IMPLEMENTATION OF A DYNAMIC RAIL-HIGHWAY GRADE-CROSSING TRANSITION

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ABSTRACT

A concern of railroad maintenance engineers is the abrupt change in vertical track stiffness or "modulus" associated with railroad/highway grade crossings. This abrupt change frequently results in increased dynamic wheel loading, increased/accelerated track degradation and poor ride quality. In order to control these increased loading effects and their associated maintenance problems (and costs) the concept of a transition grade crossing design was developed. The intent of this design was to "smooth" the transition from normal track to the stiffer grade crossing structure to minimize the dynamic impact forces associated with the stiffness transition into the crossing. This paper presents the results of an FRA sponsored study of a modified crossing system. The study consisted of an analytical phase, which determined the type of transition required, a design phase which took a conventional concrete crossing design and introduced a series of transition zones, and a testing phase. In the latter phase, a modified PREMIER Concrete Railroad Crossings STEP-PANEL Crossing was manufactured and installed at the Bates Mill Road Crossing of the high-speed NJ Transit Atlantic-City Line, in the vicinity of Atco, NJ. Results of high-speed vertical -dynamics measurements, performed on the Bates Mill Crossing, supported the results of the analytical modeling, and showed that the use of the transition resulted in the elimination of approximately 60 - 70% of the additional dynamic loading at the crossing.

Keywords: Rail-Highway Grade-Crossing, Dynamic Impact, Ride Quality

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INTRODUCTION

A recurring concern for railroad maintenance engineers is the sudden change in the vertical support condition or "modulus" of the track structure associated with railroad/highway grade crossings, bridge abutments, and other such locations. This abrupt change in stiffness frequently results in increased dynamic wheel loading, increased/accelerated track degradation and poor ride quality. To reduce these loading effects and their associated maintenance problems (and costs) the concept of a transition grade crossing design was developed with the intent to "smooth" the transition from normal track to the stiffer grade crossing structure. In order to implement this concept, the structural characteristics and stiffness distribution of a rail/highway grade-crossing system were investigated and modified so as to optimize the vertical dynamics in the transition zone. This activity was performed under the sponsorship of the Federal Railroad Administration's High Speed Technology program.

Based on the first phase theoretical study, a dynamically stable grade crossing system was designed, based on an existing PREMIER concrete crossing design. This modified design, referred to here as the PREMIER "STEP-PANEL" Crossing was manufactured and then installed at the Bates Mill Road Crossing of the high-speed NJ Transit Atlantic-City Line, in the vicinity of Atco, NJ. This paper presents the results of this FRA sponsored project "Implementation of a Dynamically Stable Rail-Highway Grade-Crossing System and Transition", including the analytical activities, crossing optimization and design, installation and testing.

PROBLEM FORMULATION

Transition problems are associated with a change, usually an abrupt or sudden change, in the support conditions of a structure. This problem was presented, for the railroad track environment, by Kerr and Moroney [1] who described in extensive detail the nature of the problem and an overall approach for the definition of this analytical problem. They note that the standard method for analyzing railroad track assumes that the track structure is a beam (rail) resting on a continuous elastic foundation (representing the cross-ties, ballast, and subgrade).

In the formulated model, the elastic spring constant k represents the vertical track stiffness and is defined as the support condition of the rail. The elastic support encompasses everything below the rail, including cross-ties, ballast, and subgrade support. The contact pressure between the rail and the subgrade is then defined as follows:

$$p(x) = k \cdot w(x)$$

where $w(x)$ is the deflection at point x, and $p(x)$ is the pressure which is directly proportional to the deflection and is dependent on the track stiffness. The stiffer the track, the larger the value of k will be. A typical railroad track structure (conventional cross-tie track) and a typical grade crossing design will have significantly different values of track modulus (k) due to the change in stiffness associated with the grade crossing structure itself. This is illustrated in Figure 1.

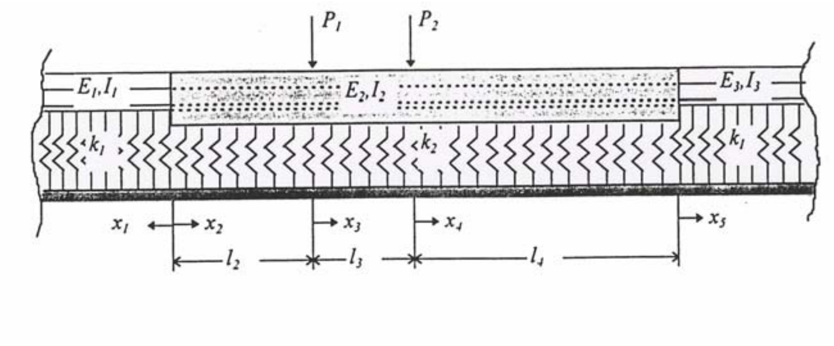


Figure 1. Model of Crossing and Track Structure.

For typical grade crossings, the stiffness under the crossing *(k_2)* will be greater than that of the parent track structure *(k_1)* as shown in Figure 2. This large and rapid change in stiffness can result in a significant dynamic impact force most commonly in the:

- Crossing area when entering the crossing
- Parent track structure when leaving the crossing

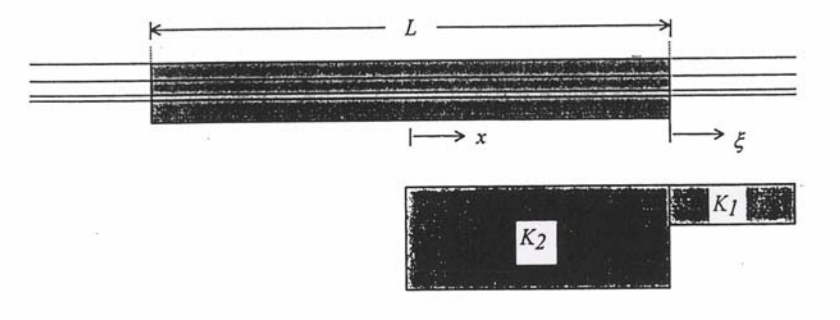


Figure 2. Distribution of Track Modulus.

Figure 2 shows the abrupt change in vertical track stiffness that can typically exist in the track where the grade crossing is located. This abrupt change in vertical track stiffness will cause a change in vertical acceleration of a moving vehicle. The change in acceleration will be related to the speed and suspension characteristics of the moving vehicle, as well as the magnitude of the change in vertical track stiffness. Thus, at high speeds, the impact behavior is more severe than at lower speeds. As a result, for high speed passenger service, this phenomenon represents a significant problem area.

Ideally, it is desirable to have vertical track stiffness values that are constant throughout the track structure. If they are not, then it is desirable to have a smooth transition between those areas that have abrupt changes in vertical track stiffness. This transition zone must match the different stiffness values in the track and crossing zones so as to allow for a smooth change in dynamic behavior at the wheel/rail interface and thus eliminate the dynamic impact forces associated with typical crossing designs with no transition.

The method developed in this study utilizes a defined length of track, in the parent (softer section) track immediately before the crossing (stiff section of the track) and develops a transition zone in this region that allows for a dynamically smooth transfer from the "soft" (parent track) zone to the "stiff' (crossing) zone as described above. The length and nature of the transition zone depends on the difference in vertical track stiffness values between these two zones.

The transition zone is developed using a series of transitions of increasing stiffness that will effectively bring the track modulus values up to those corresponding to the stiff portion of the track. This is done using a series of discrete steps of a defined length that change the track stiffness in a step-wise fashion, as illustrated in Figure 3.

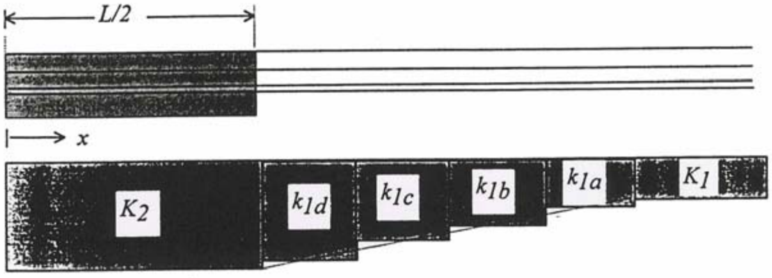


Figure 3. Distribution of Track Stiffness with Transition.

The number of discrete changes in vertical track stiffness depend on the difference in track stiffness values in the two different zones of the track (k_1 and k_2). The values of the incremental changes in stiffness through the transition zone are minimized to reduce (if not eliminate) the significant dynamic forces at these interfaces.

$$EI\frac{\partial^4 w(x,t)}{\partial x^4} + m(x)\frac{\partial^2 w(x,t)}{\partial t^2} + k(x)w(x,t) = q(x,t)$$

where

$w(x,t)$ = vertical deflection of the beam
EI = flexural stiffness of beam
$m(x)$ = varying track mass
$k(x)$ = varying vertical track modulus
$q(x,t)$ = weight and vertical inertia of moving object

For a moving wheel load of a railroad vehicle, the resulting applied load is as follows:

$$EI\frac{\partial^4 w(x,t)}{\partial x^4} + m(x)\frac{\partial^2 w(x,t)}{\partial t^2} + k(x)w(x,t) = q(x,t)$$

where

P = applied wheel load
M = concentrated mass of applied load
δ (x,t) = the Dirac delta function

The resulting boundary/initial conditions are regularity at. infinity for all time, or:

$$\lim_{x\to\infty}\left(w(x,t), \frac{dw(x,t)}{dx}\right) \to finite \qquad \lim_{x\to-\infty}\left(w(x,t), \frac{dw(x,t)}{dx}\right) \to finite \qquad \text{for all } t$$

The resulting formulation is extremely complex and research has suggested that the formulation cannot be readily solved in its current form. Therefore, in order to facilitate analysis of this formulated problem, the approach was divided into two distinct (and separate) analytical tasks extracted from the "global" formulation as follows:

- Formulation of the dynamic vehicle moving over a transition zone. This allows for the analytical definition of the dynamic wheel load *P(w)* as a function of track deflection *w*. This definition will permit a closed form solution, without any expected loss of accuracy
- Formulation of the multiple transition problem. This allows for the solution of the rail on multiple elastic foundations problem for deflection w, which, in turn, allows for a transition zone geometry definition close to reality. This approach further eliminates the extremely complex mathematical problems inherent in the initial formulation.

The transition zone analysis, resulted in the equation (see Reference [2]):

$$\ddot{y}_1 + \frac{c}{m_1}y_1 = \frac{cV}{m_1}t$$

with initial conditions:

$$y_1(0) = 0$$
$$\dot{y}_1(0) = 0$$

The transition model of a beam *(i.e.* rail) with two values of track modulus (with a discrete boundary) subjected to a concentrated force *(i.e.* wheel load) is shown in Figure 4.

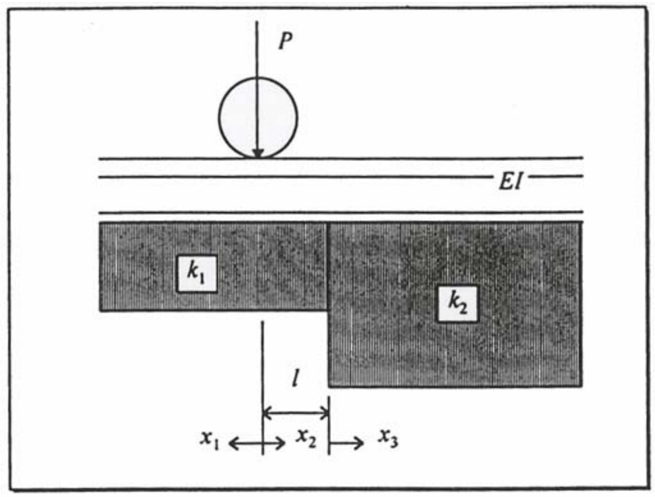


Figure 4. Transition Model

where

EI = the properties of the rail
P = the wheel load (factored for dynamics)
k_1 = the track modulus of the parent track structure
$k2$ = the track modulus of the crossing track structure
x_i = the longitudinal coordinate for the three zones
/ = the location of the load

The formulation for this physical problem results in three differential equations and twelve boundary/matching conditions as follows:

Differential Equations:

$$EI\frac{d^4 w_1(x_1)}{dx_1^4} + k_1 w_1(x_1) = 0 \qquad -\infty < x_1 \leq 0$$

$$EI\frac{d^4 w_2(x_2)}{dx_2^4} + k_1 w_2(x_2) = 0 \qquad 0 < x_2 \leq l$$

$$EI\frac{d^4 w_3(x_3)}{dx_3^4} + k_2 w_3(x_3) = 0 \qquad 0 < x_3 \leq \infty$$

The general solution for each of the differential equations (and corresponding boundary conditions) is as follows:

$$w_i(x_i) = e^{-\beta_{n(i)}x_i}\left[A_{1i}\cos(\beta_{n(i)}x_i) + A_{2i}\sin(\beta_{n(i)}x_i)\right] + e^{\beta_{n(i)}x_i}\left[A_{3i}\cos(\beta_{n(i)}x_i) + A_{4i}\sin(\beta_{n(i)}x_i)\right]$$

where

$w_i(x_i)$ = deflection for zone $i = (1 \text{ to } 3)$

$n(i) = 1, 1, 2$

$$\beta_{n(i)} = \sqrt[4]{\frac{k_{n(i)}}{4EI}}$$

A_{ji} = integration constants, ($j = 2$ to 4, $i = 1$ to 3)

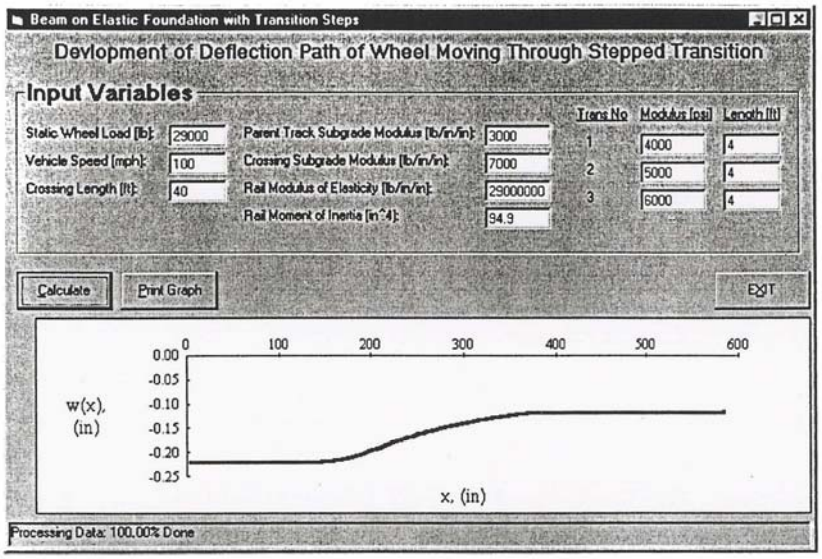
This solution can then be completed by determining the integration constants using the boundary and matching conditions, which is described in Reference [2].

Reference [2] presents the complete formulation of the problem together with the detailed solutions.

ANALYSIS OF CROSSING TRANSITION

Using the analysis approach described above (and presented in detail in Reference [2]) a set sensitivity analyses were performed for a representative grade crossing configuration. Input parameters were selected to represent those typical of North American railroads, and are representative of the normal system design and conventional operating conditions. This group includes the static level of the wheel loading P_{st}, vehicle speed V, rail stiffness $E1$, and crossing length L. Additional input parameters consisted of those design variables which are part of transition system design, and which directly affect the level of crossing dynamics. As such they directly determine the configuration of the improved crossing design. This group includes all track stiffness involved, specifically, that of the parent track, transition zone steps, and crossing itself (k_i), and length of the transition step L.

Figure 5 presents a representative numeric result of the final model investigation, and shows the typical behavior of the deflection curves. Note that elastic transition curves were analyzed for different lengths of the transition step *(L)* corresponding to 4 ft and 8 ft lengths that are typical of current concrete crossing panel designs. These lengths are standard manufacturing lengths for grade crossing "panels" and as such have been used here in order to facilitate designs to be used in the field testing phase of this project. Further note that high passing vehicle speeds *(V)* of the order of 100 mph were used since a primary focus of this study is to develop crossing design modifications for *high speed traffic conditions*



Devlopment of Deflection Path of Wheel Moving Through Stepped Transition

Input Variables

Static Wheel Load [lb]: 29000
Vehicle Speed [mph]: 100
Crossing Length [ft]: 40
Parent Track Subgrade Modulus [lb/in/in]: 3000
Crossing Subgrade Modulus [lb/in/in]: 7000
Rail Modulus of Elasticity [lb/in/in]: 29000000
Rail Moment of Inertia [in^4]: 94.9

Trans No	Modulus [psi]	Length [ft]
1	4000	4
2	5000	4
3	6000	4

Processing Data: 100.00% Done

Figure 5: Deflection Path in Transition

K_2/K_1 = 7,000/3,000 lb/in/in, L = 4 ft.

Figure: 5 presents a graphical presentation of the track deflection [*w(x)*] in the transition zone, based on the specified input parameters. Note that the deflection transition curves are continuous smooth lines containing no singular points. Also note that the deflection *w(x)* decreases as the wheel approaches the crossing, where it reaches its minim\lm, deflection value (corresponding to the stiffest portion of the system).

Table 1 presents a summary of the results of the sensitivity analyses.

Sensitivity Analysis
Dynamic Forces in Track – Crossing Transition System

P static = 29000 lbs/wheel, V = 100 mph

Number of Trans. Steps	Step Length (ft)	k_1	Pandrol	k steps		k_2	Deflection Slope dw/dx	P dynamic	A	P dynamic crossing total	P dynamic	Pcros/Parea
		Track	k_{1a}	k_{1b}	k_{1c}	Crossing		transition	Crossing		AREA	%
0	0	3000	4000	5000	6000	7000	0.006089	16123	2.56	74123	58000	128%
0	0	3000	4000	5500	7000	8500	0.007126	18867	2.65	76867	58000	133%
0	0	3000	4000	6000	8000	10000	0.007915	20956	2.72	78956	58000	136%
3	4	3000	4000	5000	6000	7000	0.002698	7145	2.25	65145	58000	112%
3	4	3000	4000	5500	7000	8500	0.002868	7598	2.26	65595	58000	113%
3	4	3000	4000	6000	8000	10000	0.003431	9085	2.31	67085	58000	116%
3	8	3000	4000	5000	6000	7000	0.003742	9907	2.34	67907	58000	117%
3	8	3000	4000	5500	7000	8500	0.003741	9905	2.34	67905	58000	117%
3	8	3000	4000	6000	8000	10000	0.004418	11698	2.40	69698	58000	120%

Table 1: Transition Dynamics

Noting that Table 1 represents the full spectrum of the dynamic forces caused by a vehicle passing over the defined rail-highway grade crossing (which is shown in both absolute and relative form), the following observations and conclusions can be made:

- Typical existing crossing designs, without transition zones, exhibit a dynamic overload of 28% to 36% above standard (AREA) dynamic force levels.
- Introduction of 8 foot transition steps reduces the dynamic load to 17% to 20% above standard (AREA) dynamic force levels.
- Use of 4 foot transition steps in the analytical crossing model produces a further reduction in vertical dynamic forces to the range of 12% to 10% above standard (AREA) dynamic force levels.

Overall, the analytical investigation and sensitivity analysis performed show that about 60% of the additional dynamic overloading in the crossing can be eliminated by incorporating transition steps in the design of the crossing.

Based on this analysis and the theoretical evaluation of transition designs for rail-highway grade crossings, it was determined that 4 to 8 foot transition steps be used in the design of a transition zone. It was further determined that the design of a gradual softening of the transition zone represents a promising direction in the optimization of the vertical dynamics of the rail highway grade crossing system.

DESIGN OF MODIFIED PREMIER GRADE CROSSING WITH TRANSITION

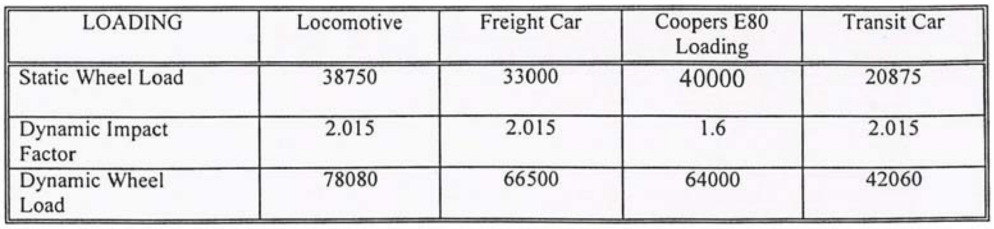
Using the results of the sensitivity analysis, a transition to an existing grade crossing was developed and designed. The crossing selected was a Premier Concrete panel crossing which is typically used for a broad range of grade crossing applications in the United States.

In order to design this transition, a determination of the structural capacity of the existing Premier Concrete Crossing design was performed, together with an assessment of the potential possibilities for optimization and modification. As part of this analysis, the following steps were performed:

- Determination of the extreme wheel load conditions, both railroad and highway that can occur in service
- Development of the longitudinal crossing model.
- Study of the existing crossing design and ultimate structural capacity.
- Sensitivity analysis to component design and type of traffic.
- Fatigue strength and cracking investigation.

In making this assessment, representative highway loadings, as well as representative railroad loadings were considered. The dynamic railway vehicle loads used in this analysis are presented in Table 2.

Table 2. Dynamic Wheel Loads for Analysis.



LOADING	Locomotive	Freight Car	Coopers E80 Loading	Transit Car
Static Wheel Load	38750	33000	40000	20875
Dynamic Impact Factor	2.015	2.015	1.6	2.015
Dynamic Wheel Load	78080	66500	64000	42060

The highway loads (see Table 3) are directly applied to the crossing structure as the vehicle moves across the crossing's surface.

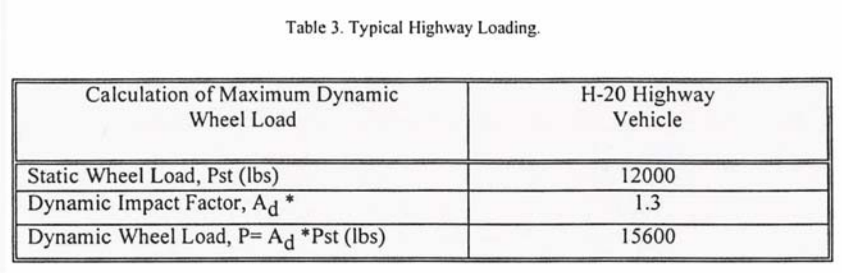


Table 3. Typical Highway Loading.

Calculation of Maximum Dynamic Wheel Load	H-20 Highway Vehicle
Static Wheel Load, Pst (lbs)	12000
Dynamic Impact Factor, A_d *	1.3
Dynamic Wheel Load, P= A_d *Pst (lbs)	15600

The detailed analysis of the crossing is presented in Reference [2].

The design of the transition was based on the difference in stiffness between parent track and the crossing, taken to be wood cross-ties with cut spike fasteners and the crossing itself. Typical vertical modulus values of standard track under different conditions were obtained from a number of field experiments. It can be seen from these experiments and historical data available [3, 4, 9], that for track on wood ties with cut spike fasteners, typical values for vertical track modulus k_1 can lie in the range of 1000 to 3000 lb/in/in (minimal levels for "soft" track) and 6,000 to 10,000 lb/in/in for track within grade crossing (maximum levels for “stiff” conditions).

According to the method proposed above, the transition zone between the standard track and crossing was developed using the following discrete stiffness steps {from "soft" to "stiff" sections):

1. The parent track with wood ties, and cut spikes
2. The parent track with wood ties, and elastic Pandrol System fasteners
3. The Premier Concrete Crossing (field panel only)
4. The Premier Concrete Crossing (gage panel only)
5. The Premier Concrete Crossing (full set of panels) with maximum stiffness

This series of transition steps utilizes an existing concrete panel crossing design, and modifies it to include a transition zone panel. This method will eliminate much of the dynamic "blimp" associated within the crossing area since the stiffness change will be of the order of 3,000 lb/in/in to 8,000 lb/in/in. Figure 6 illustrates the transition zone configuration.

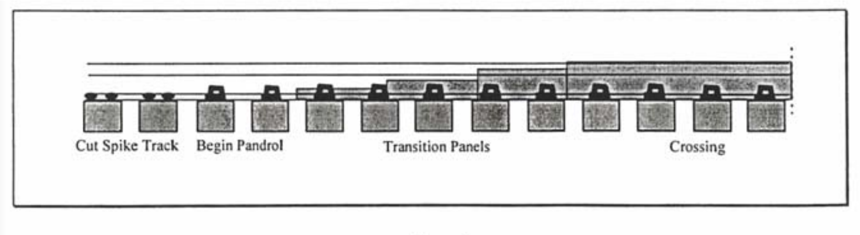


Figure 6

The initial transition is obtained by changing the track construction from standard cut spike track to Pandrol fasteners. This adds a change in stiffness (which has already been used in the field and which performs satisfactorily) as well as provides for a stronger and safer track structure. The Pandrol fasteners extend through the transition, through the crossing, through the opposite transition, and into the parent track structure.

The next transition zone consists of a system of modified crossing panels that extends to the outer edges of the crossing and provides a gradual change in structural stiffness. Note that these panels are not part of the roadway surface, but rather are a stand alone transition area.

This system provides for a gradual change in track deflection with the overall change being minimized.
This is illustrated in Figure 7 below.

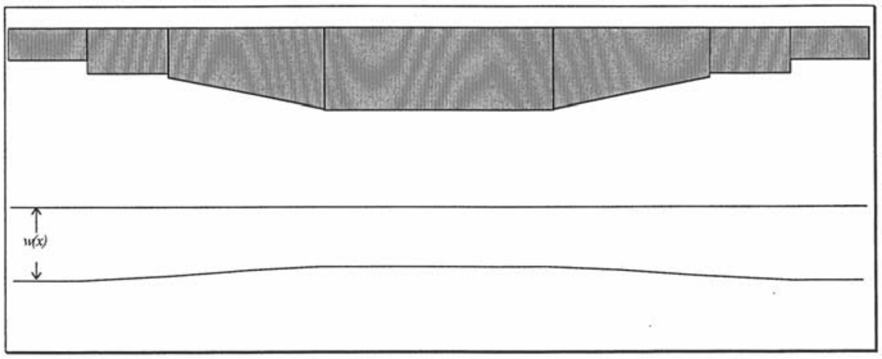


Figure 7

Figure 8 presents a detailed view of the crossing and transition track configuration.

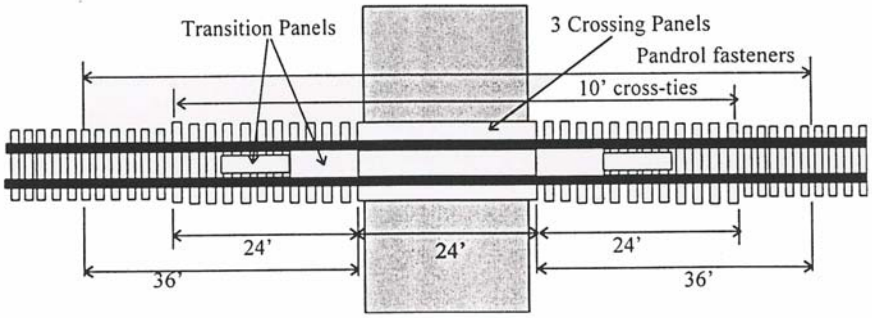


Figure 8. Transition Zone Structure

Based on the length of the transition zone and the available crossing components, it was determined that 8 foot crossing panels were to be used, along with an elastic fastener zone to make up the final step-wise transition.

The corresponding stiffness distribution was determined to be as follows:

- The regular track (cut spike fasteners) *kl* = 1000 lb/in/in
- The regular track (Pandrol fasteners) *k1a* = 1500 lb/in/in
- The Premier Concrete Crossing (field panel) *k1h* = 3000 lb/in/in

- The Premier Concrete-Crossing (gage panel) k_{klc} = 4500 lb/in/in
- The Premier Concrete Crossing (full set of panels) k_2 = 6000 lb/in/in

MODIFIED CROSSING INSTALLATION AND TESTING

The test location was chosen on the New Jersey Transit, Atlantic-City Line, in the vicinity of Atco, N.J., at the Bates Mill Road Intersection. This is a high speed (80 mph) crossing with significant traffic density. The high-speed transit traffic (80 mph maximum) was required to provide the level of vertical dynamics, necessary for testing and comparison of the crossing modifications.

The crossing was installed in the Spring of 1998, using New Jersey Transit field forces. Prior to installation, a series of test runs were made over the crossing using a portable accelerometer based ride quality measurement system to measure vertical accelerations along the track, at the test crossing and several crossings on either side of the test crossing. These initial measurements were used for the definition of the "before" condition.

Also a series of track modulus measurements were carried out. This set of measurements was performed at the Bates Mill Crossing location, before the modified concrete panel and transition systems were installed. The measurements were performed to determine the value of the current track modulus *(k)* throughout the site. The resulting modulus values were as follows:

- track modulus for the regular track on both ends of the crossing is in the range of k_{track} = 1000 to1500 lb/in/in
- track modulus for the crossing itself lies in the range of k_{cross} = 5500 to 6000 lb/in/in

Additional vertical dynamics measurements were taken after the installation of the dynamically stable concrete grade crossing system. Again, measurements were performed with the portable ride quality measurement system.

The purpose: of this on-board investigation was to monitor the level of vehicle/track dynamic interaction, and to determine if there was an improvement in the dynamics of the passenger car crossing the dynamically stable grade crossing vs. the conventional grade crossing.

Two methods were used to examine the level of accelerations:

- Plotting the acceleration vs. distance (time) along the track, to identify all existing crossing locations and corresponding vertical acceleration levels for baseline comparison.
- Plotting the acceleration vs. distance (time) in the Bates Mill Road Crossing, before and after installation of the new step-module system

The maximum speed of the NJ Transit train was maintained at a level of 80 mph through the crossing. The portable ride quality measurement system was placed in a New Jersey Transit passenger car and seven test runs were made before any modifications were made to the Bates Mill Road grade crossing. Each test run measured the vertical acceleration of the passenger car through six grade crossings. After the Bates Mill Road crossing was modified, there were eight additional test runs on the same six crossings. Several of the same cars were used on both sets of test runs. Figure 9 presents the final results of the statistical analysis, of the test data (all cars) collected in the Bates Mill Road Crossing before and after modification. Figure 10 shows a direct comparison of the maximum accelerations for the same car # 5641.

Bates Mill Crossing					
Asphalt			Dynamically Stable Concrete		
Before Modification			After Modification		
Test Run	Vertical Acceleration (g)	Car #	Test Run	Vertical Acceleration (g)	Car #
1	0.159	5802	1	0.094	5641
2	0.102	5622	2	0.102	5638
3	0.159	5641	3	0.123	5613
4	0.130	5613	4	0.098	5638
5	0.121	5641	5	0.103	5641
6	0.184	5802			
7	0.100	5613			
Mean	0.136		Mean	0.104	
STD	0.032		STD	0.011	

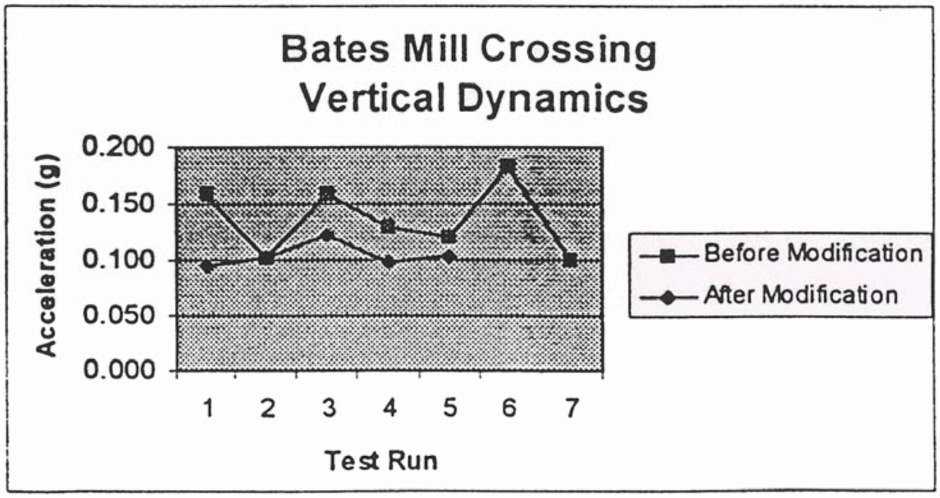


Figure 9

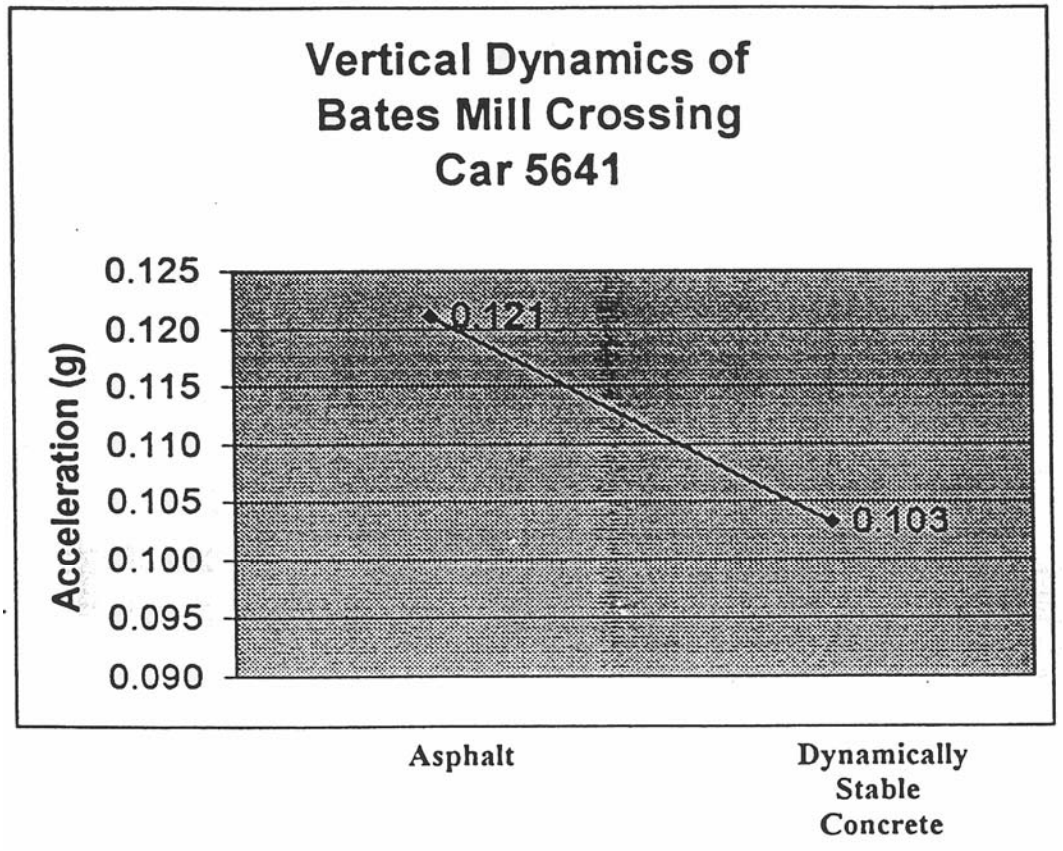

Vertical Dynamics of Bates Mill Crossing Car 5641
Acceleration (g)
0.125
0.120
0.115
0.110
0.105
0.100
0.095
0.090
0.121
0.103
Asphalt
Dynamically Stable Concrete

Figure 10

Analysis of the test data for **all** sets of measurements performed resulted in the following:

- Maximum vertical acceleration level (all cars) for the Bates Mill Road Crossing *before modification* is in the range of 0.1 0 to 0.18g, with the mean value equal to 0.136g
- Maximum vertical acceleration level (all cars) for the of the Bates Mill Road Crossing *after modification* is in the range of 0.094 to 0.12g, with the mean value equals 0.1 04g
- Maximum vertical acceleration level for the same car (#5641) was reduced from initial level of 0.121 g for the existing crossing (Figure 10) to 0.1 03g after introduction of the transition.
- Overall, the field measurements, and subsequent statistical analysis show that about 70% of the additional dynamic overloading in the crossing can be eliminated by incorporating transition steps in the crossing design (Table 4).

Note, good agreement was observed between the results of analytical modeling (53% overloading reduction) and field test measurements (70+% overloading reduction).

Thus, the test measurements presented here confirm the results of the crossing analytical modeling, and show that a gradual softening of the transition zone represents a promising direction in the optimization of the vertical dynamics at the crossing transition.

In addition, conversations with railroad personnel indicated that there was a noticeable difference in the ride quality of the Bates Mill crossing, after the newly designed crossing was installed. In fact, the railroad personnel commented that the crossing was in pretty good shape (from a dynamic standpoint) to begin with, and was in better shape after the dynamically stable grade crossing was installed. This coincides with the results of the research effort.

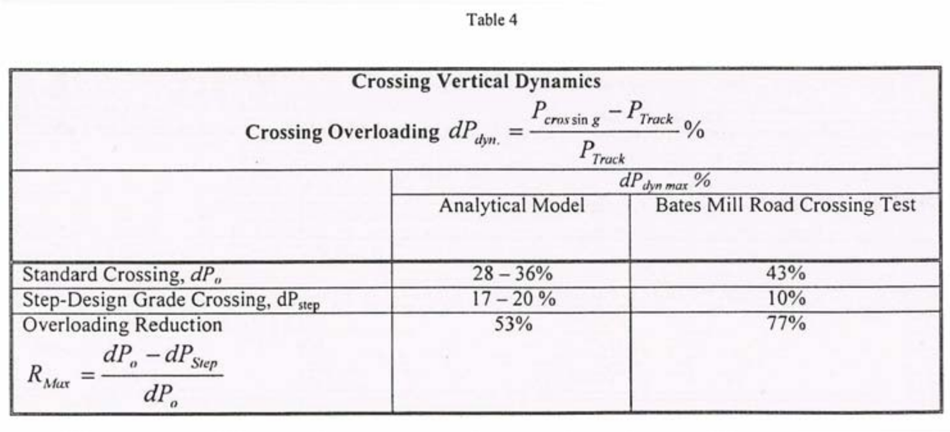


Table 4

Crossing Vertical Dynamics

Crossing Overloading $dP_{dyn.} = \frac{P_{cros\sin g} - P_{Track}}{P_{Track}} \%$

	$dP_{dyn\,max}$ %	
	Analytical Model	Bates Mill Road Crossing Test
Standard Crossing, dP_o	28 – 36%	43%
Step-Design Grade Crossing, dP_{step}	17 – 20 %	10%
Overloading Reduction $R_{Max} = \frac{dP_o - dP_{Step}}{dP_o}$	53%	77%

SUMMARY OF RESULTS

This paper presented the theoretical formulations and analytical models that have been developed in order to fully understand the dynamic behavior of a rail vehicle as it passes through the stiffness transit10h between parent track and a rail-highway grade crossing.

The method utilized here-in defines a length of track, in the parent (softer section) track immediately before the crossing (stiff section of the track) and developed a transition zone in this region that allowed for a dynamically smooth transfer from the "soft" (parent track) zone to the "stiff" (crossing) zone. The length and nature of the transition zone depended on the difference in vertical track stiffness values between the two primary zones.

The transition zone was developed using a series of transitions of increasing stiffness that effectively bring the track modulus values up to those corresponding to the stiff portion of the track. This transition zone implements the change from "soft" to "stiff' zone using a series of discrete steps of defined length, that change track stiffness in a step-wise fashion.

The proposed method, in effect, provides a zone of gradually changing vertical track stiffness values from the soft (parent) track to the stiff crossing. The number of discrete changes in vertical track stiffness depend on the difference in track stiffness values in the two different zones of the track. The value of the gradual change in stiffness values throughout the transition zone is minimized such that significant dynamic forces are not generated at these interfaces.

The results of the sensitivity study, using the newly developed formulation, showed that about 60% of the *additional* dynamic loading at the crossing can be eliminated by incorporating this multi-step transition design.

In order to evaluate this theoretical analysis, a step-design was developed using existing Premier concrete crossing components. This modified crossing design was installed on NJ Transit's Atlantic City line at the Bates Mill crossing. Instrumented cars were run over this crossing, both before and after installation of the new design, in order to evaluate the effect of this new step design crossing.

These field measurements and subsequent statistical investigation of the dynamically stable step-design grade crossing showed that about 70% of the additional dynamic overloading in the crossing was eliminated by incorporating transition steps in the crossing design.

Thus, good agreement was observed between the results of analytical modeling (60% overloading reduction) and field test measurements (70% overloading reduction).

In addition, conversations with railroad personnel indicated that there was a noticeable difference in the ride quality of the Bates Mill Crossing, after the newly designed crossing was installed. In fact, the railroad personnel commented that the crossing was in pretty good shape (from a dynamic standpoint) to begin with, and was in better shape after the dynamically stable grade crossing was installed. This coincides with the results of the research effort.

Thus, test measurements performed confirm the results of the crossing analytical modeling, and show that a gradual softening of the transition zone represents a promising direction in the optimization of the vertical dynamics at such locations with discrete changes in track stiffness.

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