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Reduction of Dynamic Wheel/Rail Impact Forces at Grade Crossings Using Stiffness Transitions

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ABSTRACT

This paper presents the results of combined analytical and field study of the use of vertical stiffness transition zones to reduce dynamic wheel/rail impact forces at the interface between conventional track and high/rail grade crossings. These interfaces are traditionally sites of severe dynamic impact forces and corresponding rapid degradation of the geometry of the track. A recent FRA sponsored research study developed a new analytical technique to define the number of and magnitude of the stiffness transition zones needed to reduce the dynamic impact forces. This technique was used to design a series of transitions for a concrete grade crossing, which were installed on New Jersey Transit's Atlantic City Line in the vicinity of ATCO New Jersey in 1998. Field tests performed on the grade crossing after installation showed a significant reduction in measured dynamic vertical accelerations across the grade crossing as compared to other crossings on the same line. Recent follow up evaluation of this grade crossing showed that it is performing significantly better than similar adjacent grade crossings on the same line and that there has been a marked reduction in degradation of the track/grade crossing and associated maintenance. This paper will present the results of the theoretical formulation. analytical study, and the field tests.

INTRODUCTION

The abrupt change in vertical track stiffness associated with railroad/highway grade crossings, bridge abutments, and other locations where there is a sudden change in the vertical support conditions or “modulus” of the track structure is an ongoing concern of railroad maintenance engineers. This abrupt change in vertical track modulus or stiffness frequently results in increased dynamic *wheel* loading, increased/accelerated track degradation and poor ride quality. To eliminate (or minimize) 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 is 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. In order to implement this concept, the structural characteristics and stiffness distribution of a

Rail/Highway Grade-Crossing System were investigated and modified in such a way as to optimize the resulting vertical dynamics in the transition zone. This paper presents the analytical approach used in the design of the modified crossing system, the modified crossing design and results of a trial installation. Based on the theoretical analysis of the crossing system, 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 analysis methodology and 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. The FRA study was performed under the sponsorship of the Federal Railroad Administration's High Speed Technology program.

OVERVIEW

In order to evaluate the transition problem, a series of analytical steps were taken as follows:

- Identification of the key engineering parameters and factors that influence the dynamic behavior at the transition stiffness zones of rail/highway grade crossings.

- Formulation and development of a conceptual design for a variable stiffness crossing that will reduce the dynamic behavior of a vehicle going over the crossing.

- Determination of the typical range of values for the key physical parameters of typical railroad/highway grade crossings.

- Determination of the levels of wheel loading, associated with variations in train speeds and axle loads, that can occur in service.

- Formulation and development of the model describing the dynamic behavior of a vehicle moving over a variable stiffness crossing.

- Investigation and comparison of two alternative analytical models (and solutions) of the grade crossing system on elastic foundation.

- Comprehensive theoretical investigation and sensitivity analysis of the effects of a gradually changing vertical track stiffness.

As a result of the theoretical study, a comprehensive model was developed and applied to the solution and a sensitivity investigation of the analytical concept performed. This model takes into particular account the specific vertical dynamic and elastic foundation behavior of the track/crossing system. The approach provides a unified theory that is analytically consistent, practical to use, and has applications for all types of grade crossings, bridge abutments, and other locations with abrupt changes in vertical track stiffness.

Based on the theoretical study performed, the task of designing a dynamically stable grade crossing system was undertaken, including:

- Formulation and development of a Step-Design Method of the crossing structure optimization, incorporating not only stiffness, but also strength requirements according to the ACI standards.
- Modification of an existing PREMIER concrete crossing design, including sections and reinforcement, and development of the technical documentation for the manufacturing of a new crossing structure.

As a final and practical step in the dynamically stable Rail-Highway Grade-Crossing System investigation, the new modified PREMIER 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.

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) continuously supported by a series of closely spaced springs (cross-ties, ballast, and subgrade). This was first introduced by Winkler in 1867, and hence is typically known as the Winkler foundation. In this model, the elastic spring constant *k* is the representation of 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:

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

In the above equation *w(x)* is the deflection at point *x*, while *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 (addition) associated with the grade crossing structure itself. This is illustrated in Figure 1.

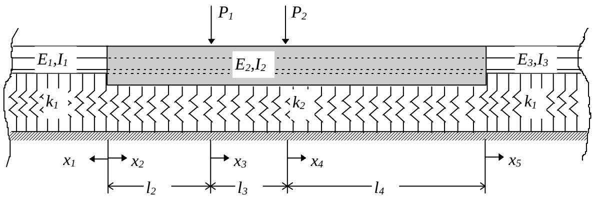


Figure 1. Model of Crossing and Track Structure.

In Figure 1, for a typical grade crossing, the stiffness under the crossing (k_2) will be greater than that of the parent track structure (k_1). This can cause a sudden change in the vertical acceleration of the vehicle resulting in a dynamic impact force in the following areas:

1) In the crossing area when entering the crossing
2) In the parent track structure when leaving the crossing

This sudden change in vertical acceleration can be associated with a change in the elevation of the moving vehicle's wheel. When the vehicle is moving, the track is deflecting under load. If the vertical track stiffness is constant, the deflection will be constant. However, when an abrupt change in the vertical track stiffness exists, the deflected path of the traveling vehicle will suddenly change. Therefore when entering the crossing, the wheel will experience a sudden change (decrease) in deflection when entering the crossing, causing a dynamic increase in the wheel force inside the crossing. Alternately, when leaving the crossing, the wheel will experience a sudden increase in deflection from the stiff portion of the crossing to the softer portion of the track (i.e. when moving from the crossing to the parent track), resulting in a dynamic increase in wheel force in the parent track structure.

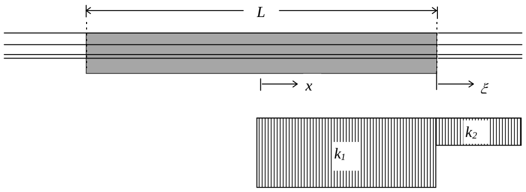


Figure 2. Distribution of Track Modulus.

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.

In practice, several methods have been developed to alleviate the problems associated with abrupt changes in vertical track stiffness. These methods all attempt to match vertical track stiffness whenever possible. Abrupt changes in vertical track stiffness have historically presented maintenance problems to railroads and empirical methods have been used to try to correct this problem. These methods include:

1) Gradually stiffening the soft (parent track) portion of the track
2) Reducing the stiffness on the hard side (grade crossing) of the track

Remedies that have historically been used to gradually stiffen the soft portion of the track include a transition zone of cross-ties with increasing length (usually switch ties) that gradually change the vertical track stiffness until it reaches a stiffness compatible with that of the hard portion of the track. Another remedy utilizes layers of geotextile or asphalt such that the thickness of the layers gradually increases towards the hard section of the track resulting in a gradual increase in track stiffness.

Another method used in reducing the stiffness of the hard portion of the track utilizes tie-pads to change (reduce) the stiffness of the hard portion of the track. This method utilizes the elastomeric properties of the tie pads to reduce the stiffness on the hard side of the track such that it matches the stiffness of the soft side of the track as closely as possible. By using the appropriate tie pad, the hard portion of the track will have stiffness characteristics representative of those in the soft portion of the track. This will in effect provide for a constant stiffness value through the crossing area.

The above methods have been incorporated in railroad service under limited conditions and have provided satisfactory results in several locations. However, they are empirical in nature and as such require "guesswork" and a "trial and error" approach in order to achieve any reasonable results. Development of an analytical approach would eliminate this guesswork and allow for a more effective matching of stiffness characteristics without the trail and error approaches of the past.

The problem addressed here-in is that of developing an appropriate transition zone to best match the different stiffness values in the track and crossing zones. This transition zone is intended to allow for a smooth change in dynamic behavior at the wheel/rail interface so as to eliminate the dynamic impact forces associated with typical crossing designs.

The methodology 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 will depend 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 transition zone will implement this change from "soft" to "stiff" zone using a series of discrete steps of a defined length, that will change track stiffness in a step-wise fashion.

The proposed method will in effect provide a zone of gradually changing vertical track stiffness values from the hard side of the track to the soft side of the track. This is illustrated in Figure 3.

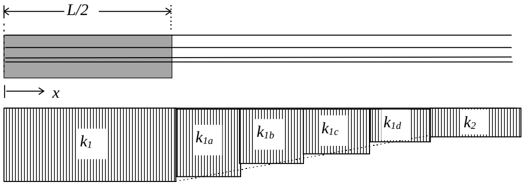


Figure 3. Distribution of Track Stiffness with Transition.

The number of discrete changes in vertical track stiffness will 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 will be minimized such that significant dynamic forces will be reduced (if not eliminated) at these interfaces.

ANALYTICAL APPROACH

The primary objective of the analysis was to formulate the physical problem described previously and solve it such that distribution of forces along the track longitudinal axis could be determined.

The main analytical steps, which were performed based on the physical features of the problem described above, are as follows:

1. The initial activity was to define and develop the equations that govern the behavior of the track as it responds within the elastic transition zone. Once these equations are defined, an analysis can be performed to develop the length and values of the constant stiffness zones (steps) required, together with the overall length of the transition zone based on the differences in track stiffness (k_1 and k_2) to be defined. In addition, the theoretical modeling will allow for the design of the individual components that can be used to develop a practical transition zone.
2. The second activity was to develop the analytical formulation describing the movement of a typical rail vehicle through the crossing, to include the approach to the crossing zone, passage through the transition area with variable stiffness, and, finally, through the crossing itself. This second model must allow for an accurate description of the vertical dynamics of the vehicle as it travels through the transition, incorporating the properties of the elastic foundation from the initial grade-crossing model.
3. In the final step of the theoretical investigation, steps 1 and 2 are combined to obtain a unified track/vehicle interface model, creating a complete description of the relative dynamic behavior of a vehicle as it travels through the transition. This allows for the determination of the difference in dynamics level between the standard existing crossing and proposed “smoothed” modification, and to allow for the definition of the optimal parameters of a new transition (step) design. These parameters and analysis results will be used at the practical design stage of the project.

The basic initial formulation used in this analytical approach is the dynamic analysis of a moving load. The overall model consists of a parent track zone (soft), the grade crossing zone (which is defined to be stiffer than the parent track zone) and a stiffness transition zone. This model is illustrated in Figure 4 below.

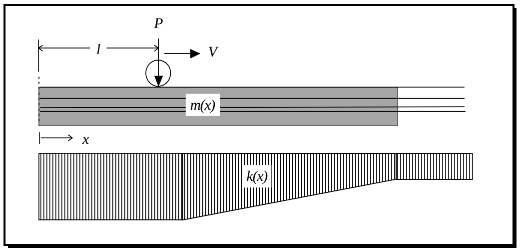


Figure 4. Dynamic Load Moving over Transition Zone.

When considering a complete dynamic formulation, many factors must be taken into account that represent the key parameters that interact between the vehicle and the track. These include the variable track modulus, variation in mass (inertial) of the track structure, mass of the vehicle, speed of the vehicle, and other rail and track properties. These factors are considered in the comprehensive formulation presented below.

The governing differential equation for a moving load on an infinite beam resting on an elastic foundation is of the form:

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

[1]

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:

$$q(x,t) = \left[P - M\frac{\partial^2 w(x,t)}{\partial t^2}\right]\delta(x,t)$$

[2]

where

P = applied wheel load

M = concentrated mass of applied load

$\delta(x,t)$ = the Dirac delta function

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

$$\lim_{x\to\infty}\left(w(x,t),\frac{dw(x,t)}{dx}\right) \to \textit{finite}$$

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

for all t [3]

The resulting formulation is extremely complex and research has suggested that the formulation can not be readily solved in its current form. Therefore, several simplifying assumptions were made to facilitate solution of this problem and are illustrated in the following analysis steps.

Note; a closed form solution of the formulation presented above is beyond the practical scope of this project, considering the complexity of the initial system of equations and the following specific factors:

- two parameters in equation [1] are not constant, as in a typical analytical formulation of the railroad track structure, namely *k(x)* and *m(x)* which represent variation in stiffness and mass along the track's longitudinal axis

- the partial differential equation above includes a defined singularity, in the form of a Dirac delta function $\delta(x,t)$, which leads to integration problems for the defined boundary conditions.

In addition to these analytical problems, the formulation contains a hidden physical "problem inside the problem" in equation [2] where the applied dynamic wheel load *P* is not only a function of speed *V* (as on the regular track) but also depends on the unknown track deflection geometry *w(x,t)*.

Therefore, in order to facilitate analysis of this formulated problem, the approach is 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 [1] 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 to the initial formulation.

Both steps of this modified problem formulation are discussed in detail in Reference 2.

As noted above, the full dynamic formulation of the analytical deflection problem is extremely complex, which makes a closed form solution impossible, and the accuracy of the potential numerical approximations questionable.

In addition the following needs to be considered:

- two parameters in equation [1] are not constant, as in a typical analytical formulation of the railroad track structure, namely *k(x)* and *m(x)* which represent variation in stiffness and mass along the track's longitudinal axis

- the governing partial differential equation above includes a defined singularity, in the form of a Dirac delta function $\delta(x,t)$, which leads to integration problems for the defined boundary conditions.

In addition, it is not known how much damping can be achieved in a real dynamic system. This can result in a limitation in the full dynamic analysis with the absence of damping leading to the distortion of a deflection curve w = f (x, t), and overstating of the real level of vertical dynamics.

Based on the above, it was concluded that conversion of the full dynamic model to a quasi-static one is an effective approximation in this situation and a commonly used simplification of a complex dynamic system. Based on the previously defined formulation and assumptions, a quasi-static (i.e., a static analysis with wheel loads factored for dynamics) model of the grade crossing system can be formulated and subsequently solved using two different approaches as follows:

1. A quasi-static model with the system stiffness changing linearly in a transition zone. Conceptually, this linearity allows for a substantial problem simplification and a reduction in the number of differential equations in the analytical model. However, the linear approximation leads to an additional unknown analytical error, connected with the substitution of the step-wise change in the stiffness that is associated with a series of transition steps (which is the "practical" design approach) to the uninterrupted linear one. Because of this approximation, only limited investigation was carried out of the linearly varying stiffness transition, including analytical formulation and numerical solution. This formulation does allow for the possibility of future applications for relatively small stiffness steps approaching a true linearly varying condition. The results of this investigation are presented in Appendix A.
2. Quasi-static model with a finite number of stiffness steps in the transition zone. This model was subsequently determined to be the most promising and closest to practical realization of the concept of a stiffness transition zone that can be designed using currently available technology. It will be shown that mathematical problems, which in this model involve large systems of differential equations, can be overcome, and a closed form solution, which is very convenient for the sensitivity study, can be derived.

Considering the advantages of this second quasi-static model, the formulation of the problem was extended to include multiple steps in the change of track stiffness as illustrated in Figure 5 below.

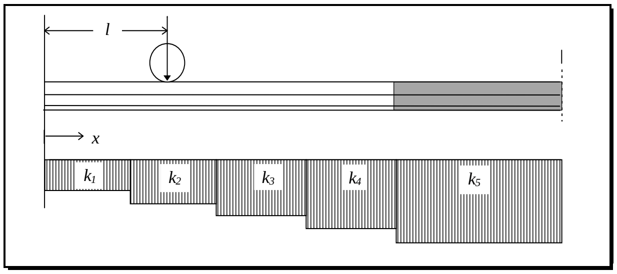


Figure 5. Quasi-Static Model

From this figure, it can be seen that a wheel will move through several zones of varying track stiffness. The first zone (where $k = k_1$), is the parent track structure with the track modulus being representative of the track stiffness for the region. As the wheel moves along the track's longitudinal axis, the first change in track stiffness will be encountered. Several zones will be encountered sequentially (where $k = k_2$, k_3, & k_4) which make up the transition zone before reaching the final zone (where $k = k_5$) which contains the crossing structure and its associated stiffness.

The figure above illustrates the "next step" track model, which must be analyzed to determine the actual path of the wheel and the resulting dynamic force that occurs as the wheel travels through the transition zone. The above model results in a formulation of 6 ordinary differential equations and 24 boundary and matching conditions.

The general form of the quasi-static differential equation is as follows:

$$EI\,\frac{d^4 w_i(x)}{dx^4} + k_n w_i(x) = 0$$

[4]

where

i = 1 - 6 for the number of zones of interest

n = 1 - 5 for the number of track modulus sections

The boundary and matching conditions are regularity at plus and minus infinity (4 boundary condition equations) and the deflection (w), slope (w'), bending moment (M = EIw''), and shear force (V = EIw''') are equal at the track modulus interfaces (16 equations). The final four matching conditions are at the load interface where the deflection (w), slope (w'), and moment (M = EIw'') are equal, and the shear force (V = EIw''') equals the applied load (P).

The generalized solution of this equation is as follows:

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

[5]

It can be seen that 24 integration constants result from the six solution equations (for each zone). This in turn results in an extremely large irregular system of algebraic equations for the A_{mi} constants. Numerical methods and computer programs used to develop the final model solution will be described in following chapters of the report.

A detailed description of a two transition step formulation, using for simplicity of presentation the basic initial model of the two-step grade-crossing system without transition steps is presented here-in. The larger systems (i.e. > 2 transition steps) with the special transition design have the same conceptual analytical description, each with its distinctive number of step-equations.

The basic physical model can be defined as a beam (*i.e.* rail) with two values of track modulus (with a discrete boundary) that is subjected to a concentrated force (*i.e.* wheel load). The physical model is shown below in Figure 6.

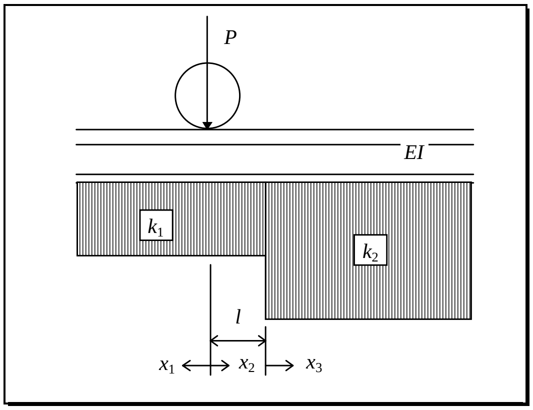


Figure 6. Standard Crossing Model

where

EI = the properties of the rail
P = the wheel load (factored for dynamics)
k_1 = the track modulus of the parent track structure
k_2 = the track modulus of the crossing track structure
x_i = the longitudinal coordinate for the three zones
l = 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:

$$EI\,\frac{d^4 w_1(x_1)}{dx_1^4} + k_1 w_1(x_1) = 0$$

$$-\infty < x_1 \le 0$$

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

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

Boundary/Matching Conditions:

$$\lim_{x_1 \to -\infty}\left(w_1(x_1), \frac{dw_1(x_1)}{dx_1} \right) \to \textit{finite}$$

$$w_1(0) = w_2(0)$$

$$\frac{dw_1(0)}{dx_1} = \frac{dw_2(0)}{dx_2}$$

$$\frac{d^2 w_1(0)}{dx_1^2} = \frac{d^2 w_2(0)}{dx_2^2}$$

$$\frac{d^3 w_1(0)}{dx_1^3} - \frac{d^3 w_2(0)}{dx_2^3} = -\frac{P}{EI}$$

$$w_2(l) = w_3(0)$$

$$\frac{dw_2(l)}{dx_2} = \frac{dw_3(0)}{dx_3}$$

$$\frac{d^2 w_2(l)}{dx_2^2} = \frac{d^2 w_3(0)}{dx_3^2}$$

$$\frac{d^3 w_2(l)}{dx_2^3} = \frac{d^3 w_3(0)}{dx_3^3}$$

$$\lim_{x_3 \to \infty}\left(w_3(x_3), \frac{dw_3(x_3)}{dx_3} \right) \to \textit{finite}$$

This formulation can then be solved. The general solution for each of the differential equations 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*
i = 1 to 3
$n(i)$ = 1, 1, 2
$\beta_{n(i)} = \sqrt[4]{\dfrac{k_{n(i)}}{4EI}}$
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. A complete description of the analysis procedure and solution is presented in Reference 2. References 3 through 11 present related analyses for dynamic loading of elastically supported structures.

PROBLEM SOLUTION

The primary initial parameters, which have to be predetermined, are as follows:

EI = bending rigidity of the rail
P = dynamic wheel load
k_1 = track modulus of the parent track structure
k_2, k_3, k_4 = modulus values for the transition zone steps
k_5 = track modulus of the grade crossing structure
L = length of transition step

Based on test data to include minimum (parent track) and maximum (grade crossing) track stiffness (modulus) values, typical distributions of the transition stiffness modulus values, k_n, are shown in Table 1. The resulting analytical formulation consists of three transitions zones (k_2, k_3, k_4) in addition to the two end zones. These three zones correspond to the intermediate stiffness zones to be defined in further detail later in the design process.

K min	**K1 (Pandrol)**	**K2**	**K3**	**K max**	**Delta**
3000	4000	6000	8000	10000	2000
3000	4000	5500	7000	8500	1500
3000	4000	5000	6000	7000	1000

Table 1: Vertical Track Modulus Distribution

Reference 2 presents a detailed solution to the formulated problem. This solution was obtained using a special optimization program, specifically the VB-Optimization Computer Program.

The program interface, along with a graphical presentation of the numerical solution for the deflection path of a wheel moving through the grade-crossing system, allowed for sensitivity analyses and selection of the optimum component parameters.

The VB (Visual Basic)-Program “Optimization of the Crossing Transition Zone” was utilized to find the general solution of the quasi-static elastic transition problem. The method of matrix inversion was used for the numerical investigation of the differential equation system.

The program itself has a structured design, which includes the following main procedures and subprocedures:

Procedure 1. Input data block

- system geometry parameters
- system elastic parameters

Procedure 2. Program Interface

- input data control
- output graphical information control

Procedure 3. Deflection Path computation

- interchangeable matrix block

- (function of the wheel location)

- matrix inversion

- general system of the boundary condition algebraic equations

- compilation

- Gauss-Seidel solution

Procedure 4. Determination of Deflection Wave

- Region passing subprocedure j = var

Procedure 5. Computational control block

Procedure 6. Graph plotting output $w = f(x)$

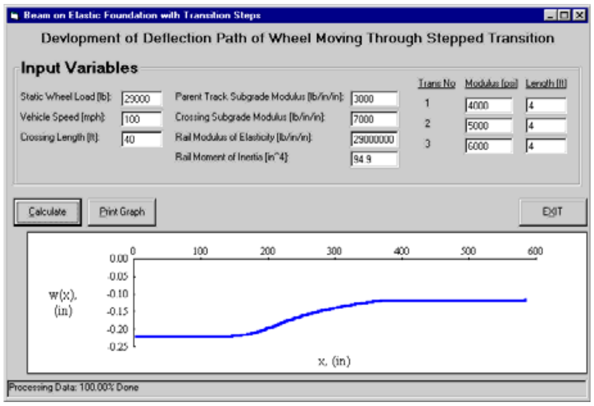
A more detailed description of the program is presented in Reference 2.

This program interface, see Figure 7, simplified the input of the key variables, and the graphical presentation of the numerical solution for the deflection path of a wheel moving through the grade crossing system, and allowed for sensitivity analyses and an optimal selection of the necessary component parameters.

SENSITIVITY ANALYSIS AND APPLICASTION TO GRADE CROSSINGS

Using this analysis approach, 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 EI, 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 stiffnesses involved, specifically, that of the parent track, transition zone steps, and crossing itself (k_i), and length of the transition step L.

The VB model output results shown in Figure 7, 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*.



Beam on Elastic Foundation with Transition Steps

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 7: Deflection Path in Transition

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

Note that the deflection *w(x)* decreases as the wheel approaches the crossing, where it reaches its minimum deflection value (corresponding to the stiffest portion of the system).

Table 2 presents a summary of the results of the sensitivity analyses (a more complete description is presented in Reference [2])

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 Track	Pandrol k_{1a}	k steps k_{1b}	k_{1c}	k_2 Crossing	Deflection Slope dw/dx	P dynamic transition	A Crossing	P dynamic crossing total	P dynamic AREA	Pcros/Parea %
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 2: Transition Dynamics

Noting that Table 2 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 incorporating transition steps in the design of the crossing can eliminate about 60% of the additional dynamic overloading in 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.

Based on the above analysis, a transition to an existing grade crossing was developed and designed starting from an existing Premier Concrete panel crossing, which is typically used for a broad range of grade crossing applications in the United States. [See Reference 12 for a more detailed description of the panel design].

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 [6,7,12,13]. 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 “bump” 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. Figures 8 and 9 illustrate the transition zone configuration.

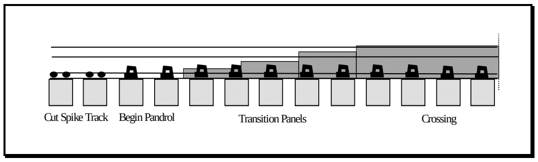


Figure 8

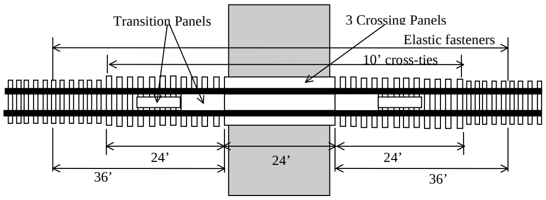


Figure 9. Transition Zone Structure

This system provides for a gradual change in track deflection with the overall change being minimized. The corresponding stiffness distribution was determined to be as follows:

- The regular track (cut spike fasteners) k_1 = 1000 lb/in/in
- The regular track (Pandrol fasteners) k_{1a} = 1500 lb/in/in
- The Premier Concrete Crossing (field panel) k_{1b} = 3000 lb/in/in
- The Premier Concrete Crossing (gage panel) k_{k1c} = 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 passenger 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. In addition, 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 in the range of k_{track} = 1000 to 1500 lb/in/in for the regular track on both ends of the crossing and in the range of k_{cross} = 5500 to 6000 lb/in/in for the crossing itself.

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

Figure 10 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.

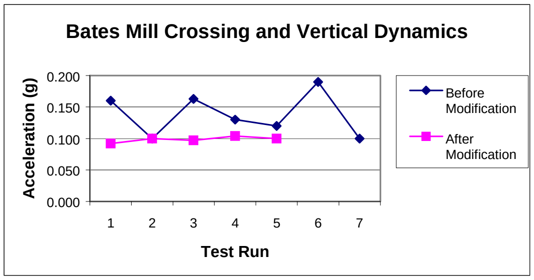


Figure 10

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 0.10 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 0.104g
- Maximum vertical acceleration level for the same car (#5641) was reduced from initial level of 0.121g for the existing crossing to 0.103g 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.

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.

Follow up subjective (riding) evaluation of this grade crossing by ZETA-TECH and New Jersey Transit personnel in 2001 showed that it is performing significantly better than similar adjacent grade crossings on the same line. Furthermore, based on discussions with New Jersey Transit maintenance personnel, maintenance of this crossing was noticeable less than that of adjacent crossings with comparable tonnage and maintenance history. This indicated that there has been a marked reduction in degradation of the track/grade crossing and associated maintenance.

SUMMARY

A series of theoretical formulations and analytical models have been developed to help understand the dynamic behavior of a rail vehicle as it passes through the stiffness transition between parent track and a rail-highway grade crossing.

The methodology develops a transition zone that allows 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 is 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 number of discrete changes in vertical track stiffness depends on the difference in track stiffness values in the two different zones of the track. 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. Field measurements 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).

Follow up subjective (riding) evaluation of this grade crossing by ZETA-TECH and New Jersey Transit personnel in 2001 showed that it is performing significantly better than similar adjacent grade crossings on the same line. Furthermore, based on discussions with New Jersey Transit maintenance personnel, maintenance of this crossing was noticeable less than that of adjacent crossings with comparable tonnage and maintenance history. This indicated that there has been a marked reduction in degradation of the track/grade crossing and associated maintenance.

Thus, both test measurements and subjective evaluation by both ZETA-TECH and railroad personnel confirm the results of the crossing analytical modeling, and show that a gradual softening of the transition zone has the potential for reducing dynamic impact forces at grade crossing transitions, with a resulting decrease in track degradation and associated track maintenance. It should also be noted that the analytical methodology developed herein is also applicable to such related

problems as bridge approaches, soft crossings and approaches, turnout approaches, etc.

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