# Plan of Approach STEM

For external purposes

**Status: Final V09 21-03-2023.**

Wim vd Poel, TNO
Stijn van Boxmeer, TU Delft
Joris van Ruijven, Deltares

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# 1 Introduction

This plan of approach is the guideline for ProRail, Deltares, TNO and TU Delft for the 1st project year of STEM and provides an outline for the 2nd , 3rd and 4th year. The Plan of Approach describes how the various activities result in reaching the goals of STEM. It is the further elaboration of the collaboration agreement (4600001882) between ProRail, TNO, TU Delft and Deltares on STEM. Therefore the collaboration agreement together with the M+P plan (M+P.RAIL.20.05.1) is the starting point for this plan of approach. The goals and research questions of STEM described in this plan of approach, correspond to these documents. With the 4 work packages (Embankment, Spatial variation, Time behavior and Tooling) as a reference, the necessary coherence to reach the STEM goals has been defined as well as the approach to organize and monitor the progress towards the goals.

The plan of approach first describes the goals and scope of STEM. The third chapter is the core of this plan and gives the view of TNO, TU Delft and Deltares on the coherence of all activities under this project with a link to the four work package descriptions. The fourth chapter describe the deliverables and their correspondence to the goals. In the fifth chapter the planning in and beyond 2023 is described. The sixth chapter describes the organizational aspects. The seventh chapter focusses on the budget. In the last chapter we present a risk matrix with mitigating activities.

The 4 work packages and the 4 PhD-profiles are presented in the Annexes A-E.

Annex F is the memo presenting the Steering Board two scenario's to align the initial plan with the set boundary conditions.

This Plan of Approach is a revision of the Plan of Approach from November 17th 2022.The Plan of Approach is yearly updated in the years to come. This plan contains the full description of the 4 different work packages, in line with the initial idea of the STEM project. As a consequence of the current revision (Annex F) the project will focus in 2023 on the Work Package Tool and the PhD-research. The activities of the other work packages in will be executed in the next phase in 2024.

# 2 Goals and scope

## 2.1 Goals of STEM

The goals of STEM are:

1. To develop knowledge about the origin and propagation of vibrations in typical Dutch railways, as well as to develop knowledge about variations and uncertainties in model parameters.
2. To develop a STEM-tool embedding the accumulated knowledge, with which interventions of rail vibrations can be calculated and mitigated based on the included models

This is an experimental process, in which a number of iterations are built in, as well as priority is set in consultation with end users and stakeholders.
The involved models focuses on the Dutch rail system and systematically takes account of parameter uncertainties and variations.

**Summary of research questions**
Within STEM progress beyond the state-of-the art is required on the following research questions:

1. What is the effect of the typical Dutch Railway construction (track structure, ballast embankment on soft soil) including discontinuities occurring in hotspots on the vibrations in the environment as a function of:
    1. The axle load and axle load configuration
    2. The speed of the rolling stock
    3. The properties of the subsoil
2. How can we characterize the track geometry under load and how does it change over time under the influence of:
    1. Dynamic loads
    2. Settlement of the subsoil
3. How can we best characterize, practically measure and process the model parameter 'dynamic stiffness’ of the rail system?
4. How can we systematically incorporate the intrinsic variation and uncertainties in the different model parameters into the models? This concerns both spatial and temporal variation?

**Summary of tool requirements**
After the program ends, ProRail will have a modeling tool that supports ProRail and its partners in the following tasks:

1. Diagnosing the cause of complaints and problems related to vibrations;
2. Choosing and dimensioning measures and interventions against vibration nuisance
3. Substantiating choices for policy making to combat vibration nuisance

The tool is focused on the Dutch rail construction and systematically takes account of parameter uncertainties and variations. The tool is made available to the sector as 'open source' and is modular in design so that it is easy to reuse parts of the model in OURS.

The STEM-tool contains a couple of different models which are the outcome of the Work Packages. The STEM-tool does not have a graphical user interface but can be connected to common available open user interfaces.

## 2.2 Scope

The goals form the basis against which priorities in this experimental development are tested. The model is not a replacement for the OURS model, but an addition to it. The intended model makes a mathematical description of the 'first 25 meters' of the track system in which vehicle, track and substructure parameters can be adjusted. That is not possible now. In addition, the intended new model has a higher spatial resolution, which makes it suitable, in contrast to OURS, to perform studies on mitigation measures at the location of local vibration nuisance. The tool enables the end-user to model mitigation measures in terms of their specific characteristics (rather than exactly modelled measures). The project does not exclude mechanisms that might lead to vibration nuisance beforehand. But iterates towards relevant mechanisms and vibration frequencies. The focus of the research program is on the description of the source and the emission of rail vibrations, as well as mitigation measures to limit the emission. The perception of local residents with regard to vibration nuisance falls outside the scope, just like the vibration propagation in buildings.

# 3 Approach

## 3.1 Introduction

The main approach is to come to a STEM-tool which is up to date with the newly developed knowledge. We propose an iterative approach in which the development of new knowledge goes hand-in-hand with the improvement of the STEM-tool based on these developments and an early involvement of the end user.

At the beginning of the project there is uncertainty which prevents us from being able to predict the causes of nuisance and effects of mitigating measures. STEM will be accumulating existing knowledge (literature study) and create additional knowledge (explorative research) which will be embedded in a STEM-tool. The STEM-tool can be seen as an integration of the different models that are developed within the different work packages.

The components of the project on the knowledge base will be on:
- literature study (what is avaliable?),
- explorative research (what is needed?),
- validation (does reality match with theory).

We choose to work in an iterative proces that offers the possibility to reduce uncertainty in the various steps in which variables and relations are defined and validated. Every year the tool will be updated.

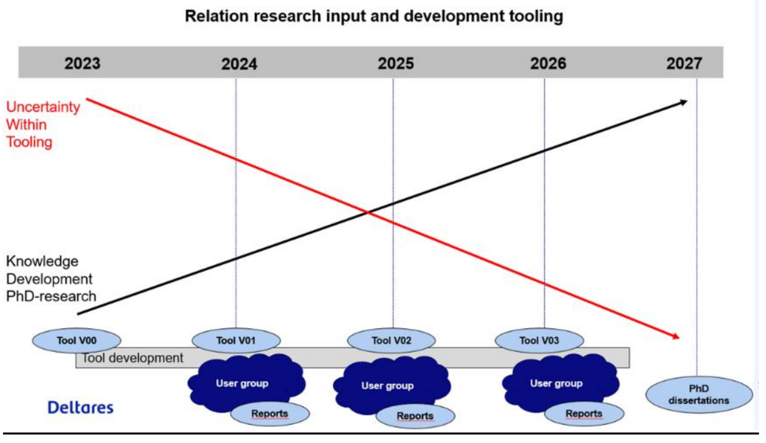



*Figure 1 iterative process to reduce uncertainty*

This chapter describes the STEM-tool, how the project is structured and which activities are undertaken to reach the goals.

## 3.2 STEM tool

Figure 22 below depicts the coherence of activities and components that are required to design, develop and validate the STEM-tool.

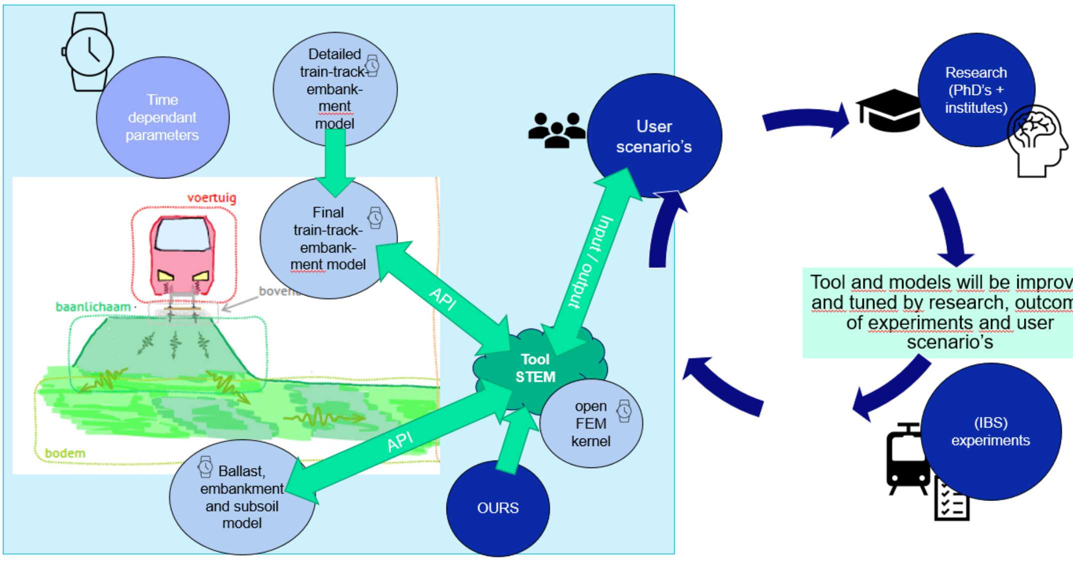



*Figure 2 coherence of activities and components for this project*

The STEM Tool (in the left blue area) is the integration of several models, i.e.:

- a FEM kernel which is the basis for STEM tool;
- a Train-Track-Embankment model in which the interaction between the train, the track and the embankment is modelled. In first instance a detailed model will be developed for research purposes. To make it suitable for the STEM tool a more simplified model, is required;
- a Ballast, embankment and subsoil model in which for the spatial variations for the first 25 meters from the source of the vibrations is modelled.

The time dependent parameters are a set of parameters that will be defined as input for the model at T = 0, T = A, T = B, etcetera, with A, B and further to be defined in terms of months or years. The end user then runs the STEM-tool with different sets of parameters.
The STEM-tool and the models will be improved, validated and tuned (right side of this figure) by research, outcome of experiments at hot spots and user scenario's in which the end users are involved to test the STEM tool based on hypothesis and mitigation actions.

## 3.3 Activities

The activities are the outcome of the preliminary study (Q3 and Q4 2022). These activities are described in the work packages (Annex A-D) and in the subparagraphs below. In these subparagraphs dependencies between WPs are described and activities which requires coordination on program level within the Integral Project Management Team (IPM). This coordination is focused on project management and reporting.

The activities in relation to program level are
- The model design as basis for the STEM-tool (goal 1 & 2)
- Integrating end users (scenario's) into the development of the tool (goal 2)
- Interaction with other programs/projects

### 3.3.1 WP's

The description of the WP's are in Annex A-D. On specifics of the WP we refer to the annexes. The WP-leaders are responsible for management of the WP to reach the goals of their project within time and budget. The 4 WP's are aligned in the preliminary study.

During the preliminary study the following dependencies between the WP's have been identified. Newly identified dependencies in the model, changes in the planning or budget require alignment with the IPM team.

| | **WP-Spatial Variation indicates** | **WP-Embankment indicates** |
|---|---|---|
| **From Spatial Variation (R) to Embankment (B)** | WP-Spatial Variation is connected to WP-Embankment in defining hotspots and dynamic track(?) stiffness properties. WP-Spatial Variation supplies WP-Embankment with knowledge and implementations regarding the spatial variabilities accompanied with efficient sampling techniques for stochastic calculations and sensitivity analysis. | Hotspots defined and selected in WP Spatial Variation will be used as inputs to WP Embankment (see §**3.1**).<br><br>If prioritized, WP Embankment and WP Spatial Variation will jointly define dynamic track stiffness and develop its measurement method. |
| **From Embankment (B) to Spatial Variation (R)** | WP-Embankment provides knowledge on the importance of the track components and a model for the train/track interaction model. | If prioritized, WP Embankment and WP Spatial variation will jointly define dynamic track stiffness and develop its measurement method. |
| | WP-Spatial variation indicates | WP-Time Behavior indicates |
| **From Spatial Variation (R) to Time Behavior (T)** | Relation with WP-Spatial variation is mostly linked to the measurement campaigns. | WP Spatial variation provides knowledge on the stochastic calculations and provides a model for the ballast and subsoil schematisation. The communication between the FEM kernel and train/track model is defined via the API specified |
| **From Time Behavior (T) to Spatial Variation (R)** | WP-Time Behavior provides knowledge on the important components that exhibit a time dependency that influence railway induced vibrations and material | Relation with WP Time Behavior is mostly linked to the measurement campaigns. |

| | | |
|---|---|---|
| | models for the ballast and subsoil layers. | |
| | WP-Spatial variation indicates | WP-Tool indicates |
| **From Spatial Variation (R) to Tool (G)** | WP-Spatial variation supplies WP-Tool with knowledge and implementations regarding the spatial variabilities accompanied with efficient sampling techniques for stochastic calculations and sensitivity analysis. | The communication between the FEM kernel and train/track model is defined via the API |
| **From Tool (G) to Spatial Variation (R)** | WP-Tool provides a tool that performs finite element calculations with dynamic train/track interaction on a stochastic ballast and subsoil. | WP Spatial variation provides knowledge on the stochastic calculations and provides a model for the ballast and subsoil schematisation. The communication between the FEM kernel and train/track model is defined via the API |

*Table 1: Dependencies between WP's*

### 3.3.2 The model design

The 4 WP's will integrate the variables and relations as defined in the ballast, embankments and subsoil model, the Detailed train-track-embankment model (outcome of the PhD study), the Final train-track-embankment model (More simplified model that is suitable to integrate within the STEM-tool) and the FEM kernel.

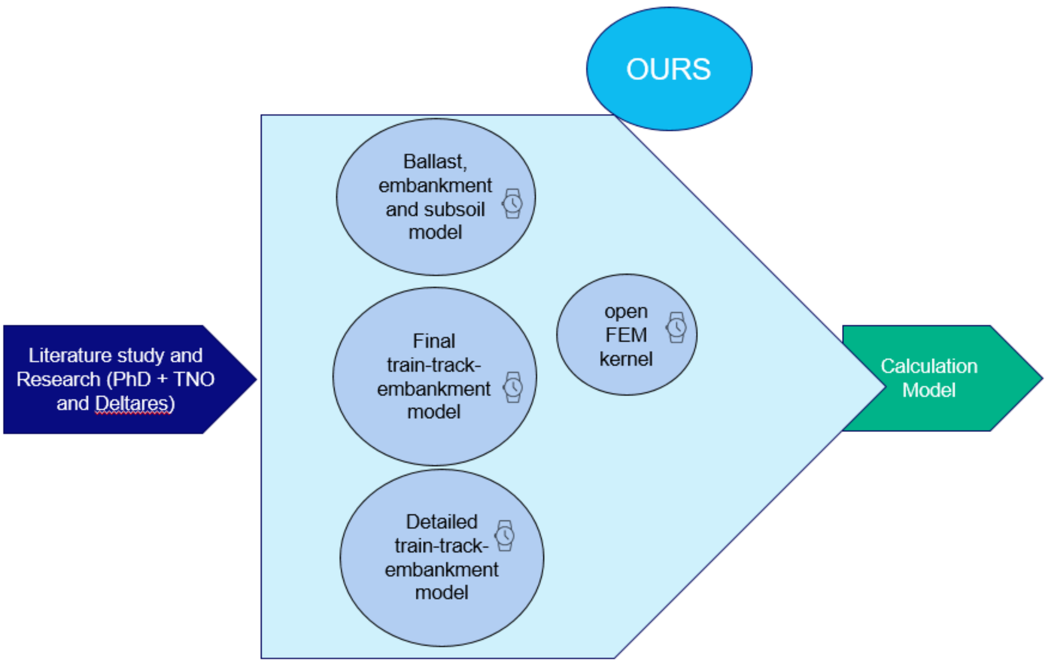



*Figure 3 Model design*

The model design will give insight in the known variables and relations and gaps at the start of the project. This will give the WP's a more schematic overview on the level of variables, relations, identified interferences. This model design is used during meetings of/with IPM to discuss scope, planning and budget.

A starting set for the variables and relation for the model can be derived from the following table.

| | Hotspot related components | Critical parameters | Measures |
|---|---|---|---|
| Vehicle | Suspension | stiffness, damping | 1. Re-design |
| | Wheel | wheel diameter | 2. Reprofiling<br>3. Replacement |
| | | wheel profiles (e.g., flange height and thickness) | |
| | | Wheel flat/out-of-roundness | |
| | Train types | axle load | |
| | | Speed | |
| Track | Switches & Crossings | angle, type, geometry, stiffness | 1. Grinding<br>2. Reprofiling<br>3. Replacement |
| | Joints/welds | Geometry | |
| | Rail | Geometry of surface defects | |
| | Sleeper | Distance between sleepers, material, (concrete/wood/plastic) support stiffness | 1. Replace with different type of sleepers<br>2. Under sleeper pads |
| | level crossing | | |
| | Curves | curvature, cant | |
| Ballast | Ballast (degraded) | Ballast condition (what are the parameters?) | Tamping |
| Embankment | Transition zones | sub-soil condition (settlement, compaction of ballast after tamping, approach slab (length and angle), impedance jumps | 1. Changing the ballast profile<br>2. Sheet wall/piles,<br>3. PSS layer,<br>4. Adjusting track geometry to the upper limit at the end of the approach slab |
| | Subsoil | Cross-section geometry of embankment, | |
| | | Soil type | |

*Table 2 Critical parameters and mitigating measures related to hotspots*

In the first half of the year the design of the integrated model will be provided in which known and expected variables and relations are defined. This model will be operationalized as basis for the tool.
During the years the uncertainty in the model design is reduced by validating variables, relations and identifying interference. (see 3.3.4)

*Projectmanagement:* Adjustment of the model after the first year could indicate needed changes in the planning and budget for following years.
Adjustment in later years can be expected after validating research or mitigation of identified interference.
*Reporting:* Biannual adjustments and effects on the planning are reported to the Steering Board. Also the impact of the models, in terms of increased accuracy of the predictions is

reported.

### 3.3.3 Integration of the end user scenario's

The end user of the STEM-tool will evaluate the tool on:
1. Diagnosing the cause of complaints and problems related to vibrations;
2. Choosing and dimensioning measures and interventions against vibration nuisance
3. Substantiating choices for policy making to combat vibration nuisance

The order of the three goals for the tool also reflects the information (model) needed, choice in variables/boundary conditions and possibilities of the tool. End users will be involved during the year on major choices and informed on the year version. In these sessions the steps for next year will be discussed and given an insight on the expected progress.

Within WP Tooling the requirements towards the 3 other WP's are defined. See annex A

The STEM tool will, in first instance, consist of a 3D FEM coupled model, with various levels of complexity. This will require a significant computational effort. In order to reduce this computational effort, possible simplifications to the tool will be explored, e.g.:
- Subsoil model: 3D, 2.5D, 2D, 1D
- Train model: 3D / 2D / moving loads / no train
- Working with databases of calculations.

The minimum viable product (MVP) of STEM is a tool that performs finite element calculations with dynamic train/track interaction on a stochastic ballast and subsoil (Figure 5). The findings and new insights obtained in the different WPs will be incorporated in the MVP throughout the project.

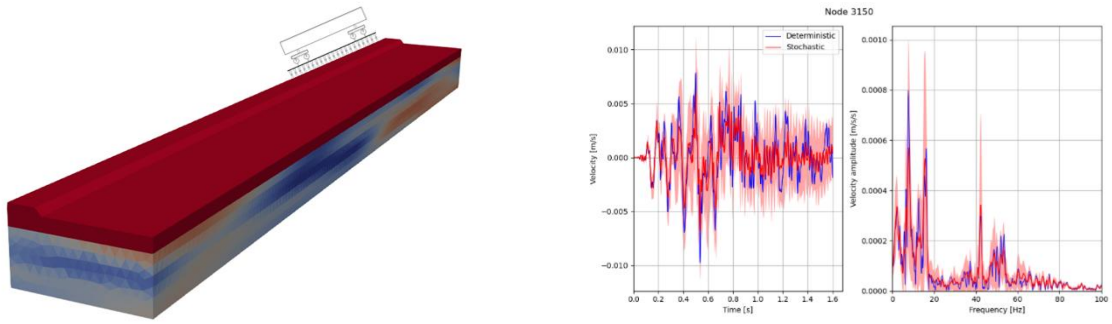



*Figure 5: MVP.*

The end-user is to be provided with a tool and could give feedback/input on the tool (WP Tooling) and the possibilities (WP Time behavior /Spatial variation /Embankment) within the scope of the project.

*Projectmanagement:* Adjustment of the activities/goals of the work package could indicate needed changes in the planning and budget for following years.

*Reporting:* Biannual adjustments and effects on the planning are reported to the Steering board. The progress in terms of identified bottlenecks or unclarities by the end-users is also reported.

### 3.3.4 Interaction with other programs/projects

STEM is part of a larger program called IBS. In the IBS-program measurements are taking place and are planned for the upcoming years. This offers STEM the possibility to do explorative research and to validate the variables and relations in the model. A first analysis has led to the following:

| Reference | Description |
|---|---|
| **WP Spatial Variation** | Experiments validating the STEM tool have to capture spatial variations in input and output. WP-R will accordingly contribute to set-ups for experiments. Relevant aspects will also be investigated in the PhD-3 proposal, e.g. “What are the optimal locations for sampling and/or monitoring, and what is the required intensity of testing in order to achieve a desired level of confidence in the results?” For this activity, close cooperation with Prorail and planned activities within IBS is needed. It is anticipated that already planned and prepared measurement campaigns and locations will be used. These campaigns may be initiated for other reasons and de STEM team will provide Prorail with suggestions for additional measurements or analyses. If needed, the STEM team will perform own measurements parallel to the already planned set up |
| **WP Embankment** | Outcomes of other research programs within IBS (such as those focusing more on vehicle dynamics) can be used to identify the most important assumptions and parameters to be included in the train-track models. Existing and planned measurement and monitoring campaigns, as well as the data, can be shared with STEM. |
| **WP Time behavior** | This activity we will collect data from past experiments from available databases. We are looking to get insight in available long-term measurement campaigns that are available from Prorail, which include time dependent behavior and preferably measurements of additional parameters. These will be analyzed and based on this analysis recommendations for further experimental campaigns will be formulated (with reference to the Meetprotocol [2]. The time scales are important for the project. Assuming a measurement duration or monitoring interval of 2 years, we can only study variations within these two years. Other parameters, or effects on other time scales will be estimated using other sources, e.g. data from literature or data that is available at ProRail, or evaluated theoretically. |

*Table 3 Interactions with other programs*

Multiple project members are involved in IBS and individually bring in expertise on both sides. The same accounts for the project RESET. To ensure that STEM as a program benefits of IBS and RESET IPM will coordinate on program-level. This will be facilitating sharing of information and combined workshops.
The WP-leader has an autonomous responsibility towards the goals of the WP (relevant Annex) and the earlier identified dependencies between other WP (3.3.1). Newly identified dependencies and interferences are reported to IPM and will be taken in account on program level.

The report of M+P was based on so called ‘hot spots’. These hot spots – if related to technical issues – and if not predicted by the model could lead to the need of explorative research. The same could be needed if interference appears in the results by not included variables in the model (see Figure 6).

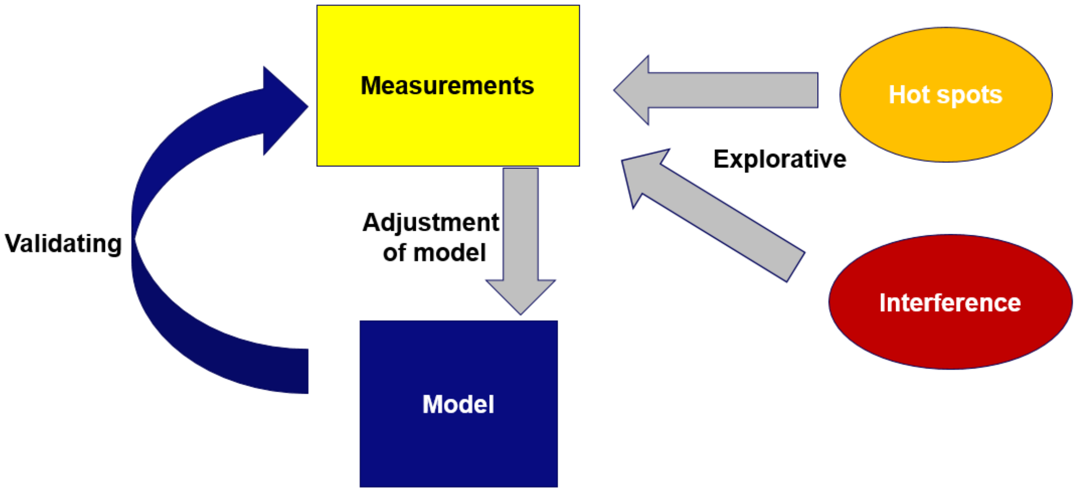



*Figure 6 Relations between model and measurements*

*Projectmanagement:* Coordinate with relevant other projects (at least IBS and RESET) to facilitate exchange of expertise on program level.

*Reporting:* Biannual reports on the cooperation with the other projects to the Steering board. The impact of additional measurements in terms of explored variables or validated models is also reported.

# 4 Deliverables

## 4.1 WP-related

The following deliverables are defined in the WP. The table also provides links to the research questions as well as the requirements.

| Workpackage deliverable | Date of delivery | Tool requirement | Research questions |
|---|---|---|---|
| WP-Spatial Variation-2.5 Suggestions for additional measurements within IBS. | Delivery dependent on IBS planning | | 4 |
| WP-Spatial Variation Description of research priorities for 2024 | Q4 2023 | | |
| WP-Spatial Variation-2.1a State of the art review | Delivery in 2024-2025 if prioritized in 2023 | | 4 |
| WP-Spatial Variation-2.1b List of performed measurements accessible through reports/databases. | Delivery in 2024-2025 if prioritized in 2023 | | 4 |
| WP-Spatial Variation-2.2a Longlist of hotspots. | Delivery in 2024-2025 if prioritized in 2023 | | 4 |
| WP-Spatial Variation-2.2b Minimum first set of hotspot scenarios. | Delivery in 2024-2025 if prioritized in 2023 | | |
| WP-Spatial Variation-2.3a Definition of dynamic stiffness behaviour from a modelling point of view. | Delivery in 2024-2025 if prioritized in 2023 | | 3 |
| WP-Spatial Variation-2.3b Appropriate measurement technique(s) capturing site-rolling stock dynamic stiffness properties for model parameterization and validation. | Delivery in 2024-2025 if prioritized in 2023 | | 1,2 |
| WP-Spatial Variation-2.4a Tooling for modelling spatial variabilities | Delivery in 2024-2025 if prioritized in 2023 | 1,2,3 | 4 |
| WP-Spatial Variation-2.4b Efficient sampling tooling quantifying variabilities. | Delivery in 2024-2025 if prioritized in 2023 | | 4 |
| WP-Spatial Variation-2.4c Efficient sampling tooling quantifying sensitivities. | Delivery in 2024-2025 if prioritized in 2023 | | 4 |
| WP-Embankment-D1 D1: hotspots and critical components/parameters (joint effort with WP-R) | V1 Q2 2023 | 1,2,3 | 1 |

| | | | |
|---|---|---|---|
| | Yearly updates if prioritized in 2023 | | |
| WP-Embankment-D2.1 Existing models and integration with the final tool | V1 Q2 2023 yearly updates | 1 | 1 |
| WP-Embankment-D2.1.1 ES-Las | V1 Q2 2024 | | 1 |
| WP-Embankment-D2.2: Models | V1 Q4 2023 Yearly update | 1 | 2 |
| WP-Embankment-D3.1 D3: Measurement plan | V1 Q2 2023 | | 1,2,3 |
| WP-Embankment-D4.2 D4: Monitoring plan | V1 Q2 2023 | | 1,2,3 |
| WP-Embankment-D5 D5: Effects of train, track and embankment on environmental vibrations based on measurements, monitoring and simulations | V1 Q4 2024 | 1 | 1,2,3 |
| WP-Time behaviour Description of research priorities for 2024 | Q4 2023 | | |
| WP-Time behaviour-3 Recommendations for monitoring campaigns. | Delivery dependent on IBS planning | | 2 |
| WP-Time behaviour-1 A priority list of parameters for which time dependence is relevant | Delivery in 2024-2025 if prioritized in 2023 | | 2 |
| WP-Time behaviour-2 Overview from available measurement campaigns, and an analysis of relevant observations | Delivery in 2024-2025 if prioritized in 2023 | | 2 |
| WP-Time behaviour-D2.3D2.3: Model validation and simulation results | V1 Q4 2024 | 1 | 1,2,3 |
| WP-Tool-1.1 Report user group 1 | Q1 2023 | 1,2,3 | |
| WP-Tool-1.2 Report user group 2 | Q2 2023 | 1,2,3 | |
| WP-Tool-3.1 Release V1.0 including release notes | Q4 2023 | 1,2,3 | |
| WP-Tool-1.3 Report user group 3 | January Q1 2024 | 1,2,3 | |
| WP-Tool-1.4 Report user group 4 | Q2 2024 | 1,2,3 | |
| WP-Tool-3.2 Release V2.0 including release notes | Q4 2024 | 1,2,3 | |
| WP-Tool-3.3 Preliminary validation report | Q4 2024 | 1,2,3 | |
| WP-Tool-1.5 Report user group 5 | Q1 2025 | 1,2,3 | |
| WP-Tool-1.6 Report user group 6 | July 2025 | 1,2,3 | |
| WP-Tool-3.3 Release V3.0 including release notes | Q4 2025 | 1,2,3 | |
| WP-Tool-3.4 Validation report | Q4 2025 | 1,2,3 | |
| WP-Tool-1.6 Report user group 7 | Q4 2025 | 1,2,3 | |

*Table 4 WP deliverables in time*

## 4.2 Program level

The deliverables on program level are directly related to the impact of the WP and incorporated in the WP deliverables. These deliverables are focussed on

#### 4.2.1 Model design

The first year of STEM mainly focusses on the STEM-tool. Tool V01 is there for mainly based on existing models. In 2024 the model will be further developed based on the input from the WP's Time behavior /Spatial variation /Embankment. This model is used to evaluate progress every half year with the 4 WP-leaders.
Identified dependencies between the WP's during the preliminary study are dealt with at WP-level. IPM is to be involved with new identified dependencies and consequence in planning or budget. Outcome and consequences of the Biannual evaluation is reported to the Steering board.

#### 4.2.2 Integration of the end user

Every half year an end user report is composed by the Practice Board. This report will give input to the WPs on progress and (re-)planning.
IPM is involved to monitor the scope and consequence in planning (on program-level) or budget

#### 4.2.3 Interaction with other projects/programs

RESET, IBS, etc.. will deliver additional insights and could strengthen STEM. On individual level expertise is used and/or gained of which the program could benefit.
Quarterly session are organised by IPM to share knowledge. Project members of STEM are invited to present and project managers of other projects/programs are invited to present their findings and progress. These meetings are also used to offer others the opportunity to collect knowledge from STEM.
The sessions are for all project members. IPM will inform the Steering board

#### 4.2.4 Midterm review

Half way the project in the second half of 2024 a midterm review will be organized in order to reflect on the scientific focus at that moment of review and the expected outcome of the project. Are the research questions still the most relevant for the defined outcome? Are additional research questions needed to reach the outcome?

# 5 Planning

## 5.1 General planning

The STEM project for the full period of time is depicted in figure 7. The iterative process will run in a couple of yearly cycles. In first instance the STEM Tool will be designed and developed by a couple of models that are already available (version 1 of the STEM tool). The next cycle will lead to an updated version of the STEM tool (version 2) by the results and outcome of the user scenario's, new insights and knowledge as an outcome from research and the results from experiments. Version 3 will be the last version as an outcome of the project as described in this plan.

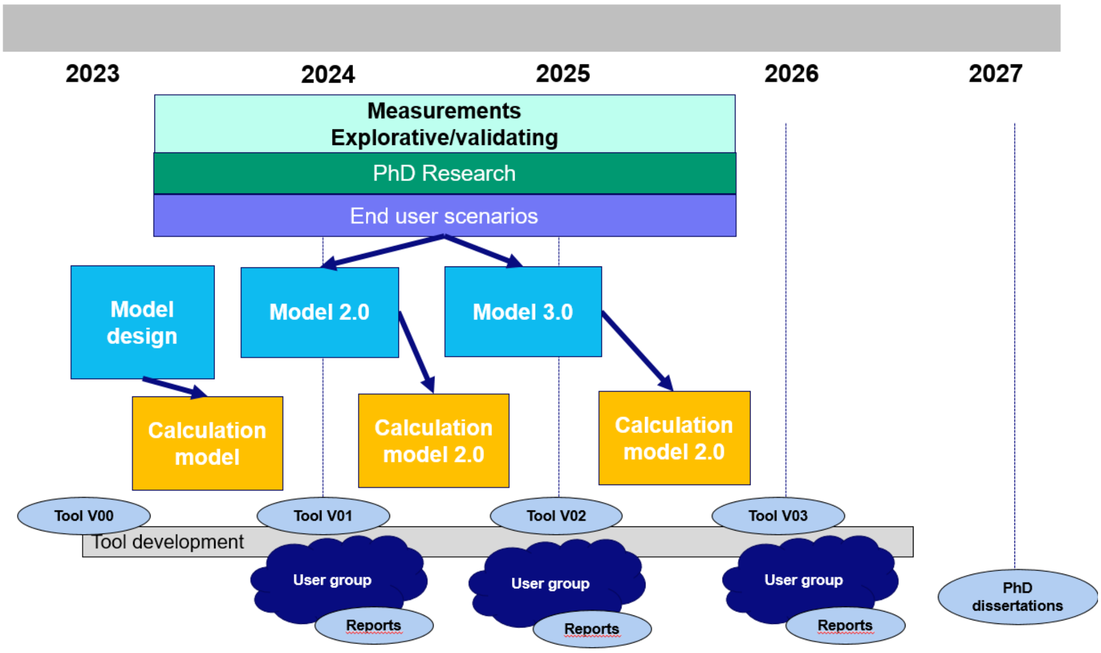



*Figure 7 Iterative process during the full period of time*

The first year of STEM mainly focusses on the STEM-tool. Tool V01 is mainly based on existing knowledge and data. The tool is validated by existing data from IBS and the hotspots. Validating the tool also gives input to new monitoring campaigns and other WP's in the years to come. Also, in 2023 the PhD-candidates start. WP Tool will therefore start in 2023 with a first iteration. Activities for TNO and Deltares in WP Spatial Variation, WP Time Behavior and WP Embankment will not yet be started in 2023. WP Spatial variation and WP Time behavior will start in 2024 with the first iteration step. The measurements and preparations for them, which will take place within IBS in 2023, are important for STEM to be able to get started in 2024. In 2023 TNO and Deltares will provide their input for the experiments that will be handled within the IBS project and will define the focus points and the priorities for the next iteration of the STEM-tool and the WP's Time Behavior and Spatial Variation in 2024.

By the end of 2025 there will have been 3 iterations of WP Tool and WP embankment and 2 iterations of the other WPs. Towards the end of 2025, a choice will be made on how the remaining budget will used in 2026.

Results from measurements, PhD-research and end user feedback is used to validate and improve the models and tool. In 2024 and 2025 the same rhythm recurs, resulting in the V03 tool end of 2025.

## 5.2 Detailed planning

From 2024 onwards during the year every 4 months a meeting with the WP's will be planned. These meetings will take place in Delft to offer all participants of the WP the possibility to attend. In April and October -additional to the above mentioned meetings - a meeting is planned between IPM and the WP-leaders to discuss the status of the model and the integration of the end-user. In the table below the planning per WP for 2023 is given. The table o.a. shows that so called 'trillingsateliers' will be planned with IBS once every 6 weeks. Also the PhD studies will start in 2023.

| 2023 | jan | feb | mar | apr | may | jun | jul | aug | sep | oct | nov | dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **WP Embankment** | | | | | | | | | | | | |
| PhD study start | | | | x | | | | | | | | |
| Deliverables WP Embankment | | | | x | x | x | x | x | x | x | x | x |
| Recommendations for monitoring campaigns IBS | | x | | x | | x | | x | | x | | x |
| **WP Spatial variations** | | | | | | | | | | | | |
| PhD study start | | | | x | | | | | | | | |
| Recommendations for monitoring campaigns IBS | | x | | x | | x | | x | | x | | x |
| **WP Time behaviour** | | | | | | | | | | | | |
| PhD study start | | | | x | | | | | | | | |
| Recommendations for monitoring campaigns IBS | | x | | x | | x | | x | | x | | x |
| **WP Tool** | | | | | | | | | | | | |
| End user groep | x | | | | | | | | x | | | |
| Definition output | | | x | x | x | | | | | | | |
| Definition input parameters | | | | x | x | x | | | | | | |
| Tools specification | | | | | x | x | x | x | | | | |
| Tool definition | | | | | | | x | x | x | x | x | x |
| Parametric study | | | | | | | | | | | | |
| Validation | | | | | | | | | | | | |

*Table 5 Planning WP's*

In addition to this the IPM team has its own planning for coordination on program level. This is shown in the table below. This planning needs further alignment with the scheduled dates for the practice board, trillingsateliers and the steering board.

| 2023 | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model design** | | | | | | | | | | | | |
| Discuss progress Model design and dependencies (Final/Detailed Train-Track-Embankment model and Ballast, embankment and Subsoil model) | | | | | X | | | | | | | X |
| | | | | | | | | | | | | |
| **Integration user design** | | | | | | | | | | | | |
| End user group (Practice Board-meeting) | X | | | | | | | | X | | | |
| | | | | | | | | | | | | |
| **Interaction with other projects** | | | | | | | | | | | | |

| 2023 | jan | feb | mar | apr | may | jun | jul | aug | sep | oct | nov | dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IBS – trillings- ateliers | Continuous every 6 weeks | | | | | | | | | | | |
| IBS – Measurement Campaigns | | | | | | | | | | | | |
| RESET | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| **Other meetings** | | | | | | | | | | | | |
| Steering Board | | | X | | | X | | | | | X | |
| IMP team: | continuous bi weekly | | | | | | | | | | | |
| Digital meeting to inform WP's on plans 2023 and 2024 | | | | X | | | | | | | | X |

*Table 6 Planning IPM team*

# 6 Organization

## 6.1 Governance

The organization and governance of STEM consist of
a. Steering board;
b. IPM Team (Integral Program Management Team);
c. Practice Board; and
d. Scientific Board.

The responsibilities and decision making has been established in the STEM program agreement. The relations are shown in Figure 8.

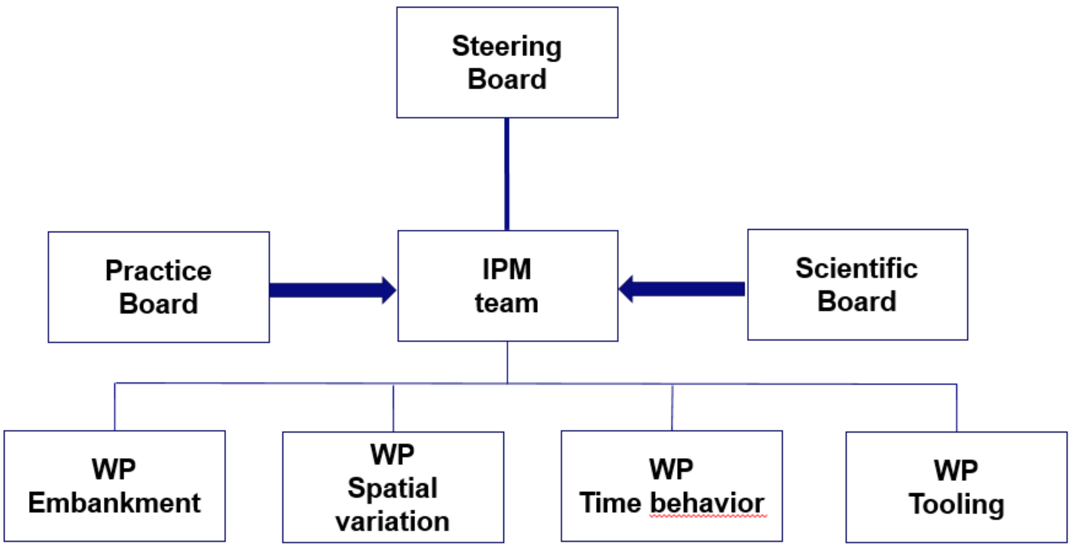



*Figure 8 Governance model*

## 6.2 Internal project organization

The organization of the WP's is done by the WP-leader. Preferably the approach how the PoA in the preliminary phase is written will be continued: choosing a set day to combine activities of multiple WP's on the same location fosters the relation and cooperation. As shown in the table below, the various organizations jointly work on the 4 WP's in combined teams, again to foster the cooperation and exchange.

| WP | TU Delft | TNO | Deltares |
|---|---|---|---|
| WP Embankment | Chen Shen, Zhen Yang, Zili Li, Rolf Dollevoet | Jitse Pruiksma | Paul Holscher |
| WP Spatial | Michael Hicks, Evert Slob | Jitse Pruiksma, Chris Geurts | Paul Holscher, Cihan Chengiz |
| WP Time | Zhen Yang, Ken Gavin | Wim Courage | Bruno Zuada Coelho |
| WP Tooling | Cristina Jommi, Michael Hicks | Jitse Pruiksma, Jelme Pennings, Davide Moretti | Bruno Zuada Coelho, Aaron Noordam |

*Table 7 Participants of the partners in the WP's*

Activities as described in 5.2 will be organized by IPM.

## 6.3 Integrating the PhD-candidates in the project

Special attention is given to the PhD-candidates. Integrating their efforts in the project is seen as of major importance. Their research is to bridge the knowledge gap related to the tool. Goal is to apply the developed knowledge. The awareness of the requirements of the tool, the transfer of the knowledge and implementation in code is of the utmost importance.

The expected contribution of the PhD research to the WP is displayed in the following table.

| % | WP embankment | WP spatial | WP time | WP tooling |
|---|---|---|---|---|
| **PhD 1** | 85 | 5 | 5 | 5 |
| **PhD 2** | 10 | 5 | 80 | 5 |
| **PhD 3** | 10 | 85 | 0 | 5 |
| **PhD 4** | 40 | 40 | 15 | 5 |

*Table 8 Contributions PhD research to WP's*

PhD-candidates are expected:

- to attend the relevant WP- and program level meetings,
- to assist WP-Tooling in the transfer of code by providing pseudo code or specifications on the implementation.

# 7 Risk matrix

The most important risks are indicated in the table below. Risks per WP are given in the appendix

| Nr | Risk | Mitigation |
|---|---|---|
| 1 | Models and tools STEM appear not to be applicable by the sector | Several user scenarios for STEM are being developed.<br>Go/no go moments are built into the development of the models and STEM tool.<br>Priorities are set in consultation with end users and stakeholders.<br>Communication plan for expectation management of all stakeholders, throughout the entire process |
| 2 | Dynamic stiffness measurement method – development does not fit within scope | The relative relevance in the total package is reassessed by means of a literature study and simulation.<br>Inventory of existing techniques and their margin of error.<br>Elaborate a concept measurement method suitable for small-scale or national roll-out and offer it to the market for implementation |
| 3 | Model is not representative of the effect of measures on the receiver (i.e. the building) | Validate the model and the entire chain on the receiver side in a number of cases.<br>Communication to stakeholders about the scope of STEM.<br>The perception of local residents with regard to vibration nuisance falls outside the scope.<br>Vibration propagation in buildings falls outside the scope. |
| 4 | Model is not suitable for diagnostics, but is suitable for forecasting in scenarios | Include input/source mechanisms in model building |
| 5 | High accuracy expected from forecasting with STEM | Communication plan for expectation management of all stakeholders, throughout the entire process.<br>Quantifying uncertainties |
| 6 | Knowledge institutions work on an 'island' in the rail sector | The Practice Board determines user scenarios that fit with partial and end products.<br>Requirements on attendance and support of PhD-candidates is defined. |
| 7 | End result Research program not yet clear | Start with substantive Phase 1 jointly by the knowledge institutions. Here, the scope is explored and refined in terms of content and feasibility. |
| 8 | Larger measurement campaigns, data acquisition are time consuming and costly | Early in the project work on potentially relevant trials<br>Interact with the accompanying experimental program.<br>Measurements are used from the practical trials of the IBS |
| 9 | Availability and ownership of data potentially problematic | ProRail provides central access to the data collected in the context of the IBS |
| 10 | The budget is not sufficient to further develop the tool in such a way that it is immediately usable for the end users | The feasibility of the desired end goals is tested annually.<br>If the budget turns out to be insufficient halfway through the duration of the research programme, ProRail will make an effort to seek additional funding. |
| 11 | Availability of staff has an impact on lead time | Within the PhD-research and within the WP at least three employees (two staff members and a PhD) are involved.<br>The availability of staff is a returning topic in the IPM team meetings. |
| 12 | The subject of rail vibration hindrance is politically sensitive | Periodic communication with the Ministry of Infrastructure and Water Management about STEM |

| | | |
|---|---|---|
| 13 | No regret activities in 2023 in WP Time Behavior, WP Spatial Variation and WP Embankment fall later in time. | No regret activities must be prioritized for 2024. |
| 14 | TNO's activities will be very limited in 2023, which means that the cooperation that has been built up between TNO, Deltares and TU Delft may come to a standstill in 2023. | TNO will be involved in the development of the tool and in the IBS measurement recommendations. |

# A WP Tooling

Authors: Bruno Zuada Coelho; Wim Courage; Michael Hicks; Jelme Pennings; Joris van Ruijven.

## 1. Literature scan

Railway induced vibrations are found to cause public nuisance to inhabitants living on the vicinity of railway tracks. In the Netherlands it is estimated that 20% of the inhabitants living within 300 m of a railway track experience severe nuisance due to railway induced vibrations [1].

In 2016 the RIVM performed an inventory of the models available in literature to model railway induced vibrations [2]. The study focused on national and international models. The study identified the different groups:

- Empirical models
- Hybrid models (analytical transfer functions and empirical transfer functions)
- Train-track model coupled with 2.5D FEM/BEM (and similar variations) (soil)
- Train-track model coupled with 3D FEM (soil).

In STEM discontinuities, spatial variation and time dependency have been identified as two important aspects for the modelling of railway induced vibrations. However, these two aspects have not received much attention in literature.

The application of stochastic soil modelling in problems related to propagation of vibrations is scarce. Jones and Hunt [3] use random fields in combination with the two-dimensional Thin-layer Method to compute the vibration resulting from underground railways. Papadopoulos *et al.* [4] combine a three-dimensional Finite Element-Perfectly Matched Layers Model with random fields to study the response of a building to ground-borne vibration. Auersch [5] combines a three-dimensional FEM with a simplified model of soil variability to illustrate the importance of the soil variability on train induced vibrations. The use of stochastic soil modelling is more established in earthquake engineering and site response analysis.

The study of time dependency effects on railway induced vibrations have not yet been established in literature. Most of the work on time dependency effects relates to railway track geometry degradation. The majority of work related to the cyclic behaviour of soils concerns accumulation models The working principle of the accumulation models is the combination of a mechanical constitutive relation to model the first load cycle(s), with accumulation functions to predict the deformation for the remaining number of loading cycles [6, 7]. The accumulation models were initially developed for granular materials [6, 7, 8, 9], however, more recently accumulation models for soft soils have also been presented [10, 11, 12].

## 2. Activities in STEM

### 2.1. Definition of the end-user group

Half yearly meetings with the end-user group to show the progress, discuss and prioritise the future activities. Involve the end-users of STEM at early stage, to create awareness and clarity about the objectives and scope of the end-product, and have discussions about I/O.

### 2.2. Definition of the output

The output for the assessment of the performance of the model needs to be defined. The following activities are foreseen:

- Check existing proposals (e.g.):
    - OURS
    - RIVAS
    - CargoVibes
    - SBR-B

- Collect input from end-users
- Define the performance measure (e.g.):
  - Maximum value
  - RMS value in time
  - Frequency domain
  - New definition (e.g. wavelets)
- How to forward the output to building model.

### 2.3. Definition input parameters

STEM input parameters should be aligned with the mitigation techniques that are envisaged by ProRail. The following activities are foreseen:

- Overview of existing mitigation techniques:
  - From existing measurements
  - From ProRail catalogue
  - Collect input from end-users
- Define the minimum parameters set (from the previous mitigations technique list) that need to be available in the tool
- Define how to parameterise the minimum parameters set.

### 2.4. Tool specifications

In order to have a continuous development of the tool and to incorporate the developments of the different work packages in STEM, it is necessary to define the specifications for the tool:

- Definition of the framework
- Definition of I/O
  - Allow for the extension of inputs (in relation to 2.3)
  - Allow parsing to OURS
  - Connect with opensource pre/post processor software for input generation and visualisation
- Definition of APIs for communication between modules
- Definition of cloud specifications
- Generation and automatisation of the input (linked with WP Embankment/WP Spatial variation/WP T)
- Parametric modelling (linked with WP Embankment/WP Spatial variation/WP T).

### 2.5. Simplification of the problem

The STEM tool will, in first instance, consist of a 3D FEM coupled model, with various levels of complexity. This will require a significant computational effort. In order to reduce this computational effort, possible simplifications to the tool will be explored, e.g.:

- Subsoil model: 3D, 2.5D, 2D, 1D
- Train model: 3D / 2D / moving loads / no train
- Working with databases of calculations.

### 2.6. Parametric study

Perform a parametric study with the STEM tool in order to identify the governing parameters for railway induced vibrations and assess the effect of different mitigation techniques. The mitigation techniques will be defined together with ProRail.

### 2.7. Validation

The STEM tool is to be validated against case studies. These should be defined together with ProRail, and should incorporate not only extreme cases, where there is excessive a vibration level, but also with cases where the vibration level is moderate and low. In this way, the accuracy of the tool can be tested is all the expected ranges of vibration. The cases for validation need to have the input and output data definitions (see §2.2 and §2.3) available.

# 3. Minimum Viable Product

The minimum viable product (MVP) of STEM is a tool that performs finite element calculations with dynamic train/track interaction on a stochastic ballast and subsoil (*Figure* ). The findings and new insights obtained in the different WPs will be incorporated in the MVP throughout the project.

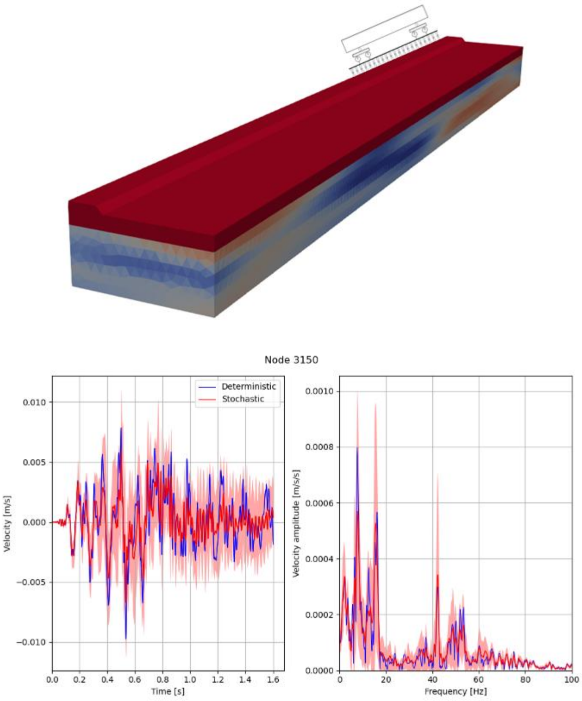



*Figure 2: MVP.*

# 4. Connection with other WPs

Figure 4 shows the framework of the STEM tool and the relation between the different WPs.

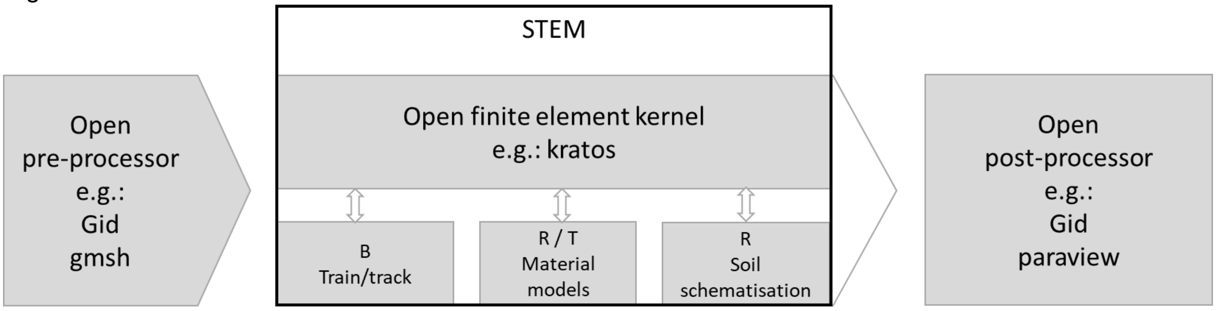



*Figure 3: Connection between WPs.*

### 4.1. B: Embankment

WP B provides knowledge on the importance of the track components and a model for the train/track interaction model. The communication between the FEM kernel and train/track model is defined via the API specified in §2.4.

### 4.2. R: Spatial Variation

WP R provides knowledge on the stochastic calculations and provides a model for the ballast and subsoil schematisation. The communication between the FEM kernel and train/track model is defined via the API specified in §2.4.

### 4.3. T: Time behaviour

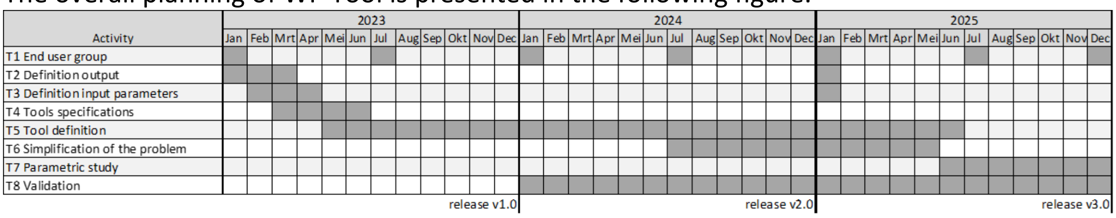
WP T provides knowledge on the important components that exhibit a time dependency that influence railway induced vibrations and material models for the ballast and subsoil layers. The communication between the FEM kernel and train/track model is defined via the API specified in §2.4.

# 5. Risks

| Risk | Mitigation |
|---|---|
| Model is too complex for end-users:<br>• Requires too much input parameters<br>• Requires information that end-users do not have access to (e.g. stiffness of primary suspension of the train)<br>• Requires parameters that cannot be measured or are too costly to measure. | The end-user group is involved with the developments of STEM since early stage:<br>• During the definition of the input parameters. |
| It requires too much computation time. | During the development of STEM attention will be paid to model simplifications that can reduce the computation time. Moreover, STEM will be cloud ready. |
| The model does not provide enough accuracy (not enough data to validate, or not enough data to calibrate) or provides too large uncertainty. | Attention is paid to the validation of the model, at different vibration levels. |
| The model does not capture the relevant physical mechanism that causes excessive vibration. | The STEM model is going to developed in phases. The MVP will be constantly assessed about its performance and adjustments can be made throughout the project. |
| The model does not account for the building, so it might not be directly used in combination with SBR-B to assess vibration annoyance. | This is a risk of STEM project. |

# 6. Planning

The overall planning of WP Tool is presented in the following figure.




# 7. Budget

The overall budget estimation of WP Tool is presented in the following figure.

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# B WP Train-Track-Embankment

Chen Shen, Zhen Yang, Paul Hölscher, Jitse Pruiksma, Stijn van Boxmeer

## 1 Introduction

Vibration nuisance caused by rail traffic has attracted a lot of attention at ProRail in recent years. It is necessary to better control the generation of vibrations and their transmission to the environment. The objective of STEM is to develop a tool to calculate vibrations at hotspots and mitigating measures.
For this it is necessary to understand the generation and transmission mechanism of vibrations in the train-track-embankment system, especially the role each component plays. Based on that, appropriate assumptions and complexity can be determined for each component in the final tool of STEM. This work package (WP Embankment) will provide knowledge on the relative importance of different components and develop a train-track model for the final tool. We propose renaming this WP to Train-Track-Embankment, as its scope now encompasses more than just embankment.
This WP will consider the generation of vibration at the rail-wheel interface including the substructure for several situations and it will consider the influence of the ballast and embankment on both the generation of vibrations on the wheel-rail interface and the radiation of the vibrations towards the environment. The final purpose is to create models and input for the STEM Tool in WP Tooling.
Train-induced vibrations are primarily generated at wheel/rail discontinuities and where track stiffness changes. At the very short ES-joints a highly non-linear elastic and highly dynamic process is taking place. Traditional models that are based on beam equations, do not model this correctly. Advanced 3-D modelling of the rail and joint is necessary [1]. This model seems also to explain that the quality of the joint decreases in time and leads to higher impact at the joint. The model needs to be validated by a field test and the consequences of the environmental vibrations in the vicinity must be elaborated. Moreover, the implementation of the advanced model in a simplified model for the tool must be considered.
Other discontinuities that are important for environmental vibrations will be studied in this WP are level crossings and switches. These problems are less demanding for the calculation method, it is expected that these can be evaluated by traditional beam models for the track. Within this WP the parameters that influence the vibrations from these discontinuities, a proper modelling approach for the problem and suggested methods for the reduction of these vibrations will be evaluated.
The influence of the embankment on the vibration level in the environment is multiple and relatively unknown. A stable embankment will lead to a lower variation on track level and reduces the roughness of the track in the lower frequency range. This is a time-dependent aspect that should be evaluated in WP Time behavior and is maybe related to the RESET program. In the rail-track model the support of the sleepers (or ballast) is given by a spring dashpot system, which is often frequency-independent. The influence of this assumption on the vibrations that are radiated to the environment is unknown. Finally, the embankment may influence the distribution of the vibration over the direction of the radiation. This has a direct influence on environmental vibrations.

In train-track models, the embankment is usually not explicitly modelled; its effect is considered in the dynamic stiffness under rail or sleepers. This is where the definition and measurement of track stiffness become important. Various techniques exist for measuring track stiffness, including trackside [2–5] and train-borne measurements [6–13]. These techniques were mostly aimed at evaluating the equivalent stiffness experience at the track, and therefore represent the combined effects of the substructure, such as railpad, ballast, embankment, and subsoil. Additionally, there seems to be a lack of field validation for the

train-borne track stiffness evaluation method; they have only been validated through numerical examples [9,11,12] or simple lab setups [10]. In order to get a valid value of the force that is transmitted into the embankment and environment, an accurate value of the dynamic stiffness is important.
Within this WP it will be evaluated which properties of the embankment are important for the transmission of vibrations to the surrounding. This leads to the more fundamental question: is a design of a low-vibration embankment possible, e.g. by application of a PPS layer? This study is closely related to the 3D-approach in WP Tooling: The behavior of the embankment can be studied by using the tool, and the results of the study give information on the parameters that must be introduced for the embankment in the practical application of the tool.
For the study of vibration transmission through the embankment and surroundings, a train-track model needs to be coupled with a detailed model of (ballast), embankment and surroundings. WP Tooling develops such a model. In these models, the train is typically simplified, making it difficult to evaluate the effect of all train parameters in detail. It is still unclear when a more complex train model is needed and, if needed, how it can be implemented in the tool that is developed in WP Tooling. Moreover, since embankment stiffness has been incorporated into the spring stiffness of train-track models, challenges occur when train-track and embankment models are coupled, such as how to re-calibrate the spring stiffness and/or define the interface between the two models. Once we have sufficient knowledge of the important factors, the method the train-track model can be implemented in the tool will be studied in cooperation with WP Tooling.

# 2 Objectives and research questions

The main objective of this WP is to better understand, and develop models for, the **generation** and **transmission** characteristics of vibration nuisances at hotspots. Different hotspots may have different generation and transmission mechanisms for vibrations. In particular, the following research questions are to be addressed for each (selected) hotspot:

- Q1: What are the characteristics of wheel loads (spectrum and magnitude) **generated** at a hotspot?
- Q2: How do we quantify the **transmission** of vibrations (transfer spectrum and magnitude) from the *wheel-rail interface* to the *sleeper-ballast interface* and *embankment*?
- Q3: Which **critical parameters** in the train-track-embankment system play a role in the generation and transmission of vibrations?
    - What is their relative contribution to (the variation in) the outcome of the ground vibrations and the dynamic stiffness?
    - What is the influence of the embankment (e.g., geometry, material properties) on the vibration transmission to the environment?
- Q4: What **model assumptions and complexity** should be considered in the final tool? (This question focuses on the train-track model.)
    - How detailed should the vehicles and discontinuities be modelled?
    - How dynamic stiffness can be defined and measured to model the sleeper support in a coupled train-track model?
- Q5: How could we **measure** and **monitor** the critical parameters (e.g., geometry and dynamic stiffness)?

- Which parameters must be and can be monitored to get insight into the long-term behavior?
- How to validate the models using measured vibrations and dynamic stiffness?

# 3 Activities

## 3.1 Identification of critical parameters and measures related to hotspots

In WP Spatial variation, hotspots need to be defined based on specific locations where vibration nuisances occur (e.g., at discontinuities). Critical parameters for each hotspot will be identified in order to simulate them. Suggested mitigating measures limited to train-track-ballast will be investigated. Measures related to embankment may be outside of the scope of this WP. The following activities are anticipated:

*Inventory of potential parameters and measures. At this stage, a preliminary list has been made, see*

1) Figure 6 Relations between model and measurements. The distance of a structure to the track and its features may also play a significant role in determining hotspots. These characteristics are beyond the scope of this project, although they should be considered when identifying hotspots (WP Spatial variation).
2) Identify relevant (degraded) components in the train-track-embankment system for each hotspot, as well as critical parameters for each component. These could be achieved by, e.g.,
   a) Literature review of similar hotspot cases,
   b) Review of existing mitigating measures by ProRail, e.g.,
      i) Under sleeper pads and under ballast mats;
      ii) Different types of sleepers;
      iii) PSS layer (see this link for more detail);
      iv) Sheet piles.
   c) Checking existing measurement data,
   d) Consulting with other research projects within IBS,
   e) Sensitivity analysis of critical parameters (see §3.2-6)).

*Table 2 Critical parameters and mitigating measures related to hotspots*

| | **HOTSPOT RELATED COMPONENTS** | **CRITICAL PARAMETERS** | **MEASURES** |
|---|---|---|---|
| **VEHICLE** | Suspension | stiffness, damping | • Re-design |
| | Wheel | wheel diameter | • Reprofiling<br>• Replacement |
| | | wheel profiles (e.g., flange height and thickness) | |
| | | Wheel flat/out-of-roundness | |
| | Train types | axle load | |
| | | speed | |
| **TRACK** | Switches & Crossings | angle, type, geometry, stiffness | • Grinding<br>• Reprofiling<br>• Replacement |
| | Insulated joints | Geometry (gap), deformation, loose fastening (nonlinearity), ballast voids (nonlinearity), bad insulation layer | |
| | Rail | Geometry of surface defects (such as welds, squats, etc.) | |

| | | | |
|---|---|---|---|
| | Sleeper | material(concrete/wood/plastic)<br>support stiffness | • Replace with different type of sleepers<br>• Under sleeper pads |
| | level crossing | | |
| | Curves | curvature, cant | |
| **BALLAST** | Ballast (degraded) | Ballast condition | Tamping |
| **EMBANKMENT** | Transition zones | sub-soil condition (settlement, compaction of ballast after tamping, approach slab (length and angle) | • Changing the ballast profile<br>• Sheet wall/piles,<br>• PSS layer,<br>• Adjusting track geometry to the upper limit at the end of the approach slab |
| | Subsoil | Cross-section geometry of embankment, | |
| | | Soil type | |

## 3.2 Modelling

Train-track-embankment interactions at (selected) hotspots and reference tracks, will be modelled to understand the generation and transmission characteristics of vibration nuisances.
The train-track-ballast system will be modelled in three dimensions (3D). Embankment can be simplified as springs characterized by its dynamic stiffness. Multi-body (MB) modelling can be used to simulate the effects of the trains. The foreseen activities are as follows.

1) Research projects within IBS on vehicle dynamics will be consulted for the importance of different vehicle components in modelling different hotspots.
2) Develop detailed 3D FE models for the train-track, ballast and embankment. Note that the ballast and embankment models developed in this WP may rely on existing (material) models from Deltares/TNO/TU Delft or published works. These models serve as benchmarks for more complex models to be built in WP Spatial variation and Time behavior, which may take stochastic, non-homogeneous, time-dependent features in ballast and embankment into consideration.
3) Perform numerical simulations at
    a) Selected hotspot locations
    b) Reference tracks
4) Calibrate and validate the models with measurements.
5) Analyse numerical results and field measurements to identify and quantify the vibration origins and transmissions.
6) Sensitivity analysis of
    a) Different model assumptions and complexity, e.g.
        i) 3D or 1D vehicle models
        ii) Single or multiple wagons
        iii) Half-symmetrical or full train-track model
    b) Critical parameters
7) Proposing methods together with WP Tooling regarding how to define and characterize a train and track for the final tool.

a) Deltares, TNO and TU Delft will work together to create an inventory of the train-track models that are available within the three institutions. Most suitable models for different components should be combined to form the initial model for WP Tooling.
b) As WP Embankment is progressing, updates will be added to the train-track-ballast model in the final tool. This is not within the scope of PhD 1 and will be carried out by Deltares/TNO.
c) Communications between the train-track model and the final tool need to be defined via the API specified by WP Tooling. This is not within the scope of PhD 1 and will be carried out by Deltares/TNO.

## 3.3 Measurement

Field measurements will be carried out at one or more reference track locations and hotspot locations. Measurement data will be used to calibrate and validate the models, as well as to better understand the generation and transmission mechanisms of the vibrations. The activities are as follows.

1) Choose test sites.
   a) Requirement for test sites
      i) Reference track
         (1) without vibration complaints (due to the track)
         (2) representative of typical track structures
         (3) in good maintenance condition
         (4) without spatial stiffness variations
         (5) with different types of train traffic
      ii) Hotspots
         (1) Insulated joint
         (2) Level crossing
         (3) Switches and crossings (if reported)
         (4) Other hotspots of interest identified in section 3.1 and WP R.

   b) It is recommended that test sites be selected from existing or upcoming IBS measurement campaigns, and measurements for the OURS model. For instance, Ricardo has planned various measuring stations to investigate the effect of wheel out-of-roundness on ground vibrations. The measurement locations and setup in general conform to the requirements for the reference track.
2) Formulate hypothesis for the measurement based on literature, numerical simulations and expert knowledge.
3) Define quantities of interest to be measured (e.g., vibrations, geometry, displacement, etc...)
4) Design measurement setup, for
   a) Pass-by measurement
   b) In-track tests, such as hammer/falling-weight tests

   Meetprotocol developed within IBS should be followed. Data collected from existing or planned measurement setups can be used. Parallel setups can be added to existing or planned setups. A concept design for the setup is described below.

   > **<u>Concept measurement setup:</u>**
   > **Accelerometers and/or geophones can be installed on rail, sleeper, ballast, embankment and subsoil to measure the vibrations and/or displacements of corresponding components. Fibre-optic cables can be buried in the embankment and/or subsoils to measure surface wave vibrations.**
   >
   > **Measurements should be carried out under dynamic train loads (with different train types at different speeds) and controlled excitations, such as from hammer or falling weight tests. These track-side measurements**

**should be combined and synchronized with train-borne measurements (see section 3.4)**

5) Instrumentation and carry out field tests. This requires coordination with ProRail, contractors, other research programs, third parties, etc.
6) Data analysis and model validations. Measured vibrations will be analysed in both the time and frequency domains and compared to simulation results.

## 3.4 Monitoring

With the activities defined in §3.2, track vibrations are measured at discrete locations. Here, monitoring techniques will be developed so that critical track properties can be continuously observed in time and space, allowing for the monitoring of spatial variations and time-dependent effects.

1) Define track properties to be monitored, e.g., geometry, track dynamic stiffness, damping, etc. These properties should be defined so they can be modelled in the final tool.
2) Choose/develop monitoring techniques. Train-borne measurement techniques are preferred. Different train-borne techniques can be used for measuring different track parameters. A concept design for train-borne monitoring is described below.

**Concept design monitoring**

- **Axle-box accelerations (ABA) can be used, in combination with Quo-Vadis, for the estimation of static and dynamic train load. ABA can also be used to estimate track stiffness.**
- **Laser Doppler Vibrometry (LDV) can measure the responses of track and embankment under train load.**
- **ABA and LiDar [14] can be used to estimate track/rail geometry.**
- **Combined with ground penetration radar (GPR) data for soil layers and water contents, the characterization of the track and embankment structures and materials can be done at a larger depth.**

3) Develop algorithms that translate measured vibrations into track properties. If there is a direct link between track properties and model parameters, this can be solved as an inverse problem via optimizations, in which differences between simulations and measurements are minimized by tuning model parameters.
4) Carry out measurement campaigns with measurement/operational trains. Train-borne measurement should be synchronized with track-side and in-track measurements at reference tracks and hotspots (see §3.2).
5) Propose recommendations for maintenance and design based on the insight gained. Performance indicators can be further proposed to ProRail based on the monitoring.

# 4 Connections with other WPs, PhD projects and IBS

WP Embankment focuses on hotspots and measures related to train-track-ballast system (embankment is simplified as stiffness), Measures related to embankment are dealt with in other WPs.
Measurement and monitoring activities should be coordinated with other WPs.

## 4.1 WP Spatial variation:

Some hotspots in Table 1 above will likely need to be computed in WP Spatial variation, such as level-crossings and transition zones, see also Risks, Table 2 in Section 5.

WP Embankment and WP Time Behavior will jointly define dynamic track stiffness and develop its measurement method.

## 4.2 WP Time behavior:

Train models developed in WP Embankment can be used to examine the effect of rolling stock changes over time on track vibrations.
WP Embankment and Time behavior will jointly plan measurement and monitoring campaigns.

## 4.3 WP Tooling:

WP Embankment makes recommendations on the important components, assumptions and parameters to be considered in the train-track model for different simulation scenarios (hotspots).
WP Embankment develops a train-track model that can be connected to the ballast/embankment model in the final tool. WP Tooling provides the API for the communications between the train-track model and the final tool

## 4.4 PhD projects

In the first and second years of the 3 PhD projects, a greater emphasis should be placed on practical tasks that contribute to the overall project, such as performing measurements and building models, while working closely with Deltares and TNO to acquire the necessary skills and knowledge. Activities defined in WP B provide good starting points for the 3 PhDs to be directly involved in STEM (Activities 3.2-1), 3.2-2), 3.2-7)a) and 3.3).

## 4.5 IBS

Outcomes of other research programs within IBS (such as those focusing more on vehicle dynamics) can be used to identify the most important assumptions and parameters to be included in the train-track models.
Existing and planned measurement and monitoring campaigns, as well as the data, can be shared with STEM.

# 5 Risks

Table 3 lists the risks identified at this stage and corresponding mitigating measures.

*Table 3 Risks and mitigations*

| Risk | Mitigation |
|---|---|
| The PhD work focuses mainly on the joints and to do so should model also the train behavior. The hotspots other than joints from Table 1 should be modelled by Deltares/TNO. The current budget of 150k Deltares+TNO does not allow for these to be modelled. | Allocate more budget to WP Embankment for Deltares/TNO to model these hotspots and measures that are excluded from the PhD plan. In particular the PSS, under sleeper pads, ideas for vibration-free embankment and other hotspots that are not related to other WPs<br><br>Some hotspots may be modelled in other WPs, like level-crossings which relates to WPSpatial variation |
| A long list of hotspots<br>• Difficult to model and validate every scenario | Consult with WP Spatial variation and ProRail to select a few most representative hotspots |

| | |
|---|---|
| • Difficult to model interventions/measures | Some rough assumptions on resulting track geometry/stiffness can be computed to approximate the effect of hotspots and measures. |
| The definition and measurement method for dynamic stiffness may not fit in the model | Prioritise this activity during the first half year.<br>Involve WP Spatial variation, Embankment and Tooling in consultations |
| Measurement and monitoring<br>• Hypothesis may not always be correct<br>• Measurement campaign involves other parties/stakeholders<br>• Delay and cancellation of planned measurement due to unforeseen reasons | Plan measurement well ahead<br>Make use of existing data |
| Activity 3.2-6a aims to investigate the effect of different assumptions in the train-track model. It could be the influence of some assumptions is significant. The risk is that incorporating them in the final tool is not feasible within the time and budget. | |

# 6 Planning

See overall Plan of Approach

# 7 Budget

See overall Plan of Approach

# 8 References

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# A WP Time Dependency

Authors: Chris Geurts, Paul Hölscher, Jelme Pennings; Wim van der Poel, Zhen Yang, Jitse Pruiksma

## Introduction

Railway induced vibrations are found to cause public nuisance to inhabitants living on the vicinity of railway tracks. In the Netherlands it is estimated that 20% of the inhabitants living within 300 m of a railway track experience severe nuisance due to railway induced vibrations [1].
The aim of the work package WT T: Time behavior is to determine the effect of time dependent behaviour of the train-track-embankment system on free field vibration levels in the field at 20 m distance from the track. The time scale of interest is much longer than the time scale of a single train passage, and is envisioned to be anything from the order of 1 month to the track lifecycle.

## 1. Scope

Due to the wide variety of time behavior a limitation of scope is necessary. Which is described here.
The focus of the work package will be on cyclic degradation of railway track and subsoil (embankment) due to train passages, soil settlement due to creep, and the wear of the wheel material (wheel flat) over time.
In the original research question, time behavior were categorized into a change of geometry and change in stiffness. In this work package the change of geometry is assumed to be the most important factor with respect to free field vibrations. The amount of publications on stiffness change is scarce by comparison. A change of stiffness with time will only be considered here for behaviour near joints, and not for the other cases, such as the continuous track.
The rail wear, other than joints, is assumed to have negligible influence to vibration levels and will not be considered. The wear of the wheel material (wheel flats) is expected to have much more influence.
For the degradation of ballast and subsoil two situations will be distinguished: behaviour of a normal continuous track and behaviournear discontinuities :

1. For the continuous track only relative settlements will lead to a change in free field vibration levels (if stiffness is considered unaltered), because only relative settlements lead to a geometry change along the track. Therefore the time dependent behaviour for the continuous track has to be evaluated based on relative settlements. Because relative settlements involve the inclusion of heterogeneity of ballast, subsoil, and periodicity of the track, a numerical description requires a very detailed and complex approach. The approach that will be followed for the continuous track will be based on the ProRail track quality definition. There is a track quality threshold where maintenance (tamping) has to be carried out, and there is also knowledge about track quality right after maintenance. This track quality will be converted to track geometry such that simulations can be made for these extremes to determine free field vibrations. This can also be done for track quality quantifiers in between these situations to study the effect of preventive maintenance which was part of the original research question.
2. Near discontinuities, such as transition zones and level crossings, ballast and subsoil degradation can be described in terms of absolute settlements if the degradation on the level crossing is considered much less than in the ballast+subsoil in the transition zone. Here models for cyclic degradation may

be applied in absolute sense. The same holds for time effects near a joint which may be considered separately as well.

The effect of climate change is not subject of our research, but seasonal effects will be taken into consideration in the form of temperature effects (in the summer-winter range) and the possible impact of periods of heavy precipitation.
Furthermore, time behavior will be studied only in relation to free field vibration levels. Impact on the train and comfort for train passengers will not be considered. The influence of time effects on track stability (slope failure, track failure/derailment) is likewise not in the scope.

## 2. Literature quick-scan

Time dependency effects on railway induced vibrations have not been addressed explicitly in the literature. Most of the work on time dependency effects relates to railway track geometry degradation. The majority of work related to the cyclic behaviour of soils concerns compaction strain accumulation models based on the number of train or axle passages. The working principle of the accumulation models is the combination of a mechanical constitutive relation to model the first load cycle(s), with accumulation functions to predict the deformation for the remaining number of loading cycles [6, 7]. The accumulation models were initially developed for granular materials [6, 7, 8, 9], however, more recently accumulation models for soft soils have also been presented [10, 11, 12].

## 3. Activities in STEM – WP Time Dependency

**1. Literature search**
The WP starts with an in depth literature search with regard to the time effects mentioned in the scope. This literature search will be performed by Deltares, TNO and TUDelft in collaboration and leads to an overview of the state-of-the art on time behavior, related to vibration emission of railway tracks.
The literature review proceeds along the following topics/mechanisms

- Effect on geometry change as a function of time due to:
  - Cyclic degradation of ballast dependent on axle loads, number of train passages as a function of time
  - Cyclic degradation of the subsoil dependent on axle loads, number of train passages as a function of time
  - Cyclic degradation of rail discontinuities (joint)
  - Creep of the subsoil
  - Seasonal temperature differences
- Effect of a period of heavy precipitation on vibration emission and its recovery
- The wear of the material, in particular wheel geometry/wheel flats as a function of time

The literature review should lead to an insight into which of the above mechanisms contribute significantly to vibration emission and which mechanisms are less relevant. Cases where literature is scarce but which are considered to potentially have significant influence on vibration emission will be identified. Such unverifiable hypotheses can be evaluated by monitoring.
Another goal of the literature search is to determine models to be able to quantify the above mechanisms as a function of time and or number of train passages. The literature search focusses on simplified models that establish the time behavior quantitatively and can be used in the STEM tooling with relative ease and require little calibration of parameters to evaluate time dependent effects.
Advanced models are often superior and may be identified as well during the literature search, but have the problem that a large number of parameters is required for each of soil-creep, soil

cyclic degradation, ballast cyclic degradation. Combining these in the STEM tool leads to an even larger number of parameters that need to be calibrated with experimental data.

### 2. EBR Session

- In addition to the literature review we propose to organise an Electronic Boardroom session (EBR-session). The basic principle is that many (say 15) experienced participants with different, but relevant background, make an evaluation about the influence on vibration levels for the mechanisms identified above for the literature review. Another goal of the EBR session is to identify important mechanisms that are overlooked in the literature search. The EBR session takes the following steps:

1. Establish if the list is complete and add extensions based on the participants' input
2. for the extended list, the importance of each mechanism on the vibration emission effect is evaluated (the list can then be ordered with respect to importance)
3. for the extended list, the timescale is determined
4. for the extended list, it is determined if the effect is easily measured by monitoring
5. The filled in list can be ordered to level of importance, orded by time scale, or measurability

example of the list with possible options (may be more refined in terms of score from 1 to 10 instead)

| **mechanism** | **Effect on vibration emission [low/medium/high]** | **Time scale [weeks/months/ years]** | **Measurability [low/medium/high]** |
|---|---|---|---|
| Cyclic degradation of ballast | | | |
| Cyclic degradation of the subsoil | | | |
| Cyclic degradation of joints | | | |
| Subsoil creep | | | |
| Rail wear | | | |
| Wheel flat | | | |
| Rail geometry change due to seasonal temperatures | | | |
| Heavy precipitation | | | |

The EBR session should be completed before the literature search is fully completed such that important findings of the EBR session that were initially overlooked can be investigated during the literature review.

### 3. Collection and analysis of empirical data

In this activity we will collect data from past experiments from available databases. We are looking to get insight in available long-term measurement campaigns that are available from ProRail, which include time dependent behavior and preferably measurements of additional parameters. These will be analyzed and based on this analysis recommendations for further experimental campaigns will be formulated. Vibration measurements are considered together with information about time effects on the material (wheel flats) and maintenance thereof. With reference to the Meetprotocol [2]).

The time scales are important for the project. Assuming a measurement duration or monitoring interval of 2 years, we can only study variations within these two years. Other parameters, or effects on other time scales will be estimated using other sources, e.g. data from literature or data that is available at ProRail, or evaluated theoretically.

**4. Monitoring campaigns**

Based on the output of the evaluation of existing empirical data (seeactivity 3.), monitoring of time dependent variations is foreseen. For this activity, close cooperation with Prorail and planned activities withing IBS is needed. It is anticipated that already planned and prepared measurement campaigns and locations will be used. These campaigns may be initiated for other reasons and the STEM team will provide Prorail with suggestions for additional measurements or analyses. If needed, the STEM team will perform own measurements parallel to the already planned set up.

**5. STEM tool simulations of time effects**

A number of simulations is foreseen with the STEM tool, where time effects are either implemented or simulated. In the first year of this activity (2023) a small selection will be made of the simulations that will be implemented during this 2$^{nd}$ half of this year.
For a normal continuous track runs will be performed for different track qualities that will be shortly before and after maintenance (tamping), where track quality will mapped to rail geometry. These will be combined with different trains with maintenance states just before and just after (with regarding to wheel geometry). Simulation runs will be carried out for a variety of soil conditions and embankment geometries, to determine the free field vibrations. If significant differences are found between states just before and just after maintenance, evaluation of track and train vehicle qualities in between these extremes will be evaluated to investigate preventive maintenance.
A number of discontinuities will be selected to evaluate the effect of the track/embankment degrading with time in the interaction with these discontinuities.

**6. Definition of the implementation of the selected time effects in the STEM tool and input parameters**

For the selected time effects (as determined by the above work packages), the output of this WP is a workflow/procedure based on which the user of STEM can define scenario’s as input for the STEM model. This is envisioned as a set of parameters that describe the state of the train vehicle wheel degradation at different times just before and just after maintenance for different train vehicles, as well as parameters for defining track geometry in the STEM tool representing track quality before and after maintenance as well as in between. These allow STEM runs for continuous tracks for different configurations of embankment and soil types.
If the result of the other activities lead to significant time effects due to seasonal temperature and/or periods of heavy precipitation, and a method was found in literature to include them, parameter sets for these will be provided as well such that they can be combined with the track quality and train vehicle wheel degradation.

**7. Validation**

The implementation of the selected time effects of activity 6 will be validated using results from monitoring and literature. This validation is carried out in two ways. Selected parameters for the STEM tool are validated with available information, and where possible the output of the STEM tool computations of activity 5 will be validated using results from monitoring.

# 4. Deliverables

1: Report of the literature search

2: The results of the EBR session: a list of time dependent mechanisms prioritized to their influence on train-induced vibration emission, the time scale and their measurability.
3: Overview from available measurement campaigns, and an analysis of relevant observations with recommendations for monitoring campaigns.
4: Definition of additional monitoring and analysis of results.
5: Report of the mapping of track quality to rail geometry shortly before and after maintenance (tamping), and results of simulation runs that establish the effect on free field vibrations for a continuous track on a variety of soil/embankment conditions and trains.
6: Workflow/procedure recipes to model selected time behavior with the STEM tool. These include both modelling recipes and parameter sets.
7: report with results of the validation, this will be combined with 6: and 5:

# 5. Connection with other WPs

**1. WP Tool**

WP Time behavior provides knowledge on the important components that exhibit a time dependency that influence railway induced vibrations and material models for the ballast and subsoil layers. Some time behavior defined in WP Time behavior can be modelled in the STEM tool WP Tooling without much additional implementation, while some of the time behavior from the extended list from the EBR session in WP Time behavior can not be modelled easily and require implementation in the STEM tool WP Tooling.

**2. WP Embankment**

WP Embankment provides knowledge on the importance of the track components and a model for the train/track interaction model. It focusses on discontinuities which are expected to be an important aspect in the time behavior. One of the two PhD's will study discontinuities related to joints and another PhD is investigating ballast behaviour, which is defined in this WP Time behavior as being subjected to cyclic degradation. It is expected that valuable input from WP Embankment can be injected to WP Time behavior to allow inclusion of time effects.

**3. WP Spatial Variation**

WP Spatial variation provides knowledge on the stochastic calculations and provides a model for the ballast and subsoil schematisation. Relation with WP Time behavior is twofold. In activity 5, simulations need to be carried out which preferably have a stochastic component to evaluate the time effects stochastically. Also with respect to validation, if the STEM tool is used in activity 7, the WP Spatial variation allows stochastic results from the STEM tool to be produced in order not to compare one stochastic realisation with measurements but a range of realisations that are considered possible on the location where measurements are carried out.

# 6. Risks

| Risk | Mitigation |
| --- | --- |
| Too many time dependent mechanismsare defined that can't be all simulated | The limitation of the scope is made in the beginning of this document to remedy this. |
| EBR session leads to too many time behavior that are considered important | This is related to the above. The scope defined is such that the budget should be able to cover the scope. It is possible that the EBR session suggests that the scope should be extended. In that case it means |

| | |
|---|---|
| | that budget/time is not sufficient and need to be extended, or it needs to be decided to focus on a limited set of time behavior first |
| For some time behavior that are considered important not enough literature may exist to incorporate them in the STEM tool, in addition, some may not be able to be monitored | |

# 7. Planning

No activities are planned for 2023.

# 8. Budget

See overall Plan of Approach

# 9. References


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# B WP Spatial variation

Authors: Wim Courage; Michael Hicks; Evert Slob; Bruno Zuada Coelho; Jelme Pennings; Wim van der Poel.

## 1. Context of Spatial Variation within STEM

Spatial variations are known to play an important role in vibration levels due to train traffic in e.g. the built environment. From a (very) far point of view one can – on the one hand – identify sources of vibration in the train track interaction due to irregularities and spatial variations in rolling stock, track and embankment and – on the other hand – the transmission of vibrations through track, embankment and soil in which spatial variations will play an important role as well. In principle, the chain is to be completed with the emission and propagation of vibrations into buildings. However, within the Stem project the scope is confined to free field near track locations. Nevertheless, completing the chain with software outside the Stem tool, e.g. OURS , is to be arranged for, which will result in specifications of the calculated free field vibrations and the spatial variations thereof. A preliminary list of relevant literature is presently composed [1-32] and studied addressing hotspots, spatial variation, and dynamic stiffness. It is partly setting the research questions in the plan of approach for WP Spatial variation with respect to spatial variations.

## 2. Activities in STEM

### 2.1. Literature scan.

The literature scan will be extended during the project leading to a review of the state of the art. Next to that, specific literature/reports/data will be sought related to performed measurements.
Deliverables:

- WP-R-2.1a State of the art review.
- WP-R-2.1b List of performed measurements accessible through reports/databases.

### 2.2. Identifying hotspots.

Hotspots – locations where nuisance occurs – are to be identified studying literature, measurements, hinderance as well as through discussions with partners. This will be done in close collaboration with WPEmbankment. WP Spatial variation will also focus on describing variability aspects conducive to modelling. As reference or in contrast to, also a “non-hotspot” is to be taken into account. In case the hotspots lead to a large set of scenarios a minimum (first) set of scenarios is to be defined teamwise with all project members.
Deliverables:

- WP-R-2.2a Longlist of hotspots.
- WP-R-2.2b Minimum first set of hotspot scenarios.

### 2.3. Dynamic stiffness

WP Spatial variation will take the lead in describing the dynamic stiffness aspects to be taken into account in the STEM project. The definition of “dynamic stiffness” in relation to STEM is yet to be defined and will take place in the first half year of the project. A balance will be sought in modelling aspects as well as corresponding measurement techniques. It is foreseen that dynamic stiffness will not be a simple input parameter for the tooling, but a “behaviour” of the train-track-soil system to be appropriately modelled by the tooling. WP Spatial variation and WP

Embankment will closely collaborate on this topic with contributions from WP Tooling. For validation as well as site identifications corresponding measurement technique(s) for dynamic stiffness are to be identified. No new measurement techniques will be developed, as this will not be feasible within the current STEM project. Instead, a review will be given w.r.t. existing measurement techniques.
Deliverables:

- WP-R-2.3a Assessment of usability and need of dynamic stiffness in STEM tooling
- WP-R-2.3b Definition of dynamic stiffness behaviour from a modelling point of view.
- WP-R-2.3c Appropriate measurement technique(s) capturing site-rolling stock dynamic stiffness properties for model parameterization and validation.

## 2.4. Spatial variation

WP Spatial variation provides a model for the ballast and subsoil schematisation, parameterising the spatial variabilities. As stochastic calculations are apparent, efficient methods and sampling techniques are needed for quantifying variabilities in input and output as well as sensitivities. WP Spatial variation will study these methods and deliver implementations of methods to be preferred based on suitability and efficiency.

- WP-R-2.4a Tooling for modelling spatial variabilities.
- WP-R-2.4b Efficient sampling tooling quantifying variabilities.
- WP-R-2.4c Efficient sampling tooling quantifying sensitivities.

### 2.4.1. Track Geometry

Methods for stochastic modelling of the track geometry will be studied and provided to WP Embankment, who then will investigate the influence of short wavelengths through sensibility calculations. When relevant, this will lead to specifications for corresponding measurement techniques.

### 2.4.2. Critical parts of track

Methods for stochastic modelling have to capture critical parts of the track and once enabled in WP Tooling, facilitate the identification and efficiency of hindrance reducing measures.

### 2.4.3. Longitudinal and Transversal path

Apart from track, spatial variation aspects predominately are foreseen in embankment and soil impacting respectively the longitudinal and transversal paths in vibration transmissions. WP Spatial variation will strongly interact with the PhD-3 proposal, in which the relative influence of spatial variation within the ballast and soil layers, as well as the spatial variation of soil layering, on wave propagation is investigated through 3D RFEM (random finite element method).

## 2.5. Experiments and site investigations

Experiments validating the STEM tool have to capture spatial variations in input and output. WP Spatial variation will accordingly contribute to set-ups for experiments. Relevant aspects will also be investigated in the PhD-3 proposal, e.g. “What are the optimal locations for sampling and/or monitoring, and what is the required intensity of testing in order to achieve a desired level of confidence in the results?” For this activity, close cooperation with Prorail and planned activities within IBS is needed. It is anticipated that already planned and prepared measurement campaigns and locations will be used. These campaigns may be initiated for other reasons and de STEM team will provide Prorail with suggestions for additional measurements or analyses. If needed, the STEM team will perform own measurements parallel to the already planned set up
Deliverables:

- WP-R-2.5 Suggestions for additional measurements within IBS.

## 3. Minimum Viable Product

The minimum viable product (MVP) of WP Spatial variation is a model for the ballast and subsoil schematisation, parameterising the spatial variabilities accompanied with efficient sampling techniques for stochastic calculations and sensitivity analysis.
Deliverables:

- WP-R-2.1a State of the art review.
- WP-R-2.1b List of performed measurements accessible through reports/databases.
- WP-R-2.2a Longlist of hotspots.
- WP-R-2.2b Minimum first set of hotspot scenarios.
- WP-R-2.3a Assessment of usability and need of dynamic stiffness in STEM tooling
- WP-R-2.3b Definition of dynamic stiffness behaviour from a modelling point of view.
- WP-R-2.3c Appropriate measurement technique(s) capturing site-rolling stock dynamic stiffness properties for model parameterization and validation.
- WP-R-2.4a Tooling for modelling spatial variabilities.
- WP-R-2.4b Efficient sampling tooling quantifying variabilities.
- WP-R-2.4c Efficient sampling tooling quantifying sensitivities.
- WP-R-2.5 Suggestions for additional measurements within IBS.

## 4. Connection with other WPs

Figure 4 shows the framework of the STEM tool and the relation between the different WPs.

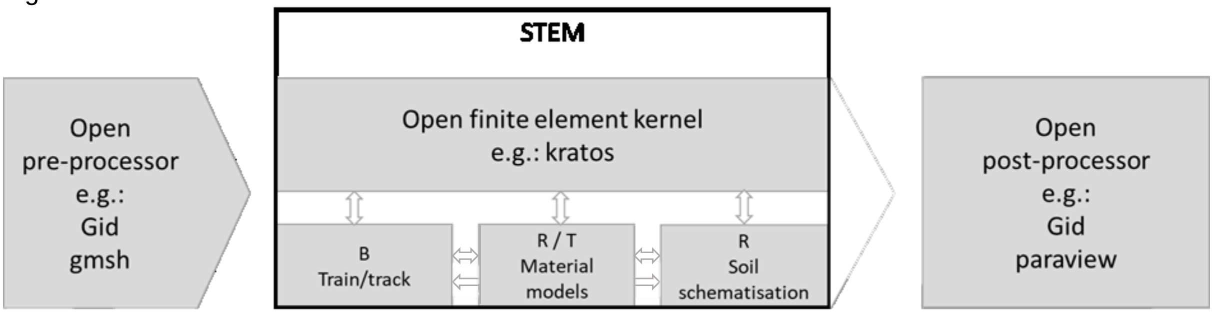


*Figure 4: Connection between WPs.*

### 4.1. WP : Embankment

WP Embankment provides knowledge on the importance of the track components and a model for the train/track interaction model. WP Spatial variation is connected to WP Embankment in defining hotspots and dynamic stiffness properties. WP Spatial variation supplies WP Embankment and WP Tooling with knowledge and implementations regarding the spatial variabilities accompanied with efficient sampling techniques for stochastic calculations and sensitivity analysis.

### 4.2. WP Time behaviour

WP Spatial variationT provides knowledge on the important components that exhibit a time dependency that influence railway induced vibrations and material models for the ballast and subsoil layers. Relation with WP Spatial variation is mostly linked to the measurement campaigns.

### 4.3. G: STEM tooling

WP Tooling provides a tool that performs finite element calculations with dynamic train/track interaction on a stochastic ballast and subsoil. WP Spatial variation supplies WP-Tooling with knowledge and implementations regarding the spatial variabilities accompanied with efficient sampling techniques for stochastic calculations and sensitivity analysis.

## 5. Risks

| Risk | Mitigation |
|---|---|
| WP-R-2.1b List of performed measurements accessible through reports/databases.<br>• Too late, causing delay<br>• Non informative/conclusive | • Start with theory/expert knowledge<br>• Confined to theory/expert knowledge |
| WP-R-2.2a Longlist of hotspots.<br>• WP-R-2.1b too late, causing delay<br>• WP-R-2.1b Non informative/conclusive.<br>• Too long | • Start with theory/expert knowledge<br>• Confined to theory/expert knowledge<br>• WP-R-2.2b: Minimum set of scenarios |
| WP-R-2.3b Definition of dynamic stiffness behaviour from a modelling point of view.<br>• Miscommunication with WP-B | • Regular meetings |
| WP-R-2.3c Appropriate measurement technique(s) for dynamic stiffness<br>• too complex/non practical<br>• no inverse modelling towards tooling | • Fall back options/less is more<br>• Inverse modelling options in specs |
| WP-R-2.4a Tooling for modelling spatial variabilities<br>• too complex/non practical<br>• missing level of detailing<br>• too time consuming | • From coarse to fine |
| WP-R-2.4b Efficient sampling tooling quantifying variabilities<br>• too time consuming | • At least one minimal fallback option |
| WP-R-2.4c Efficient sampling tooling quantifying sensitivities<br>• too time consuming | • At least one minimal fallback option |
| WP-R-2.5 Suggestions for additional measurements within IBS.<br>• not feasible<br>• too late | |
| Synchronisation with PhD’s 1-3 | |

# 6. Planning

To perform after agreement in the content

No activities are planned for 2023.

# 7. Budget

See overall Plan of Approach

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**Background Information for STEM on Modelling Heterogeneity**

Michael Hicks, TU Delft

**Modelling of Embankment Stability Accounting for Soil Heterogeneity**

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**Current Relevant Projects:**

<u>*SOFTTOP (2019-2024)*</u>

The aim of this project is to investigate the influence of the shallow subsurface (up to 30 m depth) on the transfer of energy (due to induced seismicity) to the ground surface; specifically, what is the influence of the cyclic loading of soft deltaic soils (organic clay, peat and sand) on the site response? This is linked with induced earthquakes in Groningen, in the north of the Netherlands, due to shale gas extraction. The influence of the shallow subsurface on the site response is being quantified probabilistically using coupled RFEM analyses accounting for the spatial variation of the soil properties at 3 scales: (a) small scale heterogeneities, for example in the form of laminations in sand and fibres in peat, are being accounted for through the development of constitutive models incorporating soil anisotropy and fabric; (b) medium scale heterogeneity, which is the spatial variation within material layers, is being accounted for by random fields; and (c) large scale heterogeneity, which is the spatial distribution of geologic layers, is being accounted for using both a coupled Markov chain model and random fields. The stratification of the Groningen area is being determined from a grid of CPTs with approximately 30 m spacing, using Bayesian updating to account for uncertainty in stratification at the CPT locations and coupled Markov Chain Monte Carlo and random field simulation to predict soil stratigraphy between the CPTs. However, a detailed representation of spatial variation between CPTs, both of soil layering and within individual soil layers, is difficult, and this was the motivation for a new project, *3DSOIL (2021-2025)*. This project is using high frequency full-waveform immersion geophysics, correlated with CPT data, to generate detailed 3D images of the subsurface. In addition, machine learning will be used to develop a probability-based model for predicting CPT data based on geophysical measurements conditioned to known CPT data.

*RESET (2021-2026)*
This project is funded by Prorail and is in collaboration with Deltares. It is motivated by the need of the Dutch rail network to accommodate (in the future) an increase in rail traffic, both in terms of the magnitude of applied loadings and the frequency of rail traffic, and also by the need to satisfy new safety guidelines and account for climate change. The main product of the project will be the probability-based framework for quantifying uncertainty and embankment performance: it is expected that 2 PhDs will work on this aspect, while 6 other PhDs will primarily be involved in obtaining various sources of laboratory, field and numerical model data for calibrating and benchmarking the probabilistic framework. The framework itself will build on developments made in previous research; for example, the stochastic characterisation of sites will utilise multiple data sources, and extend the earlier work on using CPT data in the now project *Reliable Dykes (2014-2021)* and current research on using geophysical measurements and machine learning in 3DSOIL. Meanwhile, the reliability-based framework for embankment performance under train loading will build on the advances made in safety assessments for the flood defence industry in Reliable Dykes, as well as on experience gained in SOFTTOP on the dynamic loading of heterogeneous subsoils (including research on boundary conditions).

# C PhD profiles

**PhD1: Characterization of the origin of vibration nuisance, especially at discontinuities**
Supervisors: Chen Shen, Zhen Yang, Rolf Dollevoet, Zili Li

Background: Train-track interaction, especially at discontinuities (insulated joints, compensation joints, switches and crossings, level crossings, rail and wheel defects), is the origin of train-induced vibration nuisance. This nuisance primarily takes place at certain locations, e.g., the hotspots. It is necessary to understand why the nuisance occurs at these locations, and then develop a tool and counter measures to predict, remedy, remove and prevent the nuisance through maintenance and design.

Goals: (a) to develop numerical models to describe the train-track interaction, to identify and characterize the origin of the vibration nuisance, as well as characterize and quantify the vibration that is transmitted into the ballast; (b) to develop simplified and fast methods that can be used to define and characterize a train and track, with or without discontinuities, in the tool; (c) to propose methods for long-term monitoring of contact and track geometry, track stiffness and train load; (d) to provide insight, methods, guidelines for predicting vibration nuisance, for improving the related track design and maintenance.

Components of PhD research may include[1]:

1. Analyzing measurement data, (a) to compare them with nominal/normal values for diagnosis and identification of the vibration origins, (b) to quantify the vibration that is transmitted into the ballast, (c) to use the measurements as input to and for validation of the numerical models for diagnosis and identification of causes which cannot be directly identified from the measurements. The measurements can be from hotspots, reference track and IBS test sites, done in-track, pass-by and train-borne.
2. 3D numerical modelling: Multi-body (MB) modelling will be used to simulate the effects of the trains. FE modelling will be employed to focus on the effects of the structures, geometry, interfaces, materials, and the non-linearity and variability of the train-track system. The aim of this 3D modelling is to answer why the vibration nuisances occur at some discontinuities and not others, to bridge the knowledge gaps and to support the tool development. The steps include (a) developing numerical models, (b) calibrating the models with some of the measurements, (c) validating the models with other measurements, (d) performing numerical simulations, (e) analyzing the numerical results and field measurements jointly to identify and quantify the vibration origins and the transmission, (f) proposing methods regarding how to define and characterize a train and track, which can be implemented in the tool.
3. Developing methods for long-term monitoring of contact and track geometry, track structure (e.g., stiffness) and train load. Correlate the origins of the vibration nuisance to the measurements. Possible starting points may be the existing train-borne LIDAR and ABA systems. The monitoring collects data that can be used for validating and updating the models, for input to and training of the tool, for following time dependent effects, for signaling up-coming hotspots, for identifying the vibration causes, and for maintenance decisions.
4. Proposing recommendations for maintenance and design based on the insight gained. Performance indicators can be further developed, e.g., based on monitoring.

Connections with other projects:

1. This project will provide loading to PhD2 and 3, and will use results of PhD2 and 3 for modelling.
2. The project builds on previous and current NWO, EC and ProRail research projects in collaboration with the departments DCSC and MSE of TUD, ProRail and European partners, on modelling of train-track interaction (InnoTrack, PRIME) and the related measurement, data analysis and model validation (DrTrack, PMnIDEA, NeTIRAIL-INFRA, In2Track2 and In2Track3).
3. It is expected that the PhD student will liaise with Deltares and TNO throughout the project to facilitate exchange of ideas and knowledge (equivalent to around 1 day/week averaged across the whole project).

**PhD-2: Time dependent material and numerical modelling of wave propagation in the ground**
Supervisors: Cristina Jommi and Ken Gavin

Background: Ballast is a key component in distributing and partly dissipating the static and dynamic load components towards the ground. The dynamic component of the load causes differential settlements over time, which are compensated by adding new material to level the differences during maintenance operations. However, degradation of the existing ballast caused by inclusion of finer particles from the wheel-track system, grain crushing from complex rotational stress path and addition of new material upon maintenance are the source of heterogeneous response. Extreme climatic events will exacerbate the sensitivity of the system over time, by further degradation of the dynamic properties of the soil, including the layers beneath the ballast. This project aims to parametrise the dynamic performance of the ballast and the sublayers over time, to provide reliable input for wave propagation in the ground. The project is based on a combination of experimental information and modelling development effort, to quantify the dynamic response of the ballast and the sublayers over time, as a function of the different sources of degradation. The models will be validated numerically with experimental data in the laboratory and in the field, to serve the spatial variation analysis and the general tool, including uneven degradation along the line.
Goals: (a) to collect information from the field on the state and heterogeneity of the ballast and subsoil; (b) to use existing experimental models and equipment in the laboratory to investigate the changes in the dynamic response of the ground to characteristic loads from the train-track system; (c) to systematically investigate the role of degradation, maintenance operations and possibly climate on the dynamic response of the ground ; (d) to provide usable models for the time dependent dynamic response of the ground, to be used in the analysis of spatial variation and in the general calculation tool.

Components of PhD research include:

1. Back-analysing existing data from the field to detect the main characteristics of the dynamic response of the ballast and the subsoil, especially identifying variation of the properties over depth and length;
2. Experimentally investigating the response of the ballast and relevant sublayers in the laboratory to include stress rotation and degradation under dynamic loads, using already available equipment at TU Delft. The investigation will answer the question: “to what degree are the dynamic –stiffness and impendence – properties of the ballast and sublayers significantly affected by degradation and maintenance operations over time?” and “how much will these properties be affected by increasing climatic stresses?”
3. Enhancing 3D-material models to predict the response of the ballast and subsoil over time under different scenarios. The models will be calibrated and validated on controlled experimental data from available physical tests. The component will answer the question: “how can we parametrise changes in the response of the railway ground components over time including degradation, maintenance operations and climate?”
4. Using the models with input from PhD-1 to provide PhD-3 a description of the dynamic response over time, to assess the influence of spatial and temporal variability on wave propagation in the ground

Connections with other projects:

- This project provides the key link between PhD-1 and PhD-3. It will utilise data from PhD-1 for defining the input loading from the track and will provide PhD-3 the necessary information to assess the role of variability over space and time.
- The project builds on current joint research between the sections of Geo-Engineering and Railway Engineering (RESET) and on previous experimental research effort supported by the NWO research programme DeepNL (SOFTTOP). The two projects provide the experimental equipment, which will be used to investigate and quantify the response of the ballast and subsoil under different scenarios.
- The project integrates information from parallel initiatives, however, it focusses on the time dependent dynamic response, which is not addressed elsewhere.
- It is foreseen that the PhD will collaborate on average 1 day/week over the duration of the project with TNO and Deltares to collect field information, discuss needs and implement the results in the general tool.

**PhD-3: Numerical and geophysical modelling of wave propagation due to rail traffic**
Supervisors: Michael Hicks and Evert Slob

Background: The dynamic loading of rail track and supporting ballast due to the passage of rail traffic induces vibrations and the propagation of waves through the shallow subsurface. In order to assess, and mitigate for, surface vibrations and their impact on surface structures, it is necessary to investigate the mechanisms and characteristics of wave propagation in the ground. This project utilises numerical and geophysical modelling techniques to investigate the propagation and monitoring of waves due to rail traffic, with a particular emphasis on the impact of track-ballast, surface (ballast-subsoil interface) and subsurface heterogeneities at different scales, different soil types and groundwater level on wave propagation.
Goals: (a) to utilise numerical models and geophysical data to investigate wave propagation in the embankment and shallow subsurface and its influence on the magnitude and extent of surface vibrations; (b) to perform 3D modelling of wave propagation using the random finite element method (RFEM), to develop guidelines on input parameters for numerical models relating to, for example, domain size, subsoil schematisation and properties, and discretisation level; (c) to utilise 3D RFEM modelling in conjunction with geophysical data to identify optimal locations for data acquisition; (d) to develop a strategy for characterising subsoil schematisation and parameterisation at a given location, based on numerical models constrained by geophysical measurement data.

Components of PhD research include:

5. 3D RFEM modelling of typical rail embankment profiles to investigate wave propagation in the embankment and shallow subsurface due to rail traffic. This will investigate the relative influence of spatial variation within the ballast and soil layers, as well as the spatial variation of soil layering, on wave propagation: “Is it possible to simplify numerical models in practice, by neglecting variability within layers?” In addition: “Is it possible to identify a representative “worst case” scale of fluctuation for numerical models in practice, for those locations where little data are available.
6. 3D RFEM modelling to identify the impact of domain size, discretisation level and boundary conditions, for example: “How is the length of embankment that needs to be analysed to identify the salient processes involved in wave propagation influenced by the cross-sectional geometry of the embankment and the horizontal scale of fluctuation?” Although WP4 already has plans on the size of the domain to be analysed in the final design tool, for the purposes of investigating the mechanisms and characteristics of wave propagation it is important for the PhD student to investigate ways to optimise (and thereby increase effectiveness of) analyses.
7. A detailed investigation of the mechanisms and characteristics of wave propagation in the ground, carried out by 3D numerical (e.g. RFEM) models constrained by geophysical field data. As well as gaining insight into the important parameters influencing surface vibrations, which will impact the guidelines on input parameters to the final design tool, a main focus of this principle research component will be strategies for data acquisition in practice. For example: “What are the optimal locations for sampling and/or monitoring, and what is the required intensity of testing in order to achieve a desired level of confidence in the results?”

Connections with other projects:

- This project will utilise data from PhD-1 and PhD-2 for defining the input loadings.
- This project builds on current joint research between the sections of Geo-Engineering and Applied Geophysics and Petrophysics for the NWO research programme DeepNL. The project 3DSOIL is being used to link geophysical data with geotechnical testing data for deriving detailed pictures of 3D spatial variation. The project SOFTTOP uses this data for RFEM simulations of the shallow subsurface subjected to dynamic loading from induced seismicity.

- It is expected that the PhD student will liaise with Deltares and TNO throughout the project to facilitate exchange of ideas and knowledge (equivalent to around 1 day/week averaged across the whole project).

**PhD Proposal-: Frequency-dependent characterization of the railway track by means of decomposition of the measured response field under moving axles**
Supervisors: Michaël Steenbergen (MPS), Andrei Metrikine (DSS), Karel van Dalen (DSS)

**Background**
One of the major challenges in the framework of the desired STEM model for improved control of traininduced vibration, with particular attention for the role of the infrastructure itself, is precisely the adequate description of the railway track. This includes not only quantitative accuracy but also the proper and often strongly situational modeling choices. When considering the railway track and its role in the vibration generation process, both the track geometry and the track stiffness profile (with a spatially variant stiffness) are primary sources of traininduced, radiated vibration from railway tracks. Both are fundamental, system-inherent mechanisms of generating a dynamic component of the axle load which causes surface wave radiation. Apart from these
mechanisms, also the static axle load is a primary source of surface vibration, though the generated field, which depends on the track stiffness, is not radiated and limited to the near-field. In the practical state of the art, for the geometry, measurement systems are in place, while this is not the case for the stiffness and its profile.
While these sources can be theoretically defined, distinguished and analysed, this is much less so in practice. The relevant stiffness, as perceived by the moving axle in the wheel-rail contact position, is a dynamic one (impedance). It therefore depends, for a given train axle with a known static load and speed,
on both space (position) and frequency. While in theory such a dynamic stiffness can be uniquely defined for spatially invariant systems, this is much less obvious when non-uniformity is introduced and the axle load gets a dynamic component. In practice, the stiffness cannot be measured simultaneously both as a function of position (space) and frequency. Therefore, compromises have been tested for railway
applications, in which the stiffness was either measured at a limited amount of positions for a wide range of frequencies (falling weight or hammer testing), or for a predefined frequency (or frequency band) as a function of the position (the Swedish rolling stiffness measurement vehicle RSMV). Both approaches have their own advantages and disadvantages; however, their indiscriminate or generalised application to generate input to describe the track at a global level in vibration prediction models may lead to erroneous results.
There is a second reason why both primary sources are difficult to establish distinctly in practice. The geometry of the track that is measured and established is different from the geometry that occurs and would be measured in the moving wheel-rail contact position (the loaded geometry). The reason is the interference between differential stiffness and geometry of the rail under the moving axle. For example,
in the case of a hanging sleeper, the first part of the contact displacement (or rail deflection) is due to support contact recovery between rail support and substructure (leading to a change in track geometry), while the second part of the contact displacement is indeed governed by the stiffness of the local support
conditions. This is a second reason of practical difficulty in the identification of stiffness properties along the track.
The current proposal aims to resolve the above theoretical difficulties and practical drawbacks by developing a new method for analysis and interpretation of the information already contained in the response fields under moving train axles in the rail for different static axle loads and train speeds.
The advantage of using the actual displacement fields to identify the frequency-dependent properties of the track is that they are automatically determined for the practically relevant preloading levels and train speeds, and moreover that they take into account the actual,

situational material properties of the constituent layers of the railway track under consideration. This involves parameters such as ambient
temperature and ground water level. Moreover, this is done in such a way that an 'aggregated' stiffness is derived, taking into account these layers and their complicated interaction in a physical, realistic manner, ending up with one global stiffness defining the composed track and its interaction with the substructure.

**Goal**
The goal of this work is twofold:
- Firstly, its results are expected to allow for an improved description of the track itself in traininduced vibration prediction models (and specifically the STEM model) by incorporating actual values of the track stiffness and its spatial variation, thereby improving the situational prediction power of such models.
- Secondly, the work is expected to lead to a diagnostic tool which will allow for (automated) detection of specific track configurations that are sensitive to be (or to become) vibration emission hotspots.

**Research components**
The rail displacement field under moving train axles, which is available for different static axle loads and train speeds, is a position-dependent, load-dependent and speed-dependent (and to some extent temperature-dependent) composition of the eigenfield that corresponds to the static load and the wave field that is induced by the dynamic axle load and 'distorts' the moving eigenfield in space and time.
The work aims to:
- Develop a method for decomposition of the radiating and non-radiating parts of the response field
- Interpret both contributions in terms of dynamic stiffness (and/or loaded geometry) and stiffness profile
- Investigate the relationship of both parts with the environmental vibration
- Investigate the dependence of stiffness on speed, static loading, and seasonal parameters such as ambient temperature and phreatic level
- Develop a robust method for real-time identification of track stiffness on the Dutch rail network.

This study aims to combine both results from experimental measurement campaigns and simulation work, where the simulation work will be a starting point and the experimental part needs further elaboration in terms of practical and budgetary possibilities within or outside STEM.

**Connections with other projects**
The M+P PVA document describes on page 9 the coherency between different activities in terms of content and time path for STEM. On the critical time-path of this scheme is B2: 'meting dynamische stijfheidsvariatie'. At an earlier stage it has been established that this activity is critically important but does not fit within the practical constraints in terms of budget and time of STEM. This proposal provides an alternative which, as far as possible given these constraints, meets the needs behind B2 within STEM.

Further, more specifically, this proposal relates to the M+P workpackages as follows:
*WP1: Embankment*
The proposal aims to characterize the railway track itself and its substructure at an aggregated level, which is a minimal description of the track but at the same time sufficient to capture fundamental mechanisms of vibration generation.

*WP2: Spatial Variation*
The proposal aims to characterize the spatial variation in system properties along the track, relevant for vibration generation, via the stiffness profile.
*WP3: Time behaviour*
The proposal aims to capture time-dependent effects (such as seasonal variation, water table, ambient temperature, settlement) via the stiffness profile.
*WP4: Tool*
The proposal aims to contribute to the tooling WP (mainly developed by Deltares) by allowing for an implementation of actual stiffness values and their profile.