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Reducing the Adverse Effects of Wheel Impacts on Special Trackwork Foundations

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13. ABSTRACT

This report deals with damage to special trackwork due to high impact loads and the beneficial effect of increasing damping in these foundations. Additional damping attenuates the high magnitude and high frequency of impact generated transient vehicle-track vibrations. This report covers the first phase of means, manners, and options for analyzing and enhancing the damping at the special trackwork locations, especially the crossing diamond foundations.

A conventional wood-tie ballasted track at TTC's Facility for Accelerated Service Testing had a damping value of about 56 lbs/in/sec/tie/rail. A conventional concrete-tie ballasted track on the Railroad Test Track (RTT), on the other hand, had a damping value of about 164 lbs/in/sec/tie/rail. The measured values were very low compared to the value of the optimal damping of about 300 lbs/in/sec/tie/rail determined in a previous study conducted by TTCI. Since the traditional crossing diamond foundation is very similar to a conventional open track foundation, the damping in existing crossing diamond foundations cannot be expected to be more than the ballasted track on the RTT; i.e., 164 lbs/in/sec/tie/rail. The damping of crossing diamond foundations therefore needs to be increased. The measured damping values at other modified track beds on the RTT consisting of rolled ballast mat and under-tie pads were found to be respectively 319 and 237 lbs/in/sec/tie/rail, and appear to meet the optimal damping provision criterion. Similar modifications then could be used to increase damping in crossing diamond foundations.

This work was conducted under Task Order 139 of the FRA's Research and Development Plan. During Phase 2, and in concert with a companion AAR program, results of laboratory tests on various damping pads will be analyzed to produce rank-attenuation relationships. Pads will be tested in heavy axle load environment to determine the deterioration of the dynamic performance and to gage their durability.

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Executive Summary

Transportation Technology Center, Inc (TTCI) has developed track designs and evaluated available materials and components for reducing impacts at special trackwork frogs. The results of this study are promising. Significant improvements in the performance of special trackwork foundations appear to be technically feasible. Some of the commercially available products evaluated may provide the additional damping that is lacking in conventional ballasted frog foundations.

One of the most significant maintenance problems in mainline track today is associated with impact loads at special trackwork, bridge approaches, and road crossings. Impacts result from sharp changes in loaded running surface and elevation changes that occur at track stiffness transitions. These impact loads can be as high as 3 to 5 times the static wheel load. Of the special trackwork, crossing diamonds are likely to be the worst locations compared to those of switches and frogs. The high magnitude and frequency of impact loads on crossing diamonds result in shortened component lives and increased deterioration of the ballast layer and the subgrade. Due to the short lives of conventional components, a premium track structure may be economical for these locations. This premium track must provide good load transmission and work as an efficient mechanical filter against high frequency wheel/rail loads.

Based on the damages seen at the crossing diamonds as well as dynamic modeling of vehicle-track interactions, it is desirable to add and enhance damping of crossing diamond foundations. This will protect more components from the effect of high frequency transient vibrations due to wheel impact loads. The main objective therefore was to investigate those design options for crossing diamond foundations that will effectively attenuate both the high frequency impact load on the flangeway gap corner as well as those loads associated with the wheel bounce following the impact.

An extensive literature review of track dynamic design and component properties was conducted. The tools now exist to measure and analyze the effects of changing track foundation properties on vehicle performance. With these tools, TTCI developed design concepts for reducing impacts at special trackwork. Findings include:

- The effect of crossing diamond foundation stiffness on maximum vertical wheel impact loading was almost nil due to an increase in track modulus up to 30,000 lbs/in/in. An increase beyond this value was found to actually increase the wheel impact loading on the flangeway gap corner of the crossing diamond.
- An optimal track damping value of about 300 lbs/in/sec/tie/rail was determined that minimized dynamic vertical loads for typical freight cars.
- Conventional ballasted track was found to have a damping value of only about 56 lbs/in/sec/tie/rail.
- Vehicle dynamics modeling suggests that diamonds with optimal damping will have 20 percent lower maximum forces.

- Subgrade strengthening methods can also affect damping. A subballast cellular confinement system consisting of GEOWEB™ was found to have 25 percent more damping than similar conventional track. A Portland Cement Concrete slab used as subgrade improvement was found to reduce damping. And, a hot mix asphalt subgrade improvement was found to have no significant effect on damping as compared to conventional track..

The optimal damping value determined from modeling high angle crossing diamonds is optimal for minimizing forces. It is relatively stable over a wide range of track stiffnesses. Damping was varied in the study until the peak vertical forces were minimized. A typical freight car was modeled going over conventional high angle crossing diamonds. The optimal range of damping occurs when impact and rebound forces are similar. At lower damping values, the initial impact forces dominate. At higher than optimal damping, the rebound forces are higher.

More radical track/crossing diamond foundation design changes are needed to achieve the level of damping desired. TTCI has developed three concepts for achieving the desired track properties. These are broadly defined as:

- Tie pad designs. These use rail seat or platework pads to provide the necessary damping.
- Modified tie layer designs. These provide damping within the tie material.
- Modified foundation designs. These expand on the subgrade modification theme to provide damping in the subballast and subgrade layers. Current applications are designed to stiffen the track only.

Test sections at TTC, installed for noise and vibration attenuation testing under high-speed traffic, were evaluated for track damping. Two of the four test sections, a ballast mat section and an under tie pad section, had damping values near the design optimal. Further laboratory testing of available noise and vibration reduction pads is proceeding under AAR project funding. This work is necessary because data on the damping characteristics of these pads is not available.

However, based on the in-track testing of noise attenuation sections, a preliminary conclusion is to use a combination of rolled ballast mat and rail-seat pads for new construction of special trackwork locations needing enhancement of foundation damping to reduce impact loads. For retrofitting existing locations or where ballast excavation is not possible, the combination of under-tie pads and rail-seat pads appears to provide an adequate solution for impact reduction at special trackwork locations.

The report describes a scenario for testing the proposed crossing diamond frog foundations and components in a controlled load environment, such as the Facility for Accelerated Service Testing (FAST). TTCI recommends that a follow-on project be commissioned to build and evaluate crossing diamond foundation prototypes.

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1.0 INTRODUCTION

1.1 BACKGROUND

One of the most significant maintenance problems in mainline track today involves track stiffness transitions at bridge approaches, road crossings, and special trackwork. Impacts result from the sharp changes in loaded running surface and elevation changes that occur at track transitions. The worst of these transitions are likely to be at special trackwork because these locations include switches, frogs, and crossing diamonds. In these locations, there are running surface discontinuities and/or abrupt track structure/stiffness transitions. The dynamic wheel/rail forces and track responses associated with such abrupt track irregularities are mostly of high frequency and high magnitude. Increased deterioration of the track support including the ballast layer and subgrade thus results.

Special trackwork locations, especially those with crossing diamonds, Figure 1, sustain very high impacts. The load environment and track structure in these locations are different from the rest of the track. Transitions are abrupt and problem locations are well defined. Track component lives are relatively short due to the severe load environment.

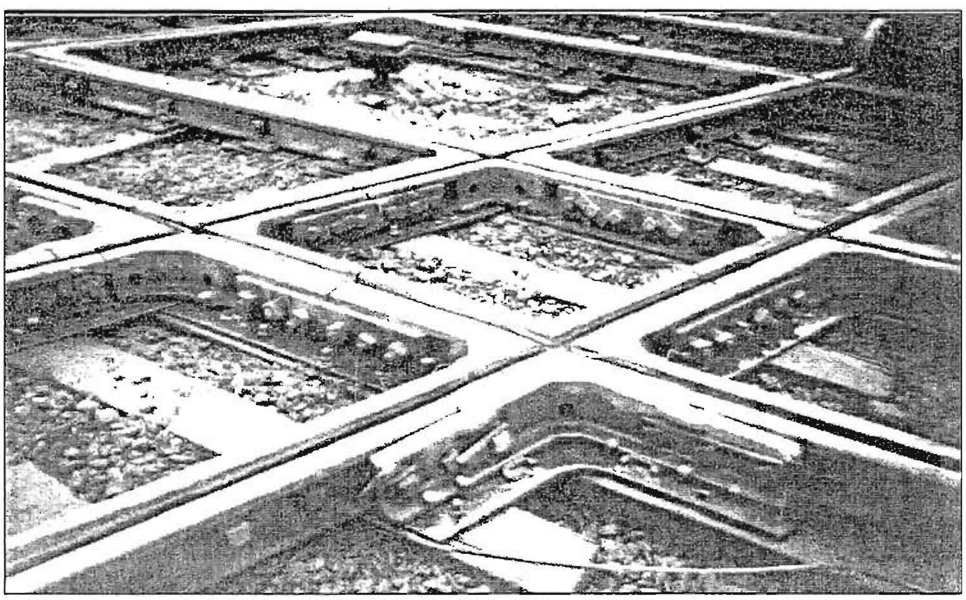


Figure 1. Typical 90-degree Manganese-Construction Crossing Diamond

A premium track structure may be economical for these locations. It must provide good load transmission as well as work as an efficient mechanical filter against high frequency wheel/rail loads. The premium track should have the following four characteristics:

(1) Enhanced bearing capacity; i.e., increased allowable pressure from the supporting substructure.

(2) Special timber layout to decrease applied pressure on the supporting substructure.

(3) Increased damping in the track superstructure (rails, ties and their interfaces).

(4) Enhanced energy dissipation in the track substructure (tie/ballast interface, ballast and the subballast).

Item 3 is very important to maintain the integrity of the ballast because it will reduce ballast pressure oscillation about its quasi-static value; which will thereby reduce pulverization (i.e., maintain angularity and reduce rounding of ballast pieces). Item 4 deals with the overall integrity of ballast/subgrade foundation. Items 1 and 2 are needed to ensure that the increases of quasi-static ballast pressure due to the increase in the car weight are withstood within the AREMA-specified limits.

The impact loads generated at special trackwork locations are of two types:

(1) Higher frequency loads (impact), due to the vibration of the unsprung mass (wheelset and side frame, or three-piece truck) on the wheel/rail contact surface, that are dependent on wheel/rail stiffness.

(2) Lower frequency loads (wheel bounce), resulting from the vibration of the unsprung mass on the track, that are dependent on track stiffness. The latter vibrations may resonate with the movement of rails and ties on the ballast; and thus produce surface and alignment degradation due to ballast and subgrade deterioration. The former are transient vibrations, and the absorption of these vibrations is highly influenced by enhanced damping in the track superstructure (rails, ties and their interfaces).

Unless completely eliminated, for example, by using ramps on the flangeway gap corners of high angle crossing diamonds, the frequency content of the 1st type is almost a given; not much can be done about it. The frequency content of the 2nd type can however be manipulated by changing the track stiffness. Softer track stiffness should lower the highest frequency content in the 2nd type. Softer track stiffness, however, goes against the enhanced bearing capacity demanded in item 1 of the requirements for a premium track. As can be seen, special trackwork requires an optimal design, consisting of the best possible combination of stiffness and damping, for its premium foundation. An ideal special trackwork foundation would have sufficient strength (track modulus), softness (damping), and thickness (durability).

As Figure 2 shows, the typical modes in which the ballasted track might respond to the vertical excitation are (1) rail-tie in-phase bending mode at approximately 200 Hz, (2) rail-tie antiphase bending mode at approximately 500 Hz, (3) rail bending, "pinned-pinned," mode between 800 and 1500 Hz, and (4) the movement of ballast and the track above it on the subgrade between 25 and 40 Hz.[1] Optimal design of a premium foundation must therefore ensure that the higher frequency impact loads do not resonate with its pinned-pinned bending mode by increasing the damping in the track superstructure; and that the lower frequency modes do not resonate with its rail-tie in-phase and anti-phase bending modes. This can be achieved by enhancing the energy dissipation in the track substructure.

Additional measures needed include decreasing permanent settlement to match the rates of surrounding track, transitioning vertical and lateral track stiffness to smoothly match surrounding track, and designing a foundation that is easier to maintain with conventional equipment.

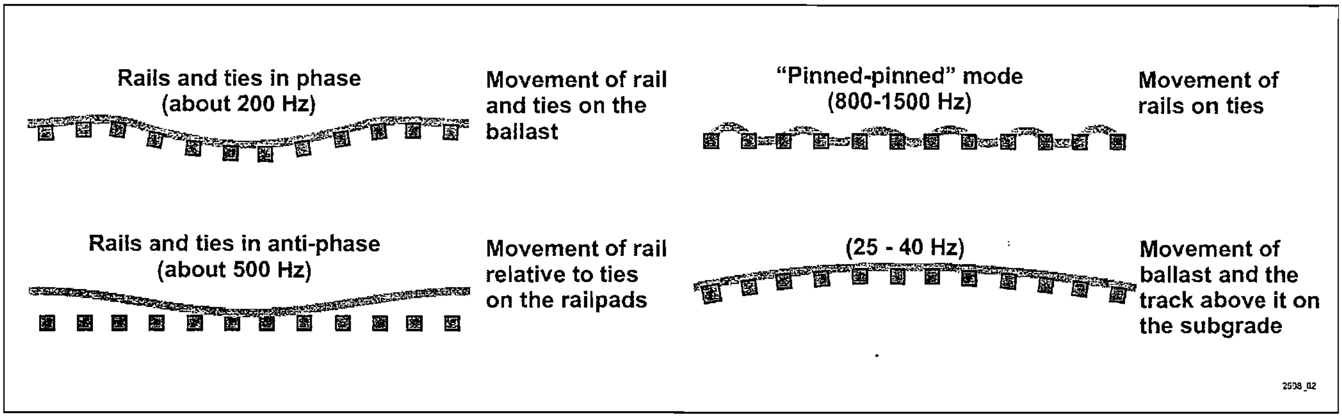


Figure 2. Typical Ballasted Track Responses

1.2 OBJECTIVE

The load environment at a high angle crossing diamond can be quite severe with vertical dynamic loads equal to 3 to 5 times the static wheel loads. Figure 3 shows a comparison of these loads between the open track and crossing diamonds measured at the Facility for Accelerated Service Testing (FAST) at the Transportation Technology Center (TTC), Pueblo, Colorado, using instrumented wheelsets. These loads occur when the wheel travels across a flangeway (i.e., a gap in the running surface). The wheel falls into the gap before striking the running surface on the other side. This impact generates a short duration dynamic load that can damage the frog and the vehicles traveling over. Furthermore, the subsequent wheel bounce can deteriorate ballast and subgrade resulting in surface and alignment degradation.

Damage that occurs to the track includes:

- Running surface deformation from metal flow
- Running surface cracking
- Casting breakage
- Fastener breakage
- Plate breakage
- Tie crushing/cracking
- Surface and alignment deterioration
- Ballast breakdown
- Mud pumping

The traditional crossing diamond foundation is very similar to a conventional open track foundation. It consists of a prepared subgrade and a granular ballast layer. Timber crossties and plate work unique to crossing diamonds are typically used. This foundation is inadequate for crossing diamonds due to the higher tonnage in the crossing, versus either crossing track, and the more severe dynamic load due to the flangeway gaps. Due to these factors, the diamond tends to settle more rapidly than the surrounding track, creating a low spot. Frequent tamping, needed to keep the track in profile, causes a significant amount of the ballast breakdown. This adverse track profile exacerbates the dynamic loading.

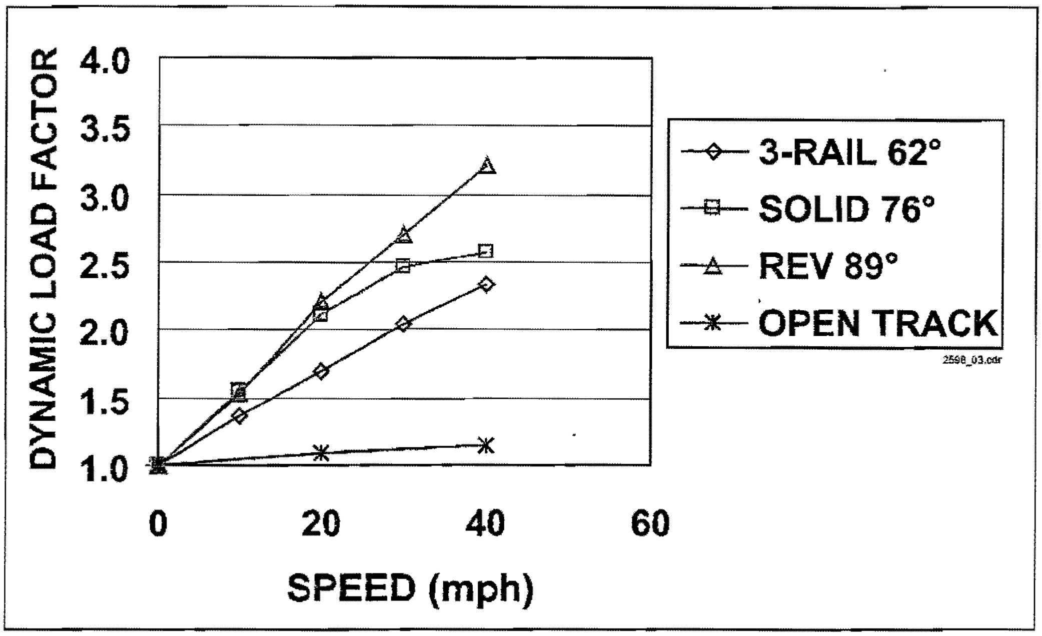


Figure 3. Dynamic Loads on Crossing Diamonds and Open Track Measured at FAST using Instrumented Wheelsets

Based on the damage seen at most crossing diamonds, it certainly seems desirable to add damping as near to the running surface as possible. This will protect more components from the effects of high frequency transient vibrations due to the wheel impact loads. As eluded earlier, the absorption of these vibrations is highly influenced by the enhanced damping near the running surface. The failure of welds used to attach fasteners and lateral stops to plates used under frogs are examples of the effects of wheel impacts. The same welds and fasteners are used successfully on plate work for conventional track.

On the other hand, the lower frequency loads associated with wheel bounce following an impact are mostly responsible for ballast and subgrade deterioration resulting in surface and alignment degradation. It is the mitigation of these loads that is the hardest to achieve. However, recent findings by TTCI suggest that relatively more success is possible in modifying the track foundation. Improvements to subgrade strength with subsequent decreases in track settlement and surface deviations are possible by adding layers with enhanced damping and improved stiffness properties.

The main objective of this effort, therefore, was to investigate those design options for crossing diamond foundations that will effectively attenuate both the high frequency impact loads on the flangeway gap corners as well as those loads associated with the wheel bounce following impact.

1.3 APPROACH

Previous work done by Transportation Technology Center, Inc. (TTCI), under the AAR Strategic Research Initiatives Program, suggested that the effect of crossing diamond foundation stiffness (ties, ballast, subballast, and subgrade) on maximum vertical wheel impact loading was almost nil due to an increase in track modulus up to 30,000 lbs/in/in.[2] An increase beyond this value was found to increase the wheel impact loading on the flangeway gap corner of the crossing diamond (see Table 1). Even though decreases in track settlement and surface deviations are possible by adding a layer of Hot Mix Asphalt (HMA) to somewhat increase the track modulus; a popular remedy of sorts when access to the subgrade is possible.[3] In itself, this application does not deal with attenuation of loads on the crossing diamond foundation because the wheel impact loads are not decreased. This application may prove to be only a temporary measure, which may only delay the onset of differential track settlement for some time. It has been used without regard to its damping properties. Similarly, other materials, such as granular layers, cellular confinement layers, or granular subballasts, have been used in this limited respect with some success. Irrespective of the purpose of use, these layers probably added some damping to the track substructure.

The need to increase track damping is based on field observations as well as dynamic modeling of vehicle-track interactions. Evidence of the need for increased damping includes the impact related damage seen at crossing diamonds. These include crushed castings, broken fasteners, broken plate work, crushed ties, and pulverized ballast. The need to reduce impact related damage and increase service life and safety is driving the interest in increased damping.

Table 1. Effect of Track Modulus on Predicted (NUCARS) Maximum Vertical Wheel Load @ 50 mph for 100-Ton Loaded Hopper Car at 90-Degree Crossing Diamond

Diamond Foundation Stiffness kips/in/tie	Diamond Track Modulus lbs/in/in	Maximum Wheel Load lbs	Difference relative to 104kips/in Foundation	% Change from 104 kips/in Foundation
104	5200	107,552	0	0
200	10,000	107,403	-149	-0.14
300	15,000	107,255	-297	-0.28
400	20,000	107,217	-335	-0.31
500	25,000	107,308	-244	-0.23
600	30,000	107,531	-21	-0.02
800	40,000	108,254	702	0.65
1000	50,000	109,270	1718	1.6
2000	100,000	116,225	8673	8.1

This work done by TTCI has also suggested that there is an optimal track damping value that will minimize dynamic vertical loads for typical freight cars.[2] Increasing the damping will reduce dynamic loading, but will probably not eliminate crossing diamond problems entirely. The optimal damping value of about 300 lbs/in/sec/tie/rail was determined from dynamic simulation modeling using NUCARS™* (Figure 4). Subsequent experimental work showed that conventional ballasted track has damping values of only about 56 lbs/in/sec/tie/rail.[1]

Results of these experiments on FAST have also shown that a track section built with GEOWEB®, a cellular confinement system for granular layers, had 25 percent more damping than similar conventional track.[1] In the same test, a Portland Cement concrete slab was shown to reduce damping. HMA had no significant effect on damping, as compared to conventional granular sub-ballast track. While the 25 percent increase in damping developed by using a GEOWEB subballast layer in a good quality mainline track is significant, it is not sufficient to reach the theoretical optimal damping value. This would require about a 435 percent increase from the values measured for good mainline track; i.e., from 56 to 300 lbs/in/sec/tie/rail (see Figure 5). However, TTCI believes that more can be done in this area to achieve larger increases in truck damping.

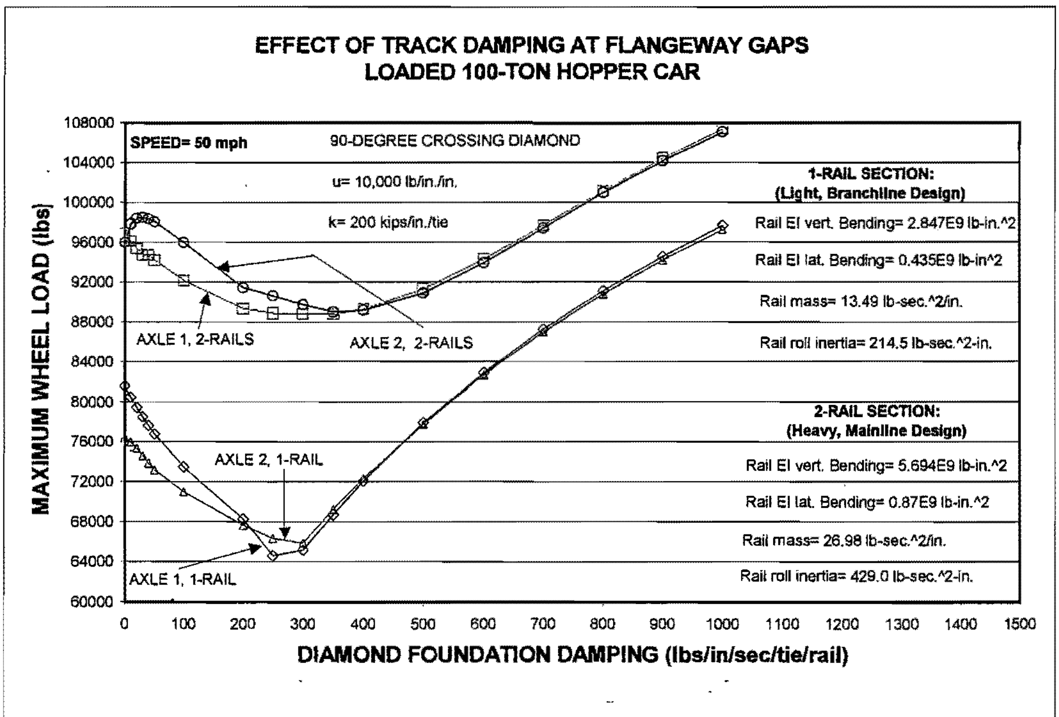


Figure 4. Effect of Track Damping on Maximum Wheel Impact Loads: Optimal Damping about 300 lbs/in/sec/tie/rail

* NUCARS is a trademark of Transportation Technology Center, Inc.

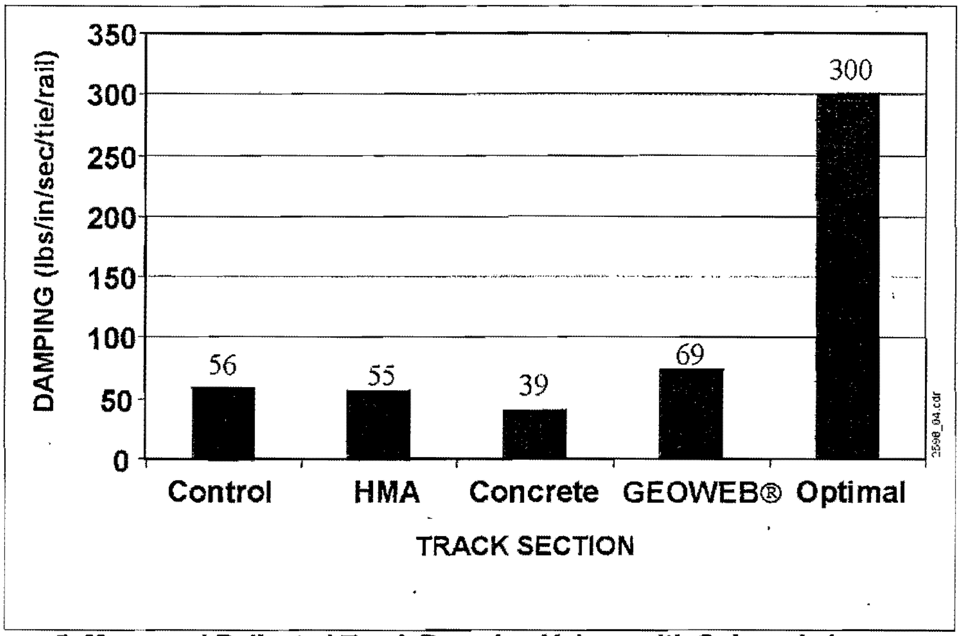


Figure 5. Measured Ballasted Track Damping Values with Subgrade Improvement Layers as compared to the desired Optimal Damping

This leaves the plate work, tie, and ballast layer as the most likely components to provide the increases in damping needed to reach the theoretical optimal level. Railroads have used tie pads and rail seat pads of various types for many years. However, recent advances in modeling and testing methods only now allow them to specify the desired damping and measure the actual damping in the field. With these tools, it is possible to evaluate designs and materials against a design damping value.

Wood ties provide significant damping compared to concrete or steel ties. This damping assists in managing impacts associated with wheel defects and track running surface discontinuities, such as mechanical joints. Rubber pads have been used with wood ties in special circumstances; e.g., on open deck bridges, to reduce the stiffness of the track on the bridge. The pads are effective at allowing more deflection on the bridge, better matching the loaded profile of the bridge with its approaches.

Pads are deemed necessary for concrete and steel ties in virtually all situations. First, they provide part of the electrical isolation of the rail from the tie. Second, they provide a sacrificial wear layer for the tie. Lastly, they provide for "impact attenuation" or damping in the track. Rubber pads provide more damping than hard plastic or urethane pads. But, they also have proven to be less durable under HAL traffic. Both types have proven to be successful in preventing or delaying concrete tie cracking due to dynamic loads from wheel defects.[4]

A wider variety of materials for pads has been employed for crossing diamonds. In this application, pads are typically inserted between the bottoms of the plate work and on top of the ties. Here again, a variety of rubber, polyurethane, and composite pads has been used. Pads are generally not inserted between the plate and rail or castings. Early failures and the expense of cutting pads to match the frog angle and plate work have made this location less popular.

Also evident in Figure 4 are the effects of the rail bending rigidity (EI) and rail mass on the maximum wheel impact loads. One-rail section provided track stiffness (concentrated force per unit rail deflection $K = \sqrt[4]{64EIu^3}$) of 653,344 lbs/in; while for the two-rail section this stiffness was 776,961 lbs/in, which is about 19 percent larger. Furthermore, two-rail section had twice as much rail mass as the one-rail section. Barring a small change in the magnitude of optimal damping, one-rail section at optimal damping reduced the maximum wheel impact loads as much as 25,000 pounds or about 28 percent when compared to these loads for the two-rail section.

Current crossing diamond designs for HAL service appear to increase (1) crossing diamond foundation modulus, (2) rail or casting bending rigidity, and (3) mass of the casting or rail. As discussed earlier, even a substantial increase in track modulus had no effect on the magnitude of wheel impact loads, yet this higher modulus probably benefited in helping to maintain alignment, elevation, and cross level of crossing diamond track for a longer time. On the other hand, the increased EI and mass, as Figure 4 shows, result in higher wheel impact loads. The higher frequency content and larger magnitudes of these impact loads not only advance breakage of the crossing diamond components, but also degrade and pulverize the ballast such that this cause and effect eventually results in the settlement of the crossing diamond location, creating a low spot.

If impact loads were lower, such as for one-rail section in Figure 4, a lower bending rigidity would be able to adequately resist the lower magnitudes of the resulting bending stresses. Furthermore, the lower impact would result not only in lower initial input velocity at the flangeway gap corner, but also would probably produce a larger duration impulse such that the higher frequency content of the impact would decrease (frequency content being inversely proportional to the duration of impulse). Lower magnitude together with lower frequency content of impacts on flangeway gap corner of one-rail section then might not be as deleterious as the much higher impacts produced in the two-rail section.

These predicted results suggest that crossing diamond designs, which are lighter but have adequate bending rigidity, will lead to lower impact loads on the flangeway gap corners. Other design concerns contribute to the massive crossing diamonds used in service today. These include provision for longitudinal rail stresses and component redundancy for safety. Fixed points like crossing diamonds and turnout frogs tend to have longitudinal stress problems due to rail thermal effects. While rail is relatively free to move in most open track, frogs, being multiple track joints, can be in locations of high longitudinal stress. As a result, the crossing diamond is designed to withstand high longitudinal forces.

North American rails have excellent safety records at crossing and turnout frogs, partly due to redundant designs. Rail bound frogs have "warp" rails that surround (i.e., bound) the castings. This design is redundant and reliable. However, the redundancy adds considerable mass to the frog.

In any case, an increase in damping, in general, decreases the impact loading on the crossing diamond. It also appears that a damping value of about 300 lbs/in/sec/tie/rail gives the largest reduction in impact loading. Methods to successfully design, build, and maintain crossing diamonds to the optimal damping value need to be developed.

The general approach consists of the following:

- Evaluate load-deflection (stiffness and hysteretic) properties of commonly used rail-seat, tie-plate, and under-tie pads and ballast mats.
- Evaluate creep properties, using load-deflection tests under reasonable load retention (about 30 minutes), in increment of loads to the expected maximum load on the crossing diamonds.
- Develop analytical methods to rank the performance of pads from the static load deflection stiffness and creep test results. Use this ranking to define the best pads.
- Evaluate stiffness and damping properties of combinations of pads and ballast mats in ballasted track with both 15 and 20-inch wood-tie spacings as follows:
  - The best rail-seat pad and the best tie-plate pad with the best under-tie pad
  - The best rail-seat pad and the best tie-plate pad with the best ballast mat
  - The best tie-plate pad with the best under-tie pad
  - The best tie-plate pad with the best ballast mat
  - The best tie-plate pad and the best under-tie pad with the best ballast mat
  - The best under-tie pad with the best ballast mat
- Evaluate stiffness and damping properties of combinations of pads and ballasted track with subgrade improvement layer consisting of HMA pavement or GEOWEB layer, at wood-tie spacings of 15 and 20 inches, as follows:
  - The best rail-seat pad and the best tie-plate pad with ballast-HMA
  - The best tie-plate pad with ballast-HMA
  - The best tie-plate pad and the best under-tie pad with ballast-HMA
  - The best under-tie pad with ballast-HMA
  - The best rail-seat pad and the best tie-plate pad with ballast-GEOWEB
  - The best tie-plate pad with ballast-GEOWEB
  - The best tie-plate pad and the best under-tie pad with ballast-GEOWEB
  - The best under-tie pad with ballast-GEOWEB
- Select two best combinations from above as follows:
  - Ballasted track having pad/pads combination with ballast mat
  - Ballasted track having pad/pads combination with subgrade improvement layer
- Evaluate these two best combinations in long-term FAST heavy axle load (HAL) service tests.
- Evaluate the best combination in revenue service.

1.4 SCOPE

The analyses, subsequent results, and consequent conclusions given in this report pertain to the following items:

- Procure commonly used rail-seat pads, tie-plate pads, under- tie pads and ballast mats (Figure 6). Secure as much data as possible on the static and dynamic compressive rigidities including hysteresis losses, stretch tests, and durometer tests.
- Perform compressive load-deflection tests on various tie pads, under-tie pads, and ballast mats to determine their quasi-static stiffness characteristics.
- Perform compressive load-deflection-creep tests on the pads to determine their hysteretic behavior at various compressive load levels.
- Test track segments at TTC's Railroad Test Track, which have tie pads, under-tie pads, and ballast mat using the instrumented hammer test technique to measure hammer impulse and the track response.
- Develop a NUCARS model, which reasonably represents a typical ballasted track.
- Use NUCARS model to match the hammer test results to evaluate respective dynamic stiffness and damping characteristics.
- Build a track panel for installation in the High Tonnage Loop at FAST, consisting of ballasted track with subgrade improvement HMA pavement, to test dynamic stiffness and damping characteristics of this track with various combinations of rail-seat, tie-plate and under-tie pads.
- Install track panel, with subsequent hammer impulse tests and HAL long-term tests at FAST to follow.

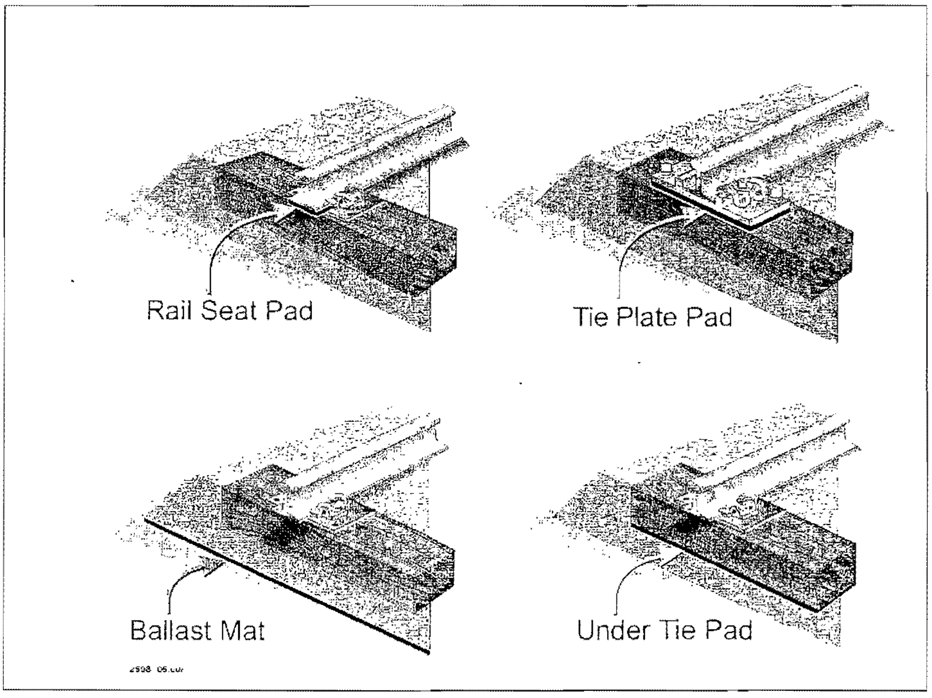


Figure 6. Schematic of Various Pads and Ballast Mat in a Track Structure

2.0 LITERATURE REVIEW

2.1 DYNAMIC STIFFNESS AND DAMPING PARAMETERS

Many vehicle/track models have been developed. These models have been used for predicting and analyzing performance and degradation of vehicle and track components. Among these models, the NUCARS vehicle and track models, developed by TTCI/AAR, have been used worldwide. Applications of such models depend, to a great degree, upon the proper representation of the track system parameters, such as stiffness and damping characteristics. In order to obtain accurate simulation results, the system characteristics must be accurately known. A vehicle/track model without adequate parameter inputs will have limited practical uses.

In 1998, TTCI conducted an extensive search and review of published papers and reports on track characterization.[5] This literature review was performed to determine track characteristics that have been measured by other researchers. These track characteristics are primarily the effective stiffness and damping of the pad/fastener between the rail and tie, as well as the effective stiffness and damping of the ballast. The summarized data of track characteristics (stiffness and damping) is given in Tables 2 to 6. Given in each table are the values of stiffness and damping parameters, corresponding track component conditions, the methods used for obtaining these values, and the sources of publications. The track parameters in the tables are:

Table 2.	Pad Vertical Stiffness and Damping
Table 3.	Ballast Vertical Stiffness and Damping
Table 4.	Pad Lateral Stiffness and Damping
Table 5.	Ballast Lateral Stiffness and Damping
Table 6.	Rotational Stiffness and Damping of Pad/Fasteners

As indicated in these tables, track parameter values vary significantly, depending upon a number of factors including track component conditions, pre-loading magnitudes, and frequency ranges of applications. This database appears to provide no practical guidance in selecting a representative value for this project. The distributions of these published vertical stiffness and damping parameters for pads and ballast materials are also plotted in Figures 7 and 8 as percentiles of various magnitudes, based on the values listed in Tables 2 and 3.

Table 2. Pad Vertical Stiffness and Damping

(1 MN/m = 5.7 kips/in, 1 kN s/m = 5.7 lb/in/sec)

Stiffness (MN/m)	Damping (kN s/m)	Component Details	Source, Test Methods, Frequency Range
Preload = 20 kN			van't Zand (Delft Univ.of Tech.):
970	32	5.2 mm rubber bonded, soft corkelastic	
1420	34	4.7 mm rubber bonded, norm corkelastic	Used hammer test, output accelerations
2990	29	4.9 mm full material, hard rubber	
3030	29	5.0 mm full material, lupolen V3510k	Frequency range:
1840	14	5.0 mm full material, Amitel EM400	400-2000 Hz
1210	12	9.4 mm full material, Amitel EM400	
380	8	9.7 foam structure, Amitel EM400	
100	3	10.8 foam structure, Amitel EM400	
420	13	8.0 foam structure, Amitel EM400	
Preload = 25 kN			
130	20	6.5 mm UK Hytrel 6358	Cited results by Spoornet
90	17	(7+6.5) mm RSA EP2 + EP2	
110	23	(6.5+6.5) mm RSA EP2 + UK6358	
375	7	12.0 mm HDPE full material	
1200	50	12.0 mm HDPE full material	
75		10 BR studded rubber	
Preload = 180 kN: 505	54	Studded 10 mm Pandrol pad for UIC60 rail, Pandrol fastenings, concrete ties	Oscarsson et al. (Chalmers Univ. 1997) Field load wagon tests: static preload, swept dynamic load up to 200 Hz, hammer excitation from 200 to 1200 Hz
Preload = 260 kN: 738	59		Parameters are sensitive to preload up to 700 Hz
110	98	Pad for Shinkansen	Ishida, Miura & Kono, (RTRI, 1997)
30	980	Resilient tie	Irregularities with wave lengths 0.03 to 2 m and heights of 1/1000 of wavelengths
50	980	Ballast mat	
100 MN/m^2	30 kNs/m^2	Rubber pad on concrete slab, light rail	Esveld, (Delft Univ. Tech.) Instrumented excitation hammer method
850	26	EVA tie pad for RE136 rail, CN 55A concrete ties	Raymond & Cai (1992)
140	45	Studded Pandrol 10 mm rubber pads for newly built track for high speed trains, UIC60 rail, Pandrol fastener, concrete monobloc tie	Igeland (Chalmers Univ., 1993)
100 to 900	30	Portec Polyurethane pad 3/16" for modeling 136 RE rail, CP Rail CT-3 concrete ties.	Dong & Sankar, (Canada, 1994)

Table 2. Pad Vertical Stiffness and Damping – Continued

(1 MN/m = 5.7 kips/in, 1 kN.s/m = 5.7 lb/in/sec)

Stiffness (MN/m)	Damping (kNs/m)	Component Details	Source, Test Methods, Frequency Range
240 90 150	3.5 40 45	Pad for ballasted track and Pad for slab track Pad under slab	Diana et al, (Italy, 1996) For ballasted track, used impulse excitation, for slab track, used harmonic excitation (not enough energy by impulse). 0 - 350 Hz
280 225	63 28	Pad for concrete tie track: 56 kg/m (113 lb/yd), Pandrol fastener, main line quality Before tamping Tamped	Grassie et al (1982) The rail was excited with force amplitude of 50 N from 50 to 1500 Hz. Obtained receptance. Not good less than 50 Hz.
250 200 250 70 350 280 225 280 300 20-100 221 76 400 350 450 540 180 360 60 300 80 (5 Hz) 150 (1 kHz) 200 (2.5 kHz)	26 7 70 63 28 50 45 2-12 η = 0.2 5 η = 0.2 η = 0.6	5-mm-thick pads wood ties 5-mm-thick pads 10-mm-thick pads HDPE pads 5-mm-thick pads, pre-tamping 5-mm-thick pads, post-tamping 5-mm-thick pads, frozen ballast 5-mm-thick pads, rail preload 10-mm-thick pads 5-mm-thick pads, booted ties 10-mm-thick pads 5-mm pads, rail preload (SBB) 5-mm pads, rail preload (SBB) 5-mm pads, rail preload (DB) 5-mm pads, rail preload (DB) 9-mm pad, (SNCF) lab tests 5-mm pad, (DB) lab tests 12-mm pad, (DB) lab tests cork-rubber pad, (NS) lab tests rubber pad, lab tests rubber pad, lab tests rubber pad, lab tests	Knothe & Grassie (VSD 22, 1993) State of the Art - track modeling paper η = loss factor
100 200 280 400 800	43 54 63 74 93	Very soft pad Soft pad Reference pad Stiff pad Very stiff pad	Ripke & Knothe,(VSD 24, 1995)

Table 2. Pad Vertical Stiffness and Damping – Continued

(1 MN/m = 5.7 kips/in, 1 kN.s/m = 5.7 lb/in/sec)

Stiffness (MN/m)	Damping (kN.s/m)	Component Details	Source, Test Methods, Frequency Range
150	50	Pad for typical European tracks	Grassie (VSD 24,1995) high frequency, benchmark case
80	20	Typical European track	Knothe (VSD 24, 1995) low frequency, benchmark case
	<u>Loss factor</u>		Vincent & Thompson (VSD 24,1995)
1300	0.25	4.5-mm groove stiff pad/conc. bibloc	Instrumented hammer testing to produce receptance followed by fitting of predicted and measured receptances
500	0.5	No pad/wood tie	
350	0.25	Medium stiff pad/concrete monobloc	
200	0.25	9-mm groove pad/concrete bibloc	
<u>40kN preload:</u>			Thompson & Vincent (VSD 24, 1995) Static loading with hydraulic jack Pad placed between two resiliently mounted masses with excitation applied to the upper mass. Characteristics are determined from the responses of the two masses. For rolling noise
170		1. 4.5-mm ribbed rubber pad	
970		2. Zw687a thin rubber pad	
26		3. 6- & 10-mm pads	
250		4. FC9 4.5-mm cork-rubber pad	
130		5. EVA 4.5-mm rubber pad	
<u>60kN preload:</u>			
300		1. 4.5-mm ribbed rubber pad	
1300		2. Zw687a thin rubber pad	
26		3. 6- & 10-mm pads	
380		4. FC9 4.5-mm cork-rubber pad	
130		5. EVA 4.5-mm rubber pad	
	<u>Loss factor</u>	Same #ed pads w/ following fasteners:	
2250	0.08	1. Nabla fasteners	
3550	0.1	2. Vossloh fasteners	
60	0.2 - 0.3	3. Rheda modifiziert	
3000	0.13	4. DE spring clip	
4000	0.13	5a. DE spring clip	
265	0.05	5b. K fastener, wood tie	
<u>preload 20 kN:</u>			
1060	0.19		
<u>preload 40 kN:</u>		4. FC9 4.5-mm cork-rubber pad	
1530	0.19		
3000 (w/ clip)			
<u>preload 80 kN:</u>			
2750	0.18		
<u>preload 20 kN:</u>			
2120	0.14	5a. 4.5-mm EVA pads	
3000 (w/ clip)			
<u>preload 40 kN:</u>			
3000	0.13		
4000 (w/ clip)			
<u>preload 80 kN:</u>			
3850	0.11		
5960 (w/ clip)			

Table 2. Pad Vertical Stiffness and Damping – Continued

(1 MN/m = 5.7 kips/in, 1 kN.s/m = 5.7 lb/in/sec)

Stiffness (MN/m)	Damping (kN.s/m)	Component Details	Source, Test Methods, Frequency Range
280	50	Pad for BR track	Grassie (IMechE, 1985) Instrumented hammer testing
 1200 120		North American concrete tie track: EVA pad 15-mm soft pad	Cox & Grassie (IAVSD, 1987)
 200 230	Loss factor 0.2 0.2	British concrete tie track (0.75-m tie spacing) British wood tie track (0.8-m tie spacing)	Grassie (PhD thesis 1979) Pad stiffness measured from static load deflection curve taking slope at typical pad static service load. Electromagnetic exciter acting vertically on the rail head with piezo-electric accelerometers measuring the response.
239 99	18.4 26.3	Standard pad Soft pad Baltimore Metro track, which has a booted tie arrangement.	Daniels (FTA, 1993) Quasi-static load/deflection tests at Battelle Laboratories on a 50 kip MTS test machine. The local slope of the characteristic was determined at the appropriate static pad load. A dynamic stiffening factor of 1.5 - 2.0 was applied. Corrugation study
  18 30 61 19	 8.7 7.4 6.4 3.5	Direct fixation track, North American: Baltimore (MTA), 0.91 m spacing Washington (WMATA), 0.76 m San Francisco (BART), 0.76 m Sacramento (RTD), 0.76 m	Grassie & Elkins (IAVSD,1997) Instrumented hammer with accelerometer to measure response. Corrugation study
   335 67	 67 6.7	Australian National's main line track, north of Adelaide. Tie spacing 0.67 m HDPE rail pads, very stiff 10-mm rubber rail pads	Grassie, (IAVSD, 1991) Determined by matching model with experimental data from rail web shear strains, tie railseat bending moments and axle box vertical accelerations. Vehicles had wheel flats.
30 - 300	15 – 150	China railway main line: range was for the following conditions: 50 kg/m rail, jointed rails, wood and concrete ties, regular ballast layer	Li (1985) Pads and ballast results by CARS

Table 2. Pad Vertical Stiffness and Damping — Continued

(1 MN/m = 5.7 kips/in, 1 kN.s/m = 5.7 lb/in/sec)

Stiffness (MN/m)	Damping (kN.s/m)	Component Details	Source, Test Methods, Frequency Range
300 770 480	45 100 49	5-mm pad, light rail, preloaded Note: values already listed under other sources are not repeated here, although they are included in Hempelman's thesis	Hempelman (PhD Thesis, VDI, 1994): Hempelman has plotted pad damping against stiffness for all of the data that he obtained from various sources. This all seems to fall close to a straight line with a slope of 0.135 ms. This seems to imply a constant time constant of 0.135 ms is a reasonable assumption for most rail pads.
150 300 1000 quasi-static 75 150 500	20 30 50	Soft pad Typical pad Stiff pad Soft pad Typical pad Stiff pad	Hunt, BR Research, UK (1996, seminar Hong Kong) General summary
49 – 147 298 – 490 Preload =57 kN 107 preload = 76 kN 210 60 – 95 Preload = 36 kN 700 – 960 preload = 67 kN 980 – 1420 22 – 30 63 – 77 6 – 7 54 – 68		Soft wood tie, DB Hardwood tie, DB Wood tie, 0.36 m plate, Battelle Pad for concrete tie, JNR Shinkansen Stiff pad/fastener for concrete ties, NEC fasteneres Good wood tie Poor wood tie	Ahlbeck, summary paper

Table 3. Ballast Vertical Stiffness and Damping

(1 MN/m = 5.7 kips/in, 1 kN.s/m = 5.7 lb/in/sec)

Stiffness (MN/m)	Damping (kN.s/m)	Component Details	Source, Test Methods, Frequency Range
		UIC60 rail, studded 10 mm Pandrol pad, Pandrol fastenings, concrete ties:	Oscarsson et al. (Chalmers Univ. 1997)
180 kN preload:			Field load wagon tests: static preload, swept dynamic load up to 200 Hz, hammer excitation from 200 to 1200 Hz
641	467	Ballast	
603	508	Subgrade	
260 kN preload:			Parameters are sensitive to preload up to 700 Hz
767	460	Ballast	
637	797	Subgrade	
810 - 2500	980	Ballast for Shinkansen	Ishida, Miurà & Kono (RTRI, 1997) Irregularities with wave lengths 0.03 to 2 m and heights of 1/1000 of wavelengths
50*tie length	34*tie length	Ballast for RE 136 rail, CN 55A concrete ties, EVA tie pad	Raymond & Cai, Canada, (1992)
at railseat: 150*tie length at track center: 10*tie length	 180*tie length 100*tie length	30 cm of 32-64-mm granite ballast for newly built track for high-speed trains, UIC60 rail, studded Pandrol 10-mm rubber pads, Pandrol fastener, concrete monobloc tie,	Igeland (Chalmers Univ., 1996)
20 to 60	50	Ballast in modeling 136 RE rail, CP Rail CT-3 concrete ties, Portec Polyurethane pad 3/16"	Dong & Sankar (Canada, 1994)
20 2300	26 25	Ballast Slab	Diana et al (Italy, 1996) For ballasted track, used impulse excitation, for slab track, used harmonic excitation (not enough energy by impulse), 0 - 350 Hz
70	30 - 82	Ballast used with concrete tie track: 56 kg/m (113 lb/yd), Pandrol fastener, main line quality	Grassie et al (1982) The rail was excited with force amplitude of 50 N from 50 to 1500 Hz. Obtained receptance, not good less than 50 Hz.
72	132	BR track: frozen ballast frozen ballast increased damping	Grassie (IMechE, 1985) Instrumented hammer testing

Table 3. Ballast Vertical Stiffness and Damping — Continued

(1 MN/m = 5.7 kips/in, 1 kN.s/m = 5.7 lb/in/sec)

Stiffness (MN/m)	Damping (kN.s/m)	Component Details	Source, Test Methods, Frequency Range
50 31.6 46.6 64.6 35 35 180 27.8 70 72 100 30.7 41.6 12 55 65 110 180 500 100 140	51 21.8 40.8 35 35 82 16.6 30 132 72 η = 0.2 η = 0.3 30 100 150 240		Knothe & Grassie, (VSD 22, 1993) State of the Art - track modeling paper
80	30	Typical European tracks	Grassie (VSD 24,1995) high frequency, bench mark case
25	25	Typical European track	Knothe (VSD 24, 1995) low frequency, benchmark case
 67 70 50 50	Loss factor 2.0 1.0 1.0 1.0	 4.5mm groove stiff pad/conc. bibloc no pad/wood tie medium stiff pad/concrete monobloc 9 mm groove pad/concrete bibloc	Vincent & Thompson, (VSD 24,1995) Instrumented hammer testing to produce receptance followed by fitting of predicted and measured receptances Particularly the low frequency peaks.
 46.6 24	Loss factor 0.2 0.2	 British concrete tie track (0.75m tie spacing) British wood tie track, (0.8m tie spacing)	Grassie (PhD thesis 1979) Ballast stiffness from static & dynamic tests performed by Birmann (ref cited). Electromagnetic exciter acting vertically on the rail head with piezo-electric accelerometers measuring the response.

Table 3. Ballast Vertical Stiffness and Damping — Continued

(1 MN/m = 5.7 kips/in, 1 kN.s/m = 5.7 lb/in/sec)

Stiffness (MN/m)	Damping (kN.s/m)	Component Details	Source, Test Methods, Frequency Range
33.5	33.5	Australian National's main line track, north of Adelaide. Tie spacing 0.67 m	Grassie, (IAVSD, 1991) Determined by matching model with experimental data from rail web shear strains, tie railseat bending moments and axlebox vertical accelerations. Vehicles had wheel flats.
30 - 400	50 - 400	China railway main line: range was for the following conditions: 50 kg/m rail, jointed rails, wood and concrete ties, regular ballast layer	Li (1985) Results by CARS
100 100 80 30.7 12 55 65 100 180 500 100 140	72 35 100 □=0.2 30 100 100 - - - - 240		Hempelman (PhD Thesis, VDI, 1994) Various testing methods, mainly European. N.B. Hempelman has plotted pad damping against stiffness for all of the data that he obtained from various sources. This all seems to fall close to a straight line with a slope of 0.135 ms. This seems to imply a constant time constant of 0.135 ms is a reasonable assumption for most rail pads.
180	82	1. British track with BS113A rail, tie spacing = 0.7 m, typical track.	
80	100	2. British track with BS113A rail, tie spacing= 0.65 m, with low ballast stiffness & high pad stiffness.	
100	72	3. German track with S49 rail, on a loco builder's test track, tie spacing = 0.625 m	Corrugation
190	100	4. German track with S54 rail, used on secondary lines, tie spacing = 0.64 m	
180	82	5. German track with UIC60 rail, typical European main line track, tie spacing = 0.6 m	
100	35	6. German track with Russian R65 rail, in use on heavy haul & main lines, tie spacing = 0.59 m	
20 80 200	50 100 150	Soft track bed Typical track bed Stiff track bed	Hunt, BR Research, UK (1996, seminar Hong Kong) General summary
quasi-static 10 40 100		 Soft track bed Typical track bed Stiff track bed	

Table 4. Pad Lateral Stiffness and Damping

(1 MN/m = 5.7 kips/in, 1 kN.s/m = 5.7 lb/in/sec)

Stiffness (MN/m)	Damping (kN.s/m)	Component Details	Source, Test Methods, Frequency Range
60	20	Typical European tracks	Grassie (VSD 24,1995) high frequency, bench mark case
25	7	Typical European track	Knothe (VSD 24, 1995) low frequency, benchmark case
 100 177 50 48	Loss factor 0.25 0.5 0.25 0.25	 4.5mm groove stiff pad/conc. bibloc no pad/wood tie medium stiff pad/concrete monobloc 9 mm groove pad/concrete bibloc	Vincent & Thompson, (VSD 24,1995) Instrumented hammer testing to produce receptance followed by fitting of predicted and measured receptances, particularly the low frequency peaks.
380 (1a) 280 (2b) 50 (3c) 22 (4d) 266 (5e) 71 (5f)		1. 4.5mm ribbed rubber pad 2. Zw687a thin rubber pad 3. 6 mm & 10 mm pads 4. FC9 4.5 mm cork-rubber pad 5. EVA 4.5 mm rubber pad a. Nabla fasteners b. Vossloh fasteners c. Rheda modifiziert d. DE spring clip e. DE spring clip f. K fastener, wood tie	Thompson & Vincent, (VSD 24, 1995) Static seat loading with hydraulic jack Pad placed between two resiliently mounted masses with excitation applied to the upper mass. Characteristics are determined from the responses of the two masses.
preload 20 kN: 141 237 (w/ clip) preload 40 kN: 178 266 (w/ clip) preload 80 kN: 200 282 (w/ clip)	 0.18 0.18 0.18	4.5 mm EVA pads	Rolling noise
43		BR track	Clark, Eickhoff & Hunt, (IAVSD, 1981) Determined from instrumented wheelset lateral forces and railhead and tie lateral motions on a track location where a lateral kink had been introduced to represent a turnout entry angle.
 51.4	Loss factor 0.5	 British wood tie track (0.8m tie spacing)	Grassie (PhD thesis 1979) Pad stiffness measured from static load deflection curve taking slope at typical pad static service load.
70 131	8.8 5.6	Standard pad Soft pad	Daniels (FTA, 1993) Quasi-static load/deflection tests at Battelle Laboratories on a 50 kip MTS test machine. The local slope of the characteristic was determined at the appropriate static pad load. A dynamic stiffening factor of 1.5 - 2.0 was applied. Corrugation study

Table 5. Ballast Lateral Stiffness and Damping

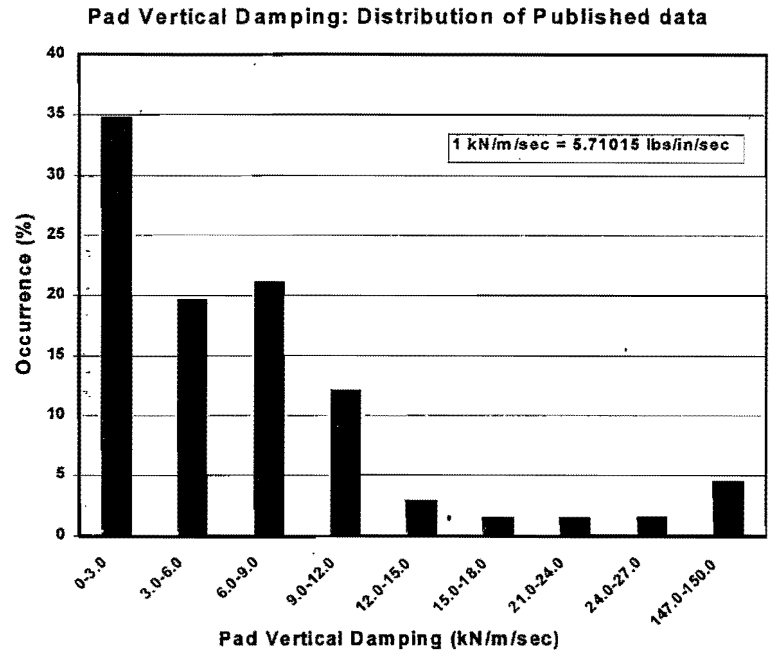
(1 MN/m = 5.7 kips/in, 1 kN.s/m = 5.7 lb/in/sec)

Stiffness (MN/m)	Damping (kN.s/m)	Component Details	Source, Test Methods, Frequency Range
60	20	Typical European tracks	Grassie (VSD 24,1995) high frequency, bench mark case
25	25	Typical European track	Knothe (VSD 24, 1995) low frequency, bench mark case
 34 70 80 70	Loss factor 2.0 1.0 1.0 1.0	 4.5-mm groove stiff pad/conc. bibloc no pad/wood tie medium stiff pad/concrete monobloc 9-mm groove pad/concrete bibloc	Vincent & Thompson, (VSD 24,1995) Instrumented hammer testing to produce receptance followed by fitting of predicted and measured receptances, particularly the low frequency peaks.
37	240	BR track	Clark, Eickhoff & Hunt, (IAVSD, 1981) Determined from instrumented wheelset lateral forces and railhead and tie lateral motions on a track location where a lateral kink had been introduced to represent a turnout entry angle.
377	Loss factor 0.2	British wood tie track (0.8-m tie spacing)	Grassie (PhD thesis 1979) Pad stiffness measured from static load deflection curve taking slope at typical pad static service load.

Table 6. Rotational Stiffness and Damping of Pad/Fasteners

(1 MN-m/rad = 738 kips-ft/rad, 1 kN-m = 738 lb-ft/rad)

Stiffness (MN/m)	Damping (kN.s/m)	Component Details	Source, Test Methods, Frequency Range
0.85 0.35	0.045 0.068	Roll – standard pad Roll – soft pad	Daniels (FTA, 1993)
6.0		Joint rotational to lateral axis	Li (1985)
0.215 (Russia) 0.429 (Hungary) 0.59-2 (Austria, Germany)		Rotational to vertical axis	Kerr
$K_pL_p^2/6$	$c_pL_p^2/6$	L_p - pad length	Oscarsson et al. (Chalmers Univ. ,1997)
0.10 - 2 spikes 0.38 – 4 spikes 0.40 – Pandrol 0.14 – Screw spikes 0.32 – Compression clip		Wood ties 57.1 kg/m rail: About vertical axis	Zarembski (1980)
0.19 - 2 spikes 0.19 – 4 spikes 0.08 – Pandrol 0.21 – Screw spikes 0.11 – Compression clip 0.19 -		About lateral axis	
0.17 - 2 spikes 0.35 – 4 spikes 0.19 – Pandrol 0.29 – Screw spikes 0.22 – Compression clip		About Longitudinal axis	
0.10 – RE115 rail w/ 2 spikes 0.38 – RE115 rail w/ 4 spikes 0.40 – RE115 rail w/ Pandrol 0.17 – RE136 rail w/ 2 spikes 0.37 – RE136 rail w/ 4 spikes 0.52 – RE136 rail w/ Pandrol		Rotational about vertical axis	Zarembski et al. (AAR, 1979) Lab. Tests



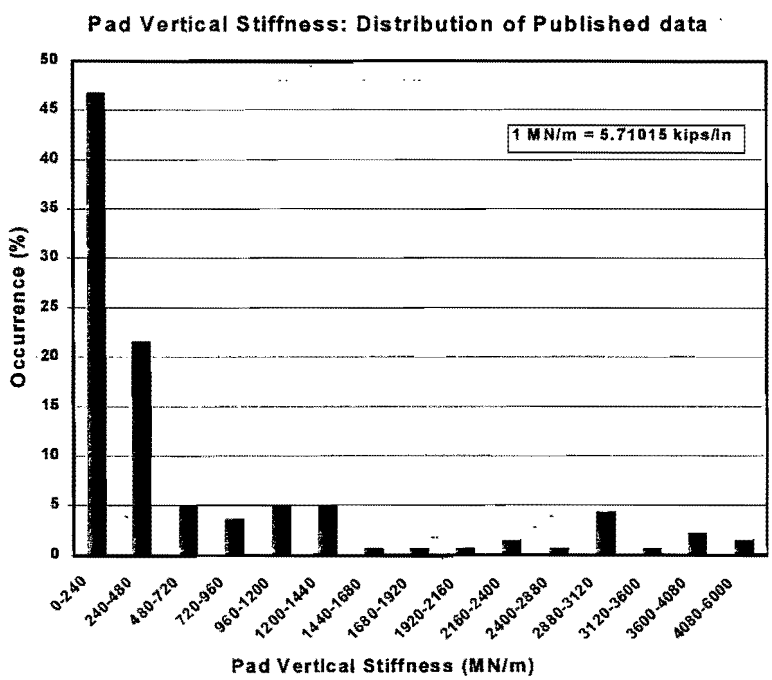
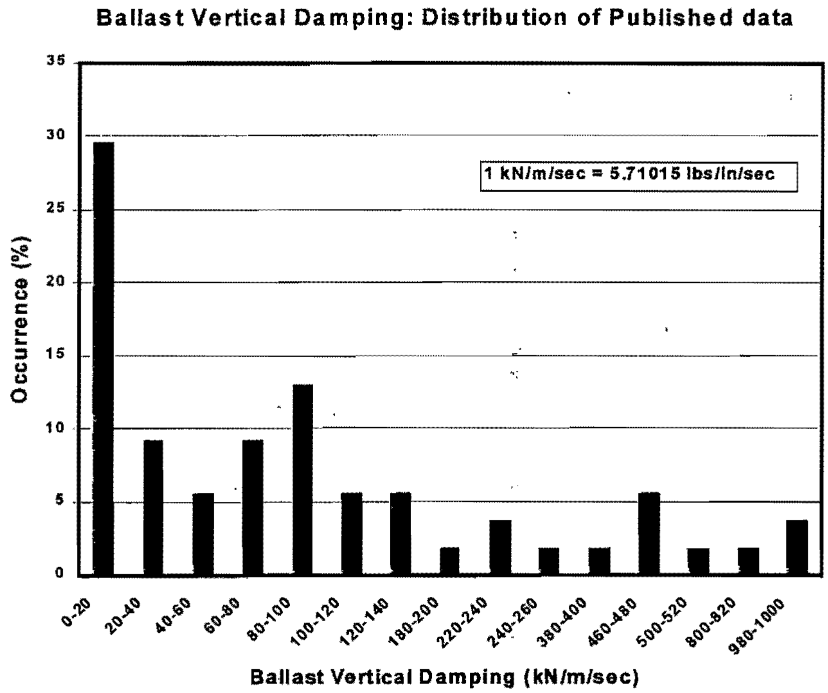


Figure 7. Distributions of Measured Pad Vertical Stiffness and Damping Values



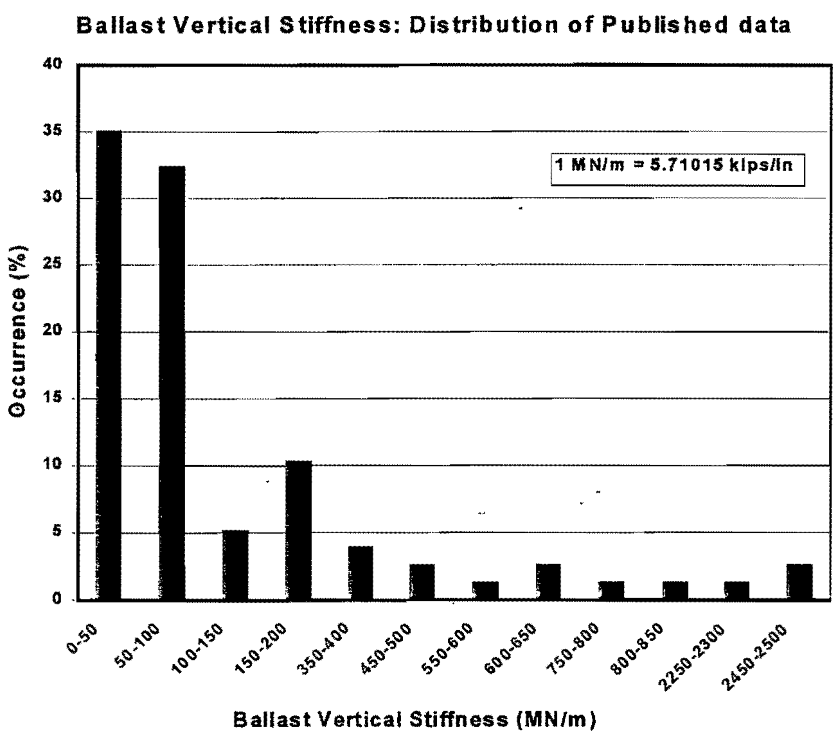


Figure 8. Distributions of Measured Ballast Vertical Stiffness and Damping Values

2.2 STIFFNESS VERSUS QUASI-STATIC TRACK STRENGTH

Several tests have been done to determine track resistances against several deformation modes; e.g., the track modulus test in the vertical direction, the gage widening test for the gage-spreading mode, and the track panel shift test for the tie-ballast interface in the lateral direction. These tests can provide results that may be converted to track stiffness values for track modeling needs.

Caution should be used, however, when converting these quasi-static track strength parameters. Firstly, these strength parameters generally represent a collective behavior of several track components responding together. Secondly, measurements of these track strength parameters often include contributions of track components in several deformation modes. For example, gage-widening strength consists of rail translational resistance and rail roll resistance. However, a track stiffness parameter in a track model is often defined only for a single deformation mode. Thirdly, some of these quasi-static parameters such as gage-widening strength and panel shift strength are strongly dependent on vertical loads.

Track modulus gives an indication of the likely performance of ties and substructure layers (ballast, subballast, and subgrade) together in the vertical direction. Assuming rail as a beam on elastic foundation, the resistance, p, of this foundation will be proportional at every point to the deflection, w, of the rail at that point:

$$p = uw \tag{1}$$

To obtain a vertical stiffness parameter per tie in the vertical direction, the following formula can be used:

$$k = ua \tag{2}$$

where, k = vertical track stiffness representing ties and substructure layers

u = track modulus

a = tie spacing

Associated with the definition of track modulus — the foundation supporting force per unit length of rail per unit vertical deflection, track stiffness (K) is defined as the required concentrated force per unit rail deflection, and is related to track modulus by:

$$K = \sqrt[4]{64EIu^3} \tag{3}$$

where, EI = rail bending stiffness.

The difference between these two stiffness parameters is that the one defined by Equation 2 does not include the effect of rail EI; whereas, the one defined by Equation 3 includes the rail EI effect.

Gage widening strength is often given in the form of "compliance"; i.e., increment in gage per gage-widening load, corresponding to a certain level of L/V ratio and tie/fastener conditions. Therefore, a rail-tie lateral stiffness (more accurately gage widening stiffness) can be considered to be the reciprocal of compliance. As discussed earlier, this stiffness represents a collective rail translation and roll deformation behavior.

Track panel strength can be obtained from two different types of tests. One is determined under a stationary test mode in which a complete load deflection relationship is obtained. In this case, a stiffness parameter can be directly derived from a load-deflection curve. The second type is determined under an in-motion test mode (similar to a gage widening test), under which lateral panel deflections are obtained for a given lateral test load (i.e., in a format of stiffness parameter). Whether stationary or in-motion, the derived panel shift stiffness is strongly dependent on a vertical axle load. Moreover, the derived panel shift stiffness should reflect the deformation behavior occurring at the tie-ballast interface, also influenced by lateral panel bending stiffness.

2.3 STIFFNESS VALUES BASED ON QUASI-STATIC STRENGTH

Many factors affect track modulus. A parametric study using analytical track model was conducted.[6] Figure 9 shows the effects of different track components on track modulus. Depending on the subgrade strength, track modulus for a concrete tie track may vary from 2,000 to 10,000 lbs/in/in. The horizontal line represents the track modulus of about 4,000 lbs/in/in for a nominal concrete tie track. Shown in this figure are the effects on track modulus of tie type, tie spacing, static fastener stiffness, ballast modulus, subballast modulus, subgrade modulus, granular layer thickness and subgrade thickness. As discussed earlier, Equation 2 should be used to obtain a vertical stiffness representing the rail foundation; whereas, Equation 3 should be used to obtain a vertical stiffness representing the entire track (including the rail EI).

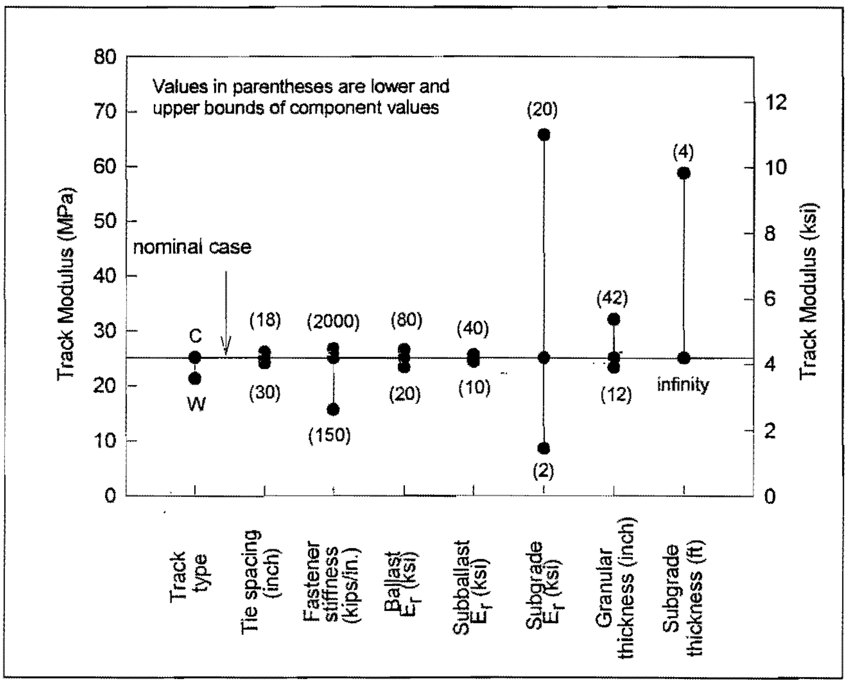


Figure 9. Effects of Track Components on Track Modulus

Lateral track strength parameters were also used in the models to derive damping values (further discussion below).Gage-widening strengths, as represented in compliance, are given in Table 7 for tests conducted on tracks at FAST and in revenue service using the TLV.[7,8] As discussed in Section 2.2, derived stiffness values from those listed in Table 7 should represent collective rail-tie translation and rail roll behaviors.

Table 7. Gage Widening Strengths

Track Conditions	Compliance (inch/kip)	L/V	Comments
Wood ties with four spikes	0.032	0.7 to 0.3	TLV on FAST track
Concrete ties, Pandrol clips	0.02 to 0.032		
Wood ties, Pandrol clips	0.018 to 0.028		
Wood ties, elastic spikes	0.018 to 0.025		
Wood ties, Safelock clips	0.0175 to 0.025		
Azobe ties with five spikes	0.025 to 0.035		
2,000 miles of tracks, various curves, various ties and fasteners	Mean = 0.024 σ = 0.0126 Normal distribution	0.55 L = 18 kips, V = 33 kips	TLV on Revenue service

Lateral track panel stiffness can be determined using Equation 4.[9] This equation correlates the effect of vertical axle load on lateral panel stiffness and was derived based on stationary tests for consolidated wood tie tracks using the TLV. The values of the two coefficients (a and b) are given in Table 8. For newly tamped tracks, at least 50 percent reduction of track stiffness should be considered as compared to consolidated conditions.

$$k_\delta = a + bV \tag{4}$$

where, k_δ = lateral track panel shift stiffness defined at deflection level δ

a, b = coefficients given in Table 8

Table 8. Panel Shift Stiffness Coefficients for Consolidated Track

Panel Shift Magnitude δ (inches)	*a* (kips/inch)		*b* (1/inch)	
	Mean	Range	Mean	Range
0.05	216	141-301	12	8.1-15
0.1	123	60-163	8.8	6.3-13

Also, in-motion TLV panel shift results on tangent wood tie tracks have indicated that under 20 kips of vertical axle load and 18 kips of lateral axle load, a strong track would generate less than 0.04 inch of lateral panel deflection; whereas, a weak track would produce more than 0.1 inch of lateral deflections.

2.4 BALLASTED TRACK WITH SUBGRADE IMPROVEMENT LAYER-DYNAMIC STIFFNESS AND DAMPING CHARACTERISTICS

NUCARS was used by AAR in previous studies of crossing diamond design to determine the optimal track damping needed to minimize vertical loading at high angle crossing frogs.[2] In these studies, the effect of varying damping on vertical forces was found to be 15- 30 percent (over the range of values considered likely to occur in the field). This significant effect of damping on vertical loading, suggested that damping be explored as a design parameter in high angle frogs. The model also suggested that a damping value of approximately 300 lbs/in/sec/tie/rail was optimal for minimizing vertical forces at high angle frogs. Another value may be optimal for minimizing train resistance vertical forces in conventional track.

In an attempt to evaluate means, manner, and materials to improve the damping characteristics of high-angle frog foundations, TTCI previously measured the damping characteristics of ballasted track test segments with various subgrade improvements (Figure 10)[1]. The subgrade improvements that are typically used under turnout and crossing diamond frogs included: a reinforced concrete slab, HMA pavement, a subballast cellular confinement system (GEOWEB). The damping of a subballast control segment was used to compare the effect on damping due to the improvements. There were differences in the damping characteristics of the four test segments. The GEOWEB section had the highest damping; but this section still had much less damping than the theoretical optimal value (Table 9).

The dynamic effects of track stiffness and damping can be significant in terms of impact forces to track and vehicles, track degradation, component lives, and fuel usage. Recent AAR estimates of industry spending suggest that North American railroads are investing well over $240 million per year to maintain roadway and ballast. In addition, the estimated annual cost of operating turnouts and crossing diamonds on heavy haul lines is over $300 million. Special trackwork, having the most severe dynamic load environment, has a relatively short life. Special trackwork also has much more to gain from a foundation designed to provide optimal dynamic performance.

Significant achievements and findings of this study:

- An experimental field method was developed to measure the damping and stiffness characteristics of a variety of track substructure designs.
- Using this method, track design and maintenance engineers can evaluate the effect of various subgrade improvements, as well as the effect of new and improved track components on special trackwork performance.

- Tests showed typical ballasted track has a damping value of 55.5 lbs/in/sec/tie/rail. This is below the predicted optimal value of 300 lbs/in/sec/tie/rail needed to minimize frog flangeway gap dynamic loading.
- Of the typical subgrade improvement methods tested, the GEOWEB was able to increase track damping (as compared to the control section) the most — by about 13.1 lbs/in/sec/tie/rail, or 24 percent. The 8-inch HMA pavement did not significantly affect track damping (55 lbs/in/sec/tie/rail) and the 12-inch concrete slab decreased damping by 30 percent to 39 lbs/in/sec/tie/rail.
- The impact hammer/accelerometer field measurement method combined with NUCARS simulation is effective in determining the damping characteristics of ballasted track. A preload is needed for ballasted track to eliminate any track structure gaps (e.g., between rail and tie).
- Three vertical track vibration modes were found:
  1. Vibration of rail and ties on the ballast (rail-tie in-phase) at about 200 Hz
  2. Vibration of rail on the ties (rail-tie anti-phase) at about 500 Hz
  3. Vibration of rail due to its own elasticity (pinned-pinned) at about 1,300 Hz
- The dynamic stiffnesses of the test sections were considerably higher than the static stiffnesses. Track stiffness appears to be very load rate sensitive. For high frequency impulse events, such as frog impacts, a dynamic modulus value is needed. Measured static track moduli were 2,600 to 3,500 lbs/in/in for the four test sections. Calculated dynamic moduli were from 18,000 and 22,000 lbs/in/in.

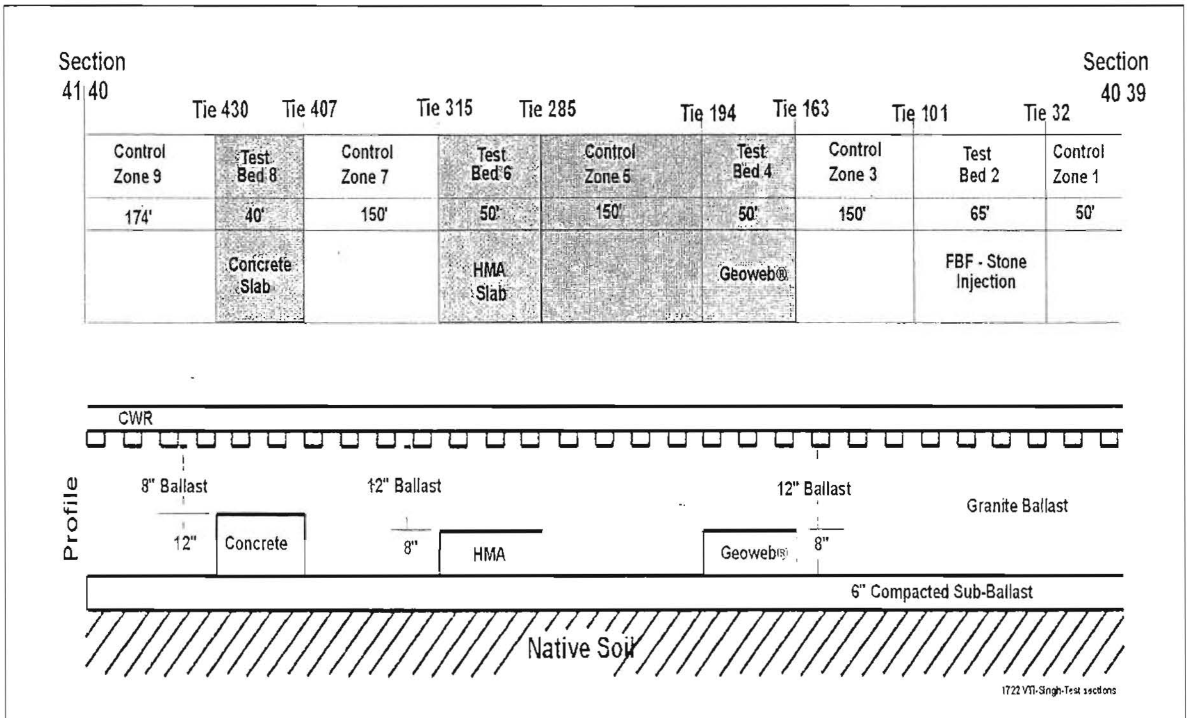


Figure 10. Schematic of Subgrade Improvement Track Segments in Section 40 at FAST

Table 9. Comparison of Ballast Performance with Subgrade Improvement Layers.

(Field Response of Track was Matched using NUCARS Two-Layer Model and Adjusted for a Center-Bound Tie)

Improvement Layer	Fundamental Frequency (Rail-tie In-phase Mode)	Per Tie-Length		Per Inch of Tie-Length	
		Dynamic Resistance	Damping	Dynamic Resistance	Damping
	Hz	lb/in	lb/in/sec	lb/in	lb/in/sec
Concrete Slab	212	962,500	77.5	9436	0.76
HMA Pavement	220	1,075,000	110.0	10,540	1.08
GEOWEB Layer	204	900,000	137.5	8823	1.35
Control Track (No Improvement)	208	925,000	111.3	9069	1.09

3.0 EVALUATION OF TRACK DYNAMIC PARAMETERS

The track structure acts as both a load-distributing and an energy-dissipating structure. While the load distribution among various components takes place according to their relative stiffnesses, energy dissipation occurs as a function of damping in the track. Even though the load is distributed through the ballast and other layers in overlapping pressure patterns to the subgrade, the overall measure of quasi-static vertical track stiffness is usually made in terms of its modulus. The evaluation of quasi-static track modulus is a simple procedure that involves measuring the track vertical deflections under a range of gradually applied controlled loads.

Dynamic track stiffness, on the other hand, is a reflexive response of the track to a suddenly applied load, i.e., impulse ($F \times \Delta t$), where F is the magnitude of the load and Δt the duration of application of this load. The resulting track response ensues because of the application of velocity, [$v = (F \times \Delta t)/m$; m = mass of track], instead of the force. Similarly, damping comprises of complicated energy dissipation due to dry friction and wave propagation. Unlike the easy evaluation of quasi-static track modulus, a simple and direct method to either measure track damping or dynamic stiffness is not available.

TTCI has, however, developed and refined a method for the field measurement of damping and dynamic stiffness of ballasted track. The method uses an impact hammer and accelerometer system to excite the track and measure its response. Modeling of the track response in NUCARS then allows TTCI to reproduce the field data and provide an estimate of the damping and dynamic stiffness characteristics of the ballasted track.

3.1 NUCARS TRACK MODEL

Components of a typical vehicle/track system are shown in Figure 11. NUCARS Version 3.0 provides the capability for modeling the interaction of rail vehicles and track. Therefore, detailed models of both the vehicle and track system can be assembled. The determination of track characteristics depends very strongly on the particular track modeling application. The required frequency range of the simulation is the primary consideration, as Figures 12 and 13 show.

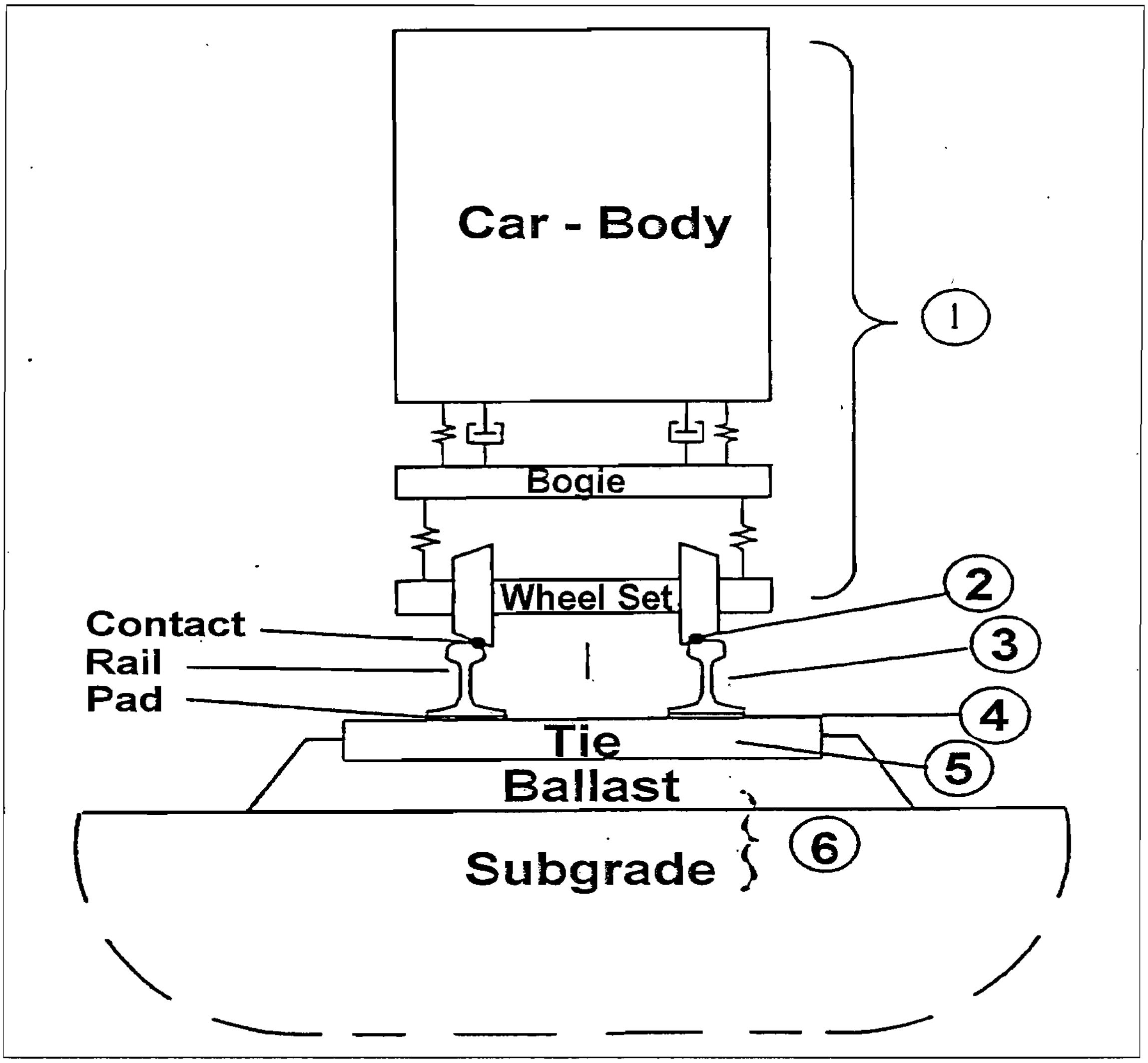


Figure 11. Components of Vehicle/Track System

Figure 12 deals with the frequency aspects in the vehicle/track interaction; whereas, Figure 13 enumerates the various frequency ranges in the vehicle/track interaction. In this sense, the typical ballasted track structure has its fundamental resonant frequency at about 200 Hz, where the combined mass of the rails and ties essentially bounces on the effective ballast stiffness (Figure 2). Characterization of track response therefore requires higher frequency modeling. Since modeling of dynamic vehicle response is significant only at frequencies lower than 20 Hz, the higher frequency modeling of track response does not require inputs of the car body parameters. Thus in this study, the mathematical models of only the ballasted track were assembled using Version 3.0 of NUCARS to compare the response of the track in the tests and to assess track characteristics.

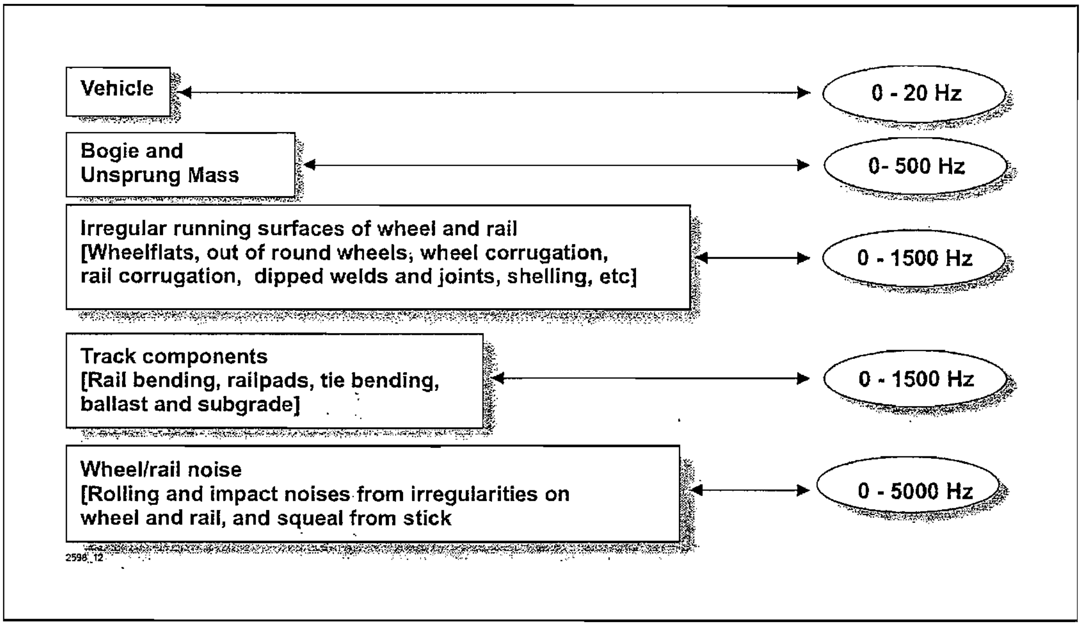


Figure 12. Frequency Aspects in Vehicle/Track Interaction

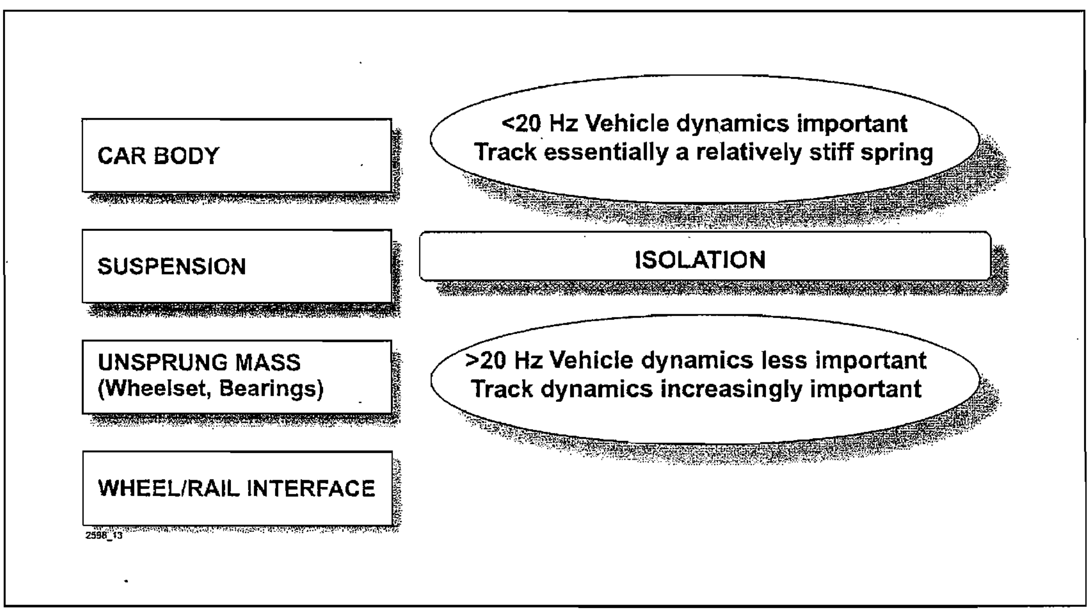


Figure 13. Frequency Ranges in Vehicle/Track Interaction

Both the one- and two-layer models were assembled to examine the effects of track parameters (stiffness and damping) on the track response behavior. In the one-layer model, the separate characteristics of rail pads, ties, ballast, and subgrade were combined in one layer to represent the rail-to-foundation (spring/damper) connections. Thus, the rail was supported by spring/damper connection at each tie location. In the two-layer model, separate spring/damper connections between rails and ties, representing the pad-fastener characteristics (in the absence of pads, representing the tie resiliency at the rail seat), were also introduced. Ties were considered as elastic beams and were divided into eight segments of equal lengths. Each of these segments was then supported by spring/damper connection representing the tie-to-ballast characteristics. The complete set of track parameters (characteristics) for various track components, in the two-layer model for example, may include those listed in the following table, Table 10.

Table 10. Track Parameters for a Comprehensive Two-Layer Track Model

Component	M	c_x, c_y, c_z	k_x, k_y, k_z	c_θ, c_ϕ, c_ψ	K_θ, k_ϕ, k_ψ	EI_x	EI_y	EI_z	GJ_{xx}
Rail	*						*	*	**
Pad/fastener		*	*	**	**				
Tie	*					*		*	
Tie-ballast Connection		*	*						

m: Mass
c: Viscous damping
k: Linear or rotational stiffness
EI (GJ): Bending or torsional stiffness
x: Longitudinal direction
y: Lateral direction
z: Vertical direction
ψ: Yaw direction
θ: Roll direction
ϕ: Pitch direction
*: Translational parameter
**: Rotational parameter

Schematics of both the one- and two-layer comprehensive models are shown in Figures 14 and 15. RE136 rails and 8-foot 6-inch-long concrete ties (28-day compressive strength 7500 psi, width 10.5 inches and depth: end 8.2 inches rail seat 8 inches and center 7 inches) at a spacing of 24 inches were used. Preloads comprising of 125-ton loaded car on each end of the test location on the track were represented in the model as static wheel load of 39,000 pounds at each wheel location of the 125-ton cars on the test track. The total rail element length was 1,500 inches (62 ties). The input force to the model was a vertical swept sine (0 to 3,000 Hz) with a magnitude of 10,000 pounds. In the one-layer model, 2 bodies (rails) having 150 rail-foundation connections were simulated. In the two-layer model 77 bodies (rails and ties) having approximately 767 rail-tie and tie-ballast connections were simulated.

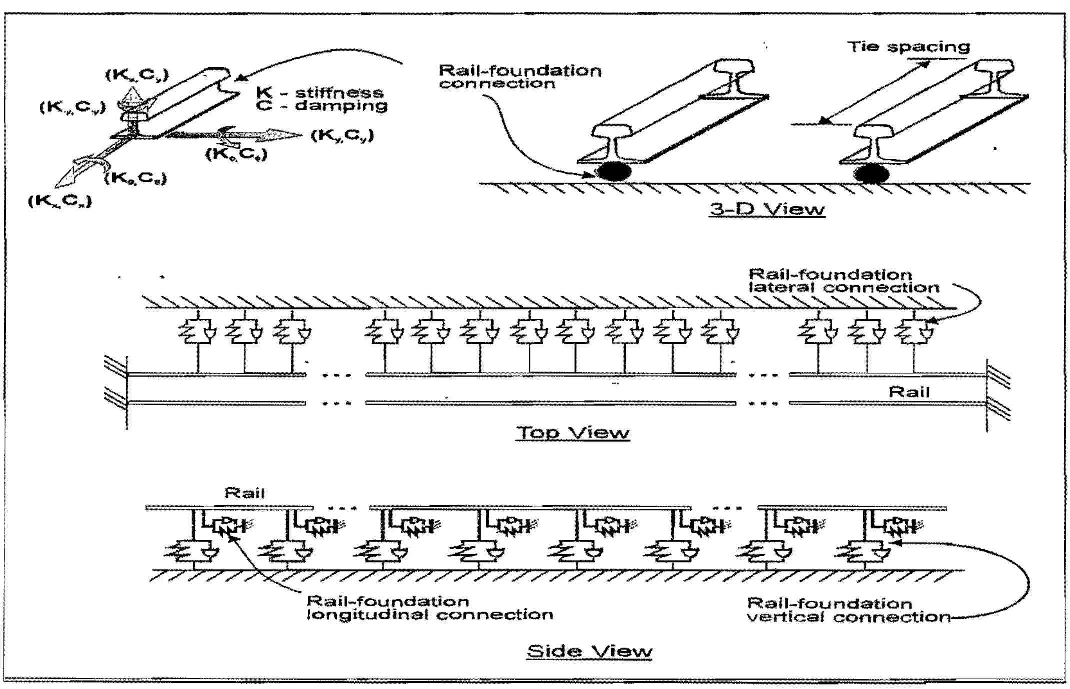


Figure 14. Comprehensive One-layer Track Model

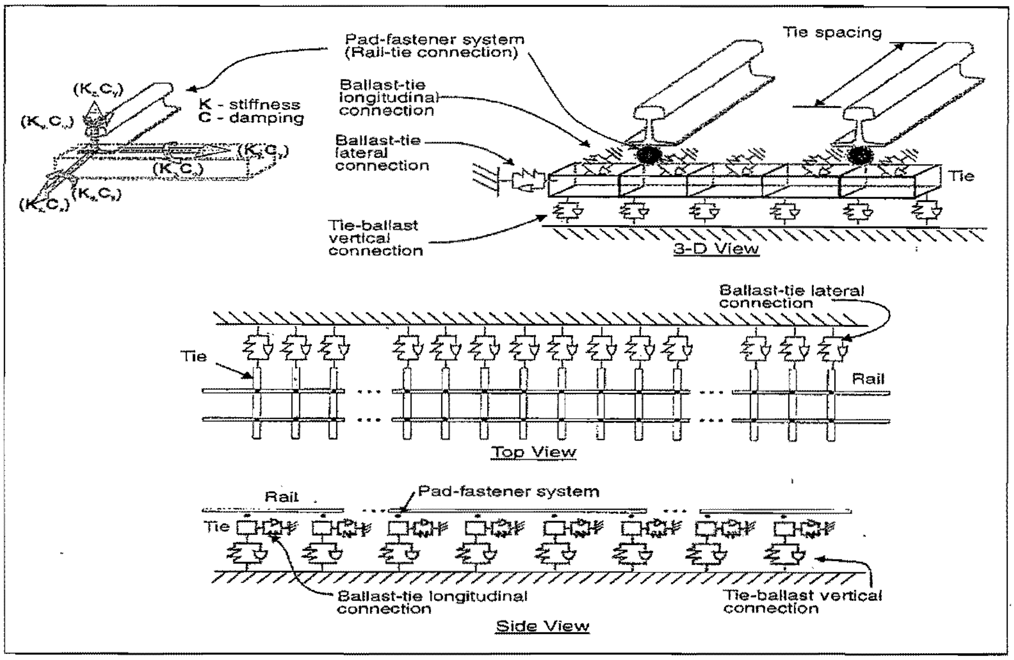


Figure 15. Comprehensive Two-Layer Track Model

The track response behavior was represented by receptance, which is defined as dynamic vertical displacement of the rail divided by the dynamic input force applied on the rail. A receptance has two components in magnitude and phase and is a function of input frequency. *The one- and two-layer NUCARS models actually used for assessing the track vertical damping and dynamic track vertical stiffness were as Figures 16 and 17 show. This simplification was achieved because the track response was restricted to be in the vertical direction only.* The preferred model was the two-layer model because the ties in this model were simulated as elastic beams to represent the field situation more realistically. A typical match between receptance measured in the test and the one generated using NUCARS two-layer track model, from a previous study, is shown in Figure 18.

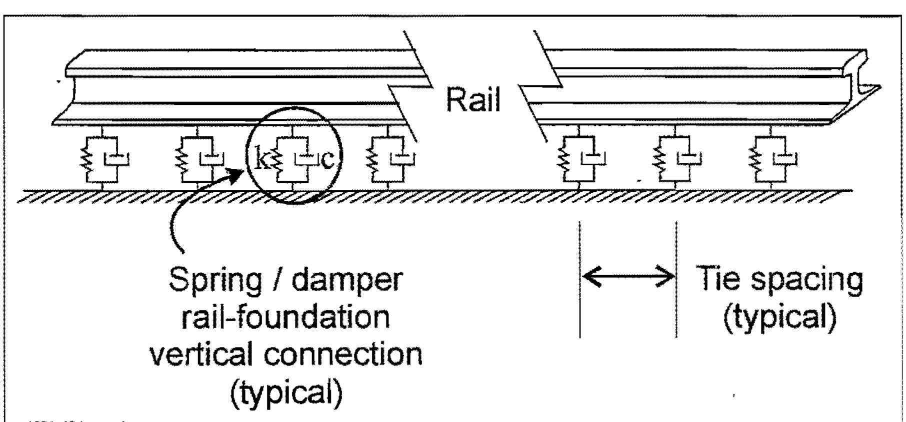


Figure 16. One-layer NUCARS Track Model for Vertical Vibrations

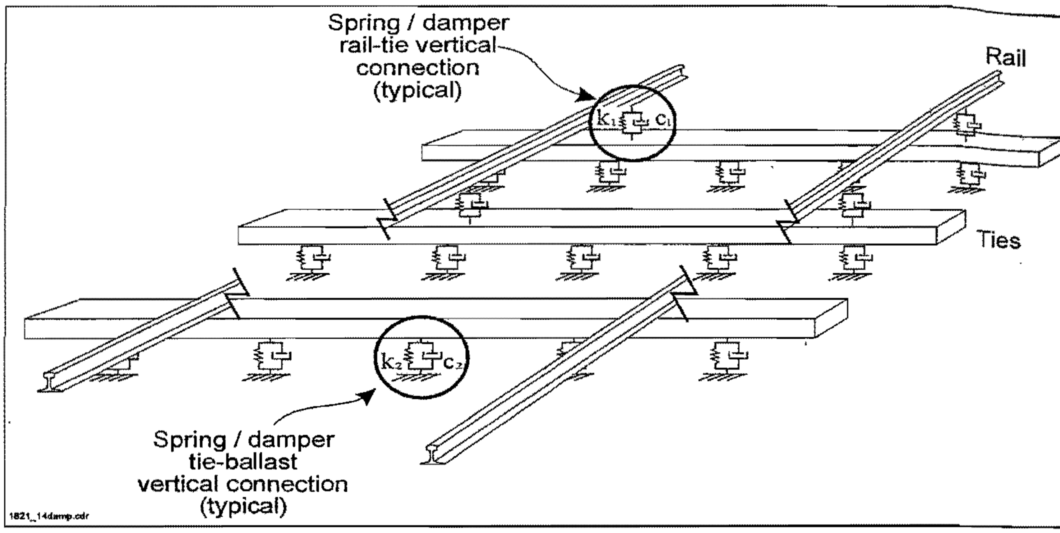


Figure 17. Two-layer NUCARS Track Model for Vertical Vibrations

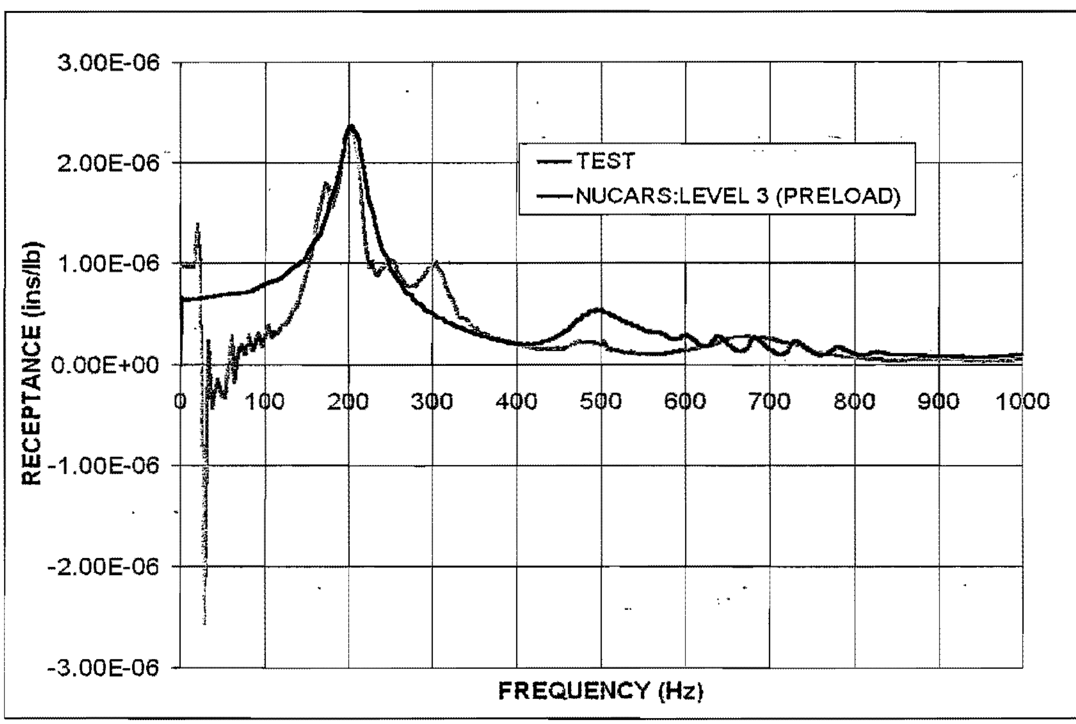


Figure 18. Test/NUCARS Model: Matching of Receptance Amplitudes

3.2 HAMMER TEST METHOD

The most promising of the available methods, for track parameter characterization, is the use of an instrumented hammer to provide the excitation and accelerometers to measure the response of the track. A typical hammer test setup may be as Figure 19 shows. Accelerometers are placed on top of the rail, and an input force is applied by hitting the rail with an instrumented hammer. The measurements of the input force and the accelerometer responses then provide the means to evaluate track characteristics. Even though the hammer method limits the characterization to linearized parameters, it provides a rapid means of testing; and the equipment required for the test is easily portable. The various concerns regarding the relatively small magnitude of the excitation provided to the track by striking it with a hammer, the required hammer characteristics for various track conditions, the data collection and interpretation procedures for determining track characteristics are discussed in the following sections.

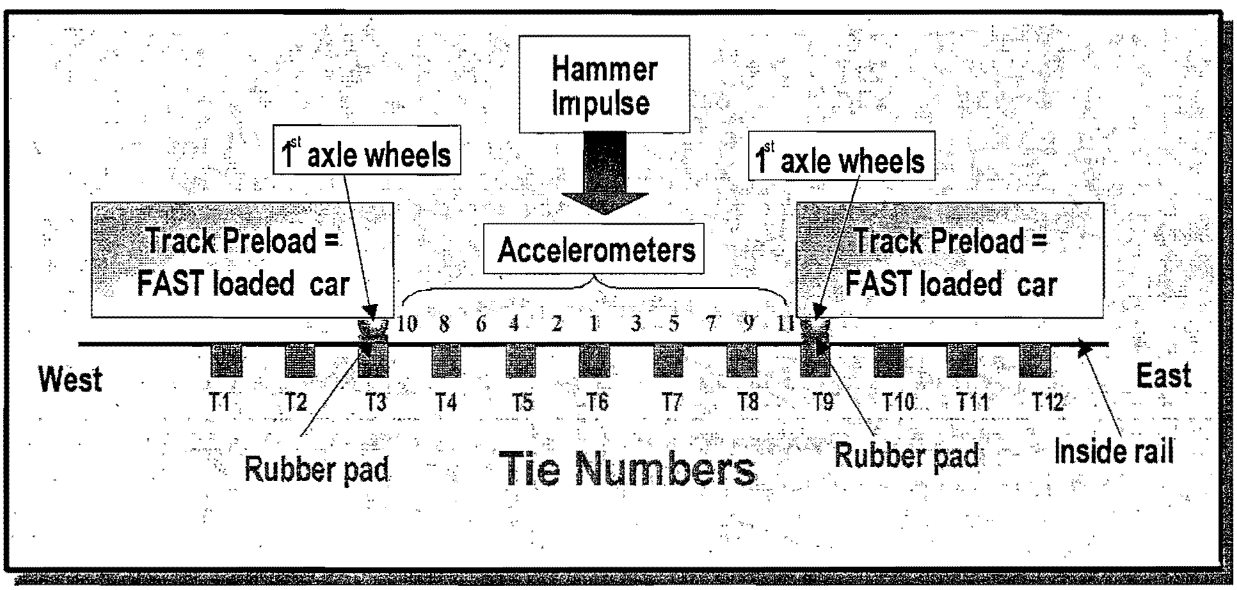


Figure 19. Typical Hammer Test Setup in a Previous Test Conducted at FAST

3.2.1 Description of Hammer Test Method

When an instrumented hammer is used to excite the track, the resulting track response is of very short duration. This response is most conveniently measured using accelerometers. The input force from the hammer (Figure 20) and the resulting rail accelerations (Figure 21) must be captured using a digital data collection system, with software specifically intended for collecting transient data. Since track consists of high frequency responses as indicated in Figures 12 and 13, the test must ensure that the hammer hit imparts frequencies to the track that are of sufficient range to excite the track in the desired resonance or normal modes. The range of frequencies imparted can be checked by making a power spectral density (PSD) calculation on the hammer force (Figure 22). The Fourier transform techniques are then used to produce transfer functions between input hammer force and the resulting track-acceleration outputs. Although the track response is most conveniently measured in terms of its acceleration, the most suitable form for the transfer function is displacement per unit force; i.e., receptance. This is calculated from the acceleration per unit force transfer function. The magnitudes and widths of these measured receptance peaks, as well as the corresponding frequencies, are directly related to the stiffness and damping characteristics of the track.

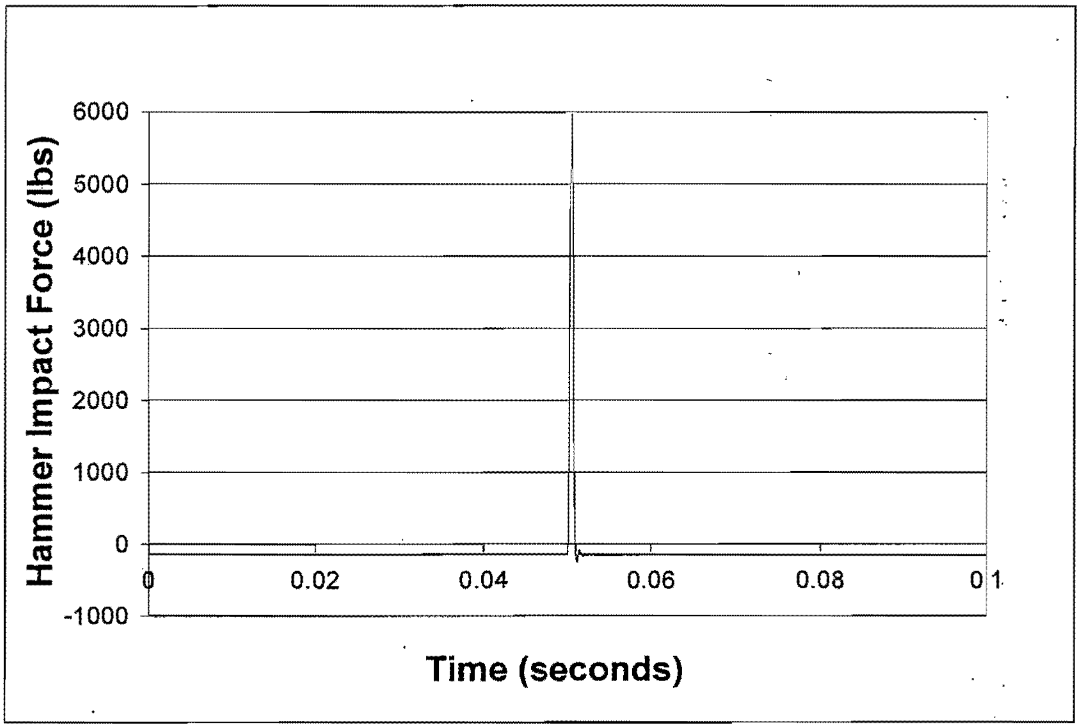


Figure 20. Time History of a Typical Hammer (Hit) Impact Force

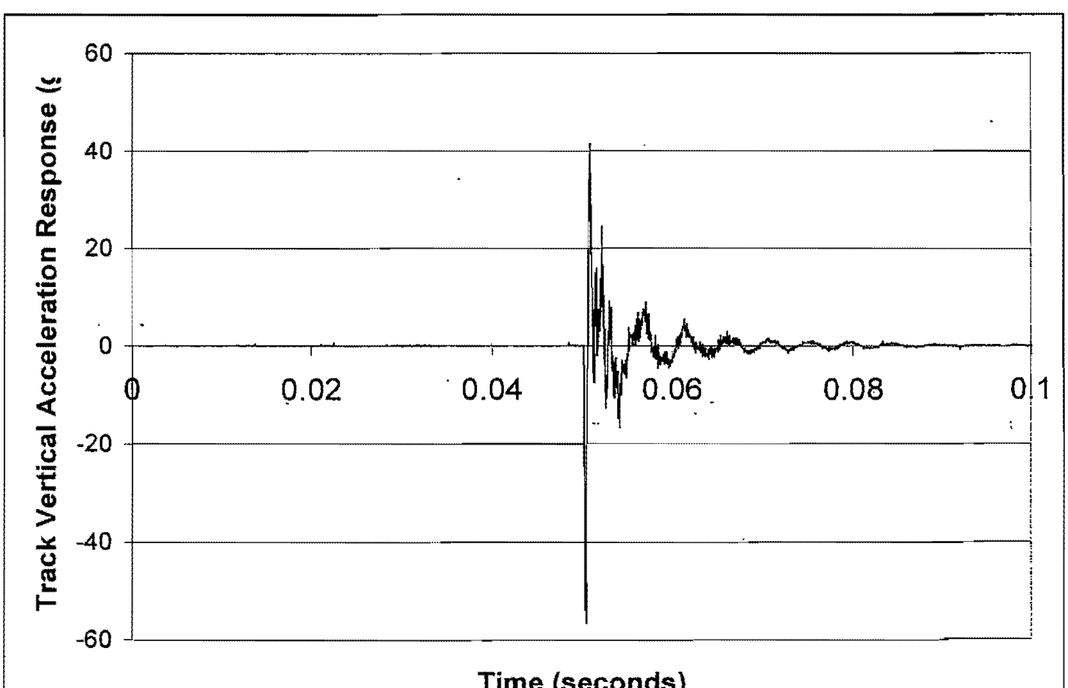


Figure 21. Time History of a Typical Rail (Accelerometer) Acceleration Response

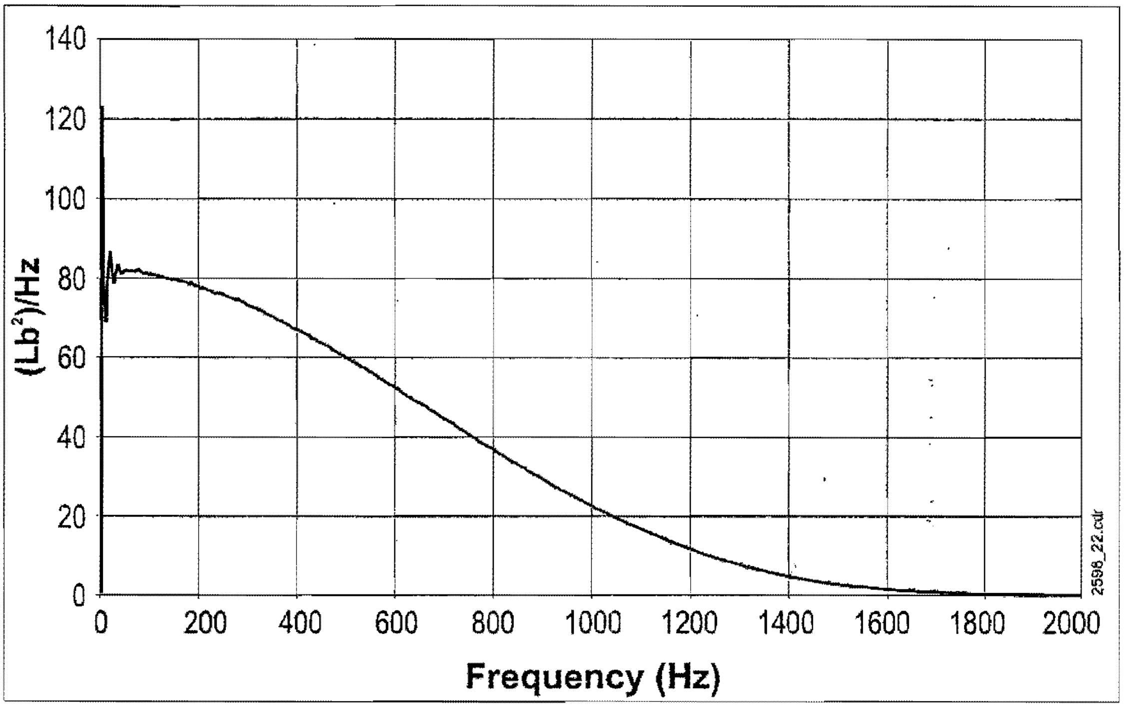


Figure 22. PSD of a Typical Hammer Force (Hit) at a frequency Resolution of 4 Hz

The method used to determine the unknown track characteristics (stiffness and damping) involves matching the predicted receptance from a track model (e.g., using NUCARS) with the measured receptance in the hammer test. The stiffness influences the frequency and magnitude of the peak in the receptance, and the damping controls its magnitude. Therefore, by adjusting the stiffness and damping values in the model, a reasonable match can be obtained between the predicted and measured receptances. This is the method used for determining the track characteristics from hammer testing. The rail's pinned-pinned frequency, which depends only on the mass per unit length of the rail, its bending rigidity EI, and the support spacing can also be verified by comparing the predicted and measured frequencies.

The magnitude of receptance at zero frequency is the track flexibility or inverse of track stiffness (Equation 1 in Section 2.2) that is related to the track's vertical quasi-modulus. The hammer method cannot directly measure this zero frequency magnitude. The low frequency receptance results could be extrapolated to provide an estimate of track stiffness at zero frequency. It should however be cautioned that human involvement in making a hammer hit does often result in double or triple hits that produce "chatter" at low frequencies in the receptance results. The reliability of the track's quasi-modulus determined by extrapolating low-frequency receptance results is not great, which is due to this chatter or peaks at low frequencies, which probably also contain spectral peaks in the hammer-force excitation.

For a wood or concrete tie ballasted track, the track model should be considered to have at least two layers; the upper layer representing the stiffness and damping characteristics of the pad/fastener system between rails and the ties, and the lower layer representing the ballast stiffness and damping characteristics below the ties. The rails and ties can be modeled as Bernoulli beams such that the effects of bending and mass inertia are considered. The identity of the resonant (normal) modes for such a track structure can be verified by calculating the cross-spectrum magnitudes between the acceleration at a particular location with accelerations at other locations on the rail in the test. As an example, the cross-spectrum magnitudes of acceleration at location 2 and accelerations at other locations (Figure 19), from test results in a previous study, are given in Figure 23. These cross-spectrum results are quite significant and reveal dominant peaks at about 200, 500, 800 and 1300 Hz.

The typical receptance characteristics for such a two-layer system will also contain these major peaks. The first peak, at lower frequency (e.g., 200 Hz), will correspond to the mode where rails and ties move in-phase relative to the ballast. The second higher-frequency peak (e.g., 500 Hz) may be associated with a mode of the system where the rail and ties move in anti-phase. The highest peak (e.g., 1300 Hz) may represent the pinned-pinned characteristics of the track. In this mode, the displaced shape of the rail has a wavelength of approximately two support (tie) spacings, with nodes close to the supports. The calculated pinned-pinned frequency for a new 136RE rail section and 20-inch tie spacing is approximately 1487 Hz. The peak at 800 Hz in Figure 23 probably represents one of the higher vibration bending modes of the tie.

The ballast characteristics are deemed to have the largest influence on the first peak in the receptance, where the rails and ties are moving in phase. The pad/fastener characteristics, on the other hand, are deemed to have the largest influence on the second peak, where the rails and ties are moving in anti-phase. If the identity of normal modes is not to be verified, measurement of accelerations at only two locations on the rail, one at the tie location and other at the adjacent crib location, should suffice in the hammer tests performed to evaluate the damping and dynamic track modulus characteristics of the ballasted track.

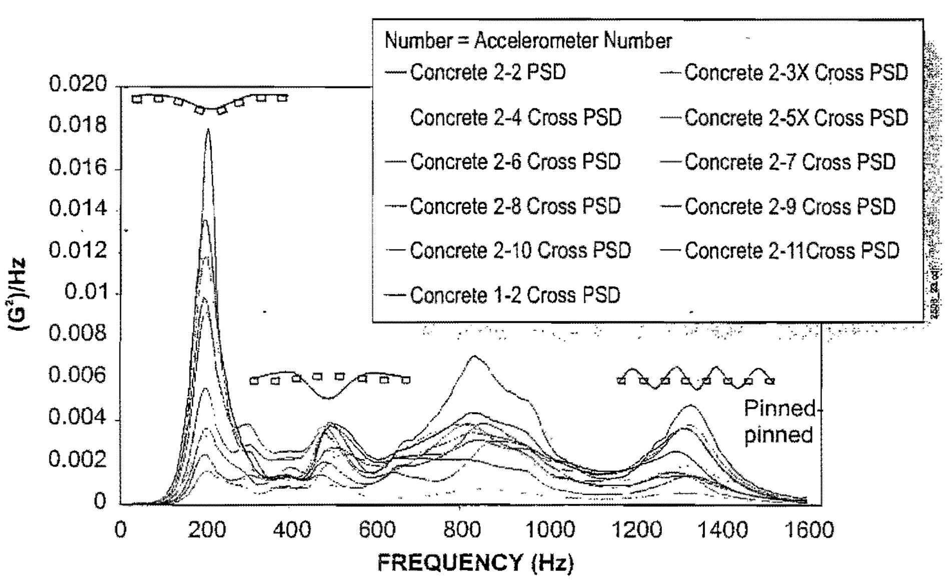


Figure 23. Cross-Spectrum Magnitudes between Acceleration at Location 2 and Other Locations from Hammer Test on Track with Concrete Slab Subgrade Improvement

3.2.2 Hammer Characteristics and Excitation

The hammer characteristics have a significant influence on the excitation of the track system. These characteristics include hammer tip stiffness and hammer tip mass. When the hammer strikes the rail, a very short pulse of force is exerted on the track. The magnitude (F) and duration (Δt) of this pulse control the amplitude and frequency content of the resulting response. If excitation is required to a very high frequency, then a very short duration pulse is required. The highest measurable frequency will be $\leq 1/\Delta t$. A hammer having a very stiff tip provides a short duration pulse. Conversely, if lower frequency response is of interest, then a hammer with a softer tip is necessary. For ballasted track testing, depending on the application, the receptance may need to be measured from a minimum frequency of about 50 Hz up to about 1000 Hz. If the pinned-pinned mode is also desired, the upper frequency may be as high as 2000 Hz depending on the section of the rail used and the tie spacing.

Two types of instrumented hammers can be used. They are the PCB models 086C20 (small hammer) and 086D50 (large sledgehammer), both with steel heads. The large sledgehammer has a wooden shaft; while the small hammer has a steel shaft encased in a rubberized handle for grip (Figure 24). Various types of tips that are screwed on to the steel head of the hammer are used to vary the frequency content of the generated hammer impulse. The tip materials include rubber, plastic, brass, and steel. The non-metallic tips are predominantly classified as super soft (gray tip), soft (brown tip), medium (red tip) and hard (black tip). The super soft rubber tip is suitable only up to a few hundred hertz. The plastic, brass, and steel tips have all been found suitable for track tests. The medium and hard plastic tips have been used more often because the hammer strikes produce less permanent deformation on the tips. Also the double-hits are less prone with these tips as compared to the metal tips.

Both the small and large hammer is rated for approximately 6000 pounds of peak force. The large sledgehammer is generally used for exciting wheelset and truck flexible and rigid body modes in a frequency range from about 5 to 300 Hz. However, for the track system, the sledgehammer with a stiff tip could be useful for frequencies up to about 1000 Hz. An impact force up to about 7000 pounds can also be generated from the large hammer for track input. The small hammer, on the other hand, has been found to be more suitable for track testing. With the added mass (shown in Figure 24 with the small hammer), this hammer generates impact forces between 3,000 and 6,000 pounds. Striking with the tips of hard plastic, brass, or steel materials, the small hammer can generate frequency responses well above 1,000 Hz.

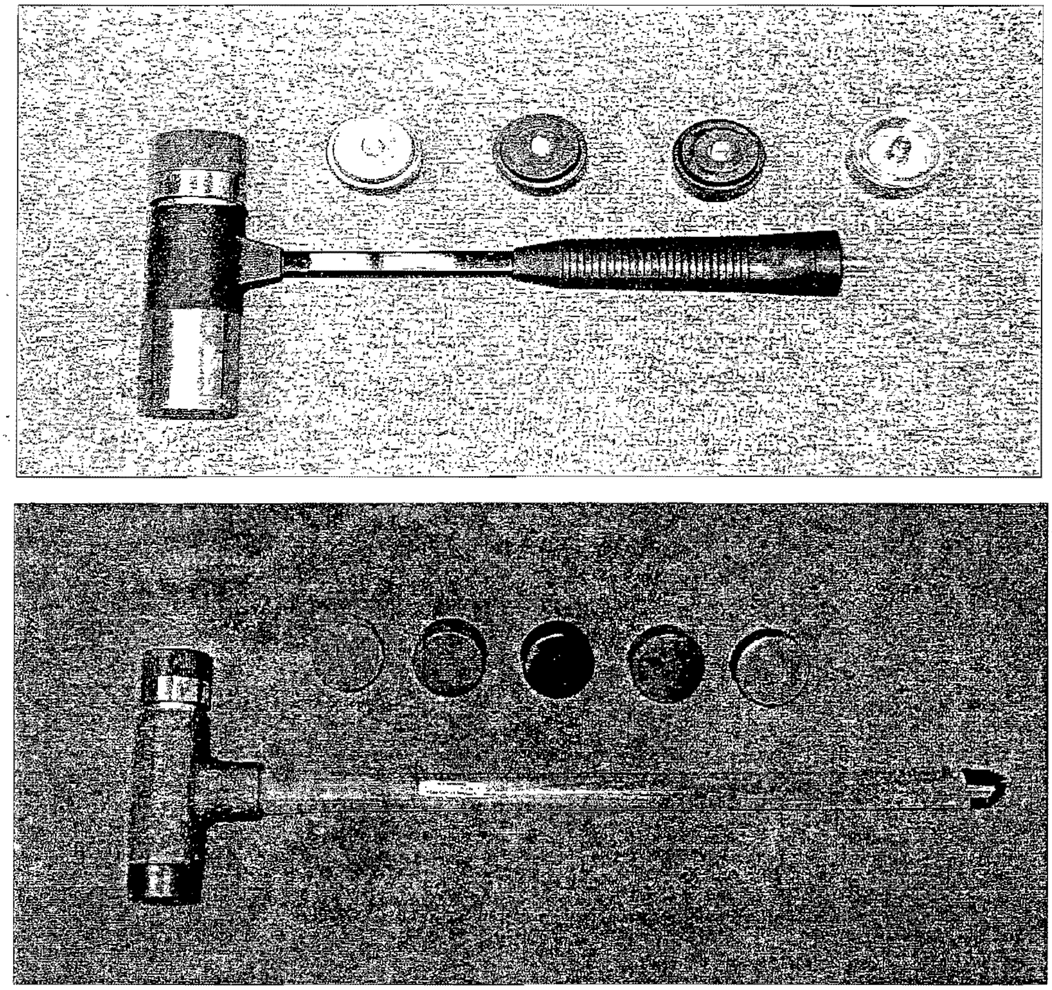


Figure 24. Small and Large Hammers: Various Tips and Added Masses

3.2.3 Impulse and Measurement

The larger the mass and the higher the hammer speed the greater the change in momentum at contact with the rail; thus, resulting in larger impact imparted to the track. This would imply that a large hammer moving with the largest possible velocity would provide the best method of excitation. However, a double hit must be avoided, which tends to be more likely the faster the hammer is traveling. Since a smaller hammer is easier to handle, a double hit in a faster-traveling impact from this hammer is less likely. A small hammer is preferred for track tests. Experience has shown that a hammer moving slightly above the free-fall speed provides the best results. In addition, the allowable force ranges of the hammer may be exceeded (signal saturation) if the impact is too hard.

With the current testing techniques used by TTCI, the large sledgehammer typically imparts a maximum force of about 5,000 to 7,000 pounds, and the pulse durations are about 0.003 to 0.014 seconds depending on the type of tip used. The small hammer (used with the added mass and the hard plastic tip), on the other hand, exerts a maximum force of about 3,000 to 6,000 pounds to the track with pulse durations of less than 0.003 seconds. Both hammers are instrumented with load cells for impact force measurements. The load cell must be calibrated with the specific tip on the hammer before the tests.

3.2.4 Track Response Measurements and Data Acquisition System

Track response should be recorded using accelerometers. Accelerometers could be specified up to a maximum 500 g in magnitude and up to 3000 Hz in frequency response. Because magnetic mountings may allow the accelerometer to "rattle" or vibrate relative to the rail, they are not to be used. Instead, accelerometers should be mounted flat on the rail using a small mounting block and a thin layer of beeswax. Beeswax ensures that positive contact is maintained at all times.

Sampling rate: Since frequency varies from zero to one-half of the sampling rate, the desired sampling rate depends on the frequency range of interest. Furthermore, frequency resolution (or spacing) and the total number of frequency points, in a frequency domain analysis, depend on the Fast Fourier Transfer (FFT) size (or sector points). So that no resonant peaks are missed in the frequency analysis, a finer frequency resolution (or spacing) should be used. For example, if a frequency resolution of 4 Hz is desired and the FFT size is 4096 ($=2^{12}$), then data should be collected at a sampling rate of 4×4096, which equals to 16384 ($=2^{14}$). This sampling rate and FFT size then will ensure that the analyzed results will contain a frequency range from 0 to 16384/2 (=8192) Hz, and a total number of frequency points of [4096/2]+1 (=2049) at a frequency spacing of 16384/4096 (=4) Hz. In a FFT analysis, sector points and a sampling rate that equals a power of two must be used. As can be seen, the data collection system needs to be able to collect data at a very high sampling rate.

Data recording length: As can be seen from the above discussion, the total number of data points needed for the frequency domain analysis equals the FFT size or sector points. For a frequency resolution of 4 Hz and sampling rate of 16,384, the total number of data points needed is 4,096 points. The required data recording length then would be 4096/16384 (=0.25) seconds. Since averaging of results over a number of sectors is preferred, the acceleration data could be recorded for a multiple of sector points. For example, a data record length of 1.0 seconds at 16,384 sampling rate will offer averaging of results over four sectors, each with 4,096 points.

Windows for impact and response: The window to use for the impact is the transient window (square window). This takes the data unweighted during the period of impact, and sets it to zero for the remaining record. The window to use for the response is an exponential window. This can improve signal-to-noise ratio for a heavily damped system, and reduce leakage error due to truncation for a lightly damped system. These two windows should be used very carefully and may be better used during the post data analysis.

3.2.5 Field Test Procedure

Testing could be performed by using both the large sledgehammer and the small hammer. The small hammer is preferred. Accelerometers could be attached to the head and/or foot of the rail to measure track response. Tests could be performed in the middle of a crib and above a support (tie) in both the vertical and lateral directions. Response of the ties is also important to understanding the characteristics of a ballasted track. Therefore, accelerometers could also be placed on the ties in addition to the head and foot of the rail.

For a ballasted wood or concrete tie track, loaded freight cars may have to be placed on both sides of the test site to load the ties against the ballast and to remove any slack between the rails and fastening system. Hand calculations, using the beam-on-elastic foundation theory, could be made to ensure that there is no uplifting of the test site due to these loaded cars. Isolation pads would be required between the wheels of the loaded cars and the rails to eliminate any chatter creeping in the acceleration data due to the vibration of the wheelsets (unsprung mass) on the wheel/rail contact stiffness.

The following information should be recorded for each test. A test log form for use in the field can be developed for record-keeping purposes:

1. Date/time, test location
2. Track type, rail weight, tie type and weight, tie spacing, pad/fastener type
3. Hammer and tip types, hammer signal conditioning
4. Accelerometer type, signal conditioning
5. Any windows for impact and response signals
6. Sampling rate, FFT size, record length, filter frequency
7. Run number
8. Hammer hitting location and direction
9. Response location and direction
10. All other pertinent comments

The measured track receptances should be compared with modeling results from NUCARS to determine pad and ballast stiffness and damping values. This is achieved by matching experimental data and predictions for the principal peaks in the receptance characteristic.

4.0 VERTICAL TRACK MODULUS AND DAMPING CHARACTERISTICS OF THE LOOP OF THE RAILROAD TEST TRACK WITH UNDER-TIE PADS AND BALLAST MAT

The existence of noise and vibration attenuation zones at the RTT at TTC provided added impetus to the search of means and materials in enhancing the damping characteristics of ballasted track at special trackwork locations. In 1998, some parts around the 13.5-mile of the RTT were reconfigured with noise and vibration abatement test beds. Five such concrete-tie test zones, each 300 feet long, were created at 900 feet on centers on a tangent section of the RTT. The typical details of cross section of these track beds are given in Figures 25 and 26. The general design scheme for the five zones are as follows:

Zone 1: Between Stations 124+50 and 127+50
10-mm-thick Rail-seat Pads, New Concrete Ties, E-Clip Fasteners
Rail-seat pads located under rail base in rail seat
Pads are color coded Red/Red, Gray/gray, alternate placement
Dynamic Engineering

Zone 2: Between Stations 133+50 and 136+50.
10 mm-thick Rail-seat Pads, New Concrete Ties, E-Clip Fasteners
Rail-seat pads located under rail base in rail seat
28-mm (about 1.1 inch)-thick Sectional Mats (Used Tires)
2'6"×5'10" Mats located under 18" ballast on Gravel Base
Mats placed in two rows, 11'8" total width and placed perpendicular to track
Dynamic Engineering

Zone 3: Between Stations 141+50 and 144+50.
10 mm-thick Rail-seat Pads, New Concrete Ties, E-Clip Fasteners
Rail-seat pads located under rail base in rail seat
Rolled Mats: 23-mm-thick Pad, 3-mm Cover Flaps
Rolled mats located under 18" ballast on gravel base
Mats cut to 11'8" and placed perpendicular to track
Advanced Track Products

Zone 4: Between Stations 151+50 and 154+50
10-mm-thick Rail-seat Pads, New Concrete Ties, E-Clip Fasteners
Rail-seat pads located under rail base in rail seat
Rolled Mats: 15-mm-thick Pad, 3-mm Cover Flaps
Rolled mats located under 18" ballast on gravel base
Mats cut to 11'8" and placed perpendicular to track
Advanced Track Products

Zone 5: Between Stations 160+50 and 163+50.
10-mm-thick Rail-seat Pads, New Concrete Ties, E-Clip Fasteners
Rail-seat pads located under rail base in rail seat
Under-Tie Pads: 26" Long × 10 ¼" wide × 1.1" thick
Under-Tie Pads are attached to Bottom of Tie with Straps
Under-Tie Pads are flush with end of tie, each side
Dynamic Engineering

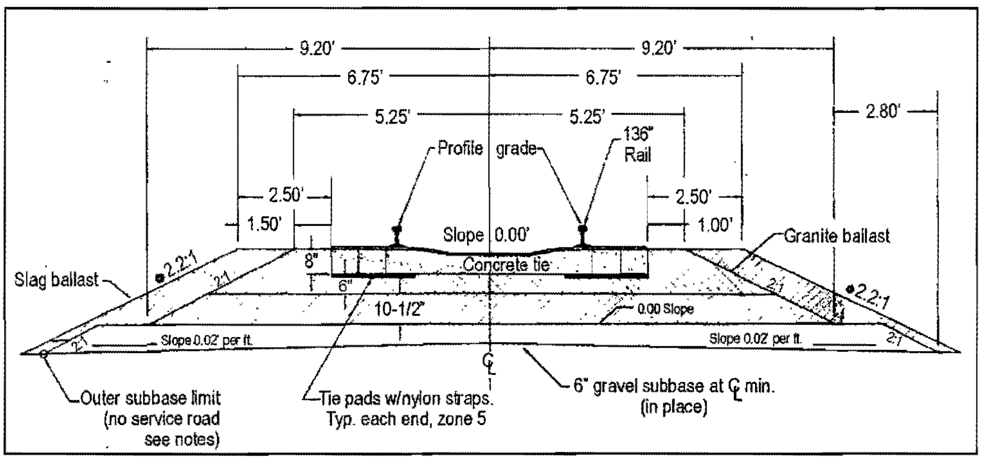


Figure 25. Typical Concrete Tie Zone with Under-tie pads

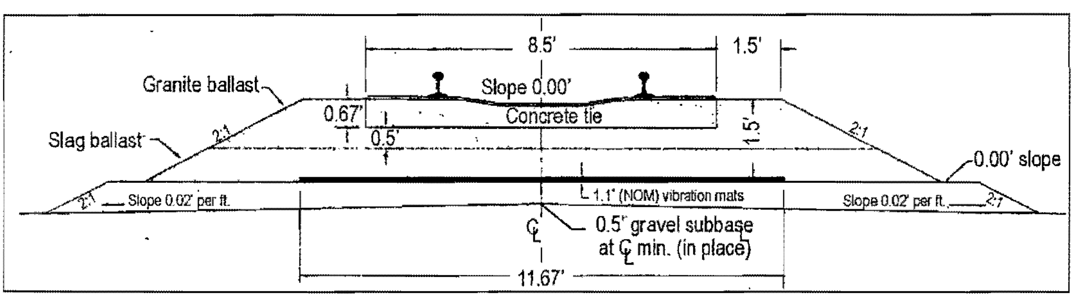


Figure 26. Typical Concrete Tie Zones with Ballast Mat

As seen above, rails in each zone were installed on the ties using 10-mm-thick rail-seat pads (Figure 27) and E-Clip fasteners. As such, the rail-to-tie connection has the same characteristics in each test zone. Zones 2 consisting of used-tire ballast mat (Figure 28), Zone 3 consisting of rolled ballast mat (Figure 29) and Zone 5 consisting of under-tie pads (Figure 30) were selected to evaluate their corresponding damping properties by using the hammer test method and

NUCARS two-layer models of Section 3.1, as Figure 17 shows. RE136 rails and 8-foot 6-inch-long concrete ties (28-day compressive strength 7500 psi, width 10.5 inches and depth end 8.2 inch rail seat 8 inches and center 7 inches) at a spacing of 24 inches were used in the model. Also, a control or reference zone was created at an adjacent portion of RTT open-track by removing the rail-seat pads and replacing them with steel shims of equal thickness. This concrete-tie ballasted control track segment thus did not have any pads or mats in it. A comparison of hammer test results on this control track was used to assess the net increase in damping provided by either using the ballast mats or under-tie pads in conjunction with the rail-seat pads.

Signal conditioning: Syminex signal conditioning was used in this test for both the hammer and accelerometers. An APC05 Charge Amplifier was used for both hammers. An EFM01 Universal Filter Module was used for the accelerometers. The APC05 Charge Amplifier is a high performance, low noise, and multipurpose preamplifier for use with piezoelectric accelerometers. The EFM01 Universal Filter Module is a two-channel programmable filter with a differential programmable gain input amplifier and output scaling capability. It can be used as a DC excitation sensor amplifier.

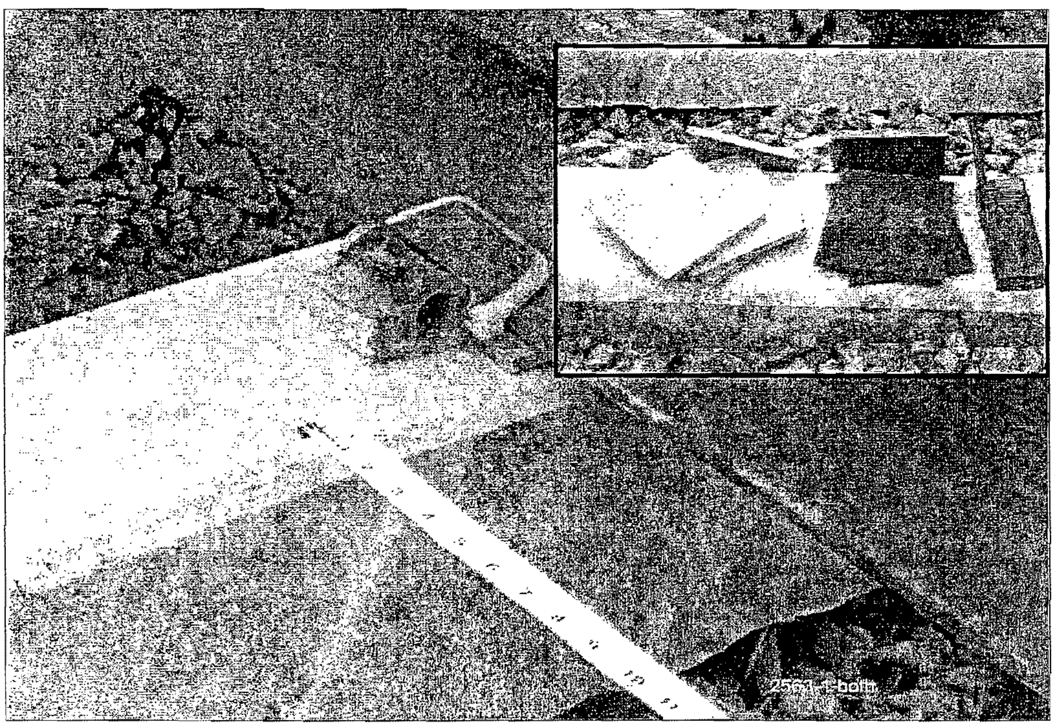


Figure 27. Rail-Seat Pads used on RTT Segments (All Zones)

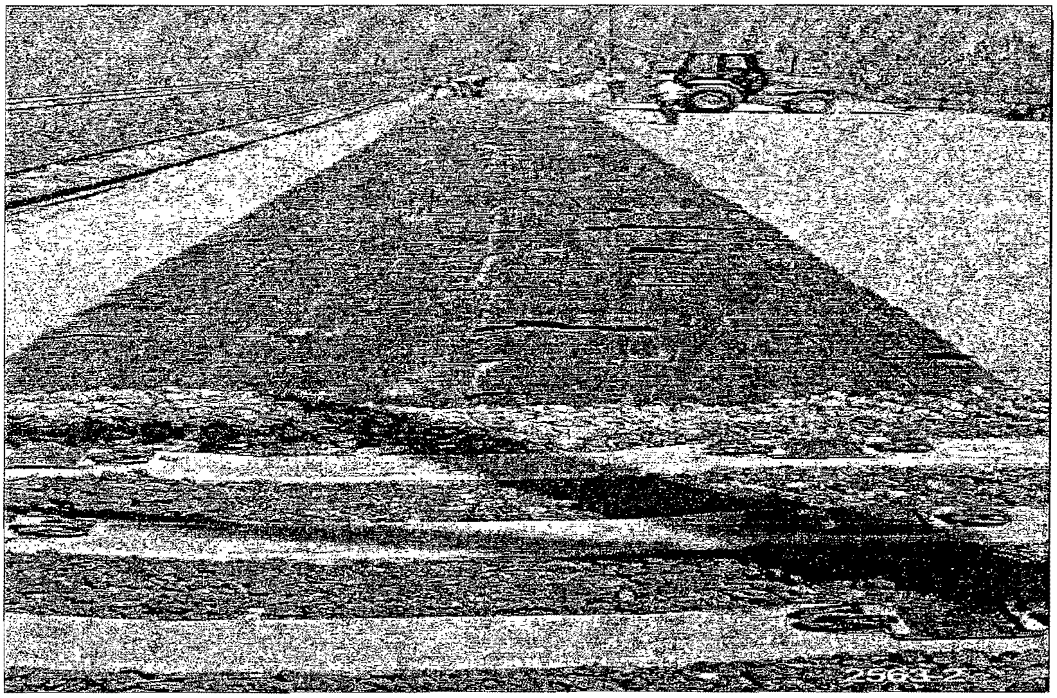


Figure 28. Used Tire Ballast Mat on RTT Segment in Zone 2

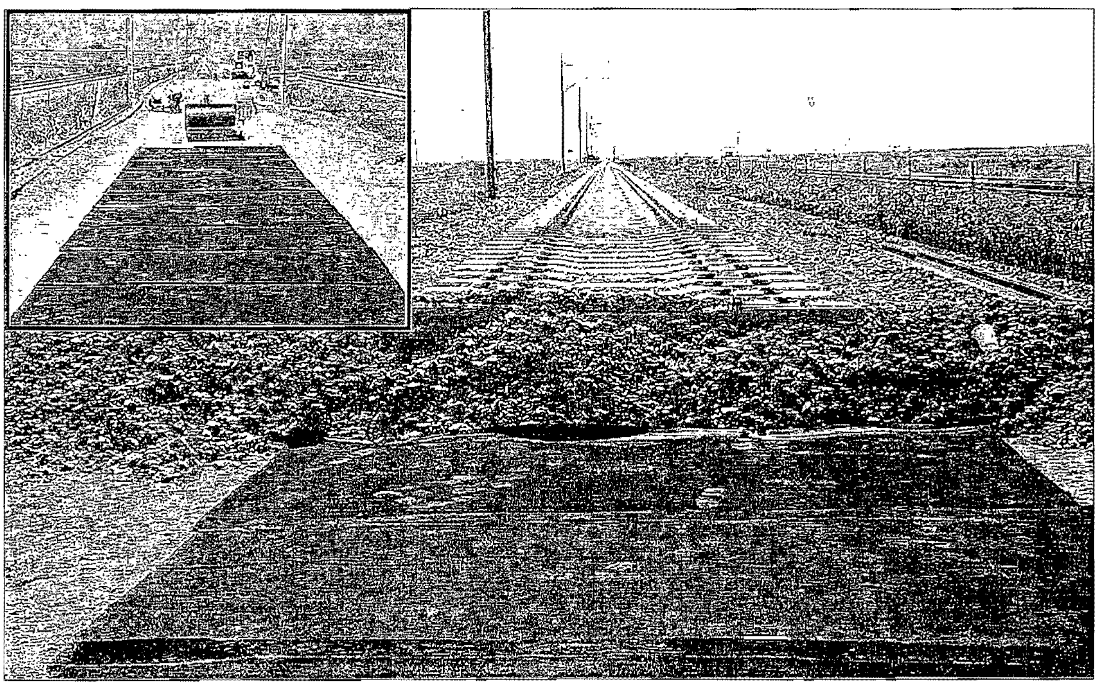


Figure 29. Rolled Ballast Mat on RTT Test Track Segment in Zone 3

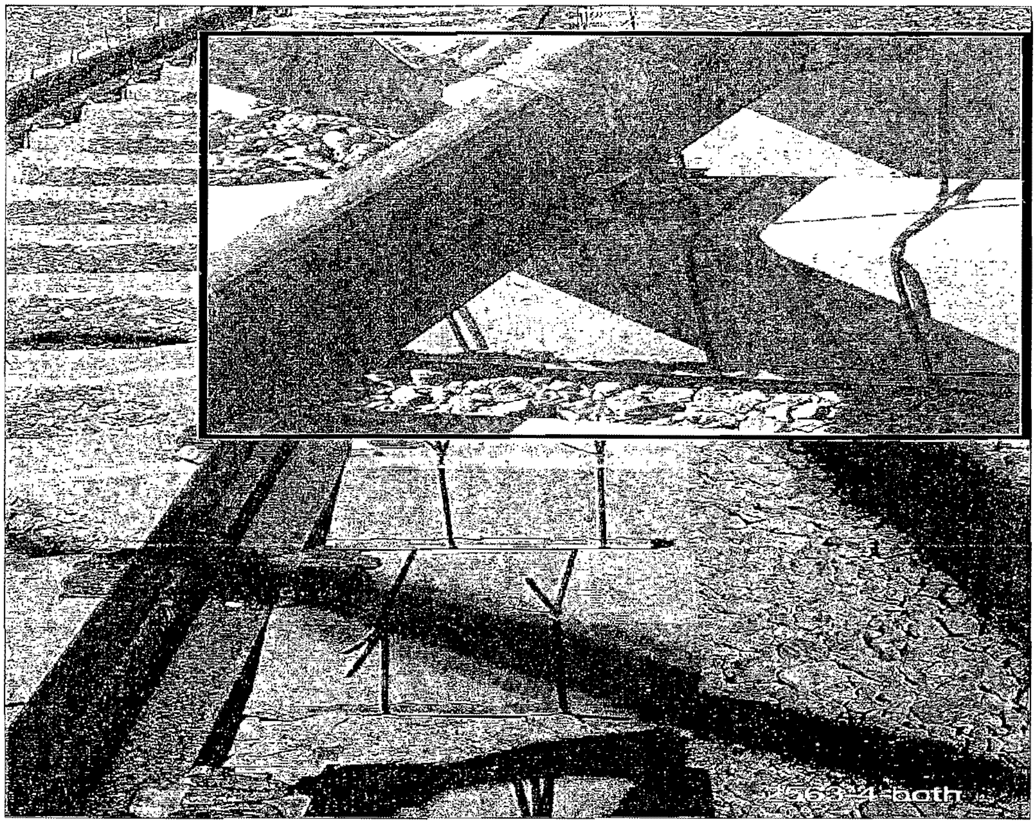


Figure 30. Under-Tie Pads on RTT Segment in Zone 5

Accelerometers: Two Silicon Design Model 2210 (100 g) accelerometers were used for these tests. Criteria for closely matching the accelerometers were based upon their calibration and natural roll-off characteristics.

Data acquisition system: A Dell 8000 laptop with a National Instrument PCMCIA DAQCard-6062E A/D card were used to collect the data. TTCI's standard Hammer Acquisition Program (Testpoint version 4.1) and PV Wave were used to collect and process the raw channels (time histories, transfer functions with magnitude and phase, receptance with magnitude and phase) from the hammer and accelerometers.

Testing procedure: For each of the test zones, two accelerometers were used in conjunction with the hammer for measuring the track characteristics. Accelerometers were placed flat on top of the rail, one over the tie and the other over the adjacent crib (Figure 31). The accelerometers were attached to the rail with beeswax. The two loaded hopper cars that were coupled preloaded the test segment of the zone (Figure 32). Wheels on each axle on either side of the test segment were isolated from the rail by using about 15 inches of rubber hosing (fire hose) under each wheel. Tests were performed with both the small and large hammers. The accelerometers were zeroed before taking any measurements. Ten good hits/measurements, with each hammer, were taken. Approximately 20 files were collected for each zone depending on the input of the hammer; i.e., signal saturation, small peak or double hit. The Hammer Program collected data at 16,384 samples per second. The pre-trigger was set for 0.25 seconds, and a total data collection time of two seconds for each measurement was used. Filtering of the accelerometer data was set for 1500 Hz with low pass filtering on the EFM01 Universal Filter Module.

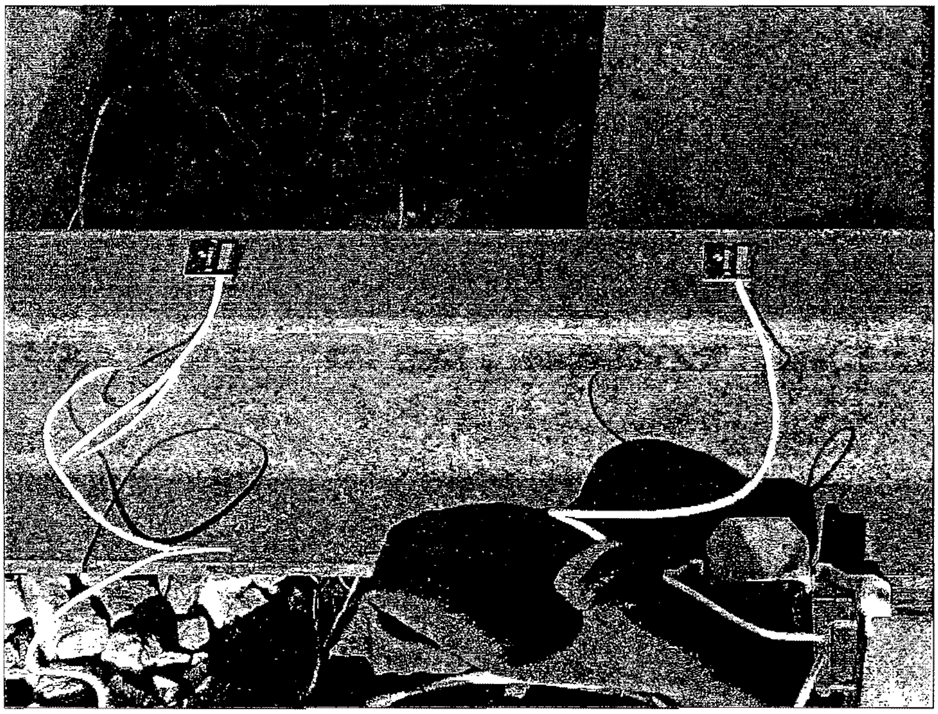


Figure 31. Accelerometers on Top of Rail in the Hammer Test

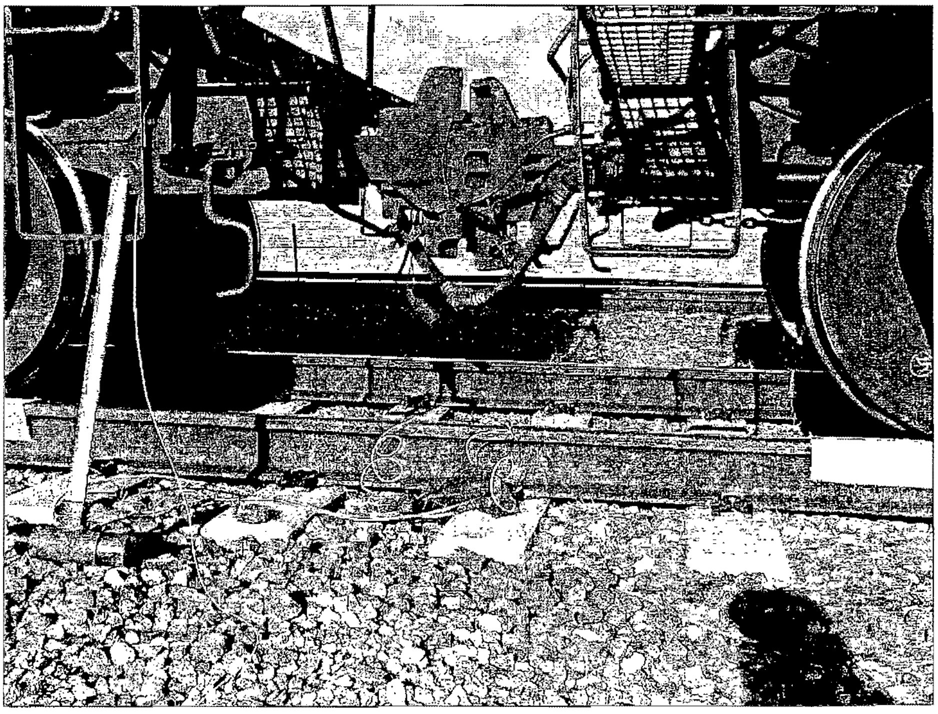


Figure 32. Preload over the Test Segment in Hammer Test

4.1 RESULTS: VERTICAL TRACK MODULUS

The FRA's 605-car was used to evaluate the quasi-static vertical track modulus (VTM) in zones 2, 3, 5, and the reference zone. The method consisted of gradually applying load on the rail in steps and measuring its corresponding deflection. The resulting point stiffnesses were then converted to track modulus by using Equation 2 found in Section 2.2. Figure 33 shows these results, with the following observations:

- Maximum quasi-static load applied in these tests was 40 kips, which approximately equals the static wheel load of a loaded 125-ton car.
- Under-tie pads in conjunction with the rail-seat pads appear to make the foundation very soft for the range of quasi-static loads in these tests.
- Under-tie pads appear to be more of a companion to the rail-seat pads by picking up most of the track vertical deflection for the range of the loads applied in these tests. In consequence, loads appear transferred more evenly to the ballast layer over the portion directly in contact with the under-tie pad. If the service loads are much higher, this might prove to be of added benefit.
- In special situations, such as the transitions from low-stiffness track on approaches to high-stiffness track on bridges, the under-tie pads may be used on the bridge to reduce the stiffness of the track on the bridge to match the stiffness of the track on the approaches. It appears the under-tie pads provide an easier retrofit option to reduce vertical track stiffness of existing track in special trackwork locations. Each transition situation needs thorough investigation lest the stiffness transition problem is aggravated.
- In general, "10-40 kip" modulus is greater than the "0-40 kip" modulus, and appears to indicate stiffening track characteristics with increasing load. Initial loading up to 10 kips appears to have closed the slack between various track components.
- The load limit to produce stiffness characteristics for the track with rolled ballast mat appears to be higher than for other tracks in these tests.
- Track modulus of track with used-tire ballast mat remains approximately the same as that of the control track.
- Track modulus of track with rolled ballast mat is about 64 percent of the control track. The "10-40 kip" modulus of 5714 lbs/in/in for the rolled ballasted mat track represents a good value to have in a robust track.

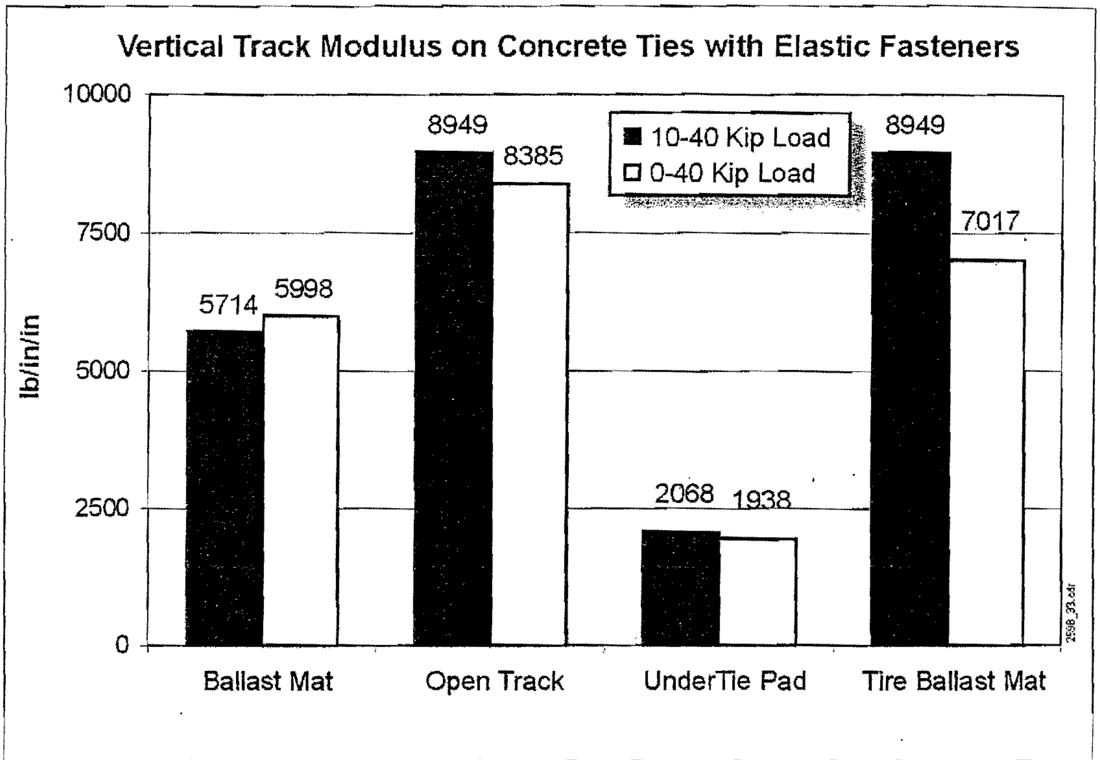


Figure 33. Quasi-Static Vertical Track Modulus in Track Zones 2, 3,5, and Open-Track on the RTT

4.2 RESULTS: VERTICAL RECEPTANCE AND DAMPING

A 10-mm-thick rail-seat pad/fastener system in test zones 2, 3 and 5 was simulated as a spring/damper pair for the support of each rail on each tie to comprise the first layer of connections in their respective NUCARS models. A dynamic stiffness of 6000 kips per inch was used for each such spring; while a damping of 60 lbs/in/sec was used for each damper. The second layer simulated the connections between the ties and the ballast. These connections were assumed to represent the aggregate effect emerging from the combination of native soil, subballast, ballast, and the mats or under-tie pads. Since ties were considered to be elastic in the model, eight equi-distant spring/damper pairs under each tie were used to represent the tie-to-ballast connections. The dynamic stiffness of 400,000 lbs/in was assigned to each of these springs. The damping of the second layer dampers was then varied to match the test receptance results.

Both the stiffness and damping characteristics of the first layer and the stiffness of the second layer springs were kept the same in the NUCARS models for each of zones 2, 3 and 5. This was required to evaluate the difference in the damping characteristics of the ballast mats and under-tie pads. These final values used for the stiffness and damping in the first layer and the stiffness of second layer springs, as given above, were actually found from the search results of an exhaustive list of trial-and-error NUCARS runs made at many combinations of such values.

On the other hand, the NUCARS match of the receptance test results on the control (reference) track was found to be comprised of the following stiffness and damping characteristics:

- Dynamic stiffness of 5250 kips/in, each rail-to-tie spring (first layer)
- Damping of 26 lbs/in/sec, each rail-to-tie damper (first layer)
- Dynamic stiffness of 305,000 lbs/in, each tie-to-ballast spring (8 springs/tie, second layer)
- Damping of 90 lbs/in/sec, each tie-to-ballast damper (8 dampers/tie, second layer)

As mentioned above, each tie was supported by eight spring and damper connections. A simple addition of stiffnesses and dampings of these connections to estimate the resultant ballast characteristics per-tie/per-rail basis will assume that the ties are rigid, but that is not true. The ties are modeled as being elastic; and most probably behave in a "center-bound" fashion when the track is vibrating in the rail-tie in-phase normal mode. If the participation of the rail-tie in-phase mode (in the longitudinal direction of track, Figure 2 in Section1.1) is the largest in the vertical track deflection, this mode then is the one that is mostly affected by the ballast characteristics. As such, for a center-bound tie, the region of ballast immediately below the rail seat must be the one most stressed and having the largest deflection or velocity. This means that at least the outermost springs on the tie are completely engaged; while the springs near the center will most probably be ineffective in providing any resistance. The deflection of the tie in this scenario then can be represented approximately by two cantilever beams (one-half tie length) supported at the tie center. Deflections of this cantilever beam at the locations of the springs, used in the NUCARS model, can then be found under a load at the very end of this beam. Proportioning the resistance provided by each spring according to the deflection at its location in the cantilevered beam, the resultant dynamic stiffness *per-tie/per-rail* basis then works out to be about 1.825 times the dynamic stiffness of one spring used in the model.

Damping is related to velocity. If the velocities of dampers are proportional to deflections of the center-bound tie (cantilever beam) from its center, the damping *per-tie/per-rail* basis will also be approximately 1.825 times the damping of one damper in the model.

Figures 34 to 37 show amplitudes of the measured (hammer test) track receptances of the RTT test segments with those matched (predicted) by using the NUCARS two-layer models of these segments. As can be seen, good matches have been achieved between the test and NUCARS results. The noise or choppiness seen in test receptances in the figures resulted from choosing 100-g accelerometers. It is advised that 500-g accelerometers be used for the hammer tests.

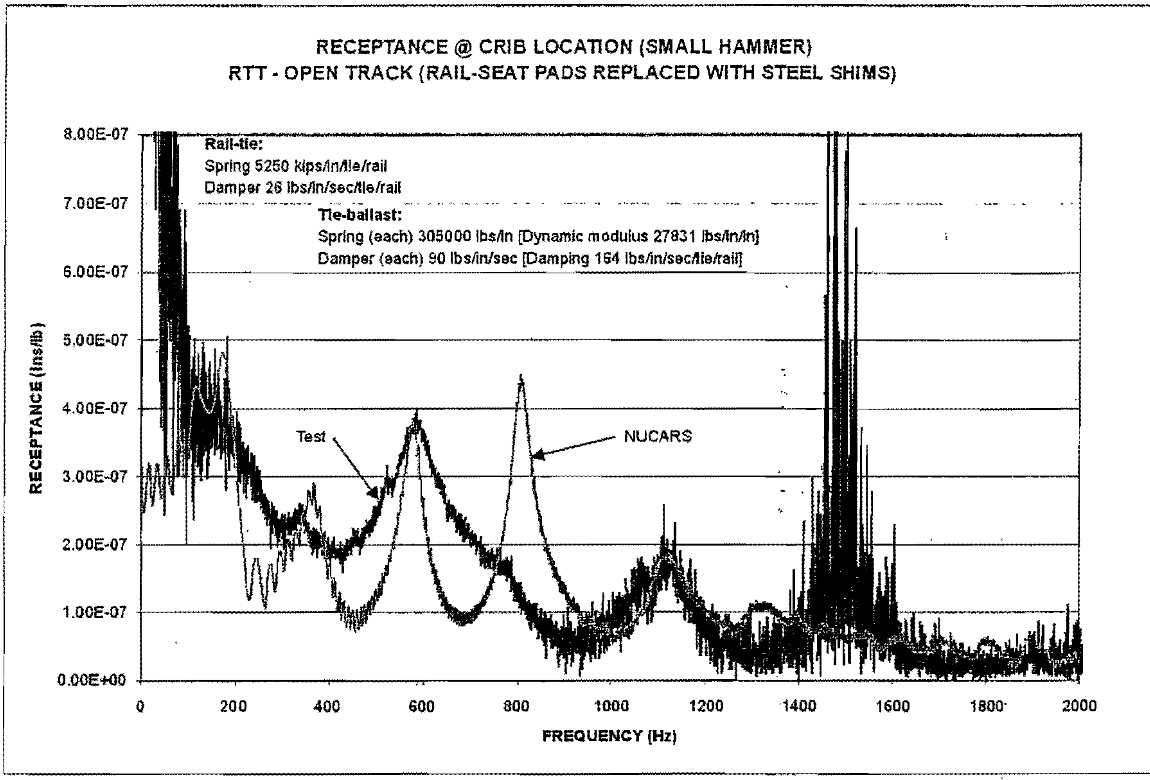


Figure 34. Receptance Crib Location: Hammer Test/NUCARS – RTT Control Track

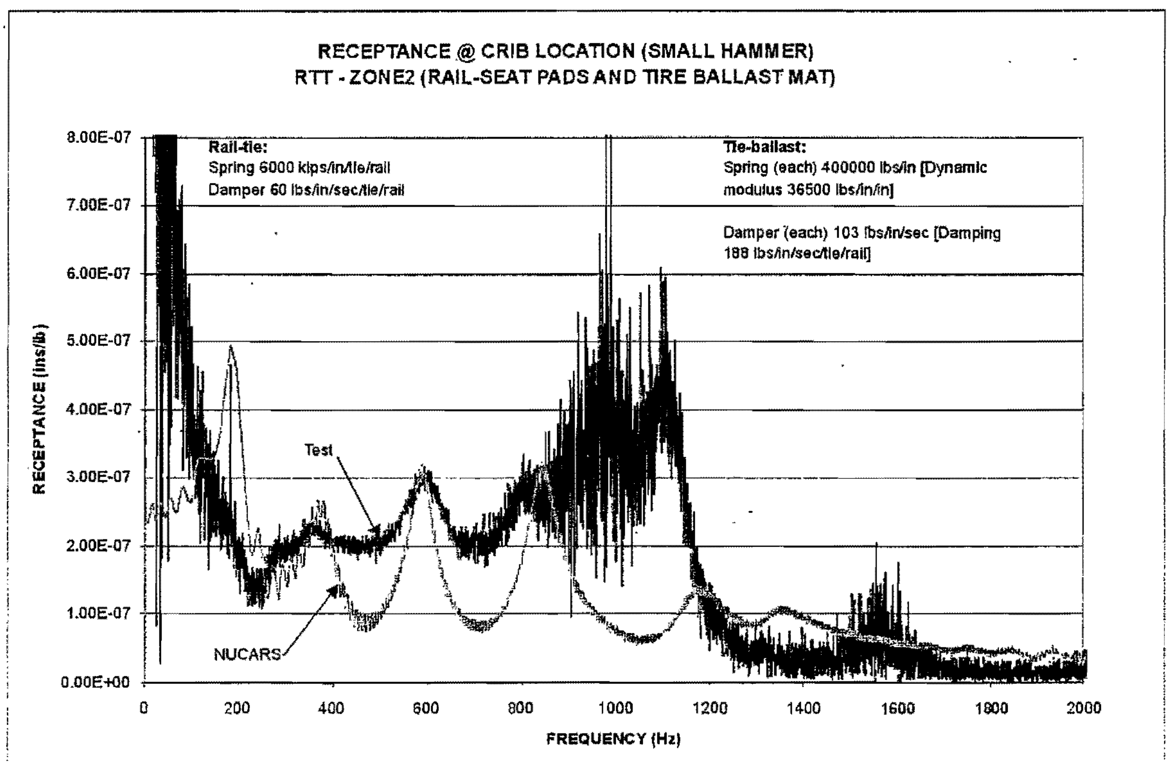


Figure 35. Receptance-Crib Location: Hammer Test/NUCARS – RTT Zone 2 – Tire Ballast Mat

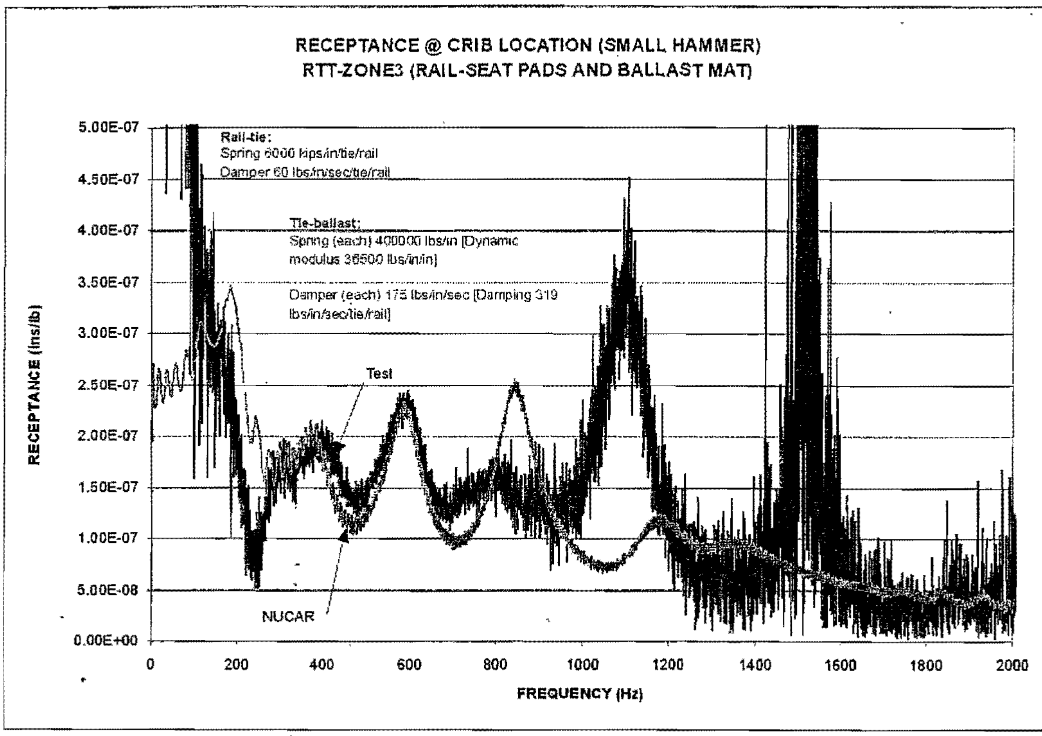


Figure 36. Receptance Crib Location: Hammer Test/NUCARS-RTT Zone 3 — Rolled Ballast Mat

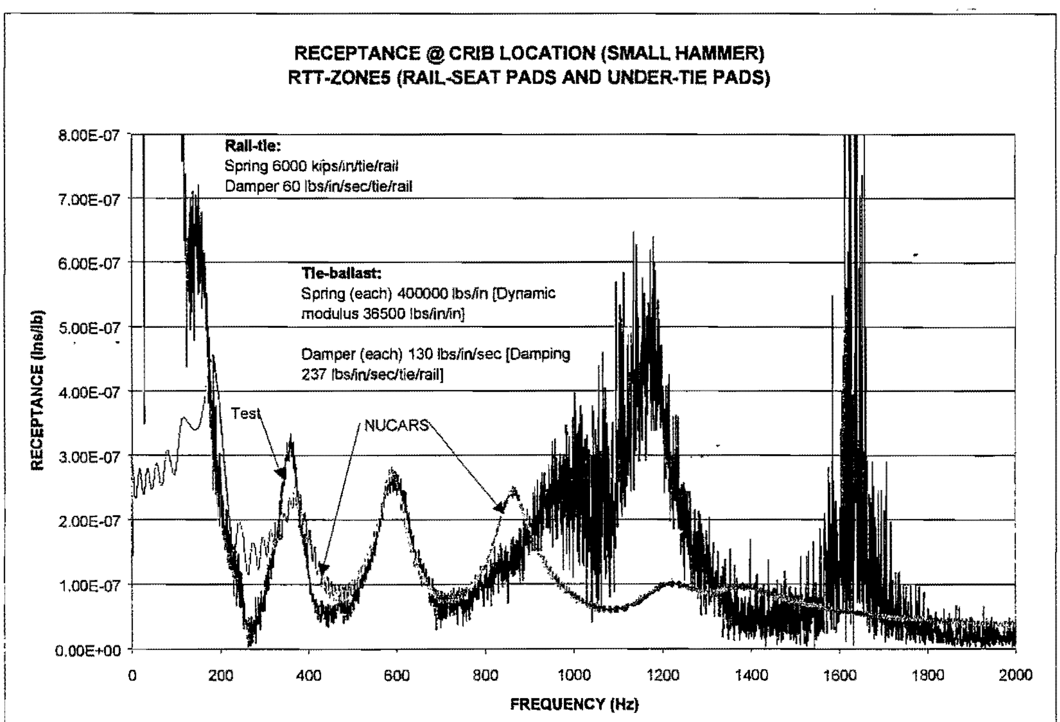


Figure 37. Receptance Crib Location: Hammer Test/NUCARS–RTT Zone 5 – Under-Tie Pads

Further investigation of the behavior of the second layer in the NUCARS models is advised. In this layer, elastic ties are supported on eight pairs of spring/damper connections. The flow of loads and foundation reactions, to and from, is therefore through the ties; which are elastic and are thus excitable in its various bending modes (probably also including the rigid body modes). The net elastic deflection of such a tie will contain a synthesis of all of its modes that are feasible with respect to the supports or constraints (nodes) provided to it by the eight springs. This net deflection will depend on the participation in it of each mode with the first few modes contributing the most. As seen in NUCARS receptances in Figures 34 to 37, it appears that the ties were vibrating in a number of modes at natural frequencies of approximately 180, 250, 370, 590, 850, 1200 and 1360 Hz. These frequencies correspond approximately to the modes of vibration of a free-free standard concrete tie seen elsewhere. Since energy imparted to the track by the hammer hit in the tests was not large, the prominence (amplitude) of some of the higher modes, in contrast to the NUCARS model, is not quite apparent in the hammer test receptance results in these figures. Nonetheless, good matches between the test and model results have been achieved.

The magnitudes of vertical damping and vertical dynamic stiffness evaluated for various track types in zones 2, 3, 5, and the reference zone, are summarized in Table 11. In reference to Figure 4, giving definition to desirable (optimal) damping being approximately between 250 and 300 lbs/in/sec/tie/rail, it appears from the test results on the RTT noise and vibration abatement beds that both the rolled ballast mat in Zone 3 and the under-tie pads in Zone 5 meet the optimal damping provision criterion. When compared to the damping in the control zone, the under-tie pads in conjunction with rail-seat pads appear to increase damping by approximately 45 percent (to 237 lbs/in/sec/tie/rail), while for the rolled ballast mat with rail-seat pads, this increase is about 95 percent (to 319 lbs/in/sec/tie/rail). Though an inexpensive option, the increase in damping provided by the used-tire ballast mat in conjunction with rail-seat pads is not sufficient to meet the optimal damping criterion.

Based on these test results on the RTT test beds, a preliminary conclusion would be to use the combination of rolled ballast mat and rail-seat pads for new construction of special trackwork locations needing enhancement in damping of the foundation to reduce impact loads. For retrofit on the other hand, the combination of under-tie pads and rail-seat pads appears to provide an adequate solution for impact reduction on special trackwork locations.

Table 11. Vertical Damping and Dynamic Resistance of Test Beds on RTT

Zone	Rail-Tie Interface		Tie-Ballast Interface		
	Per-Tie/Per-Rail Basis		Per-Tie/Per-Rail Basis		Dynamic Track Modulus
	Vertical Dynamic Resistance	Vertical Damping	Vertical Dynamic Resistance	Vertical Damping	
	kips/in	lb/in/sec	lb/in	lb/in/sec	lb/in/in
Control (No Pads Anywhere)	5250	26	556,625	164	27,831
Zone 2 (Rail-Seat Pads/Tire Ballast Mat)	6000	60	730,000	188	36,500
Zone 3 (Rail-Seat Pads/Rolled Ballast Mat)	6000	60	730,000	319	36,500
Zone 5 (Rail-Seat Pads/Under-Tie Pads)	6000	60	730,000	237	36,500

5.0 DYNAMIC PERFORMANCE AND DURABILTY OF PADS IN HEAVY AXLE LOAD ENVIRONMENT

Impact loads applied to concrete ties may cause the ties to crack early in service. These impact loads can be up to 3 or more times higher than the average quasi-static loads on the ties. The American Railway Engineering and Maintenance-of-Way Association (AREMA) therefore recommends the use of high impact factors for the design of concrete ties. One way to attenuate the effect of high impact loads on concrete ties is to use rail-seat pads to increase resiliency. Besides preventing abrasive wear of the concrete due to small longitudinal and transverse movements of the rail, they provide electrical insulation for signal circuits and serve as an elastic medium to attenuate impact forces. However, there is currently no *standard* method available that can be used to evaluate the dynamic characteristics of the pads. Meanwhile, there is evidence that the more resilient pads may either deteriorate with repeated loading or undergo hardening under impact loads in service, leading to even more severe damage to the ties. These details resulted in the following three goals:

1. Measure compressive stiffness, hysteresis, and creep of pads; i.e., load-deflection characteristics using MTS machine. Rank pads based on the load-deflection results. Relate rank of a pad to attenuation of impact loads. Assess the reliability of the rank-attenuation relationship.
2. Determine impact characteristics (dynamic performance) of pads installed in a fixture that approximately simulates the stiffness and mass of a revenue service track.
3. Determine the deterioration of the dynamic performance in a HAL environment in terms of wear and hardening; i.e., reduction of attenuation capability.

5.1 LABORATORY EVALUATION OF PAD LOAD/DEFLECTION BEHAVIOR

Damping pads: Pads, new and existing, used for this evaluation are listed in Table 12. The stiffness of rail-seat and tie-plate pads can generally vary from about 400 kips/in (very soft) to about 6000 kips/in (very stiff). Normal stiffness is considered between 1000 kips/in to 2000 kips/in. Pads nearest to normal stiffness were selected.

The new pads have already been procured and tested in the laboratory; and the results are given below. The existing pads placed in the foundation of the RTT track and listed in Table 12 were already tested for damping and dynamic stiffness using the hammer test technique. Results from these pads are discussed in subsections 4.1 and 4.2.

Table 12. Damping Pad Details and Specification

Pad ID No.	Pad Type	Pad Description	Dimension	Pad Thickness	Comment
1A	Rail-Seat	Airboss Polyurethane	6" x 8"	¼"	UP, BN, CN, CSX standard w/abrasion plate
1B		Pandrol Poly EVA	6" x 8"	¼"	
1C		Pandrol Rubber	6" x 8"	¼"	Rubber
1D		Vidamp 820	6" x 8"	¼"	Micro cellular polyurethane
1F		Fabreeka SA47	6" x 8"	¼"	
2A	Tie-plate	Vidamp Rubber	8"x 2'-6"	½"	
2B		Airboss Rubber	8"x 2'-6"	½"	New BNSF Stnd., bridge bearing pad
3A	Under-tie	Vidamp	10"x3"	1"	Existing at RTT
4A	Ballast Mat	Vidamp	10'x300'	1"	Existing at RTT

Test Setup: These tests were performed at the TTCI's calibration laboratory using a "Morehouse" (s/n M-6582) 200,000-pound capacity load frame. A 200,000-pound "Interface" load cell (TTCI# 28253) and a "Daytronics" digital readout (TTCI# 25568) were used as the standard for the tests. This combination was calibrated, before the pad tests, using the "Morehouse" proving ring attached to the load frame. The pad deflection was measured using two "Mititoyo" 0.001-inch dial gages. One gage was mounted on each diagonal corner of the pad-loading fixture to indicate any eccentric loading of the pads. During the creep tests, the holding time was measured with a precision stopwatch. The loads were held to 0.5 percent or less on each increment recorded. Photos were taken of all the pads before and after testing. Figure 38 shows the test setup.

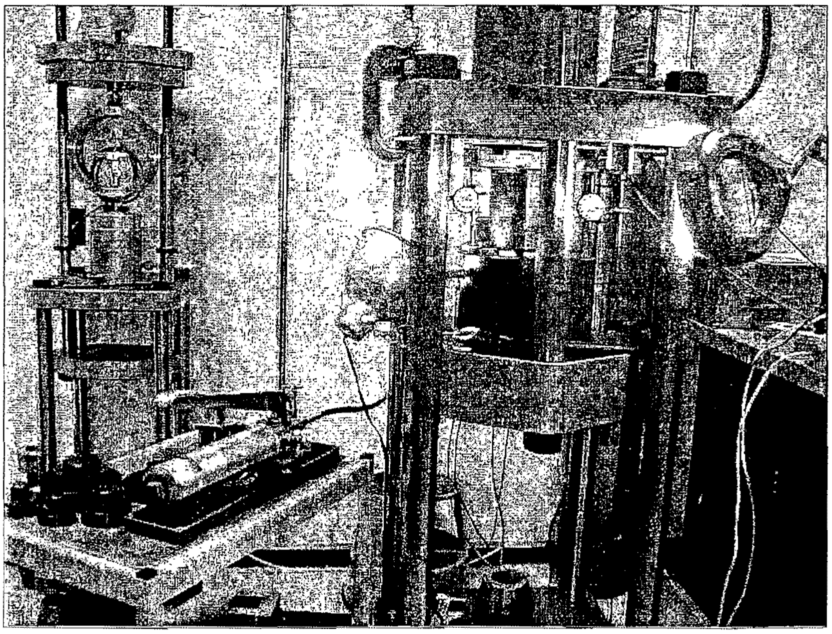


Figure 38. Typical Test Setup for Stiffness and Creep Tests of Pads

Stiffness/hysteresis tests: The sample pad was installed in the test fixture and a 500-pound load was applied and held while the dial gages were adjusted to a relative zero. The load was increased in 10,000-pound increments up to the maximum load. At each increment, the load was held while the dial gages were recorded. After recording the final deflection at the maximum load, the load was reduced in 10,000-pound decrements and was held at each decrement while the deflection was recorded. At the 500-pound level, the deflection was recorded, the load held for 20 minutes, and the deflection was recorded again.

This data has not been analyzed. Only typical load-deflection curves are given (Figure 39). As seen in this figure, the pads behave in a non-linear and hysteretic way. The definition of stiffness parameters for such a behavior may be based on the linearization of the load versus deflection relationship. Besides the initial tangent modulus, the judgment regarding the use of secant modulus or tangent modulus between intermittent points on the load deflection curve needs further investigation before results from these tests can be given.

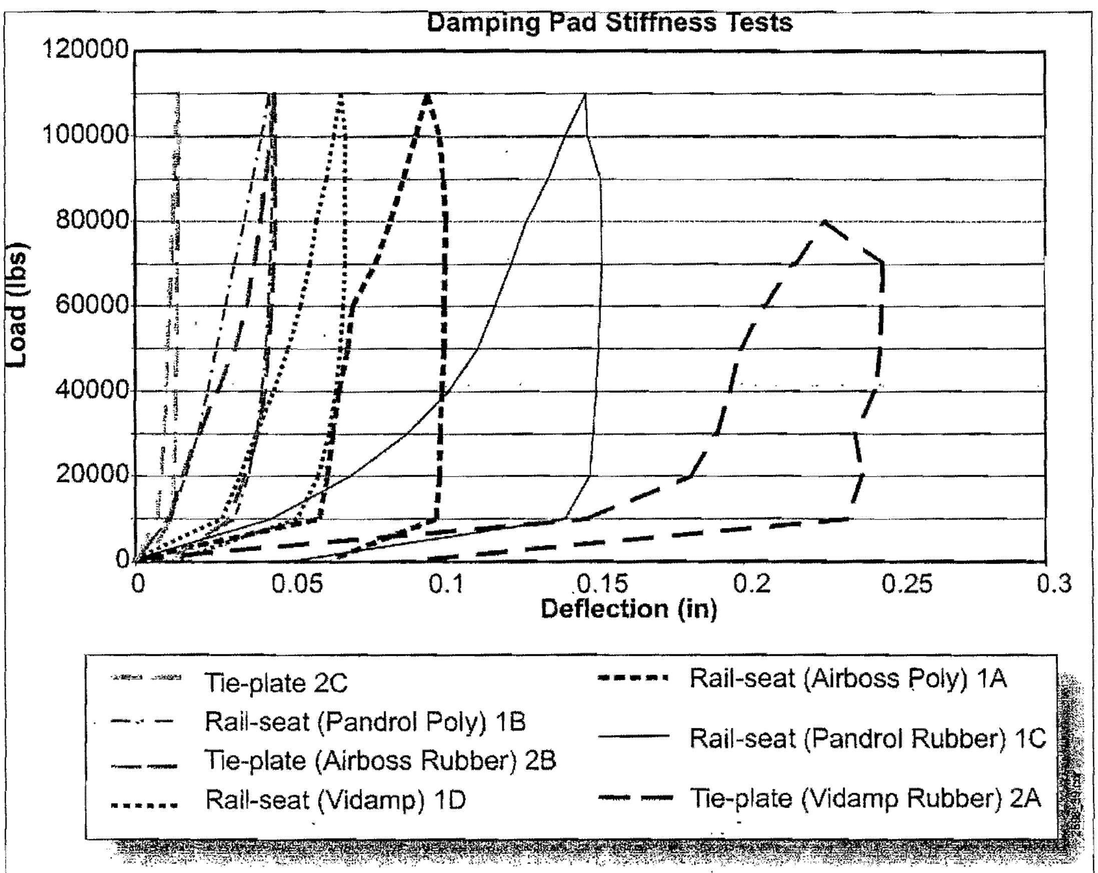


Figure 39. Typical Load-Deflection-Hysteresis Curve for a Pad

Creep tests: The sample pad was installed in the test fixture and a 500-pound load was applied. The dial gages were each adjusted to a relative zero. A 10,000-pound load was applied, and the dial gages were initially recorded. This load was held for 30 minutes, and the deflections were recorded again. The load was then dropped to 500 pounds, and this deflection value recorded.

The load was then increased to 20,000 pounds, deflection recorded, and the load was held for 30 minutes. Thereafter, the deflections were recorded again. The load was then reduced to 500 pounds and deflections were recorded. This way the pad was loaded in 10,000-pound steps in excess of the loading in the previous step and the deflection values recorded as above to the maximum loading specified for the tests.

This data has also not been analyzed. Only a typical load-deflection curve is shown in Figure 40. As shown, the maximum load used in these tests was 110,000 pounds. This load most probably exceeds the maximum loads expected in service. The high magnitude of load was used to get an idea about the possible permanent deformation of pads in service.

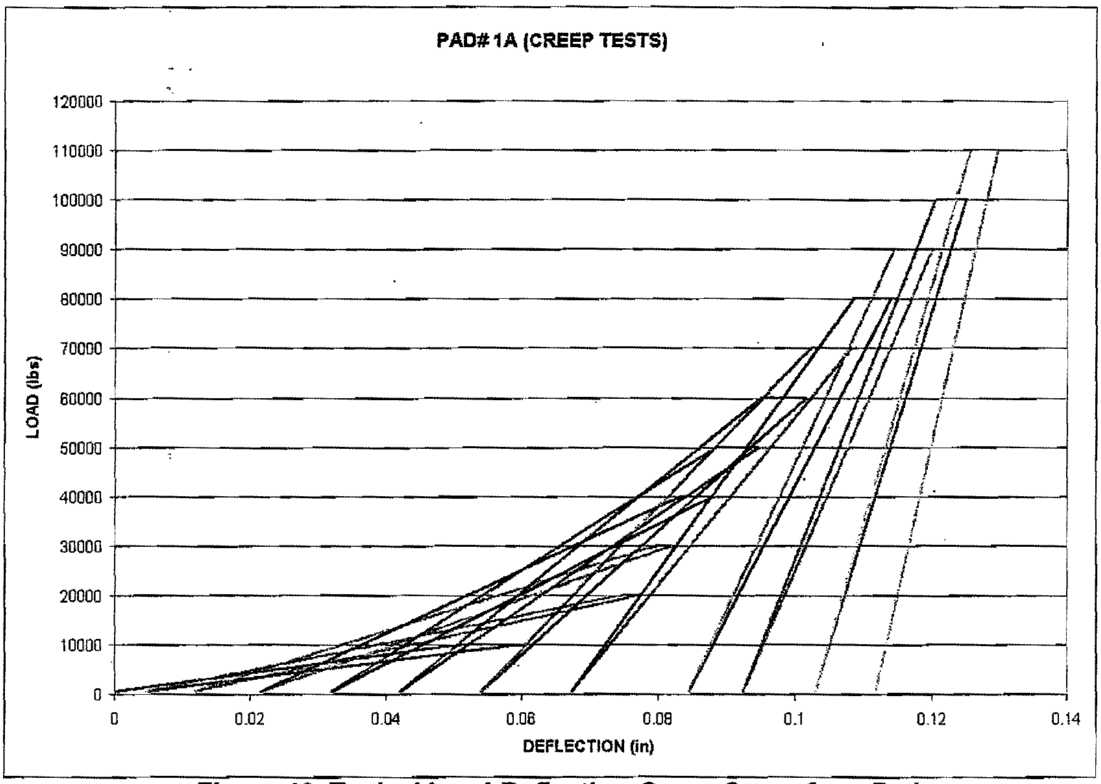


Figure 40. Typical Load-Deflection-Creep Curve for a Pad

5.2 POTENTIAL DESIGNS/PROPOSED PROTOTYPES/TEST PLAN

Three potential designs are discussed in terms of their relative advantages:

1. Tie Pad Design
2. Modified Tie Layer Design
3. Modified Foundation Design

Tie Pad Design: The tie pad design consists of conventional track except the damping pads are placed at the tie bottom (ballast interface) and also at the tie plate bottom (tie interface). Ties will be typical dimensions with the pad thickness varied with distance from the frogs. The advantages of this design are that it requires little change over conventional designs. While the tie bottom pads are relatively inaccessible, the tie plate-tie pads can be accessed more easily.

Modified Tie Layer: This design features a more radical change to the crosstie layer. The tie layer will consist of formed material with a much wider bearing area than discrete ties. This layer will be better at spreading applied load and will be easier to surface. The custom made ties will allow machine tamping by having crosstie-like wings that will extend perpendicular to each rail.

Modified Foundation: The modified foundation design will utilize two or more layers of GEOWEB and rubber-modified HMA. The foundation system will require extensive construction or re-construction of the subgrade. As such, it may be best suited for new construction or lower density lines where track time can be obtained.

Future Work: Under this program, proposed designs will be developed for reduced impact crossing diamonds. Work done under a companion AAR program has built test track that allows evaluation of potential damping components, such as tie pads and rail seat pads. Future efforts will evaluate materials and designs using these facilities. Additional prototypes will be built and evaluated using the techniques developed under these programs.

Described below is TTCI's view of the testing scenario needed for the proposed prototypes. Significant work with industry partners will be needed to develop the prototypes for testing. Once they are built, they can be evaluated with the methodology described below.

Conceptual Test Plan for Reduced Impact Track: The work done under this phase of the program will allow the development of track structure designs and the preliminary evaluation of materials for reduced impact track. The next phase of work will test these designs and materials under simulated and actual HAL traffic. The effectiveness and durability of various configurations will be evaluated to determine their applicability under revenue service conditions.

Test Methodology: Testing will determine the effects of the foundation on track properties, track settlement rate, and measured dynamic wheel loads. A control section and a test section will be installed in the High Tonnage Loop at FAST. For initial evaluation of materials, measurements can be made after a small amount of tonnage has accumulated. If the designs are successful in affecting damping, then a durability test can be conducted on each. The following measurements will be made at the intervals listed in Table 13.

Table 13. Reduced Impact Track Test Measurement Plan

Test Measurement	Method	Tonnage levels
Track Stiffness	Elevation survey of 39 and 10 kip loads	1, 10, 20 and 40 MGT intervals
Track Damping	Hammer test & Modeling	1 and 40 MGT
Track Settlement	Top of Rail Survey	1, 10, 20 and 40 MGT intervals

This methodology may be repeated for additional prototypes. Ideally, several test sections can be built and tested simultaneously so that FAST operations will be identical for each test. With several tests proceeding in parallel, progress towards a practical design will be accelerated.

Data Analysis: The effectiveness of the design will be evaluated using the above measurements. The FAST train crews will document their expert opinions on the ride quality of the test sections. Comparison of measured damping to the calculated optimum value will be made. Additional correlations between measured damping, settlement, and dynamic load will be made to verify the relationships developed in the track modeling.

6.0 FUTURE EVALUATIONS

6.1 FIELD EVALUATION OF DYNAMIC PERFORMANCE OF PADS

Pads will be installed in a track panel at FAST. The panel is designed to represent the heavy structure in special trackwork locations, especially the crossing diamonds. The fixture allows testing of various combinations of pads and thickness typess. Rail-seat pads, tie-plate pads, and crosstie size and spacing can be changed to produce parametric changes in stiffness, mass, and damping values to characterize special trackwork transition zone foundations. Cross sectional details and a schematic of the panel are shown in Figures 41 and 42, respectively. Vertical track modulus will be determined by using the 605-car apparatus, and hammer tests and NUCARS modeling will be used to determine the damping and dynamic stiffness characteristics for various parametric combinations of pads, tie sizes, and spacings. The best two combinations will be determined from the results of these tests for testing in the crossing-panel, discussed later, for long-term durability tests under HAL traffic at FAST.

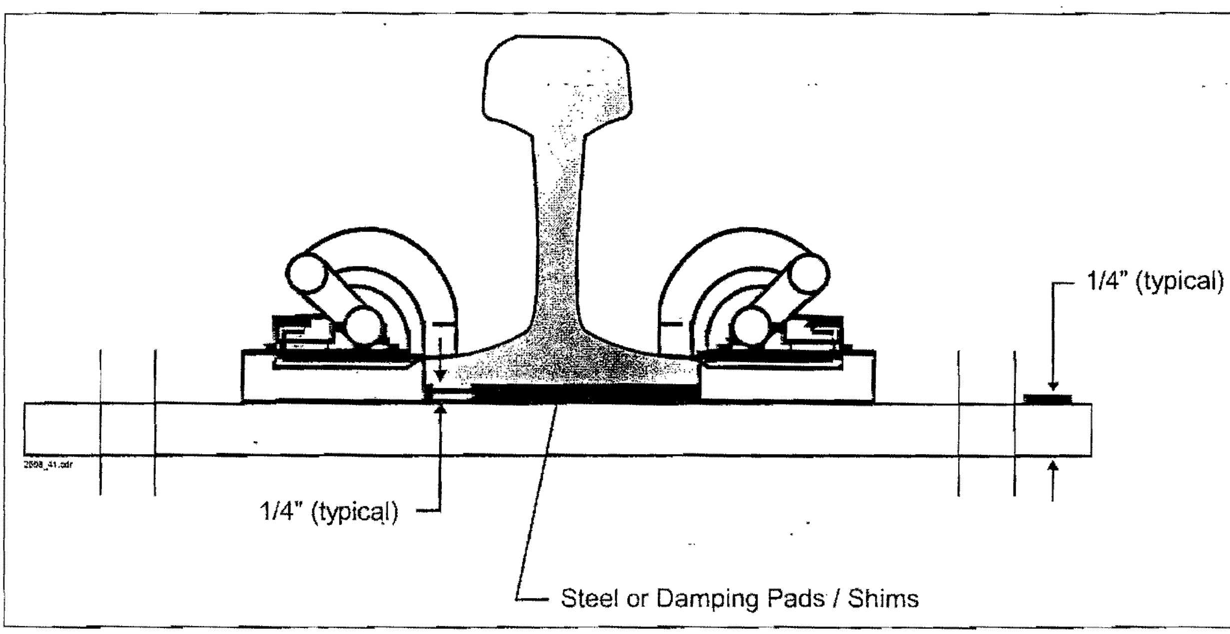


Figure 41. Cross-Section Sketch of Rail Seat & Pad

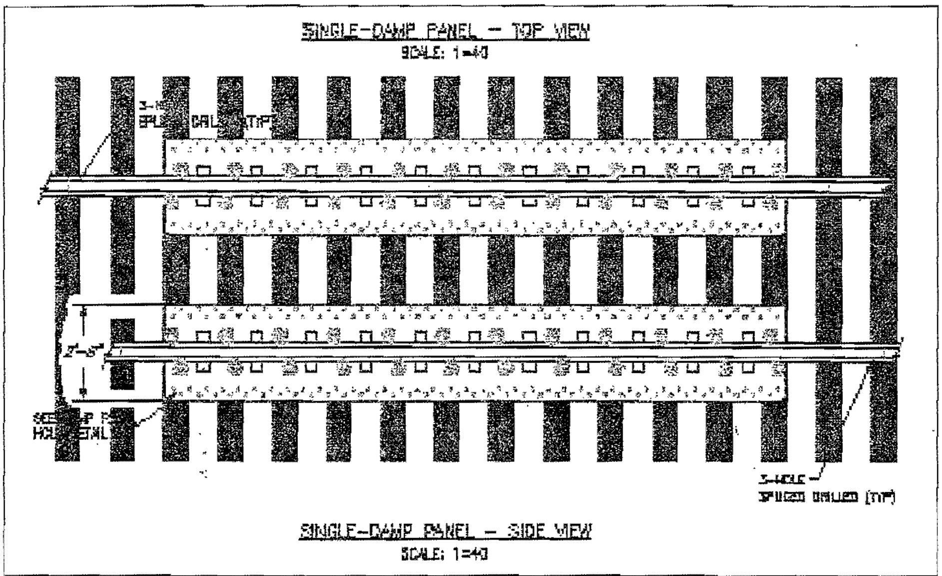


Figure 42. Schematic of Single-Rail Damp Panel

6.2 UPCOMING DYNAMIC PERFORMANCE DURABILITY TESTS OF PADS

These tests will be conducted to evaluate the deterioration of the dynamic performance of pads in HAL environment in terms of wear and hardening (i.e., reduction of attenuation capability). The crossing-damp panel, Figure 43, representing the heavy structure of a diamond crossing will be used for these tests. In addition, this panel will also be used as a test bed for fasteners. Various nut and bolt fastening systems will be monitored for breakage and loosening. Flangeway gaps measuring 1 7/8 inches in the running rails will represent actual flangeways in diamond crossings, and transverse welded gage plates will be applied for lateral stiffness. The crossing-damp panel will be used to test short- and long-term durability of pads and pad combinations.

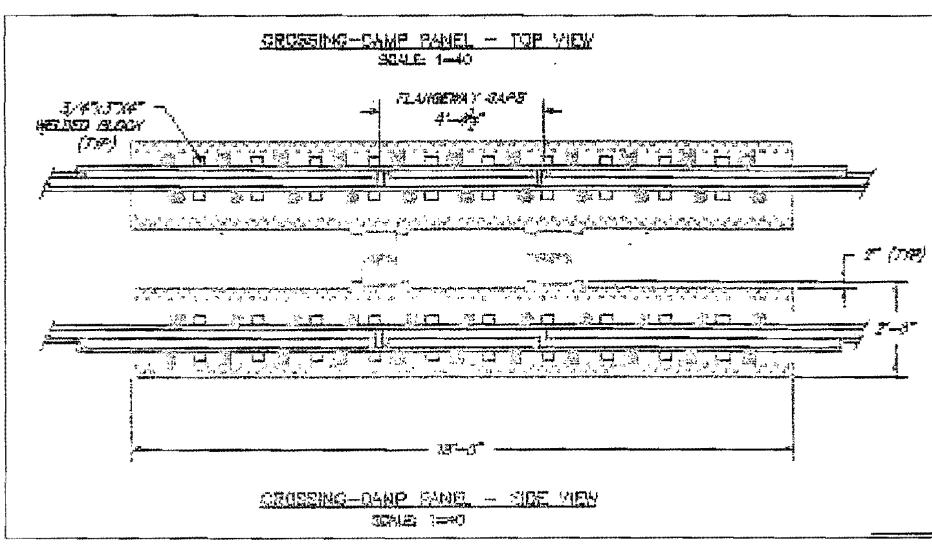


Figure 43. Schematic of Crossing-Damp Panel

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