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TTB-2D: Train–Track–Bridge interaction simulation tool for Matlab

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ABSTRACT

The software TTB-2D simulates the dynamic response of a Train–Track–Bridge system in a 2D representation. The train is represented as a succession of multiple vehicles. The track includes rail irregularities and models the rail, pad, sleeper, ballast, and sub-ballast. The bridge is modelled as a beam in finite element formulation with customizable support conditions, which effectively enables the representation of a wide range of structural configurations. This validated numerical model accounts for the vehicle–infrastructure interaction. This document provides the theoretical background to the modelling and a usage guideline supported by an illustrative example.

Code metadata

Current code version	*v1*
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-22-00221
Permanent link to reproducible capsule	https://codeocean.com/capsule/0882463/tree/v1
Legal code license	GNU General Public License v3.0
Code versioning system used	none
Software code languages, tools and services used	*Matlab*
Compilation requirements, operating environments and dependencies	
If available, link to developer documentation/manual	TTB-2D - User guide.pdf
Support email for questions	daniel.cantero@ntnu.no

1. Motivation and significance

The numerical simulation of trains travelling over a bridge is a rather complex problem. To obtain the dynamic response, it is necessary to have accurate representations of the moving vehicle (locomotive and wagons), the railway track (irregularities, sleeper, ballast, and sub-ballast), and the bridge structure itself. These need to be represented using correct numerical models, coupling procedures and appropriate numerical values, as discussed in detail in the recent state-of-the-art review [1] and the text book [2]. Train–Track–Bridge (TTB) interaction models are frequently used to evaluate for instance, ride comfort, running safety, or structural performance. Most importantly, these models are used to gain insight into the problem and explore new possibilities, such as the effect of the increase in train speed or the exploration of new strategies for structural assessment.

TTB models have been developed by many research groups [1], where each has their own custom implementation. However, these models are generally not freely available as open-source. The goal of the simulation package TTB-2D presented in here, is to provide an open-source model of a train travelling over a track and crossing a bridge, which calculates the dynamic response of the system in Matlab environment [3]. TTB-2D has been developed aiming at accuracy of results and simplicity in the implementation. The provided simulation package has been validated by direct comparison to an independently developed model in a commercial software, as reported in [4]. Also, strong emphasis was given to clarity in variable notation, script naming and overall architecture, supported by a user manual. Therefore, TTB-2D is a powerful simulation tool, which is readily available and understandable. It can be the basis of many new studies, since users can focus on the study of the simulated responses, rather than on the development and validation of such a model from scratch. Furthermore, it provides an excellent starting point for further future developments by the research community, wishing to extend the model to more complex configurations.

In fact, TTB-2D has already been used to produce multiple studies. In [5], it was used to evaluate the dynamic amplification factor on the bridge load effects for a range of structural

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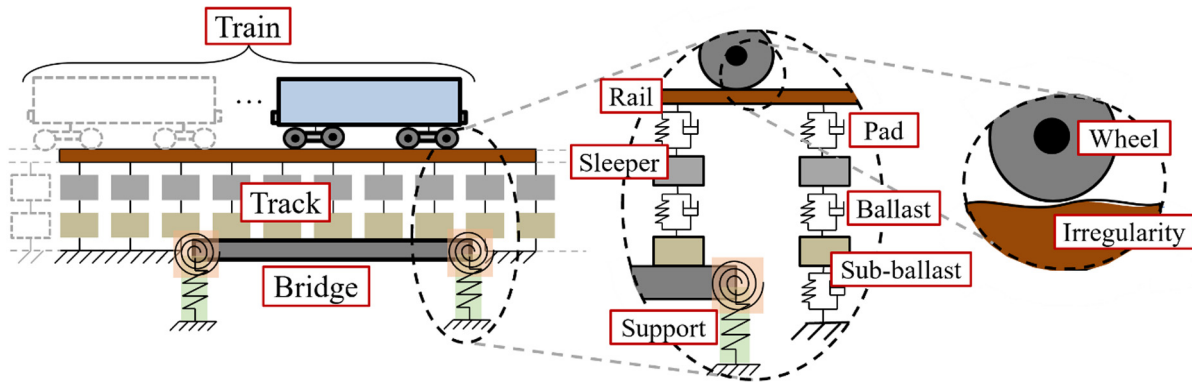*E-mail address:* daniel.cantero@ntnu.no.

Fig. 1. Overview of TTB-2D model components.

configurations. In [6], the authors studied the changes of modal properties in bridges during train passage. Also, [7] explored the possibility of bridge damage detection based on the apparent profile inferred from vehicle responses. TTB-2D has also been used for the numerical validation of ideas considering only the vehicle and track, by considering a long approach distance (track) and disregarding the results from the bridge. For instance, in [8,9], methods are proposed to determine the longitudinal rail irregularities and track stiffness profiles respectively using vehicle responses. More recently, in [10] the presented simulation framework was used to explore the possibility of detection of hanging sleepers using sensors installed on a passenger train. Furthermore, adaptations of TTB-2D were developed to model particular bridge configurations, namely multiple spans bridge resting on flexible supports [11] and portal frame bridges with walls at the abutments filled with soil [12].

2. Modelling background

To develop an accurate TTB model, it is necessary to define models for each separate component (namely, train, track, and bridge), the rail irregularity and the solving procedure of the coupled system. This section briefly reviews each of these aspects and introduces the theoretical background of the adopted modelling in TTB-2D (Fig. 1). In addition, it provides relevant references for additional information and appropriate model properties.

First, the problem has been modelled using a 2D representation. It is acknowledged that a 3D model is a more precise representation of reality. However, that would significantly increase the complexity of the model, its computational requirements, and the number of numerical variables to define. In addition, it has been shown in [13], by directly comparing a 2D TTB model to a 3D alternative, that the 2D model can predict the vertical dynamic behaviour of the system with sufficient accuracy. With this in mind, the adopted 2D representation is considered to be an appropriate trade-off between model complexity and solution accuracy. Furthermore, models like TTB-2D have been reported and used in relevant literature [1,2].

The train is represented as a succession of individual vehicles. Each vehicle is modelled following the mechanical model recommended for train–bridge interaction by the European Rail Research Institute [14]. The main body rests on 2 bogies via the secondary suspension, while each bogie has 2 axles supported/connected by the primary suspension. The vehicle equations of motion simplify to a system with 6 Degrees of Freedom (DOF) [7], which can also be derived using VEqMon2D toolbox [15]. TTB-2D provides pre-implemented train types and vehicle configurations obtained from various sources, which have been listed in Table 1. Thus, with these examples it is possible

Table 1
Train model and source of values.

Train type/configuration	Reference
• Manchester Benchmark	[16]
• ICE3 Velaro	[17]
• Chinese Star Power Car • Double Deck Passenger Coach	[18]
• Eurostar	[19]
• Pioneer M and R vehicles	[20]
• Shinkansen S300	[21]

to model a train as a succession of independent 6-DOF vehicles. Other train configurations, (e.g., including articulated wagons) must be implement by the user.

The irregularities of the rail constitute an important source of excitation and contribute to the total dynamic response of the vehicle and infrastructure. These irregularities can be defined based on random samples from predefined Power Spectral Densities (PSDs). Examples of such PSDs can be found from relevant railway authorities. TTB-2D includes the definitions from: Federal Railroad Administration [22] in the US, German high-speed lines [23], and SNCF [24] in France.

The track comprises a combination of elements (Fig. 1) that include: rail, pad, sleeper, ballast and sub-ballast. While the rail is modelled as a Euler–Bernoulli beam, the rest of components are represented as a series of lumped masses and viscoelastic layers. This representation of the track has been used by others [1] and has been deemed appropriate [24]. Numerical values for the track model can be found in [25], which have been included in TTB-2D.

The bridge is modelled as a Euler–Bernoulli beam represented by a Finite Element Model (FEM) discretization. The beam is resting on elastic supports. The number of supports, their location, vertical stiffness, and rotational stiffness can be specified by the user. This flexibility makes it possible to model a wide range of bridge configurations (e.g., multi-span continuous bridge). The numerical values of the model parameters for the beam model must be defined according to the properties of the studied bridge. As an example, TTB-2D includes the properties of a 50 m long railway bridge, reported in [26]. Nevertheless, some representative values for railway bridges in general can be obtained from [19].

All the model elements are combined into one single system. The equations of motion of the train (vehicle) and the infrastructure (track and bridge) are coupled together, and are described by the mass, stiffness, damping and force matrices [4]. These matrices change with vehicle position via the coupling procedure [27], linking together the train and the infrastructure through a direct contact between wheel and rail that does not permit any separation between them. The time-varying equations
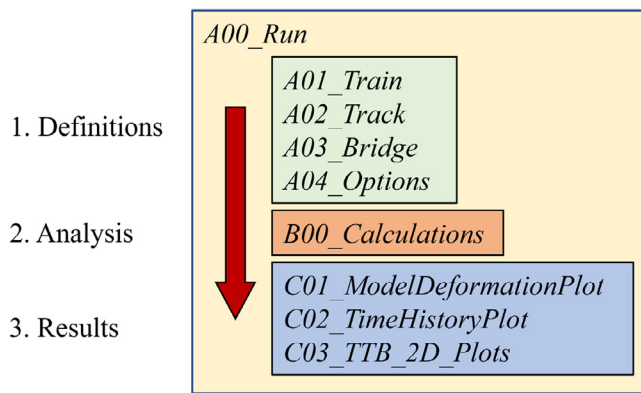
Fig. 2. TTB-2D workflow overview and corresponding script names.

of motion are solved by direct numerical integration with the Newmark-β scheme to obtain the dynamic response of the train travelling over the infrastructure.

Therefore, TTB-2D provides an accessible implementation of the train–track–bridge interaction problem, which is based on published formulations and methodologies. The software simulates the dynamic coupling of the systems including the inertial and centripetal forces arising from that interaction. For completeness, the reader is referred to [4] for extended explanations on the modelling and theoretical background for TTB-2D. In addition, [28] provides comprehensive descriptions of the coupling procedure, irregularity definitions and vehicle models. Regarding model parameters, the authors in [29] study which are the key parameters in a TTB model and in [30] identify their relative importance.

3. Software description

3.1. Software architecture

TTB-2D calculates the dynamic response of the coupled train-infrastructure system (Fig. 1). The train is defined as a succession of multiple vehicles travelling at constant speed. The infrastructure consists of the track and a bridge. The track length before and after the bridge can be arbitrarily long, while the bridge model can be adjusted to a wide range of structural configurations. The user can easily modify the model geometry and parameters, specify calculation options, and request the type of graphical output after successful completion of the simulation.

To perform a simulation, the script *A00_Run* must be executed. In here, the workflow (Fig. 2) has been implemented in a straightforward manner to perform user definitions, simulation analysis, and graphical results processing. While the script is running, the user is informed in the command window about the calculation progress and other eventual warning messages. TTB-2D uses structure type variables from Matlab to handle and store all variables and results related to the simulation in an orderly and intuitive manner. The naming of these structure variables was given to improve the readability and usability of the software. For example, the span length of the bridge is saved in *Beam.Prop.L*.

To simulate a user-defined model, the user needs to manually edit the definition scripts *A0x_yyy*. In *A01_Train* it is possible to set the speed of the train and the number of vehicles in the convoy. The user specifies here the geometry and mechanical properties of each vehicle. Similarly, *A02_Track* and *A03_Bridge* are used to define the properties and numerical values of the track and bridge respectively. These model components definition scripts

have pre-implemented values, taken from relevant references (see Section 2), for the user's convenience. Finally, in *A04_Options* it is possible to specify a range of options including, the irregularity definition, FEM discretization, time stepping requirements, and graphical output selection, among other options. The user is referred to the manual (included in the online repository) for extended explanations on the definitions and options.

The core calculations, that perform the simulation of the user-defined model, occur inside the script *B00_Calculation*. This script contains multiple functions that do the operations necessary to obtain the dynamic response of the coupled train-infrastructure system. Arguably, the most important tasks performed here are: input processing, default values definition, creation of vehicle, track and bridge models, coupling of models, numerical integration, and additional results calculation. The user does not need to edit (or understand) anything within *B00_Calculation*. The outcome, after the simulation is completed, is a new structure variable *Sol* that contains all results stored in subfields. For instance, the user can request the maximum bending moment of the bridge for the simulated crossing event in *Sol.Beam.BM.max*. Again, refer to the manual (*TTB-2D – user guide.pdf*) for further clarifications on the simulation output.

Finally, the scrip *A00_Run* also executes a series of functions to produce graphical outputs of the model and calculated simulation results. Before executing the simulation, the user is prompted with a schematic representation of the model to confirm the adequacy of the definitions. Additionally, the functions *C01_ModelDeformationPlot* and *C02_TimeHistoryPlot* provide interactive graphical environments to visually explore the results of the whole model. These functions are better explained in the example presented in Section 4. *C03_TTB_2D_Plots* produces the graphical outputs requested by the user in *A04_Options*. Possible plots of the results include time–history representations of vehicle responses, contact forces and load effects (displacement, velocity, acceleration, bending moment, and shear) of the bridge, among others.

3.2. Software functionalities

In general, the main feature of TTB-2D is that it performs the simulation of the train-infrastructure interaction, following a straightforward script that the users can readily modify to simulate the desired configuration. However, more in particular, the presented software offers a range of options and possibilities that are worth listing. A selection of the most relevant additional functionalities in TTB-2D are listed below.

- Ease specifying/modifying all model parameters and options
- Possibility to define a train with multiple locomotives and/or wagons
- Pre-implemented numerical values for various train types and convoy configurations
- Rail irregularity defined in terms of PSD
- Pre-implemented examples of standard irregularity PSD functions
- Possibility to define custom number and type of supports for the bridge
- Option to have ballast on/off on the bridge
- Option to reduce the track length at the start of the simulation (This reduces the size of the model and thus the computational time. However, it might induce a perturbance in the contact force at the start of the simulation. See the manual for more details.)
- Optimized system matrices generation and coupling procedure using sparse matrix commands (This greatly improves the computational performance. The alternative, and more readable implementation, is also included in the repository for the user's reference.)

- Option to switch on/off the interaction (coupling) between vehicle and infrastructure (Switch off the interaction to run the simulation as point loads.)
- Option to display results in graphical form using several pre-implemented figures
- Calculation of additional results based on the simulation outcome (e.g., wheel contact forces, beam bending moments, and more)
- Organization of variables and results into structure variables for easy data management
- User manual available with additional explanations, including detailed description of model variables, how to use the software, and recommendations

The TTB-2D version available in the online repository contains already a working example. To get familiar with the software operation, the user can readily run the software without any modification. That same pre-implemented example is discussed in further detail in the next section.

4. Illustrative examples

To showcase the capabilities of TTB-2D, one train crossing event is simulated, and the results are displayed using pre-implemented graphical outputs and visualization functions. In particular, the event consists of a train (single vehicle Manchester Benchmark [16]) travelling at constant speed (120 km/h), over a track (with numerical values from [25]) with 30 m approach length, a Class 6 FRA rail irregularity [22], and a ballasted simply supported 50 m long bridge (taken from [26]). The numerical solver uses a time step size of 1/1000 s and includes the interaction between the train and the infrastructure.

Fig. 3 shows a selection of possible pre-implemented graphical outputs that the user can easily generate when running TTB-2D. The selection includes time-history responses of the wheels' contact forces, the vertical accelerations of all DOFs of the vehicle, and the mid-span acceleration of the bridge. Fig. 3 also shows the bending moments of the beam in space and time presented as a coloured contour map, where the dashed lines indicate the position of each wheel. Additional plots could be requested by the user if desired. Furthermore, all the results from the simulation are accessible under the *Sol* variable for the user's own analysis.

The simulation results of this example can be visually explored using the interactive graphical tool *C01_ModelDeformationPlot*. The output is shown in Fig. 4, and it displays the vertical deformation for the track–bridge system for a given time step. Three separate subplots are generated for the results of (1) rail, (2) sleepers, (3) bridge and sub-ballast (before and after the bridge). The rail and beam results are plotted as continuous lines since they represent continuous elements, whereas the concentrated masses of the sleepers and ballast are represented as dots. The vertical lines indicate the current location of all wheels of the simulated train passage. With the interactive menu, the user can change the plot by moving forwards/backwards the displayed simulated time, and select what load effect to show (deformation, velocity, acceleration).

On the other hand, the function *C02_TimeHistoryPlot* allows the user to visualize the time–history results for one particular node in the track–bridge system. One example of the function's output is shown in Fig. 5. The upper subplot provides a schematic overview of the model and highlights the particular node under investigation. The two remaining subplots display the time–history of vertical displacement (and rotation, if applicable) of the studied node. The user can select what node and load effect to display using the accompanying menu.
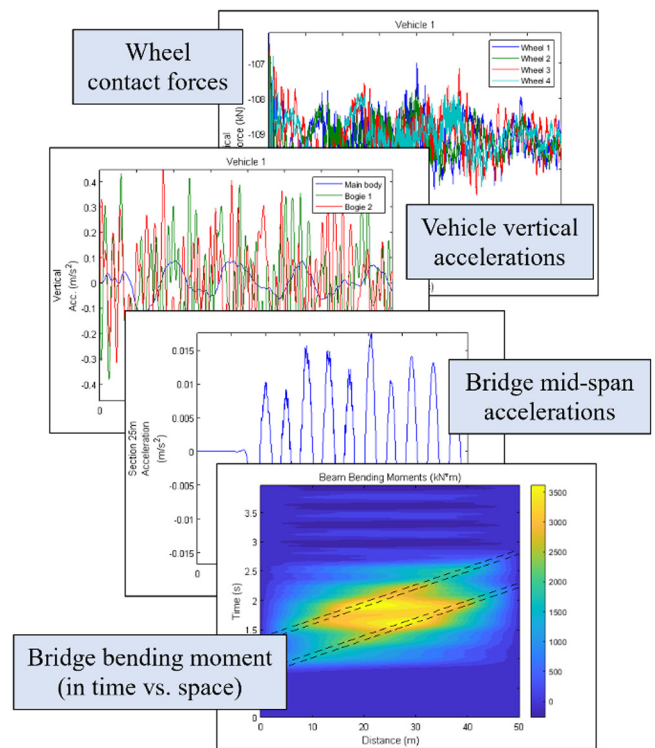

Fig. 3. Selection of graphical outputs for the illustrative example.

5. Impact

The software TTB-2D has already been used in several collaborative studies, see [4–12]. It was used to explore novel ideas and strategies for railway engineering and infrastructure maintenance. In addition, the collaborating partners reported that TTB-2D was easy to learn and use. Therefore, the author believes that it has the potential to be adopted by other research groups to investigate similar (or other) research lines. These potential new users would greatly benefit from the availability of this software. Users can save time developing and validating such models on their own and can concentrate on the analysis and exploration of novel ideas. This validated implementation of the train-infrastructure problem could also serve as benchmark for alternative implementations of the problem by others. Furthermore, the current TTB-2D version can be the starting point for future developments that extend the software's modelling possibilities and provide additional functionalities.

6. Conclusions

The software TTB-2D is a validated numerical model that simulates the dynamic response of a train travelling over a track while crossing a bridge. It is implemented for Matlab environment with a straightforward architecture and understandable notation, supported by a user manual. This document provides a brief theoretical background of the most relevant aspects of the model. In addition, the reader is given an indication on how to use the software, complemented with an illustrative example. Users of TTB-2D have reported that the software is easy to learn and use. The author believes that new users can readily adopt this software for interesting new studies or serve as a benchmark to validate other TTB implementations.
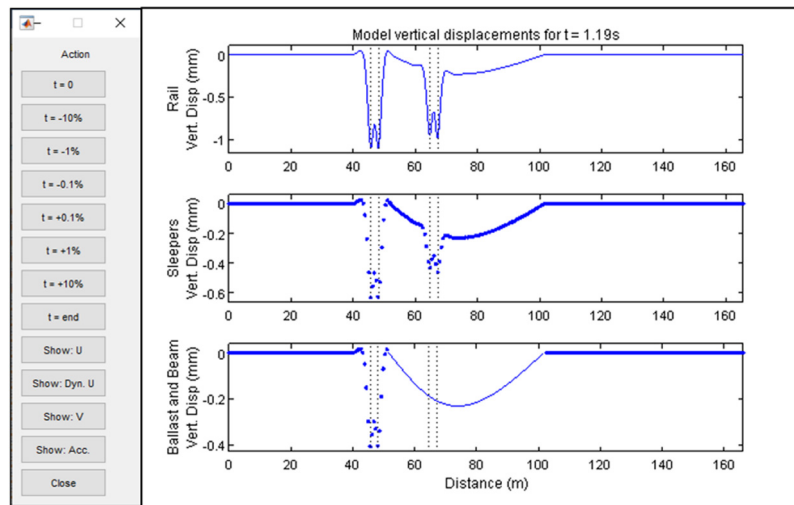
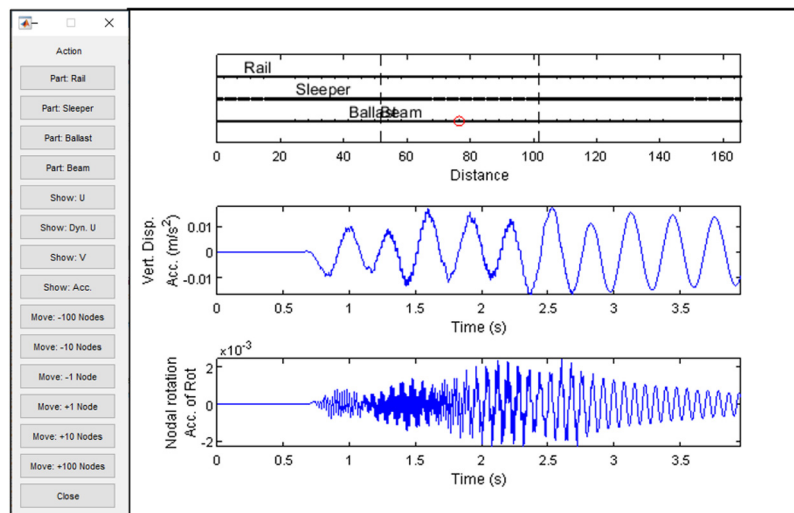**Fig. 4.** Menu and output from *C01_ModelDeformationPlot*.

Fig. 5. Menu and output from *C02_TimeHistoryPlot*.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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