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9. Analytical Tool for Track Component Response Measurement

9.1 Motivation to Develop a Track Component Response Tool

The quality and state-of-repair of the track infrastructure and its components determines the permissible wheel loads, speeds, safety, and reliability of railroad operations (Hay 1982). With the development of high and higher-speed rail corridors and increasing axle loads in North America, there is increased demand on the railroad track components. This is especially true with concrete crosstie and fastening systems, which tend to be located in some of the most demanding operating environments. Despite the fact that the mechanics of the railroad track structure has been object of extensive investigation for many years (Chen et al. 2012, Shin et al. 2013), the historically dominant design approach adopted by track component manufacturers has been largely empirical.

As part of this research program funded by the Federal Railroad Administration (FRA), researchers from the University of Illinois at Urbana-Champaign (UIUC) have undertaken a major effort to develop a detailed 3D finite element (FE) model of the concrete crosstie and fastening system (Figure 1). The model, largely described in Volume 2, Chapter 5 of this report, has been validated with both laboratory and field data, and proved to be a valuable tool for theoretical comparison between realistic loading cases and experimental testing. Additionally, the FE model facilities conducting parametric studies varying component material and geometric dimensions, is able to assist in the development of recommended mechanistic design criteria for the concrete crosstie and fastening system (Chen 2012, Chen 2013, Shin 2013).

The FE model is a powerful tool capable of accurately representing the loading environments, support conditions, component interactions, load path, and system behavior. Nevertheless, there are accessibility and computational limitations that make its use impractical for the general user. The intensive computational effort needed to conduct each iteration of the model, combined with the high level of expertise demanded from the user when programming experimental runs, motivated UIUC researchers to develop a track component response calculation tool (I-TRACK).

I-TRACK is a software based on statistical analyses of data from the FE model, where the mechanical behavior of track components is modeled using a neural network that is capable of predicting mechanical outputs with respect to certain user-defined inputs (e.g. wheel loads, components material properties, etc.). In other words, the FE model is used to generate a broad set of outputs that are correlated with different inputs, allowing the development of a statistical model that reproduces the effects of the variation of inputs on the magnitude of outputs. I-TRACK is a tool that will play a role in improving the current design process for track components and will aid in developing mechanistic design practices focused on optimized component and system performance.

9.2 Characterization of I-TRACK – Features and Capabilities

Current concrete crosstie and fastening system design recommendations are primarily based on empirical approaches, and there is a lack of clarity behind some of the critical design limits. This is due, in part, to the fact that design load specifications related to speed and traffic at the American Railway Engineering and Maintenance-of-way Association (AREMA) were developed empirically, with input loads and forces distribution not clearly addressed as part of the design methodology (Chen et al. 2012, Van Dyk 2013). In particular, the fastening system component design recommendations present an inconsistent level of detail, and many of the requirements do not represent the realistic loading demands and environments (Van Dyk 2013). Improvements to current design processes are difficult to implement without understanding the complex behavior of the track structure. Therefore, the development of an analytical tool to predict the mechanical behavior of the track system and its components can be a powerful asset in a mechanistic approach to designing the track, where the responses of these components (e.g. maximum stresses, relative displacements, deformations, etc.) are used to optimize their geometry and materials requirements (e.g. strengths, wear resistance, etc.).

I-TRACK has been designed as a practical and adaptable tool capable of quickly estimating the system and component performance based on a set of user defined input conditions. I-TRACK was developed with a degree of sophistication that doesn't demand proficiency in computer coding or knowledge in FE modeling. The primary functional objective of this tool is to provide both user accessibility and adaptability that facilitate rapid access to track component responses. When fully developed, I-TRACK can be used to assist manufacturers in improving the design of components and railroad track engineers in assessing the conditions, safety, and expected performance of the track structure.

The development of I-TRACK follows a systematic process, with its release divided into three versions, where each version adds additional capabilities and features to the tool. This phased approach expedites the development process, allows the accuracy and functionality of the model to be tested on a continuous basis, and provides interim utility to users.

First, input and output parameters were prioritized for each project phase. A Design of Experiments (DoE) based on Half Fractional Factorial Design was used to reduce the number of model iterations that were required to develop I-TRACK. DoE is a strategic way of extracting the system's behavior, optimizing the quality of the information and the effects of a response variable due to one or more factors (Krishnaiah 2012). Section 9.3 of this chapter will provide a detailed description of the techniques used to define the DoE. After the experimental matrix was completed using the DoE, the experiments were coded in the FE model, which was used to generate the track outputs. The matrix of results from the FE model runs was the database used to generate the radial basis function neural network model. This technique correlates the inputs to the output parameters with no error in the training data, allowing the correlation between input variations and their effects on the outputs magnitudes with good accuracy. Other methodologies based on multivariate regression analysis were tested in the development of the statistical model. Higher order effects and the inability to predict most of the correlations between inputs and outputs led to large errors in the results. Therefore, a neural network model approach was chosen as opposed to the aforementioned technique.

The final model was embedded in Microsoft Excel, due to the fact that it is a well-known application used throughout the world. In the future, researchers intend to launch I-TRACK in different platforms, possibly as cellular phone applications and open-source software.

9.2.1 I-TRACK – Version 1.0

I-TRACK's initial development involved determining the key inputs to be analyzed in the FE model and choosing the primary outputs to be monitored. The inputs were selected based on their capability of affecting the track and fastening system component's mechanical responses. Additionally, the ease of coding them in the model has also contributed in their selection. The limitation on the number of inputs is due to the amount of experiments that must be carried out in the FE model when extracting their effects in the monitored outputs. The number of experiments that are required for I-TRACK development grow exponentially with the amount of inputs and significantly increases the total computational effort that is required.

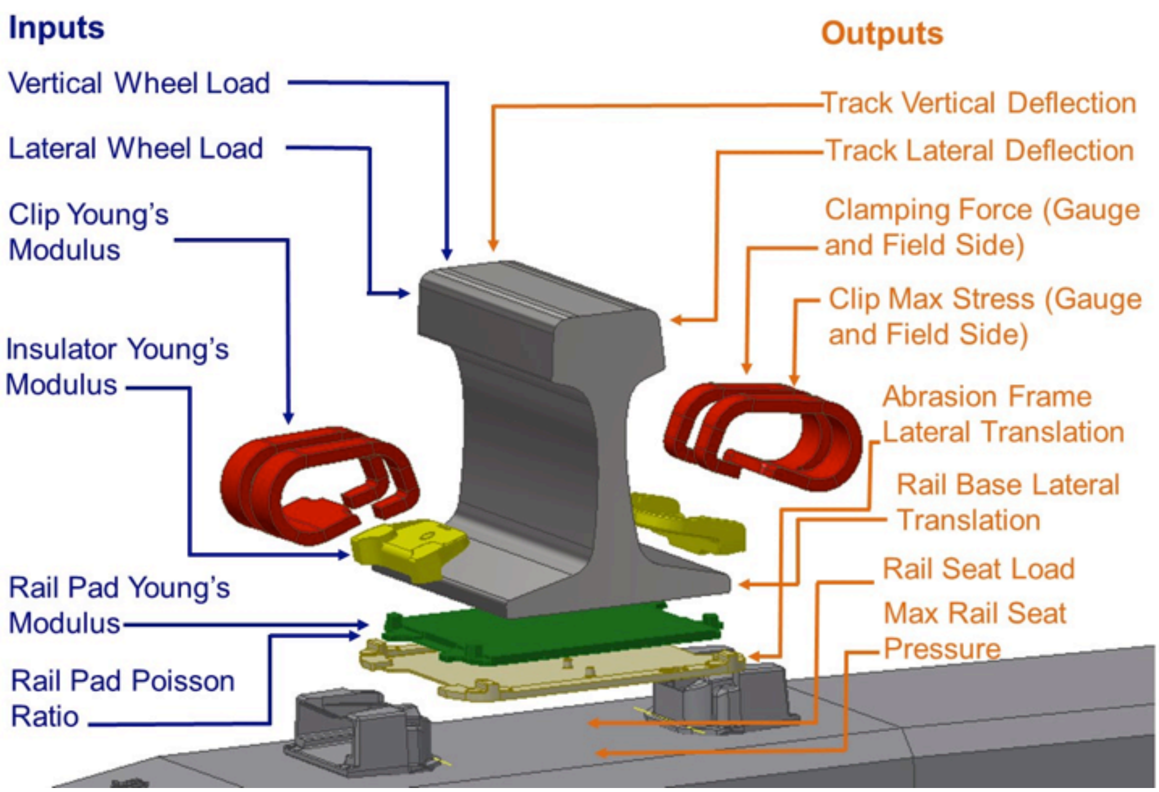


Figure 1. List of Inputs and Outputs Included in I-TRACK Version 1.0

For I-TRACK Version 1.0, static wheel loads (vertical and lateral) and some of the fastening system component's material properties were prioritized as inputs (Figure 2). The first set of outputs (Table 1) was selected to capture the general behavior of the track, giving the user insight about the behavior of key fastening system components. Figure 2 and Table 1 present the inputs and outputs captured for this version of the project and explain the relative location in which these outputs where measured in the FE model. It is important to note that the development of I-TRACK is a continuous process dependent on the FE model capabilities and is subject to a level of accuracy and variability that is related to the number of FE model runs. I-TRACK Versions 2.0 and 3.0 are still under development and additional details of these versions can be found in the next section of this chapter.

Table 1. Definition and Relative Position of Outputs Monitored in I-TRACK Version 1.0

Output	Definition and Relative Position
Track Vertical Deflection	The global vertical deflection at the top of the rail head
Track Lateral Deflection	The global lateral deflection measured at right-angles to the rail in a plane 5/8" below the top of the rail head. Positive value indicates the railhead moved to the gauge side, and negative value indicates the rail head moved to the field side
Rail Base Lateral Translation	The lateral translation measured at the middle of the rail base edge. Positive value indicates the rail base moved to the gauge side, and negative value indicates the rail base moved to the field side
Abrasion Frame Lateral Translation	The lateral translation measured at the field side edge of the abrasion frame. Positive value indicates the abrasion frame moved to the gauge side, and negative value indicates the abrasion frame moved to the field side
Rail Seat Load	The vertical component of the force resultant from the interaction between rail and rail pad on the loaded crosstie
Gauge Side Clamping Force	The vertical component of the force resultant from the interaction between the insulator and the gauge side clip
Field Side Clamping Force	The vertical component of the force resultant from the interaction between the insulator and the field side clip
Gauge Side Clip Maximum Stress	The maximum principal stress in the gauge side clip
Field Side Clip Maximum Stress	The maximum principal stress in the field side clip

9.2.2 I-TRACK – Versions 2.0 and 3.0

The second and the third versions of I-TRACK will allow the user to modify a larger number of inputs and the software will provide additional output parameters. I-TRACK Version 2.0 is designed to enable the modification of surface interactions and support conditions that will be used as inputs. Therefore, the coefficient of friction between components and the track stiffness will be added as user-defined parameters (Table 2). The monitored outputs will consist of a set of 39 parameters (Table 3), which will permit a detailed understating of the track behavior and its components. Researchers at UIUC believe these are the main values that are likely to be the most significant from a mechanistic design standpoint, since they encompass macro and micro characteristics of the track mechanical response.

Table 2. Input Capabilities for I-TRACK Versions 2.0 and 3.0

Version	Inputs
I-TRACK 2.0	All the inputs considered in version 1.0
	Coefficient of Friction between rail seat and abrasion frame
	Coefficient of Friction between insulator and shoulder
	Coefficient of Friction between rail pad and rail
	Track Stiffness
	Concrete Compressive Strength
I-TRACK 3.0	All the inputs considered in versions 1.0 and 2.0
	Insulator Post Thickness
	Rail Pad Thickness
	Abrasion Frame Thickness
	Concrete Crosstie Dimensions
	Rail Section (Size)

I-TRACK Version 3.0 will incorporate component geometry into the existing set of input capabilities. Therefore, it will allow the modification of track components, concrete crosstie, and rail dimensions. However, the variation in geometry adds a significant computational challenge when running the DoE, since the relative position between components change in every run. The current FE model uses the Safelok I fastening system, the most prevalent system on concrete crossties in North America. Even though the incorporation of different fastening systems in I-TRACK would be extremely beneficial with respect to broadening its analyses capabilities, this is a limitation of the current FE model that will not be overcome and implemented in I-TRACK in the near term.

Table 3. Outputs for I-TRACK Versions 2.0 and 3.0

Component	Outputs
Track	Track Vertical Deflection Track Lateral Deflection
Rail	Rail Base Lateral Deflection Rail Base Rotation Maximum Stress in the Rail
Rail Pad Assembly	Abrasion Frame Lateral Deflection Rail Relative Lateral Displacement (Relative to Rail Seat) Abrasion Frame and Rail Pad Relative Lateral Displacement (Rel. to Rail Seat) Rail Pad Lateral Load
Insulator	Field Side and Gauge Side Insulator-Shoulder Relative Vertical Displacement Field Side and Gauge Side Insulator-Clip Relative Lateral Displacement Gauge Side Insulator-Shoulder Relative Lateral Displacement Field Side Insulator and Rail Relative Vertical Displacement (Relative to Rail) Gauge Side Insulator and Rail Relative Vertical Displacement
Clips	Gauge Side and Field Side Clamping Force Gauge Side Clip Maximum Stress Field Side Clip Maximum Stress
Shoulder	Contact Pressure between Shoulder and Insulator Field Side and Gauge Side Shoulder Lateral Force Shoulder Lateral Load
Concrete Crosstie	Maximum Rail Seat Pressure Rail Seat Pressure at 0.5, 2.0, 4.0, and 5.5 inches from Shoulder Concrete Crosstie Maximum Compressive Stress Concrete Crosstie Maximum Compressive Stress at Center Concrete Crosstie Maximum Tensile Stress at Center Moment at Concrete Crosstie Rail Seat Moment at the Center of the Concrete Crosstie Rail Seat Vertical Deflection at Center Concrete Crosstie Vertical Deflection at Center Lateral Rail Seat Load at Center Rail Seat Load at Adj. Crosstie (Including Clamping Force) for 3 Crossties Rail Seat Load at Center

9.3 Design of Experiments (DoE) and Radial Basis Function Neural Network

The DoE is developed to allow an estimate for the interactions resulting from input variation in the output behavior. The intent of this modeling technique is to obtain the local shape of the response surface that is investigated. Under some circumstances, a model only involving main effects and interactions may be appropriate to describe a response surface when the analysis of results reveals no evidence of pure quadratic curvature in the output of interest (e.g. the response at the center is approximately equal to the average of the responses at the factorial runs). In other circumstances, a complete description of the output behavior may require higher order interactions, such a cubic model for example.

If a response behaves linearly, the design matrix to quantify this behavior only needs to contain factors with two levels (high and low). This model is a basic assumption of simple two-level factorial and fractional factorial designs. If a response behaves as a quadratic function, the minimum number of levels required for a factor to quantify this behavior is three. In this case, a Central Composite Design (CCD) based on factorial or fractional factorial design facilitates estimation of the responses' curvature.

I-TRACK's DoE used face centered CCF with an embedded Half Fractional Factorial Design (HFFD) to augment the experiments and capture the behavior of the track components responses. First, 32 experiments were developed based on HFFD and were analyzed in the FE model. Another 13 runs were included to capture the curvature of the outputs that presented a strong indication of nonlinear behavior. Additionally, the final DoE matrix considered extra 56 runs used to improve the accuracy of the outputs results and reduce errors. Ten of these runs were not used to train the model, and they were later applied to verify the accuracy of the results.

For the development of I-TRACK, a radial basis function network was trained using the function approximation method. A Radial Basis Function Network (RBFN) is an artificial neural network that uses radial basis functions as activation functions, which are the functions that define the outputs of a network node for a given set of inputs. The outputs are linear combinations of radial basis functions of the inputs and neuron parameters.

All the data points in the training set (95 observations obtained from the FE model) were taken as the centers of the radial basis functions. For each new input value, its Euclidean distance from the all the training points was calculated and the output was predicted based on their weights.

A total of 111 observations were obtained from the FE model. From this data matrix, 95 runs were used for training the model and 16 were used for testing it. The 95 observations used for training included 45 observations created using DoE. These output values were specifically chosen at the bounds of the input points and at central points. Inclusion of these observations in the model ensured high accuracy for the test data as the function approximation methodology requires output values at the extreme values of the input points. The model results have an average error of less than 20% for all the output values and highest error was less than 30%.

9.4 Functionality

The primary objective behind the development of I-TRACK is to give users the capability of analyzing track mechanics and behavior using an accessible and accurate tool that runs on a commonly supported platform. For this reason, a series of functions were developed to intuitively guide users through the analysis process, including tutorials and a graphing tool that relates inputs to outputs. These features allow I-TRACK to provide reasonable approximations of the actual response (e.g. stresses, displacements, forces) of track components under different loading conditions.

9.4.1 Tutorial

I-TRACK includes a tutorial tab explaining how to use the software. This tutorial also contains output specifications detailing the meaning of positive and negative values, direction of axes, and the specific location in the FE model where the outputs were extracted. Additionally, an example analysis routine is provided.

9.4.2 Selection of Baselines

During the analysis process, users have the option to choose from several baseline scenarios for comparing the outputs that are calculated for each combination of inputs. This feature allows users to understand how the set of inputs they choose affects the behavior of the track and its components as compared to baseline values for these inputs. Table 4. shows results extracted from I-TRACK Version 1.0 where baseline values are compared to the results given for a specific set of inputs.

Table 4. Use of Defined Baseline Values for Results Comparison

	Baseline	User's Inputs	Variation (%)
Inputs			
Vertical Load (lb)	37,500	40,000	6%
Lateral Load (lb)	12,500	20,000	38%
Insulator Young’s Modulus (psi)	400,000	1,000,000	60%
Rail Pad Modulus (psi)	202,000	20,000	-910%
Rail Pad Poisson Ratio	0.380	0.490	22%
Clip Young's Modulus (psi)	25,000,000	23,000,000	-9%
Outputs			
Track Vertical Deflection (in)	0.052	0.055	6%
Track Lateral Deflection (in)	-0.010	-0.043	312%
Rail Base Lateral Translation (in)	-0.010	-0.029	198%
Clamping Force Gauge Side (lb)	2,682	2,616	-2%
Clamping Force Field Side (lb)	2,919	2,748	-6%
Clip Maximum Stress Gauge Side (psi)	188,830	197,974	5%
Clip Maximum Stress Field Side (psi)	189,690	187,880	-1%
Rail Seat Load (lb)	28,819	25,845	-10%
Abrasion Frame Lateral Translation (in)	-0.006	-0.010	73%

9.4.3 User Interface

I-TRACK relies on a Visual Basic for Application (VBA) code embedded in Microsoft Excel (Figure 4). "Macro" functions were added to the interface of I-TRACK to guide the analysis and automate the calculations involved in the process. When possible, figures were introduced to assist users in visualizing the track components and loading application points. Once the I-TRACK spreadsheet is opened, users can access a tutorial that explains how to use the tool or to tabs where the necessary inputs are added. The outputs are accessed in a similar manner, which takes place after the user initiates the calculations. Additionally, there is the option to generate a Microsoft Word document summary report, containing the magnitude of the values of all outputs available in a particular run of I-TRACK.

To prevent unintended changes to the configuration of the spreadsheet, all cells in the I-TRACK spreadsheet are blocked except the ones where inputs are entered. However, users have the option to unblock these cells, thereby accessing the code and making modifications. Since the code can be easily accessed, modifications in the program can be made to adapt its interface and features to the specific needs of users.

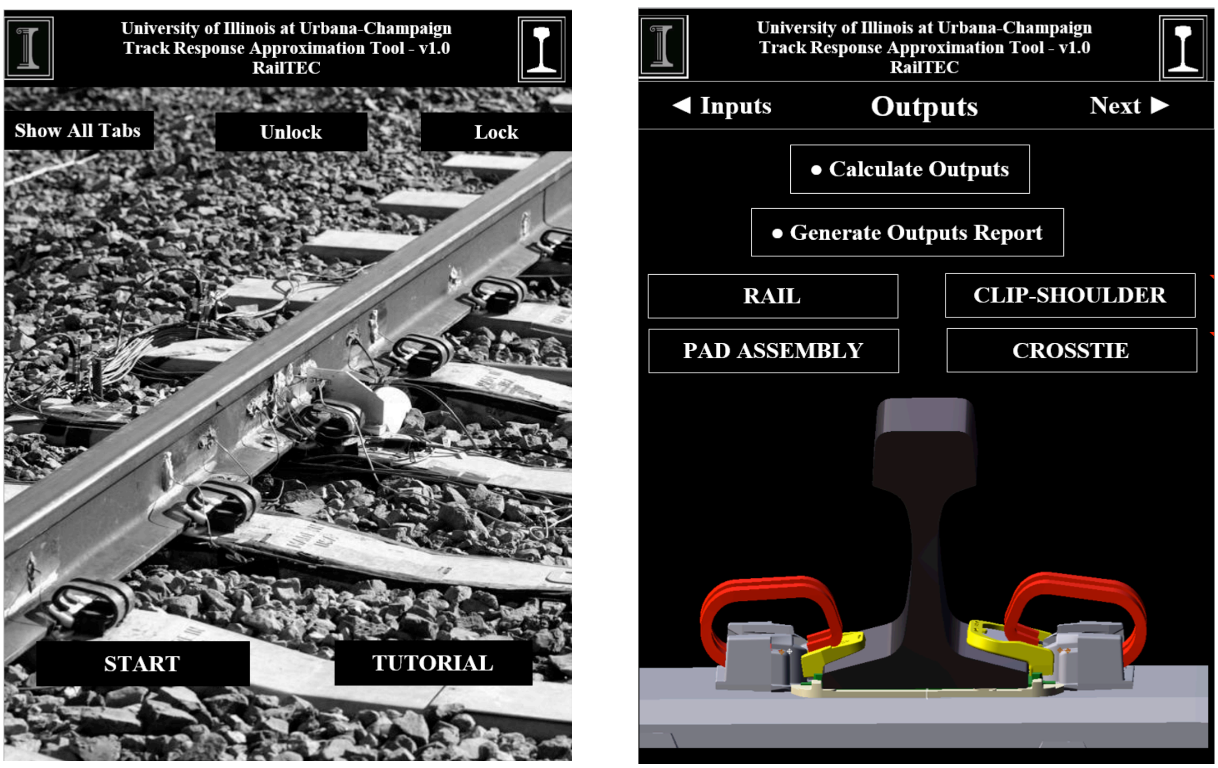


Figure 2. I-TRACK Version 1.0 Interface - Main Page and Outputs Page

9.4.4 Analysis Report

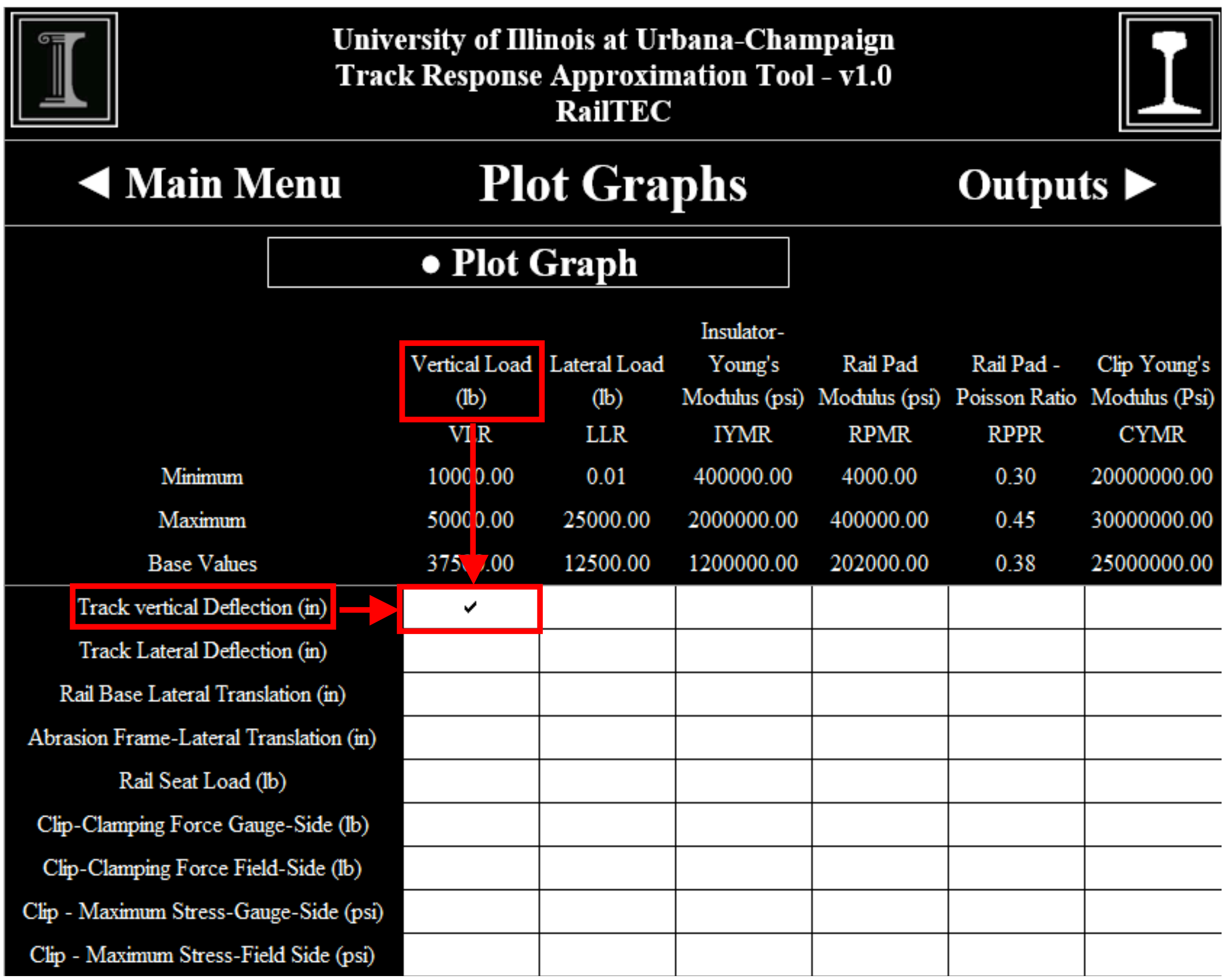
At the end of the analysis process, users have the option to generate a Microsoft Word document report containing the results for the calculated parameters. Once generated, this file is automatically saved in the same folder where the software is located. This is a useful tool for comparing multiple results from I-TRACK, and documenting results for future use.

9.4.5 *Automated Generation of Inputs vs Outputs Graphs*

I-TRACK includes a “macro” that automatically generates Input vs Output graphs. After defining a set of base values, which are the inputs that will be used to generate these graphs, users may choose specific input and output combination to be plotted. If a certain input is chosen, all the other inputs of the analysis will assume the base values.

This tool assists in the visualization of the behavior of outputs when one input is varied and all the others are held constant. Using these graphs, the user can determine how sensitive individual outputs are with respect to the variation of each input. Therefore, an analysis process may determine how track vertical deflection is affected by rail pad stiffness, for example, providing valuable information in a future mechanistic design process of this component.

Figure 5 shows an analysis routine where baseline values were chosen according to the inputs used by Chen (2012) and a graph plotting vertical load with respect to track vertical deflection was selected. Any graph can be plotted using the combination of the available inputs. However, the shape of the curves is not always intuitive due to a variety of reasons, including secondary effects from other inputs and the inherent mechanical complexity existent in some of the components interactions.



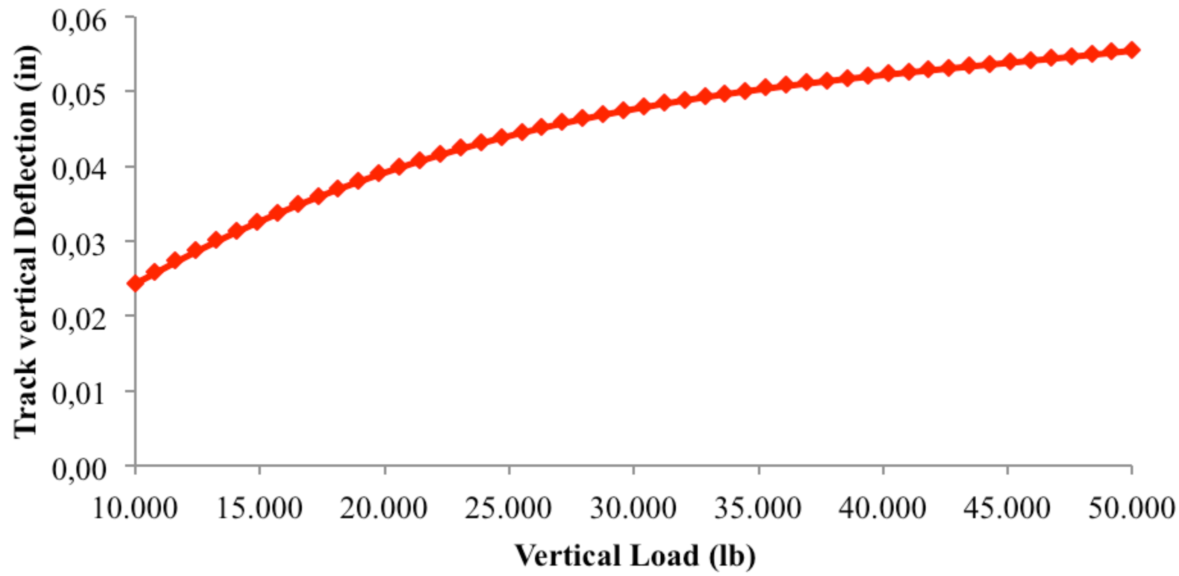


Figure 3. Automated Generation of Graphs Relating User Defined Inputs and Outputs

9.5 Validation of I-TRACK

This section is focused on the validation of I-TRACK results when compared to the FE model outputs. Additionally, a case study of rail pad assembly mechanical behavior was conducted and is included as apart of this section. The main intent is to test the accuracy of I-TRACK's outputs and demonstrate how this tool can be used when developing improved design methodologies for fastening system components. The standard wheel loads and components properties used for the analyses are specified in Table 5. They are the same properties used for the FE model parametric study described by Chen et al. (2013).

Table 5. Wheel Loads and Components Properties Used to Conduct the Case Study

Input	Magnitude
Vertical Load (lbs)	30,000
Lateral Load (lbs)	7,500
Insulator Young's Modulus (psi)	440,000
Rail Pad Young's Modulus (psi)	7,500
Rail Pad Poisson Ratio	0.49
Clip Young's Modulus (psi)	23,000,000

The accuracy of the statistical model embedded in I-TRACK was compared to the FE model results to ensure its credibility and accuracy. Using the material properties from Table 5 and vertical load equal to 40 kips, the lateral displacement of the track and the rail base was plotted for increasing lateral wheel loads. Good agreement is found between the results, with the magnitude of displacements close to each other. Error is present for all the simulated data points, but this factor is due to the amount of variables in the system and the reduced number of experiments used to develop the statistical model. Overall, I-TRACK was successfully able to capture the FE model behavior, providing results with satisfactory accuracy with R^2 value of around 0.98 for both outputs. However, the high level of adaptability of the tool brings inherent constraints of a statistical model representation of the FE model output. For the purposes for which I-TRACK was developed, the results provide reasonable correlation with the FE model.

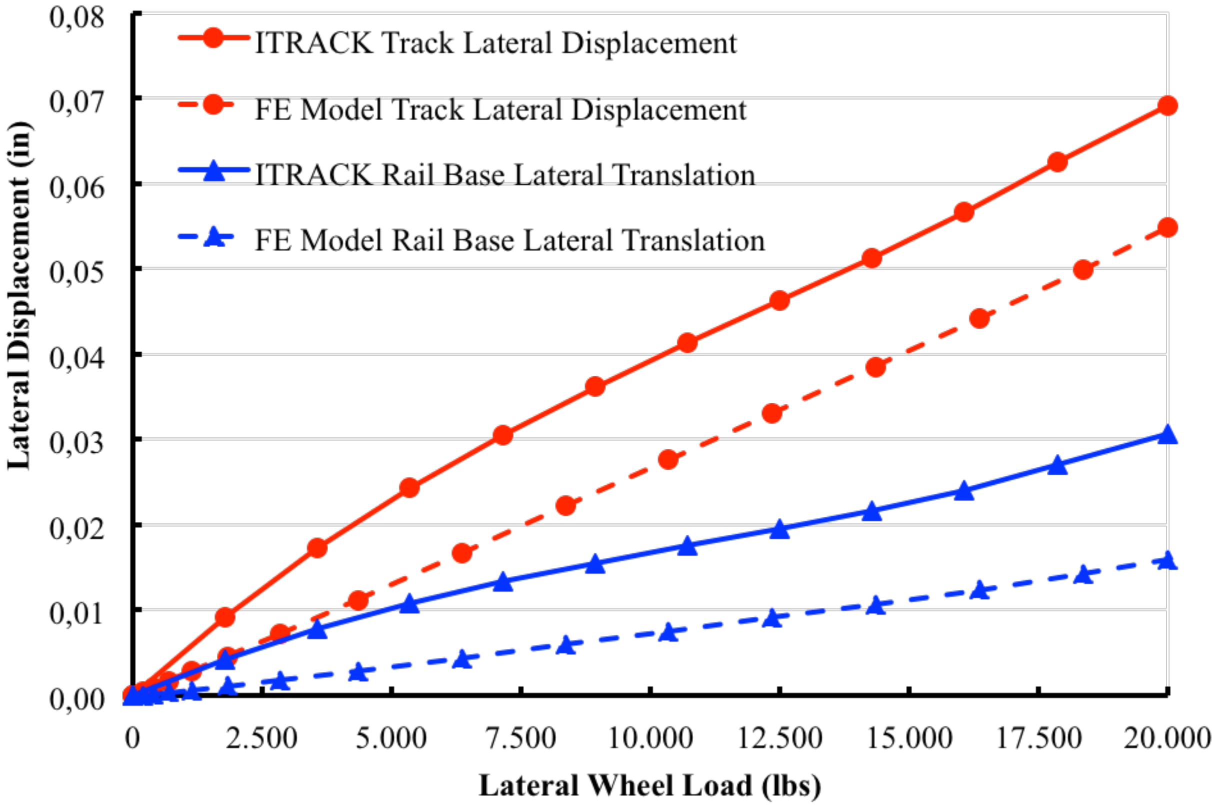


Figure 4. Comparison Between Track and Rail Base Lateral Displacement for Increasing Lateral Wheel Load

9.5.1 Rail Pad Assembly Mechanical Behavior Investigation Using I-TRACK

There are two system parameters that can be assessed using I-TRACK Version 1.0. The first is track vertical deflection, a global measurement of the of the rail head displacement when wheel loads are applied. This output is important to predict the general condition of the track structure, since large displacements must be prevented in order to maintain proper track geometry and adequate service levels. AREMA (2012) states that track vertical deflection is related to track performance and a poor performance equates to excessive maintenance and slow orders. The recommended maximum desirable range for track vertical deflection to ensure a proper balance between flexibility and stiffness is between 0.125 in (3.18 mm) and 0.25 in (6.35 mm) (AREMA 2012). Deflections smaller than the ones specified in this range may be desired to maintain adequate track geometry but are likely to cause larger loading demands on the fastening system components due to increased stiffness.

By analyzing I-TRACK's outputs, it has been shown that the rail pad assembly Young's modulus (RPM) can affect the total track vertical deflection (TVD) to a limited extent (Figure 5). An increase in the RPM from 7,500 psi to 400,000 psi was able to reduce up to 0.01 in (0.25 mm) of the total TVD, which corresponds to 4% of the maximum deflection allowed in AREMA 2012. Even though it may seem to be a small difference in a system parameter, this change in RPM can affect component responses, especially the load distribution in the crosstie rail seat area (Rapp 2013). Strains at the bottom of the concrete crosstie and the vertical load path are also other parameters that are directly affected by the rail pad assembly elastic modulus.

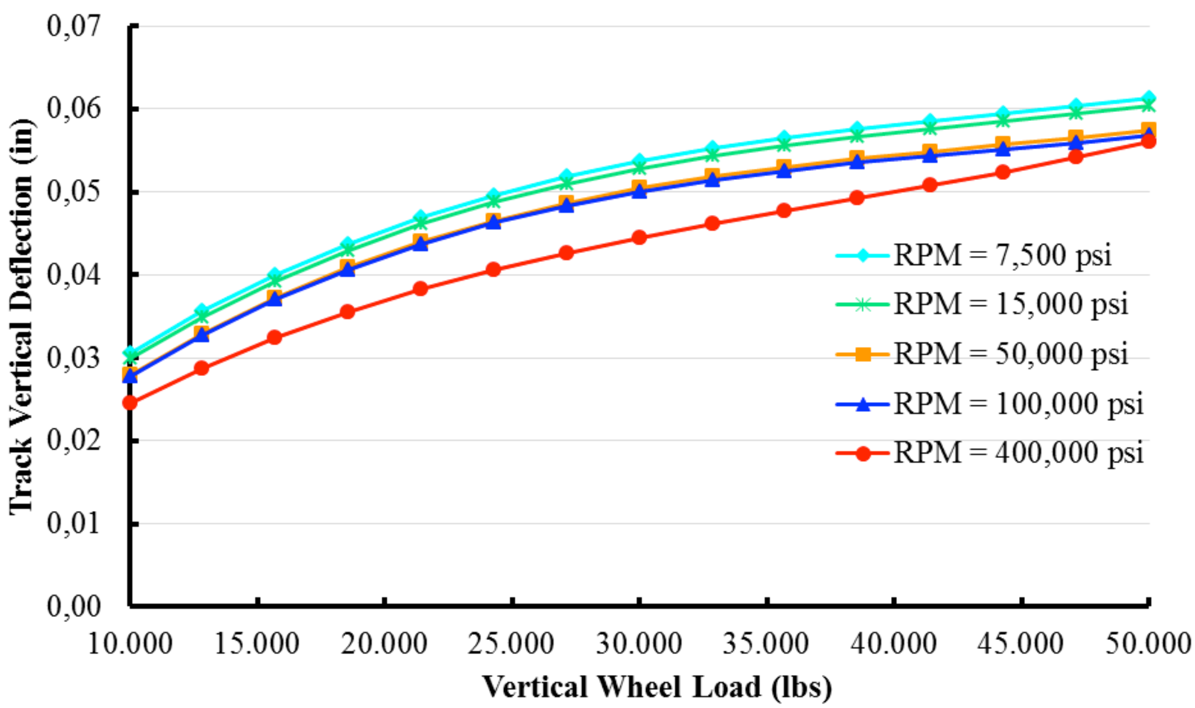


Figure 5. Relationship Between Track Vertical Deflection and Vertical Wheel Load for Increased Rail Pad Young's Modulus

The other system parameter that can be analyzed through I-TRACK is the track lateral deflection (TLD), a global measurement of the rail head lateral displacement when wheel loads are applied to the rail. This parameter is not currently used in track design, even though researchers have indicated the significant influence of lateral load distribution and fastening system lateral stiffness in track components responses (Bizarria 2013, Williams 2013). This output can also be used to assess the overall performance of the track structure, since large displacements may indicate the occurrence of insufficient frictional forces in the system and relative slip between components.

I-TRACK analyses have shown that increased lateral wheel loads cause larger track lateral deflections (Figure 6). The increase of vertical wheel loads affected the magnitude of this output, leading to smaller displacements. A 40 kip increase in the vertical load was capable of reducing the TLD by 40%, indicating the significant difference in track behavior when the system is subjected to heavier axle loads. Higher vertical loads significantly change frictional forces in the fastening system interfaces, reducing the component's lateral displacements (Kernes 2013, do Carmo 2013a, do Carmo 2013b). The development of shared passenger and freight train corridors imposes design challenges in the track infrastructure that must be overcome in order to guarantee adequate track geometry and desired service levels. Therefore, the current railroad trend to increase axle loads and combine passenger and heavy haul operations in the same infrastructure must take into consideration the impact of such loading environment in the infrastructure responses. I-TRACK can be a useful tool to predict components behavior and provide insightful data to answer questions related to the structural design of shared corridors.

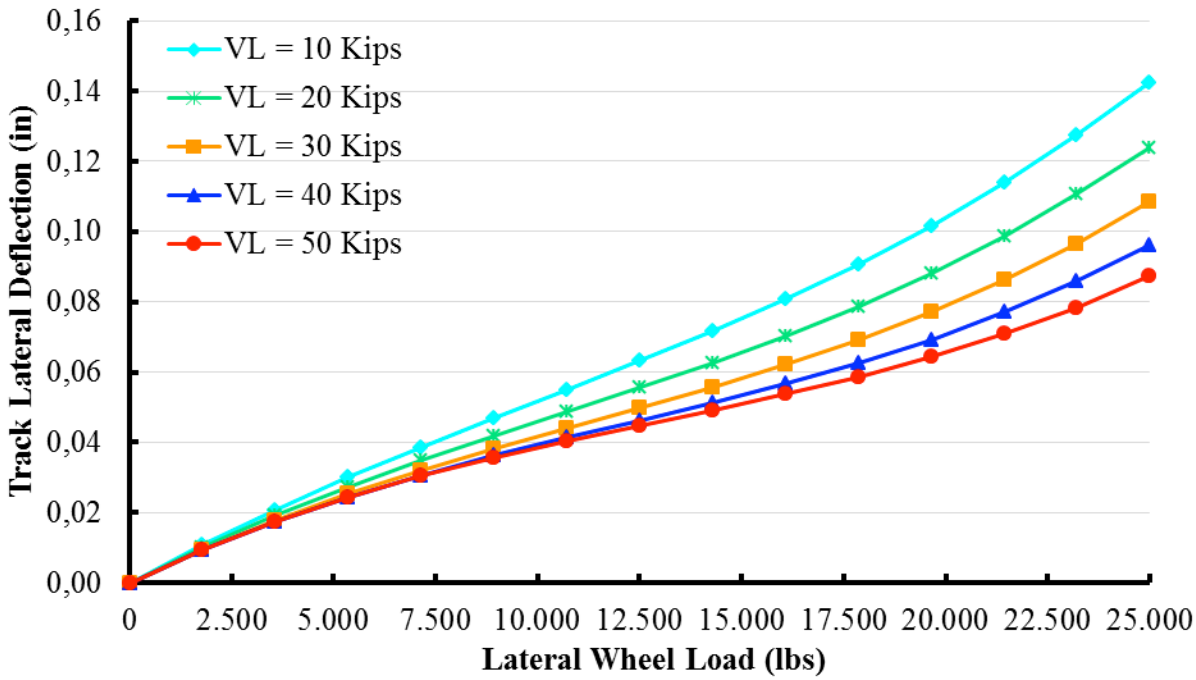


Figure 6. Track Lateral Deflection for Increasing Lateral Wheel Loads Considering Different Vertical Wheel Loads (VL)

As observed in the outputs provided by I-TRACK, the RPM is another parameter affecting TLD. A 5,200% increase in the RPM, from 7,500 psi to 400,000 psi, reduced the initial TLD by 15%. This result is likely due to the fact that softer pads allow more rail head rotation, which is the point where TLD was measured. Additionally, softer rail pads are able to undergo higher shear deformation, which also contributes to an increased magnitude of this output. Both system parameters analyzed in I-TRACK indicate that RPM may be used as a guiding parameter for track geometry. Even though its effects on TVD and TLD are limited, this is a component that can be altered to modify and achieve desired track performance parameters.

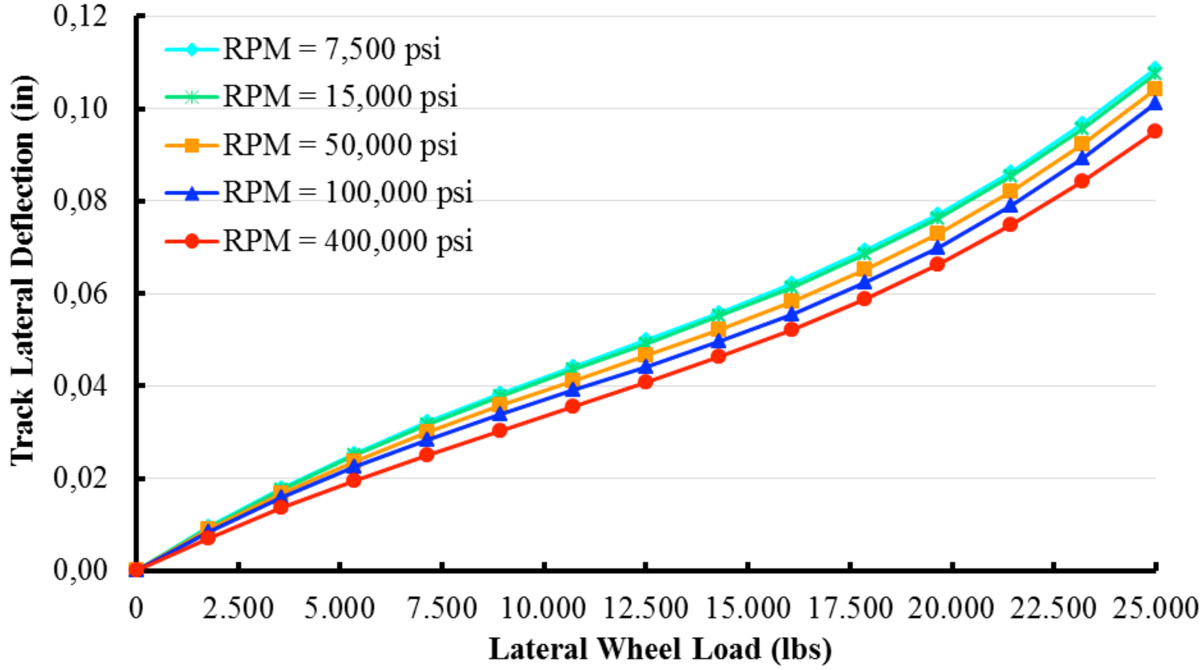


Figure 7. Influence of Rail Pad Modulus (RPM) in Track Lateral Deflection for Increasing Lateral Wheel Loads

Another important capability of I-TRACK is related to the analysis of the wheel load path throughout the system, allowing the identification of key inputs that influence the stresses distribution throughout the system. The rail seat load has been the objective of several studies, especially after deterioration of the concrete surface on this interface was identified and related to crushing mechanisms (Rapp 2012, FRA 2012).

Using I-TRACK, it is possible to predict the rail seat load for increasing vertical wheel loads when different rail pad moduli are considered. For vertical wheel loads higher than 30 kips, which corresponds to heavy axle loads, the approximate 5,200% increase in RPM resulted in a 20% increase of loads being transferred to the rail seat. These results support the studies conducted by Rapp (2012) in which the author indicates that higher modulus rail pads distribute rail seat loads in more highly concentrated areas, possibly leading to localized crushing of the concrete surface under extreme loading events. For vertical wheel loads lower than 30 kips a trend in rail seat load with respect to RPM cannot be identified. Even though results indicate that lower RPM induce higher rail seat loads, this behavior is not clear. For lower vertical wheel loads the system possibly settles before forces start to be distributed from the rail through the rail pad assembly to the crosstie rail seat. Higher RPM may settle first and start distributing loads earlier, leading to the behavior presented in Figure 8.

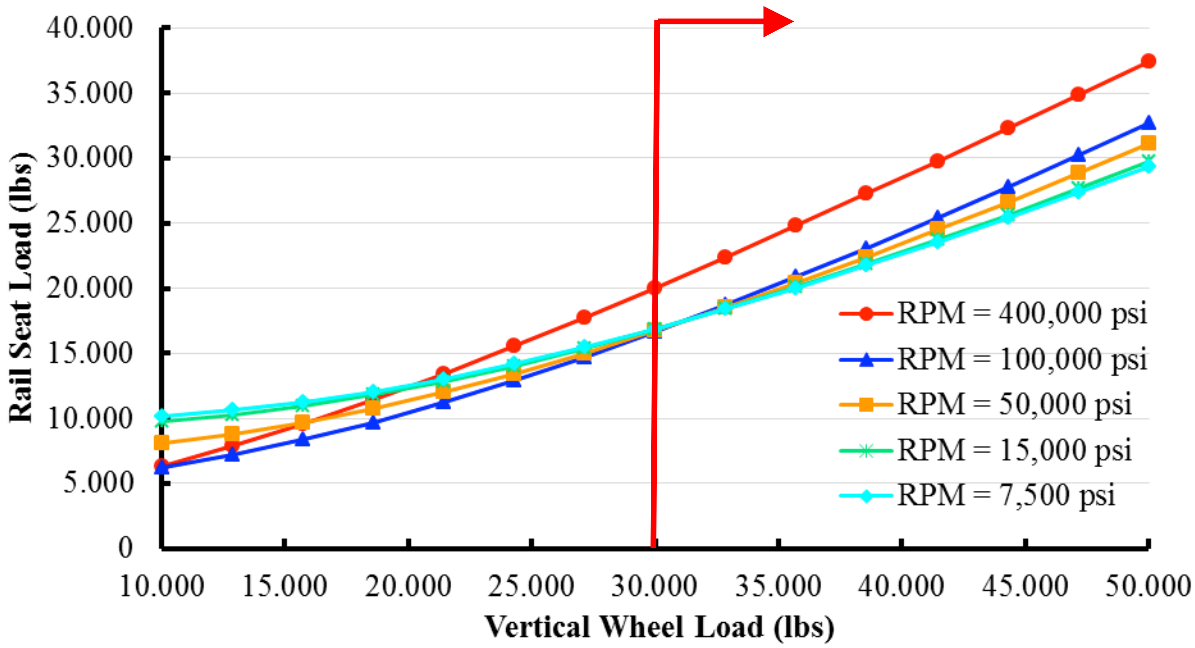


Figure 8. Effects on Rail Pad Modulus (RPM) on Rail Seat Loads for Increasing Vertical Wheel Loads

Volume 2, Chapter 3 presented a discussion related to the rail pad assembly mechanical behavior and attempted to investigate the causes of relative slip between this component and the crosstie rail seat. During the field experimentation, the rail base lateral translation (RBLT) at several rail seats was measured and compared to the rail pad assembly lateral displacement (RPLD). This comparison was important to verify the possible occurrence of shear slip in this interface. It was also capable of pointing out new areas in which future studies could be focused when investigating the mechanical behavior of rail pad assemblies.

The rail base lateral translation is a good proxy to measure fastening system lateral stiffness, a property that has been proved to significantly affect the track lateral load distribution (Williams 2013). Taking advantage of I-TRACK's capabilities, it is possible to observe the influence of vertical loads in RBLT. A 400% increase in the vertical wheel load decreased the magnitude of this output by almost 50% (Figure 9). For all the cases considered, the increase in lateral wheel loads was directly correlated to the increase in RBLT. This result also points out the difference in stiffness the fastening system may demonstrate when subjected to different magnitudes of vertical wheel loads. Improved design methodologies for the fastening system should take this difference in responses into account in order to provide adequate track geometry and maintain desired service levels throughout the life cycle of components.

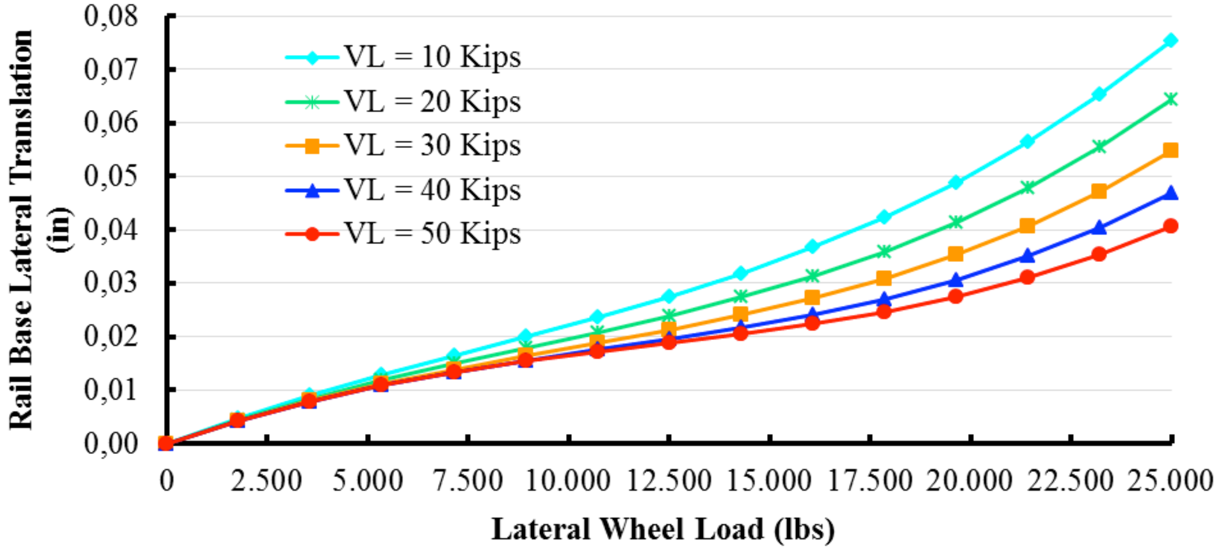


Figure 9. Rail Base Translation for Increasing Lateral Wheel Loads Considering Different Vertical Wheel Loads

An important step in validating the reliability and usefulness of I-TRACK is the comparison between the software output results and field measurements (Figure 10). By analyzing the data related to rail base lateral translation presented in Volume 2, Chapter 3 and simulating these results in I-TRACK using the same components properties, it is possible to observe a good correlation. The trend of the output to increase with the increase of lateral wheel load was successfully captured by the model. The magnitudes of the output were also close to the field measurements, even though an error close to 100% was observed for higher lateral wheel loads. It is important to note that a variety of factors are related to the difference in translation magnitudes measured in the field and the ones extracted from I-TRACK. The model is based on a static analysis of the track behavior, whereas the field results presented in Figure 10 are related to maximum track responses generated from dynamic freight train passes. The dynamic response of the track has already been shown to present a smaller magnitude of displacements when compared to static loading cases (Grassé 2013). A possible explanation for this phenomenon is the transient characteristic of the loads, and the fact that they don't allow enough time for the components to fully respond to the demands. Additionally, variability in rail seat geometry, cast-in shoulder spacing, and clamping force are also other factors that may have contributed to the differences observed between the field experimentation results for RBLT and the results provided by I-TRACK.

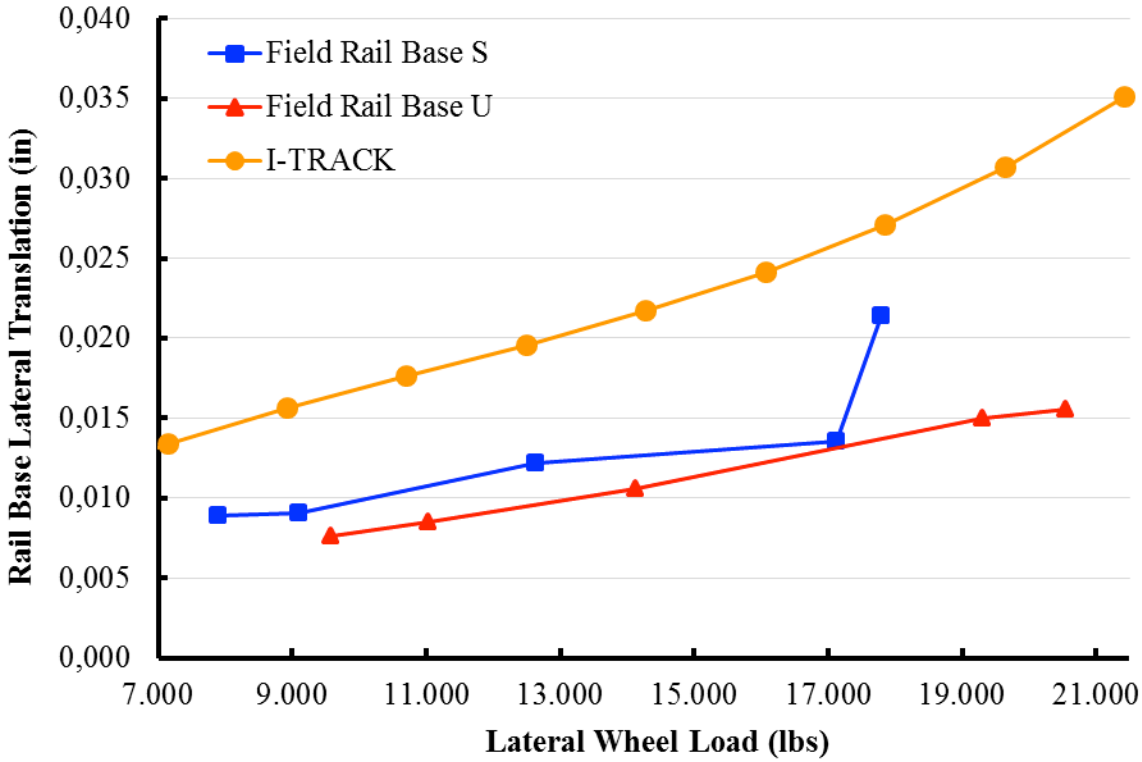


Figure 10. Comparison Between Rail Base Translations from I-TRACK and Field Experimentation Results Considering a 40 kip Vertical Wheel Load

9.6 Conclusions and Future Work

The development of I-TRACK is still in its early stages, but this tool has already proven to be useful in assisting with the development of mechanistic design practices focused on component performance. The ease of use, coupled with the capability to analyze a broad set of outputs considering multiple loading cases and different components properties, is one of the greatest advantages of this software. After it is fully developed, I-TRACK will allow track component manufacturers and railroad engineers to rapidly assess the loading conditions, safety, and expected performance of the track infrastructure.

The case studies presented in this report demonstrated good correlation between the results extracted from I-TRACK and the expected behavior for these parameters. The RBFN that was developed to capture the FE model results has successfully demonstrated to be efficient when used for this purpose. It is important to mention that I-TRACK provides estimates for the realistic behavior of the track and its components, but the user should be aware that analyses are based on static loading cases. When comparing to the dynamic loading environment, errors should be expected due to variability in the manner by which wheel loads are applied in the field, the differences in each individual fastening system configurations, and external factors such as magnitude of clamping force and presence of fines and moisture between components.

Researchers at UIUC will continue to develop and refine I-TRACK's features, and the second and third versions of the software will contain additional inputs and outputs to further improve the current analysis capabilities. The ultimate goal of I-TRACK is to provide component manufacturers and track engineers with a powerful and adaptable tool to analyze the track responses and assist the development of improved fastening system components.

References

American Railway Engineering and Maintenance-of-Way Association. 2012. *AREMA Manual for Railway Engineering: Chapter 30*. American Railway Engineering and Maintenance-of-Way Association, Landover, Maryland.

Chen, Z., M. Shin and B.O. Andrawes. 2012. Numerical Simulation of Presstressed Concrete Crosstie and Fastening System. *Accepted, Precast/Prestressed Concrete Institute (PCI) and National Brigde Conference (NBC).*

Chen, Z., M. Shin and B.O. Andrawes. 2013. Finite Element Modeling of the Fastening Systems and Concrete Sleepers in North America. In: *Proceedings: 10th International Heavy Haul Association Conference,* New Delhi, India, February 2013, pp. 139-144.

Do Carmo, T.B., J.R. Edwards, R.G. Kernes, B.O. Andrawes and C.P.L. Barkan. 2014a. Mechanistic Behavior of Concrete Crosstie Fastening System Rail Pad Assemblies. In: *Proceedings: Transportation Research Board 93rd Annual Meeting*, Washington, DC, January 2014.

Do Carmo, T.B., J.R. Edwards, R.G. Kernes, B.O. Andrawes and C.P.L. Barkan. 2014b. Laboratory and Field Investigation of the Rail Pad Assembly Mechanistic Behavior. In: *Proceedings: 2014 Joint Rail Conference*, Colorado Springs, CO, April 2014.

Grassé, J. and D. Lange. 2013. Field Testing of Concrete Crossties and Fastening Systems for the Understanding of Mechanistic Behavior. In: *Proceedings: 2013 Joint Rail Conference,* Knoxville, Tennessee, 2013.

Hay, W.W. 1982. *Railroad Engineering, 2nd ed.*, John Wiley & Sons, New York, NY.

Kernes, R.G., J.R. Edwards, M.S. Dersch, D.A. Lange and C.P.L. Barkan. 2012. Investigation of the Dynamic Frictional Properties of a Concrete Crosstie Rail Seat and Pad and Its Effect on Rail Seat Deterioration (RSD). In: *Proceedings: Transportation Research Board 91st Annual Meeting*, Washington, DC, January 2012.

Krishnaiah, K. and P. Shahabudeen. 2012. *Applied Design of Experiments and Taguchi Methods, 1st ed.,* PHI Learning, New Dheli, India.

Shin, M., Z. Chen, B.O. Andrawes, R.G. Kernes, M.S. Dersch and J.R. Edwards. 2013. Finite Element Models of Presstressed Concrete Sleepers and Fastening System in North America. In: *Proceedings: 2013 International Heavy Haul Association Conference,* New Delhi, India, February 2013.

Appendix A. Abbreviations and Acronyms

AREMA	American Railroad Engineering and Maintenance-of-way Association
CCD	Central Composite Design
CCF	Face Centered Central Composite Design
DoE	Design of Experiments
FE	Finite Elements
FRA	Federal Railroad Administration
HFFD	Half Fractional Factorial Design
RBFN	Radial Basis Function Network
RBLT	Rail Base Lateral Translation
RPLD	Rail Pad Lateral Displacement
RPM	Rail Pad Modulus
TLD	Track Lateral Deflection
TVD	Track Vertical Deflection
UIUC	University of Illinois at Urbana-Champaign
VBA	Visual Basics for Application