaled panel during the test at FAST. The flangeways on the outside rail were configured as specified by AREMA plan 701-01 for full section cut rails (i.e., flexible gap) [2]. The flangeways on the inside rail were milled out of the railhead (i.e., rigid gap). Both flangeways had a 2.5-inch gap, to simulate the effective gaps found on worn revenue service diamond crossings. Both flangeway gaps were configured as 90-degree angles in the main line direction even though the frogs are configured as 70 degrees. This was done to provide more uniform performance with small changes in wheel and/or rail running surface profiles. 90-degree gaps will also generate higher maximum forces, on average, than 70-degree gaps. Figure 11 shows the structure and illustrates the measured forces (Test Case 6) on the flexible and rigid gap of the crossing. The wheel's vertical impacts peak-to-peak value on the flexible gap are 46 percent lower than that on the rigid gap.



Rail Cut through (Flexible) Railhead Partially Milled Out (Rigid)

Figure 11. Full-Scale Three-Rail Crossing Test (Test Case 6)

Figure 12 and Figure 13 show the maximum and peak-to-peak W/R impact forces on the full-scale three-rail crossing (315,000 lb. car, 40 mph). The measured impacts varied little from run to run in comparison to the scaled panel test, which is most likely because the ballast and subgrade under the crossing were not changed during the test. Both the scaled panel test and the full-scale crossing test demonstrated that the impacts on flexible gaps are significantly lower than those on rigid gaps, because of the flexibility generated by the joint or wing rail connection.

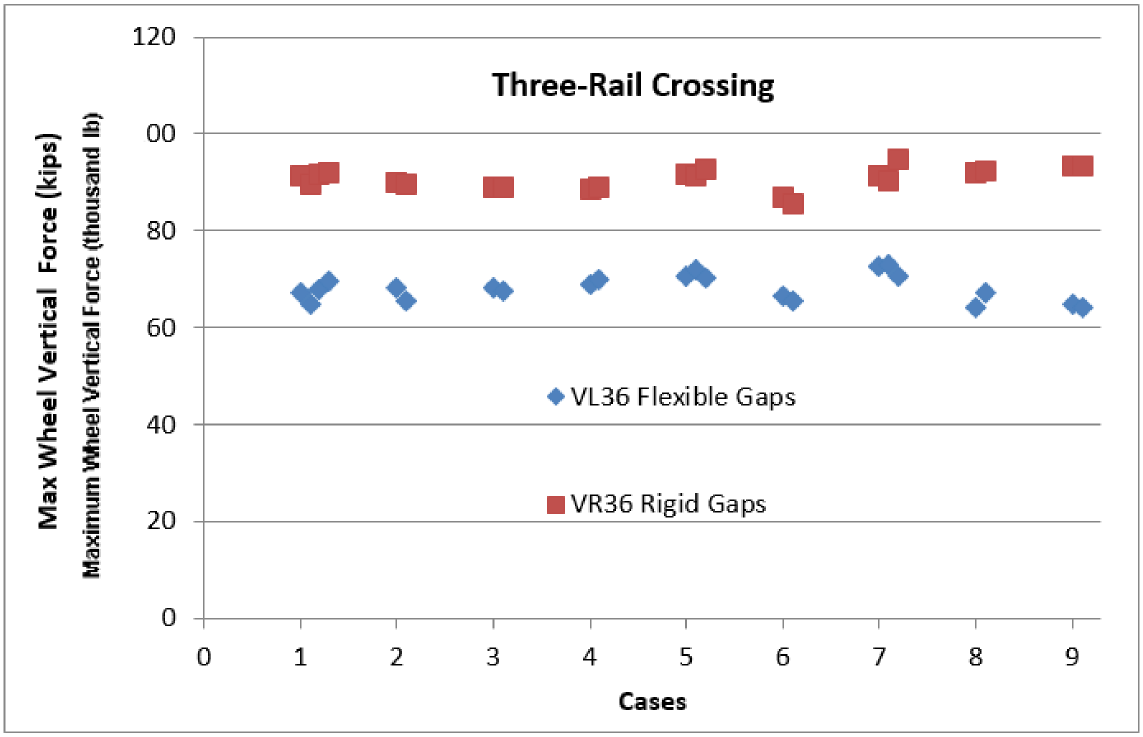


Figure 12. Maximum W/R Impact Forces on Full-Scale Three-Rail Crossing

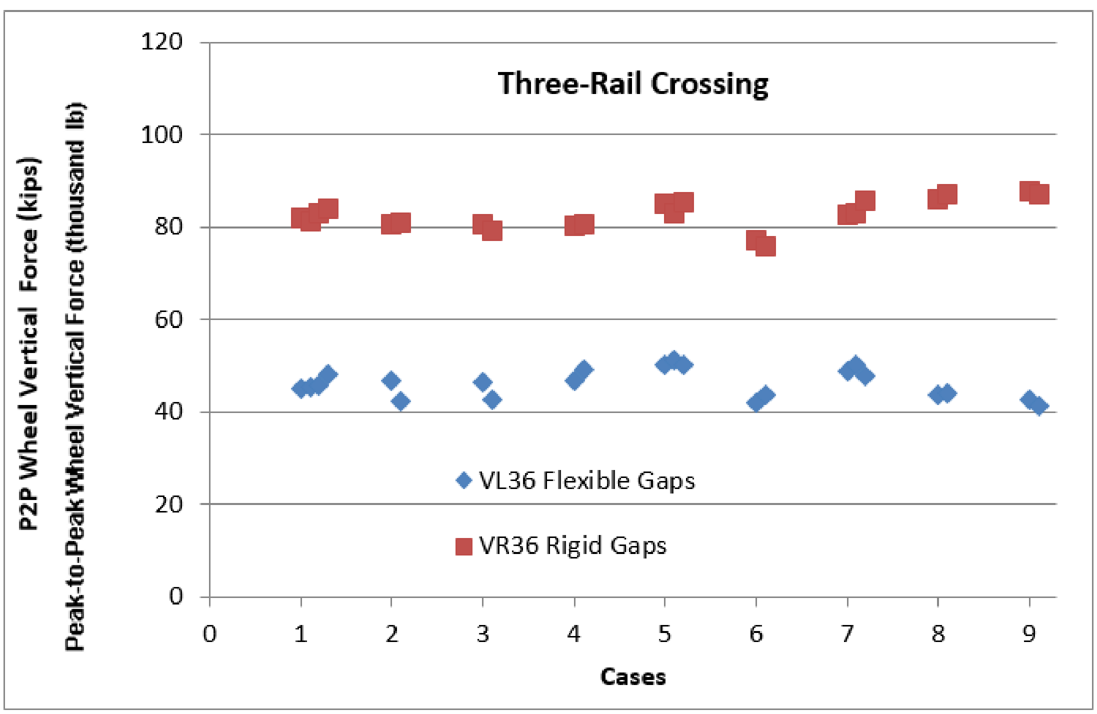


Figure 13. Peak-to-Peak W/R Impact Forces on Full-Scale Three-Rail Crossing

3. Effect of Track Stiffness and Damping on Impact

For most cases, track stiffness was measured using an empty and loaded car. The inside and outside rail elevations under the leading axle were measured when the track was loaded.

Figure 14 shows the measured track stiffness for the test cases. Clearly, the existing wood panels and non-tamped ballast (Test Case 1) had the lowest track stiffness. The wood panel was in track for more than 2 months (about 20 million gross tons [MGT]) before the test. the test panel rail deflection under a loaded car was about 0.7 inch, because of the track differential settlement accumulated in 2 months.

Track stiffness was increased and stable after tamping (Test Cases 2, 3, and 4). Non-ballast foundation test cases include two-timber and four-timber configurations. The two-timber foundation generated similar track stiffness as the ballast foundation. The four-timber foundations (Test Cases 8 and 9) were solid and generated the highest track stiffness among all test cases.

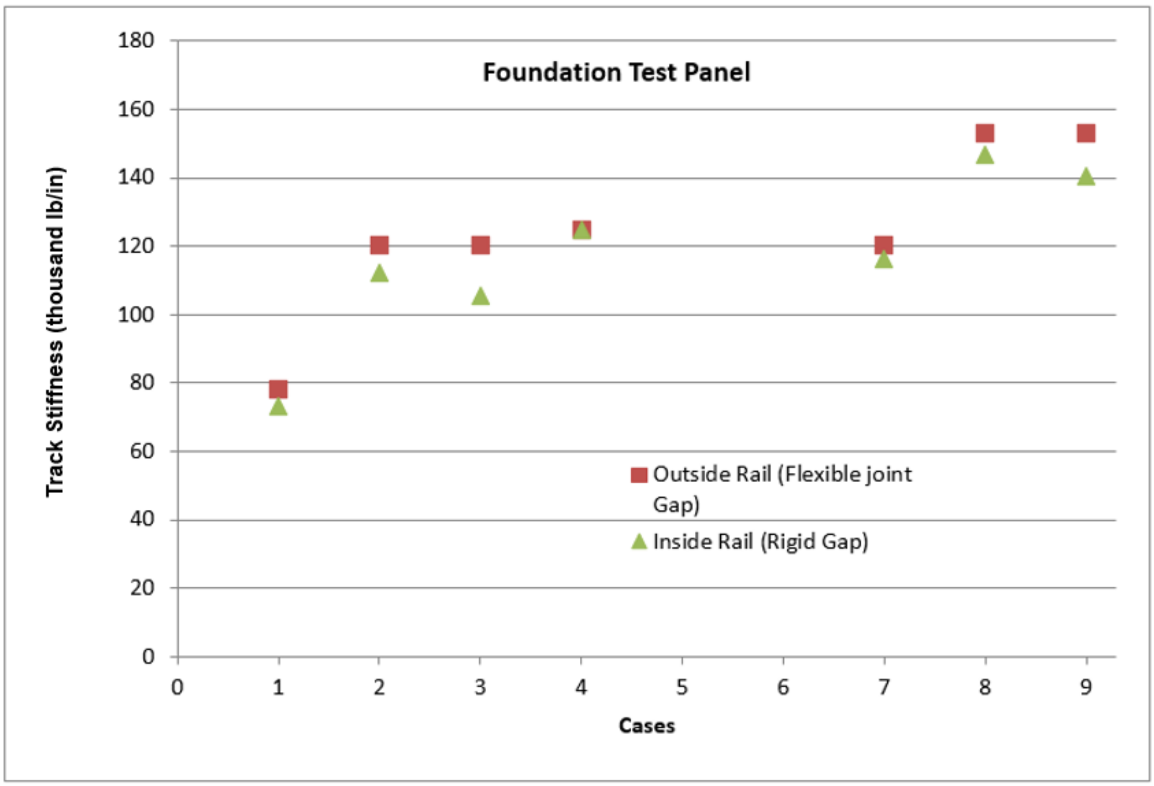


Figure 14. Measured Track Stiffness for Test Cases

3.1 Rigid Gap

Figure 15 shows the W/R impact peak-to-peak value on the rigid gap, which generally increased with track stiffness. The highest impact was generated in the non-ballast foundation condition Test Case 8 with 153,000 lb/in track stiffness. This test case consisted of steel rail seat plate, wood panel sitting on top of four-timber foundation with a hot mix asphalt (HMA) layer underneath. The steel rail seat plate was replaced with a rubber rail seat pad in Case 9, which decreased the track stiffness by 4.2 percent and reduced the impact by 8.9 percent.

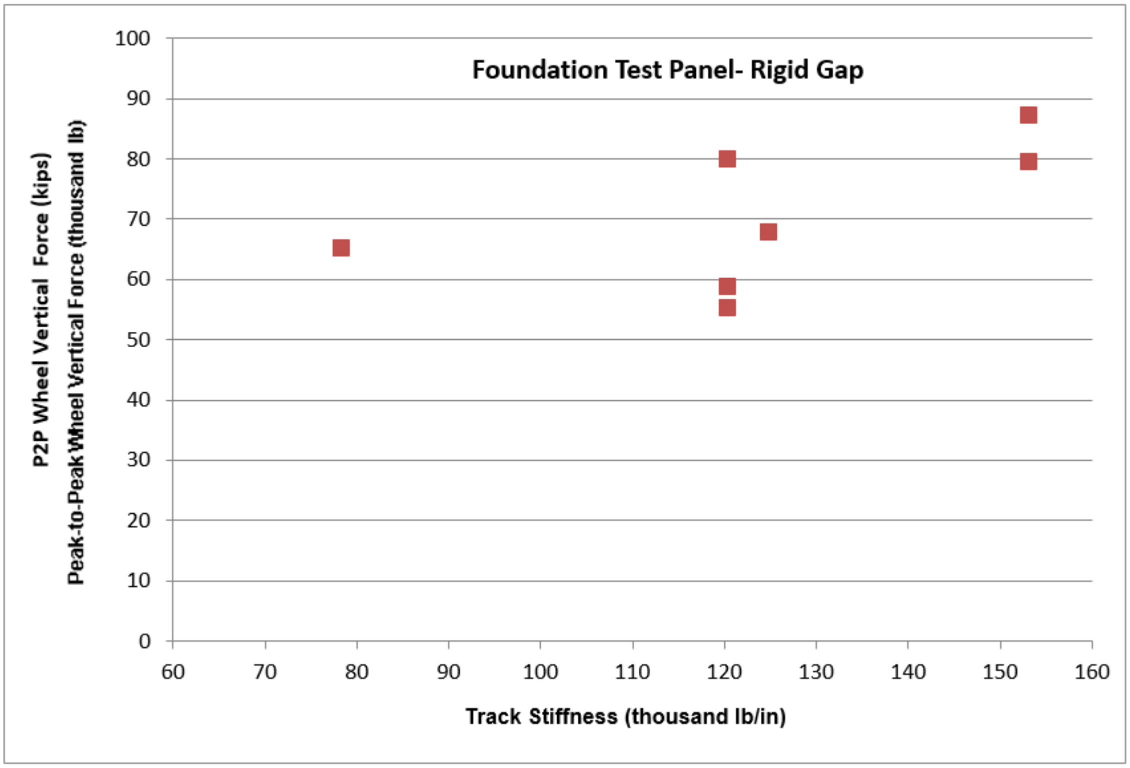


Figure 15. Effect of Track Stiffness on Rigid Gap Impact

3.2 Flexible Joint Gap

Figure 16 shows a nonlinear relationship between the W/R impact and track stiffness in the flexible joint gap. The lowest impact was generated during Test Case 3 with 105.000 lb/in track stiffness. Test Case 3 employed rubber rail seat pads, a wood panel and ballast foundation with an HMA layer underneath. However, the ballast foundation degraded quickly under impacts. In revenue service, it is likely this foundation configuration would rapidly degrade to the conditions in Case 1, which produced the highest impacts in the test series. As described in Table 1, the conditions in Case 1 are generated by a conventional frog foundation with no additional damping elements, such as rubber pads. A similar level of low impacts was generated on the solid non-ballast foundation conditions created in Case 9, which employed rubber rail seat pads, a wood panel, and a solid four-timber foundation with HMA underneath.

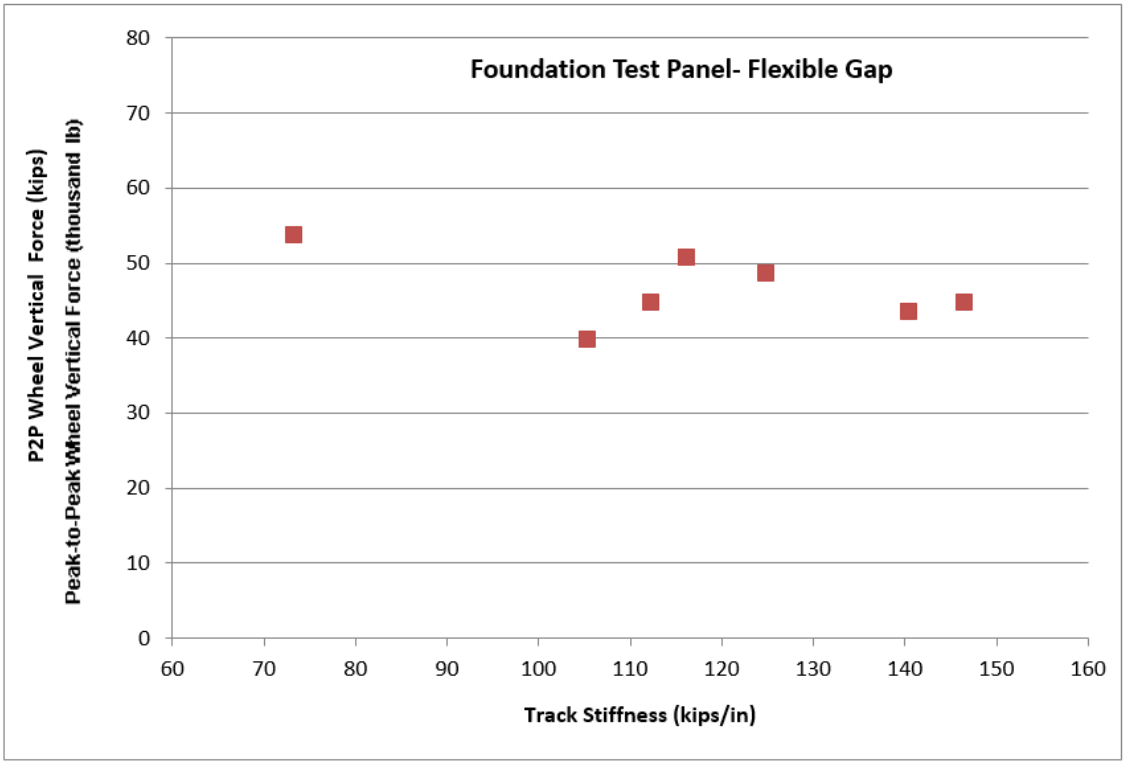


Figure 16. Effect of Track Stiffness on Flexible Joint Gap Impact

3.3 Damping Measurement (Hammer Test)

To estimate the damping in the track structure, an impact (hammer) test was conducted on the two types of flangeway gaps in the full-scale three-rail crossing. Figure 17 and Figure 18 show the instrumentation configuration on these two flangeway gap corners: an accelerometer was installed on top of the rail to measure rail acceleration under hammer impact. Hammer test sampling frequency was 16,000 Hz, with no filtering on force and acceleration channels.

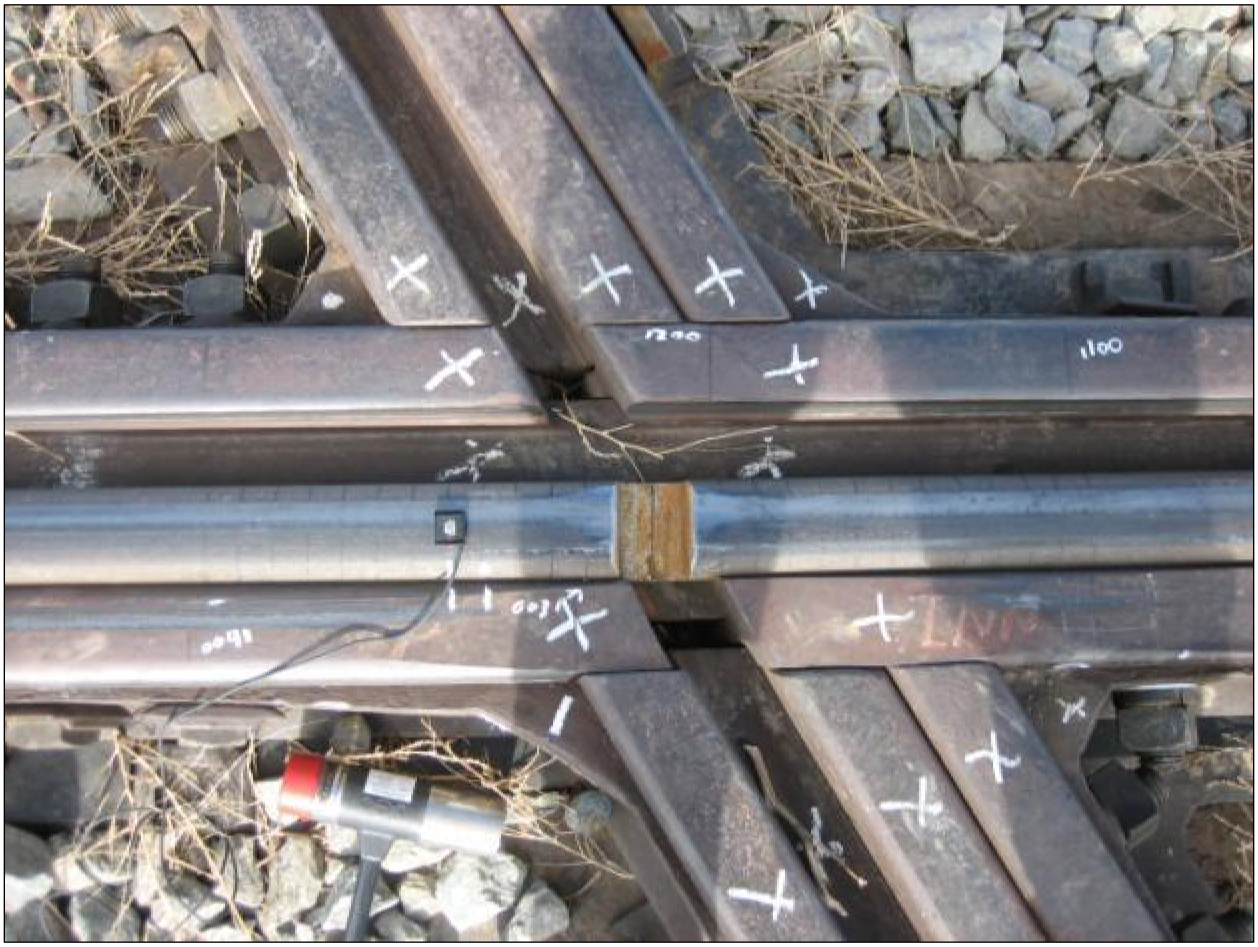


Figure 17. Hammer Test on the Rigid Gap Corner of Three-Rail Crossing

Figure 18. Hammer Test on the Flexible Gap Corner of Three-Rail Crossing

Figure 19 shows the time histories of the impact forces of the hammer and rail acceleration on the flexible gap and on the rigid gap. Damping was simply estimated by using the slope of the measured first and second rail maximum acceleration peak points. The damping on the flexible gap corner on the three-rail crossing, which was generated because of the friction in the joint, was about three times higher than that on the rigid gap. Clearly, increased damping caused the rail vibration in the flexible gap to quickly reduce to a similar level of that in the rigid gap.

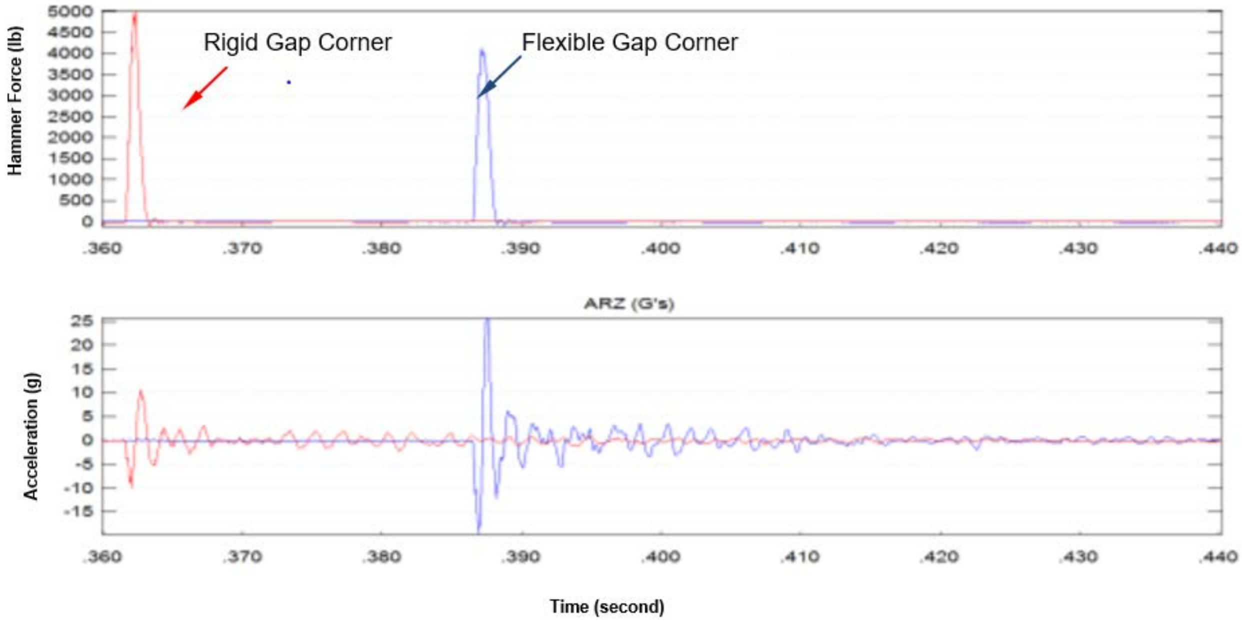


Figure 19. Hammer Impact and Rail Response on Three-Rail Crossing

4. Vehicle Dynamic Response Over Test Panel

The IFC, which was located behind the IWS car in the consist, collected vehicle response over foundation test panel. The data sampling frequency for the IFC car was increased to 500 Hz for this test, while acceleration channels were filtered at 10 Hz frequency. Figure 20 shows the measured carbody peak-to-peak vertical acceleration values for each test case. The carbody maximum peak-to-peak value was almost doubled compared to the minimum value among the different foundation test cases.

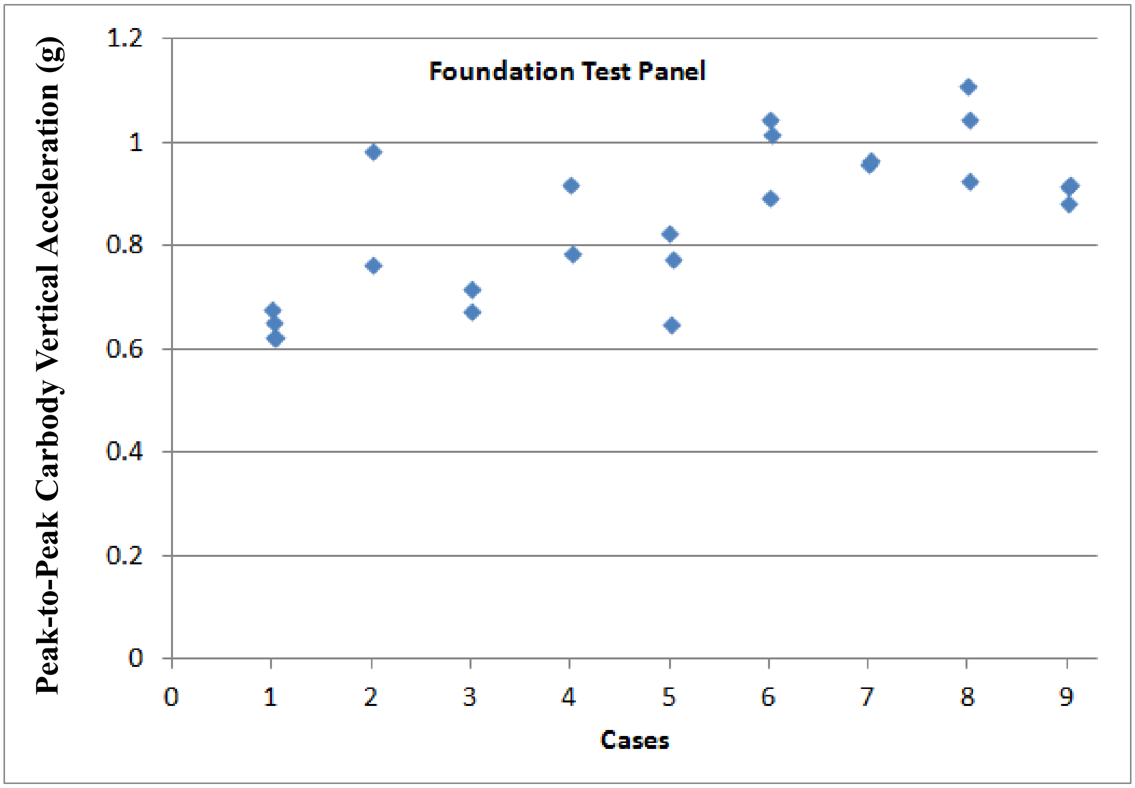


Figure 20. Carbody Vertical Accelerations (Peak-to-Peak)

The carbody vertical acceleration was plotted versus track stiffness to investigate the effect of track stiffness. Figure 21 shows the carbody acceleration impacts generally increased with track stiffness.

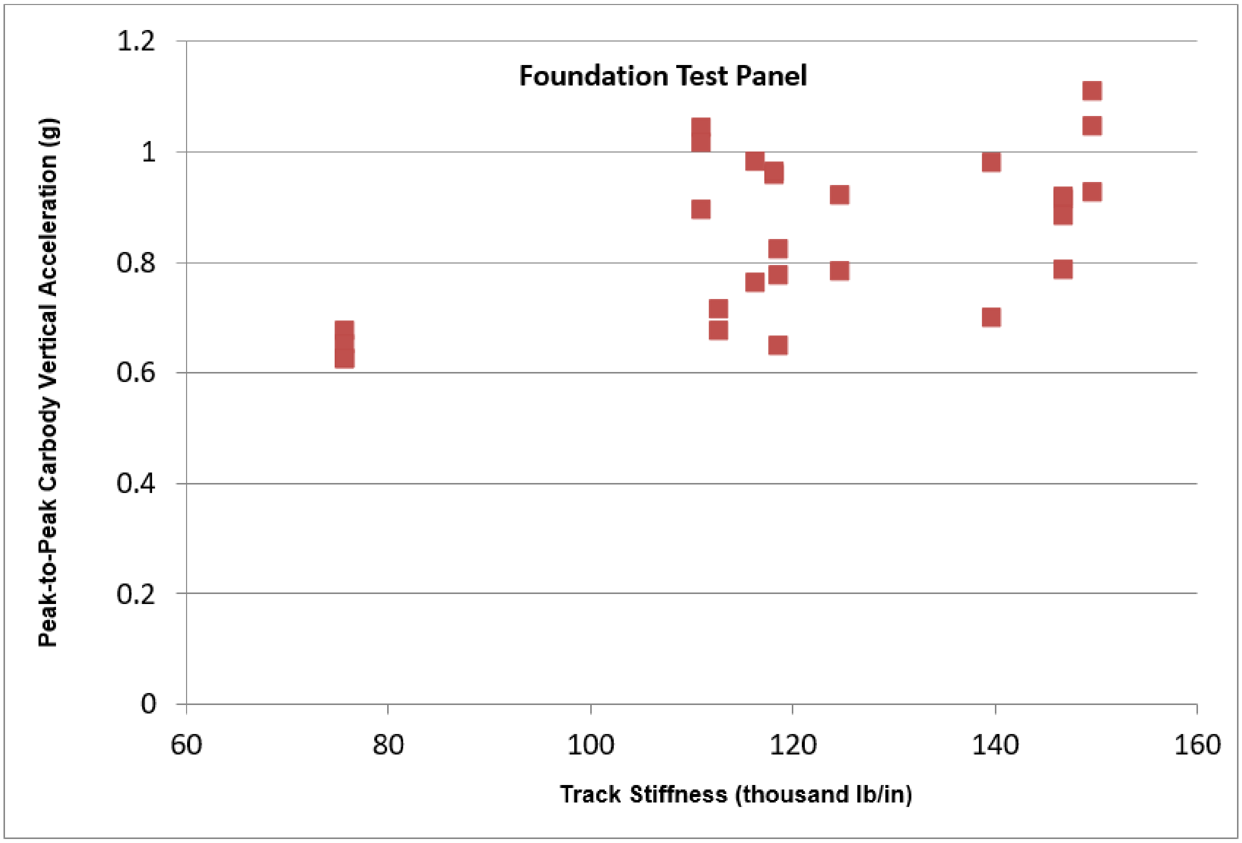


Figure 21. Effect of Track Stiffness on Carbody Acceleration

Figure 22 shows the right-side frame accelerations as they were measured on the outside rail of the foundation test panel over the flexible gap. Figure 23 shows the side frame accelerations over the flexible joint gap distributed widely over the measured track stiffness range. This may be due to the 10 Hz lower filtering and 500 Hz sampling frequency, which should be set at higher frequencies for the side frame acceleration measurement.

Unfortunately, the left side frame accelerometer on the inside rail side (rigid gap) was broken during the test and no data was available from that source.

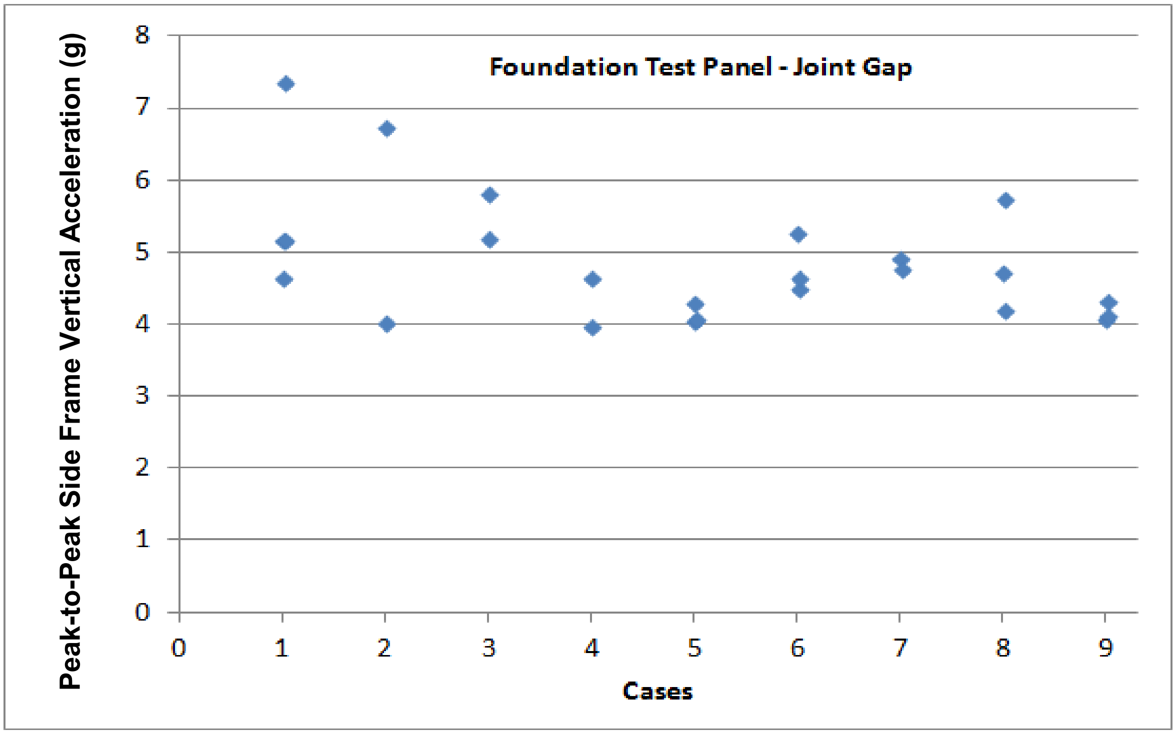


Figure 22. Side Frame Vertical Accelerations Over Flexible Joint Gap

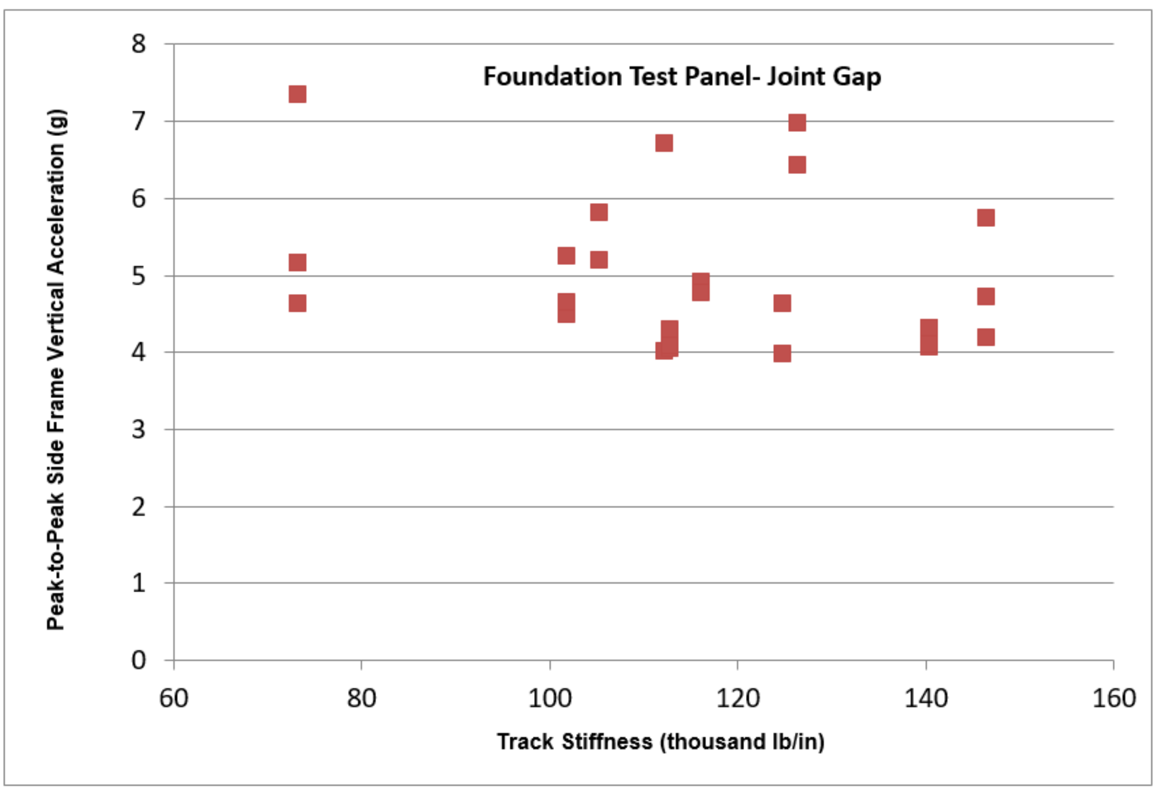


Figure 23. Effect of Track Stiffness (Flexible Joint Gap Side) on Side Frame Acceleration

5. Model Validation and Parametric Study

The effects of stiffness in a diamond crossing foundation and damping underneath the rail were investigated in the Phase I study. Measurements from this study showed that the rail stiffness between the two edges of the flangeway gap has a significant effect on W/R impact. However, using a single casting frog in diamond crossings (which is the current practice) indicates that the effect of rail stiffness between the two edges has been either ignored or wrongly understood. This effect was investigated in a NUCARS® parametric study.

5.1 Rigid and Flexible Gap Model

Figure 24 shows a rigid gap rail model used in NUCARS® for simulating a wheel passing over the flangeway of a cast frog in a diamond crossing. The NUCARS® track model modeled the rail as an Euler-Bernoulli flexible beam with spring and damper connections between the rail and ground. The relative movement between the two edges of the flangeway is negligible. The W/R contact model can capture the moment when the wheel contacts the two edges of the flangeway rather than using rail perturbations on the basis of wheel center of gravity trajectory over the gap.

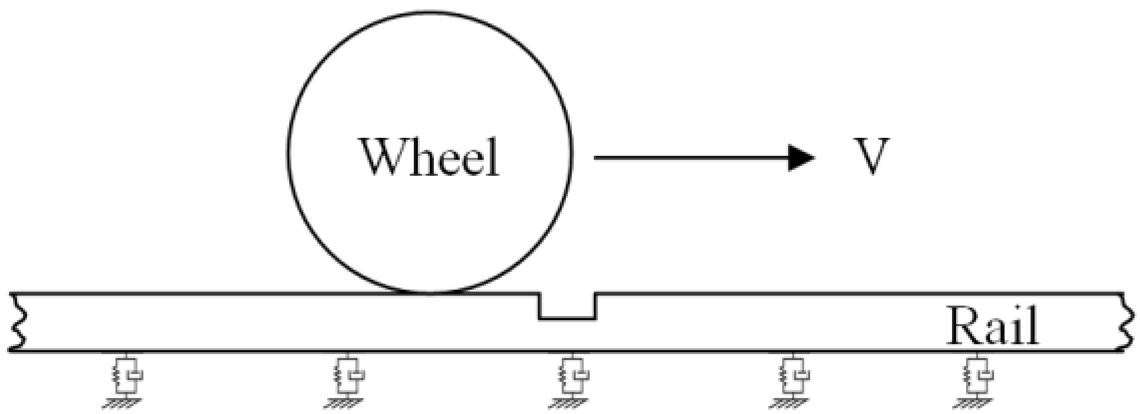


Figure 24. Rigid Gap Rail Model

Figure 25 shows a flexible gap rail model used in NUCARS® for simulating the wheel passing over the flangeway of a frog in a three-rail crossing. The rail was separated into two pieces starting from the flangeway gap, but with the same beam cross sections and rigidity. A series of rail gap flexibility spring (stiffness K_2) and damper (damping D_2) elements were added between these two pieces. The relative movement between the two edges of the flangeway depends on the rail gap support (stiffness K_2 and damping D_2).

The NUCARS® track model allows the rail support stiffness and damping and permits the rail gap flexibility (K_2, D_2) to be varied along the track to simulate their influence area along the rail.

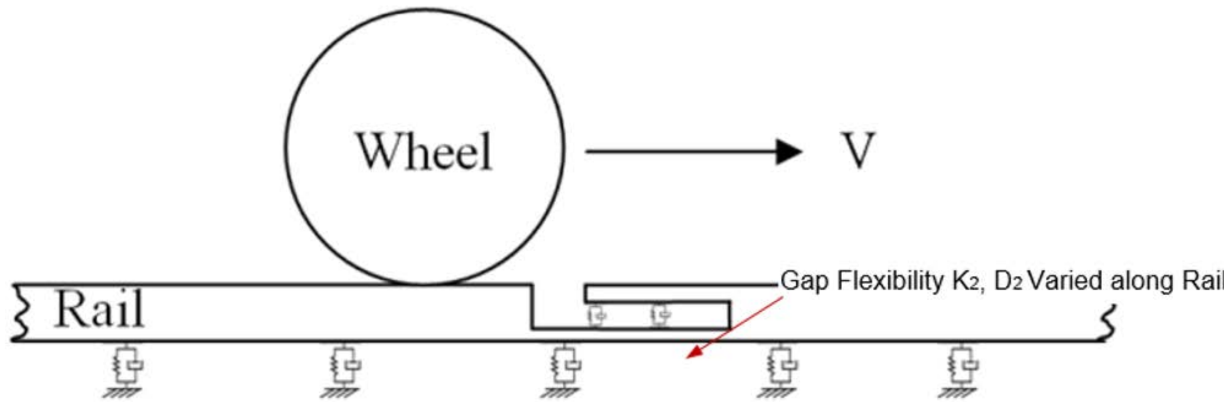


Figure 25. Flexible Gap Rail Model

A parametric study was conducted by using a 39-ton axle load hopper car running over a rigid and flexible gap crossing with 2.5 inches flangeway width. Figure 26 shows the time history of the vertical impact force and animated W/R contact over a rigid flangeway gap.

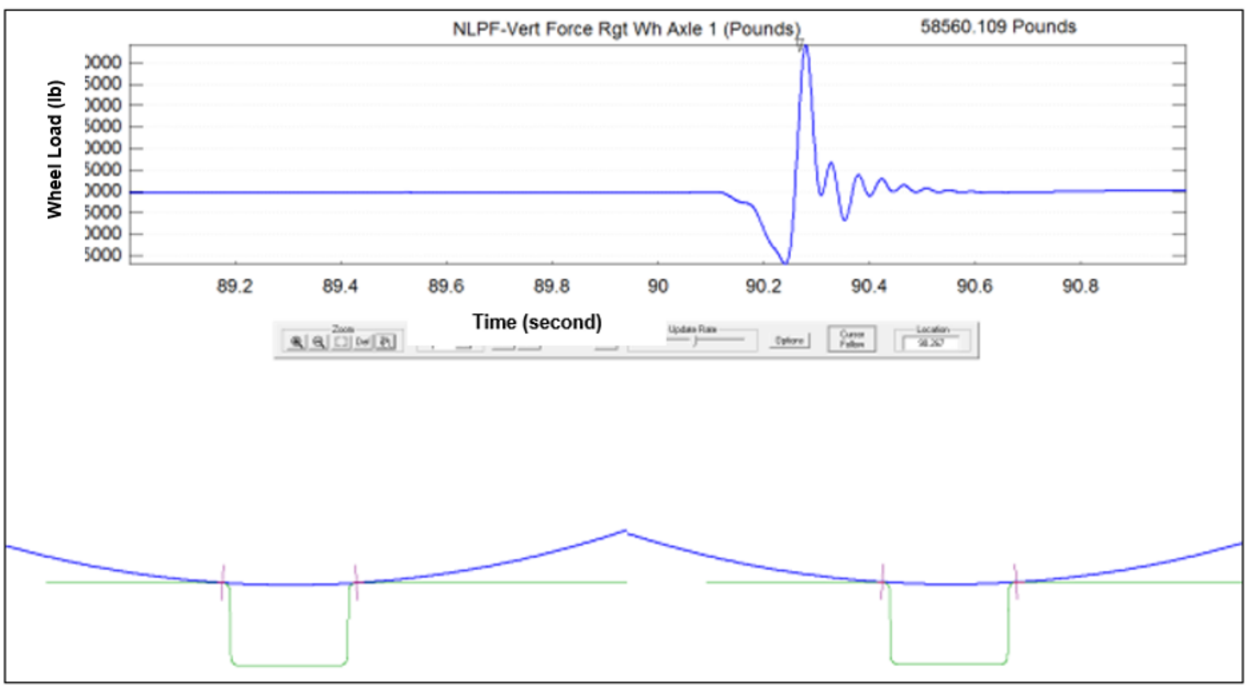


Figure 26. Vertical W/R Impact on a Rigid Gap (Connection Stiffness Between Rail and Ground K = 50,000 lb/in, 40 mph)

Figure 27 shows the time history of the vertical impact force and the animated W/R contact over a flexible flangeway gap. Compared to Figure 26, the maximum W/R impact force on the flexible gap was much lower than the rigid gap, because of the flexibility introduced by the relative movement in the flangeway.

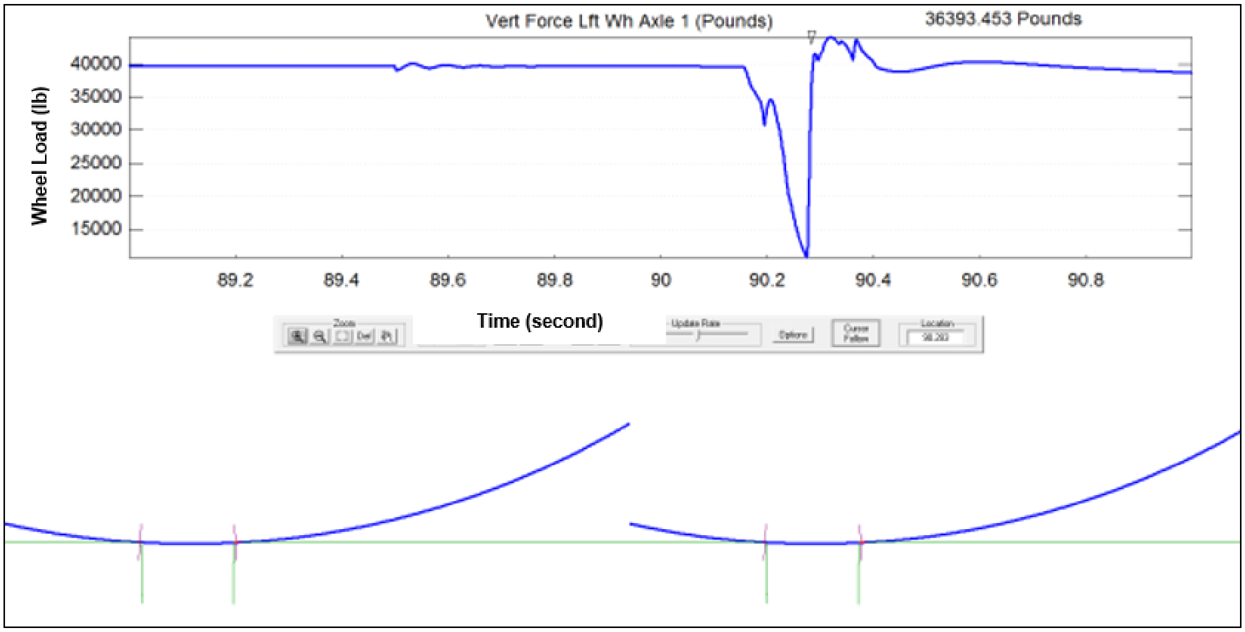


Figure 27. Vertical W/R Impact on a Flexible Gap (Connection Stiffness Between Rail and Ground K = 50,000 lb/in, Gap Flexibility K_2 = 1,000,000 lb/in, D_2 = 700 lb/in/s, 40 mph)

5.2 Model Validation

The predicted wheel impact results for flexible and rigid gaps were compared to test results generated by using running speeds from 10 to 40 mph. The flexible gap modeling results match the test results better than the data from the rigid gap modeling, as Figure 28 shows, which could be caused by the infinite rigid stiffness assumption. Even the rigid gap may still have some flexibility. The flexible gap simulation results in the following section support this judgment.

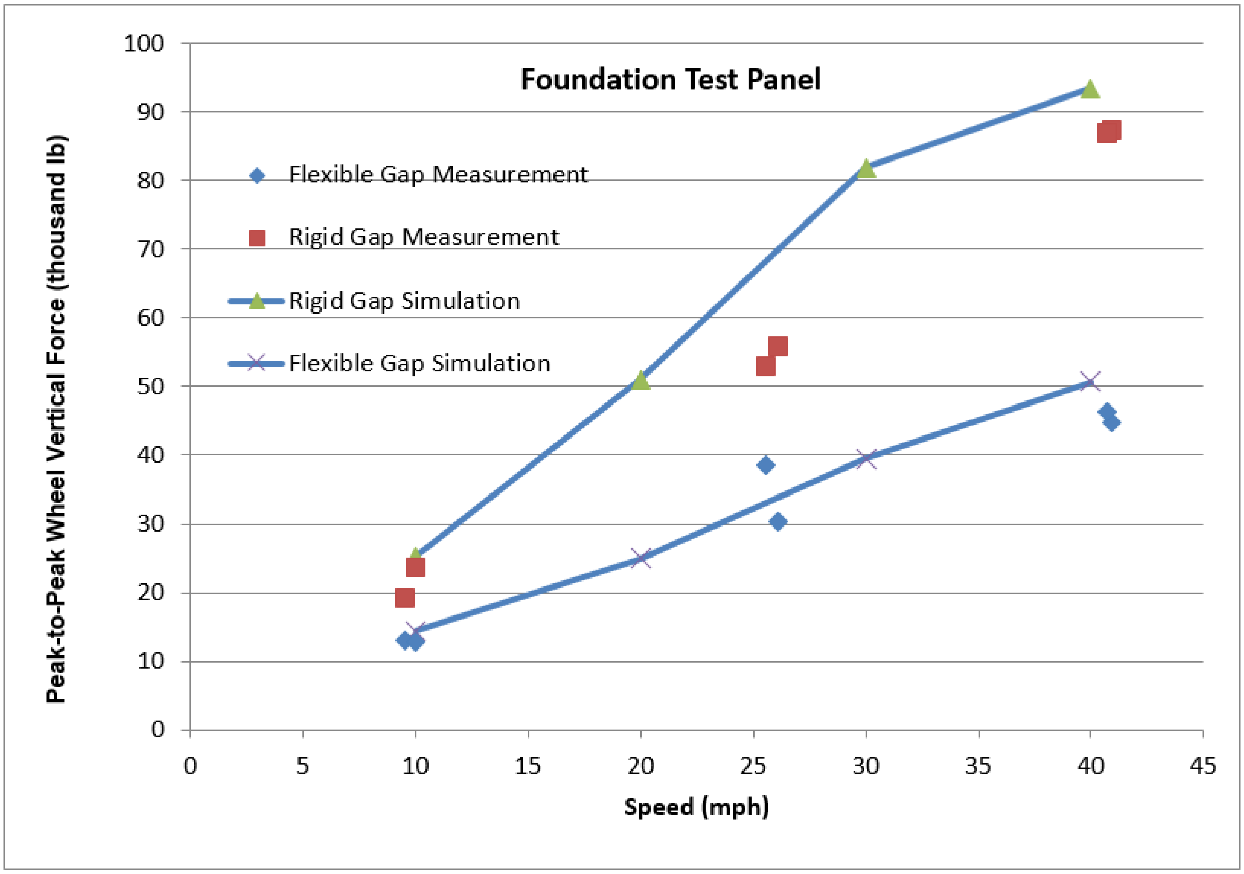


Figure 28. Comparison of Predicted and Measured W/R Impact Forces

5.3 Effect of Gap Flexibility

Figure 29 shows the test and parametric study results of changing gap flexibility stiffness. Clearly, the predicted vertical W/R impact forces at higher gap flexibility stiffness 3.0E7 lb/in are closer to the rigid gap test results, indicating the stiffness in the rigid gap could be higher than 3.0E7lb/in. NUCARS® can simulate high stiffness cases, but with limitations due to simulation instability. The measured impact on the flexible gap matches the simulation case with 2,000,000 (2.0E6) lb/in gap flexibility stiffness.

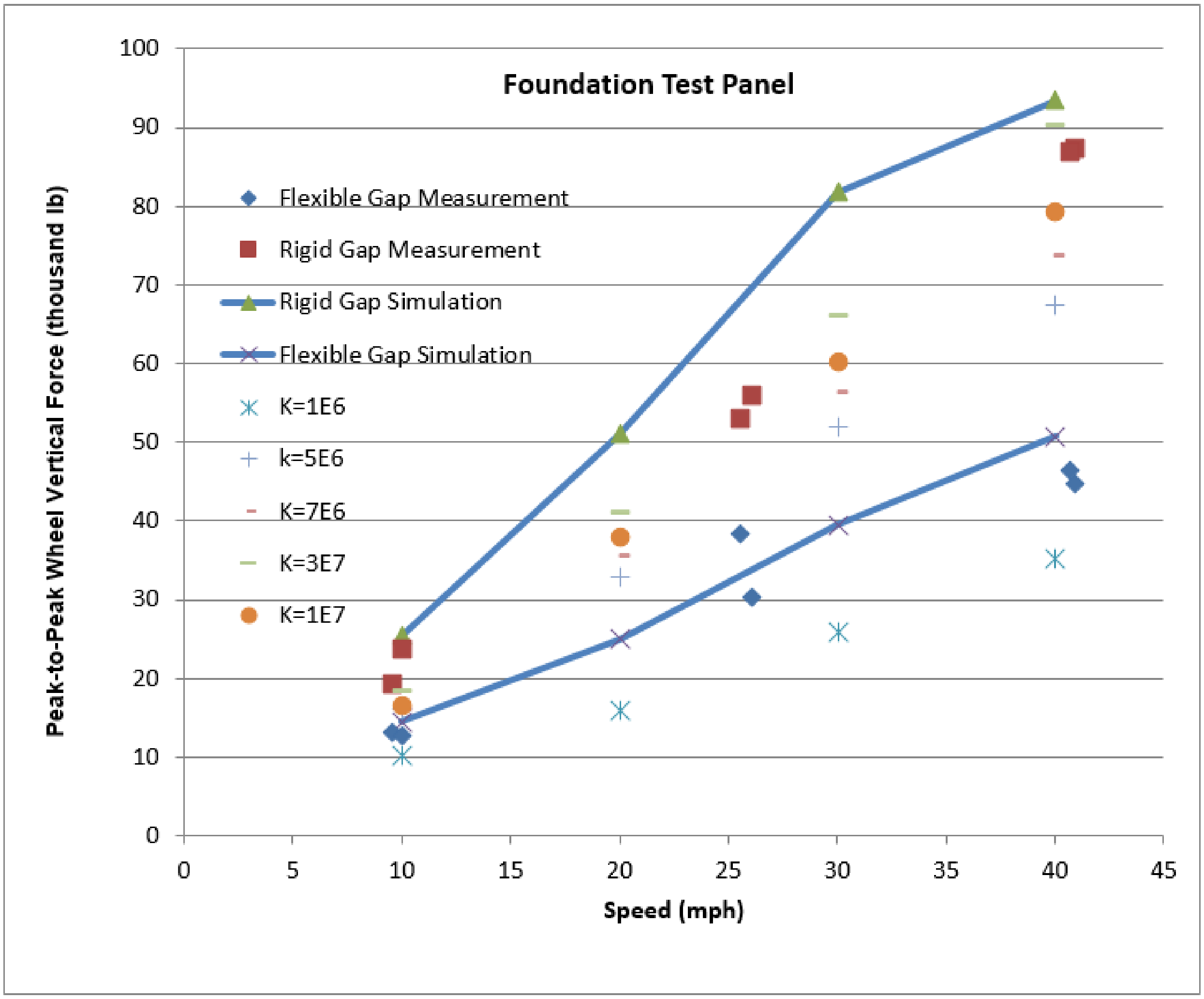


Figure 29. Effect of Gap Stiffness on W/R Imapct Over Flangeway Gap (Connection Stiffness Between Rail and Ground K = 50,000 lb/in, Gap Flexibility D_2 = 700 lb/in/s)

Table 2 shows the simulation matrix of changing the gap stiffness and damping for the parametric study. Figure 30 shows the predicted and measured maximum W/R vertical impact forces. The measured forces on rigid gaps are close to the simulated cases with 3.0E7 lb/in stiffness. The measured forces on flexible gaps are close to the simulated cases with 2.0E6 lb/in stiffness. The validated model can then be used to optimize the dynamic performance of the flexible gap crossing. Simulations predict that impacts on flexible gaps can be reduced further than the lowest measured impact when the flexible gap stiffness decreases to 1.0E6 lb/in.

Table 2. Simulation Matrix, Effect of Rail Gap Stiffness and Damping on Maximum W/R Force (Stiffness K_2 Unit: lb/in, Damping D_2 Unit: lb/in/s)

D_2 \ K_2	1.0E+06	2.0E+06	5.0E+06	7.0E+06	1.0E+07	3.0E+07
5.0E+01						X
1.0E+02		X				X
3.0E+02		X				
5.0E+02		X				X
7.0E+02	X	X	X	X	X	X
9.0E+02		X				
1.0E+03						X
2.0E+03		X				X

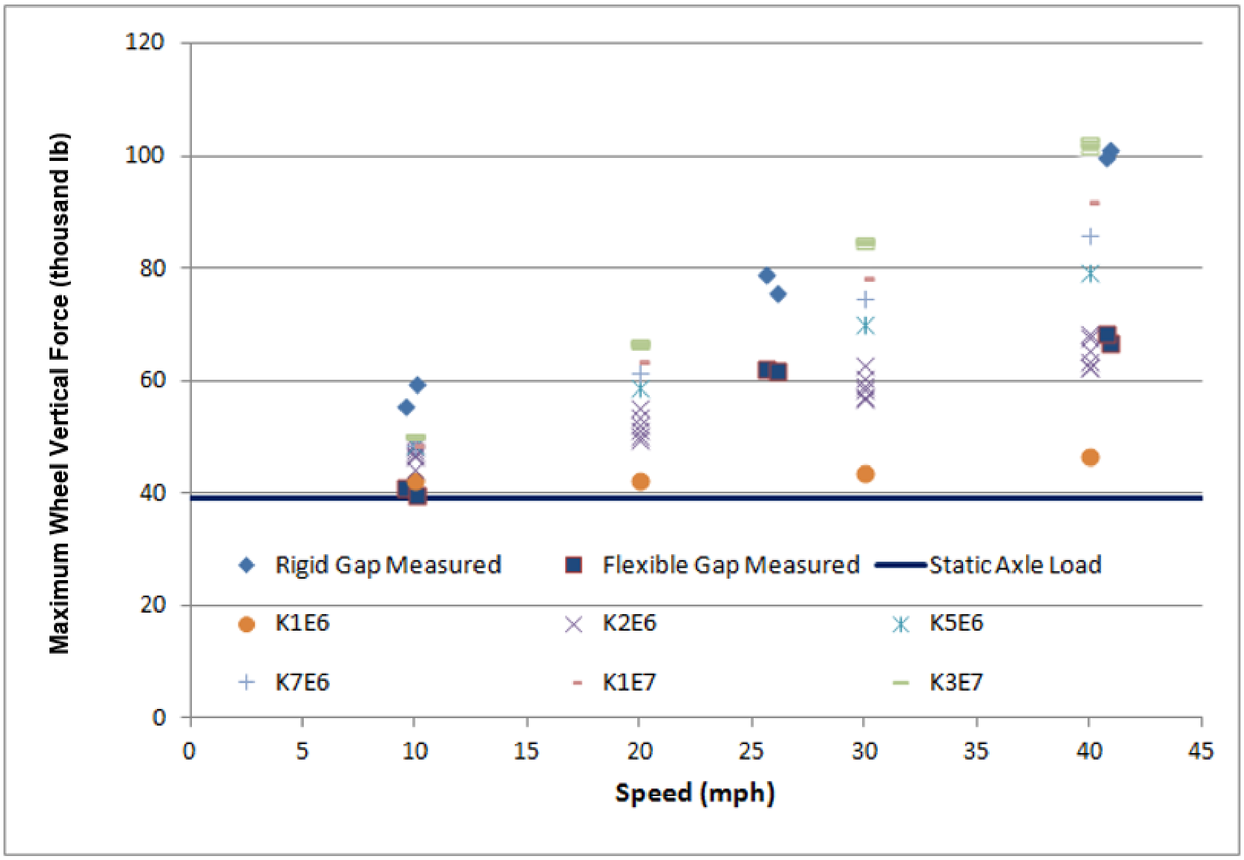


Figure 30. Effect of Flexible Gap Stiffness and Damping on W/R Impact

Figure 31 shows simulation cases for two groups of flexible gap stiffness with varied gap damping: the lower trend represents 2.0E6 lb/in stiffness, the upper trend represents 3.0E7 lb/in stiffness, the damping for the lower stiffness cases varies from 100 to 2000lb/in/s, and the damping for the higher stiffness cases varies from 50 to 2000 lb/in/s. Clearly, the effects of gap damping on W/R impact are small compared to that of the stiffness. The W/R impact decreases with the increase of the gap damping.

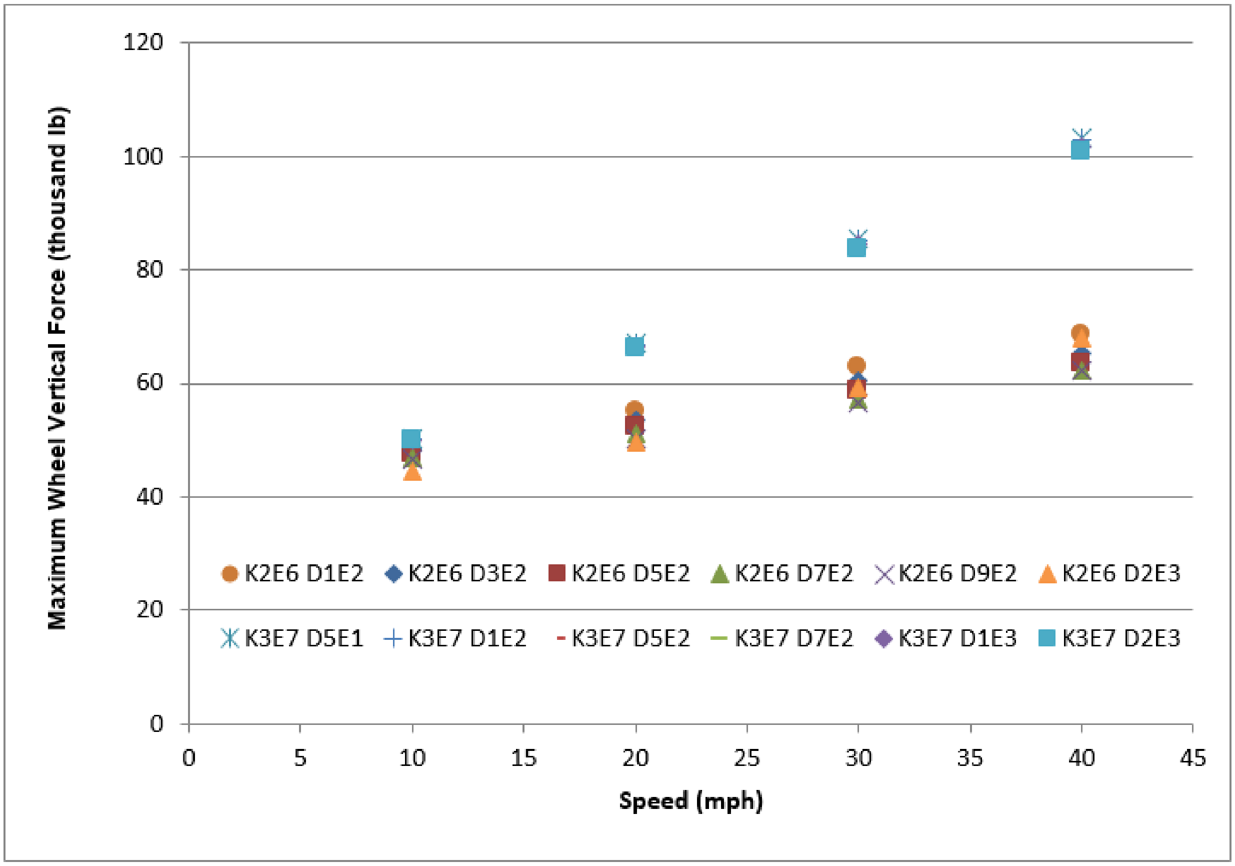


Figure 31. Effect of Gap Damping on W/R Impact (Connection Stiffness Between Rail and Ground K = 50,000 lb/in)

6. Conclusion

TTCI conducted a gapped foundation panel test at the FAST on the HTL with IFC and load measuring IWS. Test results from Phase I as well as this project were used to investigate flangeway gap flexibility and foundation effects on dynamic W/R impacts. The following conclusions can be drawn from the field measurements and modeling parametric study:

- Rail stiffness over flangeway gaps has the most significant effect on W/R impacts among the other factors investigated during tests.
  - Three-rail diamond crossings generate less impact than casting crossings.
  - Carbody impact acceleration caused by flangeway gaps increases with frog foundation stiffness.
- The effect of flexible gap damping on W/R impact is small compared to that of stiffness.
- The W/R impact decreases with the increase of the flexible gap damping. Foundation stiffness and damping optimization depends on rail stiffness and track geometry (flangeway gap width, track differential settlement, etc.).

The following tasks were recommended and implemented for the Phase III project:

- Evaluate frog structure and foundation materials (such as artificial subgrades), which will minimize differential settlement.
- Develop an optimized frog prototype design by introducing flangeway gap flexibility and changing foundation.
- Build and evaluate frog prototype and/or crossing diamond under controlled conditions.

7. References

1. Akhtar, M., Davis, D., and Shu, X. (2013, February 22). "Next-Generation Foundations for Special Trackwork – Phase I." Technical Report, DOT/FRA/ORD-13/10. Federal Railroad Administration: Washington, DC. Available at: https://www.fra.dot.gov/eLib/details/L04322#p1_z5_gD_kNext-Generation%20Foundations%20for%20Special%20Trackwork.

2. American Railway Engineering and Maintenance-of-Way Association. (2012). *Manual for Railway Engineering*. Lanham, MD.

3. Federal Railroad Administration. (2016, May 27). "Next-Generation Foundations for Special Trackwork Phase III." Technical Report, DOT/FRA/ORD-16/14: Washington, DC. Available at: https://www.fra.dot.gov/eLib/details/L17468#p1_z5_gD_kNext-Generation%20Foundations.

Abbreviations and Acronyms

AMS	Austenitic Manganese Steel
AREMA	American Railway Engineering and Maintenance-of-Way Association
FAST	Facility for Accelerated Service Testing
FRA	Federal Railroad Administration
HAL	Heavy Axle Load
HTL	High Tonnage Loop
HMA	Hot Mix Asphalt
IFC	Instrumented Freight Car
IWS	Instrumented Wheelsets
MGT	Million Gross Tons
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
WR	Wheel/Rail