



IN2TRACK

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Table of Contents

1	Exe	Executive summary		
2	Terms, Acronyms and Abbreviations			
	2.1	Acronyms and abbreviations	7	
3	Bac	kground	8	
4	The	e review process	9	
	4.1	Internal reviewing	9	
	4.2	Peer review in scientific publishing	9	
5	Ехр	erience from the review and quality assurance work	12	
	5.1	Templates and document management issues	12	
	5.2	Drafting and quality assurance of deliverable reports	12	
	5.3	Internal reviewing of deliverable reports	13	
	5.4	Independent reviewing of deliverable reports	13	
	5.5	Peer review in scientific publishing	14	
6	Сос	ordination of input to technical demonstrators	15	
	6.1	Identifying and understanding core S&C issues (D2.1)	15	
	6.2	Enhanced S&C whole system analysis, design and virtual validation (D2.2)	16	
	6.3	Enhanced monitoring, operation, control and maintenance of S&C (D2.3)	17	
6.4 Enhanced track structure – Status, key influencing parameters and prioritised a improvement (D3.1)		reas of 19		
	6.5	Enhanced track design solutions through predictive analyses (D3.2)	21	
	6.6	Enhanced inspection, maintenance and operation of track (D3.3)	25	
	6.7	Inspection and monitoring techniques for tunnels and bridges (D4.1)	27	
	6.8	Improvement of tunnels and bridges (D4.2)	29	
	6.9	Planning and design of tunnel and bridge demonstrators (D4.3)	31	
7	In2	Track deliverable reports	33	
8	Conclusions 34			
9	References 35			

1 Executive summary

Reviewing of deliverables produced in In2Track has been a key element in the quality assurance of the project. It has further paved the way for operational implementation. The review process is described in deliverable D5.1 (In2Track, 2016). In short, quality assurance of the In2Track Deliverables has been carried out at seven levels:

- 1. A deliverable skeleton is drafted and reviewed by the deliverable leader and the scientific & technical coordinator.
- 2. Each section is first reviewed internally within the partner organisation responsible for the section.
- 3. All technical deliverable reports except D4.3 were compiled in an early version and subjected to an internal In2Track mid-term review in the winter of 2017–2018.
- 4. When nearing finalisation, updated versions of the deliverable reports are compiled and subjected to internal review within the drafting team.
- 5. The finalised report is subjected to an in-depth review by the scientific & technical coordinator. This review also includes linguistic and layout issues. For that revision, the review comments are made directly in the report. The commented report is uploaded to the Cooperation Tool.
- 6. If required, the final report is also subjected to an independent review. For the technical reports, at least an independent person from the In2Track is invited. This review is made using the review comments template. Responses to the review comments are inserted in the review report and the document is uploaded to the Cooperation Tool.
- 7. After recommendation from the scientific & technical coordinator, the report is approved (or rejected and sent back for revision) by the project leader in coordination with the In2Track steering committee.

In addition to this internal review, a large number of scientific and technical papers have been produced within the project. A list of these papers is presented in section 4.2. These papers have been subjected to external peer-review before publication.

Chapter 5 discusses the experiences from the review process. The main complication originates from the fact that high-quality reviewing takes time. Combined with the fact that the deliverable reports are finalized at the end of the (short) project, this led to the need for a two-month project prolongation. In addition, the project has suffered from late deliverable of report templates and document management system. The latter was also when it arrived found to be poorly suited for this use. Additional complications were deviations from supplied templates and a poor response on invitations for reviewing. Despite these complications, it is believed that the quality assurance has been successful in ensuring a high technical and scientific quality. Much of this relates to the extensive scientific/technical publication.

In addition to quality assurance, the current report aims at supporting the development of demonstrators in later Shift2Rail and commercial implementation of research results. To this end, chapter 6 includes a summary of input to demonstrators and some main conclusions from all technical deliverable reports in In2Track. This overview is supported by a list of all technical In2Track deliverables in chapter 7.

2 Terms, Acronyms and Abbreviations

2.1 Acronyms and abbreviations
BIM Building information modelling
FE Finite element
FMECA Failure mode effect and consequence analysis
IMInfrastructure manager
KPI Key performance indicators
MEMS Micro electro-mechanical systems
PLPR Plain line pattern recognition
RCF Rolling contact fatigue
S&C Switch and crossing
TCMI Tunnel condition marking index
UAV Unmanned air vehicle
UIC International railway union
USP Under sleeper pads
WEL White etching layer

3 Background

There are 14 deliverables produced within the In2Track project. This amounts to roughly xxx pages of reports if appendices etc are included. To quality assure and disseminate such a massive body of information is a major challenge. As the project has progressed, internal review combined with scientific publication of research results has been found to be the most efficient means to this end.

The main motivations for peer reviewing are:

- 1. Quality assurance
- 2. Pave the way for dissemination

In addition, reviewing will also raise the general level of awareness and knowledge both among reviewers and authors

One important ingredient slightly outside the scope of the current report is the peer reviewing related to scientific examination in MSc, and PhD theses. Work that has been carried out as a part of such a thesis will of course be further scrutinized by examiners and grading committees.

The review model employed in In2Track and was refined throughout the project, essentially consisted of the following three stages:

- 1. Internal reviewing connected to the drafting of the deliverable report.
- 2. Internal reviewing by an independent project partner.
- 3. Peer reviewing related to scientific publication.

More details of the first two parts are presented in section 4.1, whereas the final part is presented in section 4.2.

4 The review process

4.1 Internal reviewing

The review process is described in (In2Track D5.1). In short, quality assurance of the In2Track Deliverables has essentially been carried out in seven steps:

- 1 A deliverable skeleton is drafted and reviewed by the deliverable leader and the scientific & technical coordinator.
- 2 Each section is first reviewed internally within the partner organisation responsible for the section.
- 3 All technical deliverable reports except D4.3 were compiled and subjected to an internal In2Track mid-term review in the winter of 2017–2018.
- 4 When nearing finalisation, updated versions of the deliverable reports are compiled and subjected to internal review within the review drafting team.
- 5 The finalised report is subjected to an in-depth review by the scientific & technical coordinator. This review also includes linguistic and layout issues. For that revision, the review comments are made directly in the report. The commented report is uploaded to the Cooperation Tool.
- 6 If required, the final report is also subjected to an independent review. For the technical reports, at least an independent person from the In2Track consortium is invited. This review is made using the review comments template. Responses to the review comments are inserted in the review report and the document is uploaded to the Cooperation Tool.
- 7 After recommendation from the scientific & technical coordinator, the report is approved (or rejected and sent back for revision) by the project leader in coordination with the In2Track steering committee.

4.2 Peer review in scientific publishing

In addition to the review within In2Track, the project has aimed towards broad scientific publication to further ensure the high scientific quality of the research. Naturally, an additional benefit with such a strategy is the increased dissemination and impact of the research.

To date, research results from the project has been published in the following scientific journals, conference proceedings:

PhD theses

 Robin Andersson. Squat defects and rolling contact fatigue clusters, Chalmers University of Technology, ISBN 978-91-7597-710-2, 2018 (https://research.chalmers.se/publication/502983) (Chalmers)

Licentiate theses

 Dimitrios Nikas, Effect of temperature on mechanical properties of railway wheel steels, Chalmers University of Technology, 2016. ISSN 1652-8891 (https://research.chalmers.se/publication/236833) (Chalmers) Knut Andreas Meyer. Modeling and experimental characterization of pearlitic rail steels subjected to large biaxial strains. Chalmers University of Technology, 2017(https://research.chalmers.se/publication/251873)

Peer-reviewed scientific journal papers

- Rostyslav Skrypnyk, Magnus Ekh, Jens C.O Nielsen, Björn A Pålsson. Simulation of damage in railway crossings – A comparison of rail steel grades R350HT and rolled MN13. Wear, 2019 (accepted for publication) (Chalmers)
- 2. Christof Bernsteiner, Alexander Meierhofer, Gerald Trummer, Stephan Scheriau, Klaus Six, Peter Dietmaier. Simulation and experiment based investigations of squat formation mechanisms, In review. (Virtual Vehicle, voestalpine)
- 3. Roque Borinaga, Aimar Orbe, Jos Norambuena, Javier Canales. Effect of microwave heating damage on the electrical, thermal and mechanical properties of fibre-reinforced cement mortars. (University of the Basque Country Bilbao)
- 4. Knut Andreas Meyer, Dimitrios Nikas, Johan Ahlström. Microstructure and mechanical properties of the running band in a pearlitic rail steel: Comparison between biaxially deformed steel and field samples. Wear, vol. 396–397, pp. 12–21, 2018. (Chalmers)
- Knut Andreas Meyer, Magnus Ekh, Johan Ahlström. Modeling of kinematic hardening at large biaxial deformations in pearlitic rail steel. International Journal of Solids and Structures, vol. 130–131, pp. 122–132, 2018. https://www.sciencedirect.com/science/article/pii/S0020768317304687?via%3Dihub (Chalmers)
- Dimitrios Nikas, Johan Ahlström, Amir Malakizadi. Mechanical properties and fatigue behaviour of railway wheel steels as influenced by mechanical and thermal loadings. Wear 366–367, p. 407–415, 2016 (DOI: 10.1016/j.wear.2016.04.009) (Chalmers)
- Dimitrios Nikas, Knut Andreas Meyer, Johan Ahlström. Characterization of deformed pearlitic rail steel. IOP Conference series, Materials Science and Engineering, Volume 219, conference 1, 2017. https://iopscience.iop.org/article/10.1088/1757-899X/219/1/012035 (Chalmers)
- 8. Julian Wiedorn, Werner Daves, Uwe Ossberger. Investigation of deformation mechanisms in manganese steel crossings using FE models. Submitted for international publication. (MCL, VAE)

Peer-reviewed conference papers

- 1. Knut Andreas Meyer, Magnus Ekh. A comparison of two frameworks for kinematic hardening in hyperelasto-plasticity. XIV International Conference on Computational Plasticity (COMPLAS 2017), 2017 (Chalmers)
- Emil Aggestam, Jens Nielsen, Andreas Andersson, Martin Li. Multi-objective design optimisation of transition zones between different railway track forms. Contact Mechanics and Wear of Rail/Wheel Systems (CM2018), Delft, The Netherlands, 2018 (Chalmers, Trafikverket)
- 3. Elena Kabo, Anders Ekberg, Michele Maglio. Rolling contact fatigue assessment of repair rail welds. Submitted for international publication. Contact Mechanics and Wear of Rail/Wheel Systems (CM2018), Delft, The Netherlands, 2018 (Chalmers)
- 4. Anders Ekberg, Björn A Pålsson. The role of contact mechanics in multiscale modelling of train track interaction phenomena. Contact Mechanics and Wear of Rail/Wheel Systems (CM2018), Delft, The Netherlands, 2018 (Chalmers)

- Casey Jessop, Johan Ahlström. Friction between pearlitic steel surfaces. Contact Mechanics and Wear of Rail/Wheel Systems (CM2018), Delft, The Netherlands, 2018 (Chalmers)
- 6. Casey Jessop, Johan Ahlström. Crack formation in pearlitic rail steel under uniaxial loading. Contact Mechanics and Wear of Rail/Wheel Systems (CM2018), Delft, The Netherlands, 2018 (Chalmers)
- 7. Ali Esmaeili, Johan Ahlström, Magnus Ekh. Modelling of cyclic plasticity and phase transformations during repeated local heating events in rail and wheel steels. Contact Mechanics and Wear of Rail/Wheel Systems (CM2018), Delft, The Netherlands, 2018 (Chalmers)
- 8. Dimosthenis Floros, Anders Ekberg, Fredrik Larsson. Evaluation of mixed-mode crack growth criteria under rolling contact conditions. Contact Mechanics and Wear of Rail/Wheel Systems (CM2018), Delft, The Netherlands, 2018 (Chalmers)
- 9. Knut Andreas Meyer, Johan Ahlström, Magnus Ekh. Characterization of yield surface evolution due to large plastic shear strains in pearlitic rail steel. Contact Mechanics and Wear of Rail/Wheel Systems (CM2018), Delft, The Netherlands, 2018 (Chalmers)

Technical journal paper

- 1. Johannes Kehrer, Fabian Hansmann. Fit for urban challenges Light Rail Systems. Metro Report International, p.56, September-2018 (Plasser & Theurer)
- 2. Fabian Hansmann, Johannes Kehrer. The quest for quieter trams. Railway Gazette, pp.46–48, August 2018 (Plasser & Theurer)
- 3. Fabian Hansmann, Johannes Kehrer. Auf "leichten Schienen" Mobilitätsrückgrat der Städte. Eisenbahntechnische Rundschau ETR, pp.26–30, Juni 2018 (Plasser & Theurer)
- Thomas Clover, Usani Ofem. Additive manufacture of railway crossing for Network Rail. Network Rail Insight. (https://www.twi-global.com/media-andevents/insights/additive-manufacture-of-railway-crossing-for-network-rail) (TWI/Network Rail)

D5.2

5 Experience from the review and quality assurance work

This chapter mainly contains (negative) experiences made during the course of quality assuring In2Track. The aim is to highlight areas for improvement for future projects. For that reasons, mitigating actions relating to the issues that In2Track had to deal with are proposed.

5.1 Templates and document management issues

The project has been severely hampered by the delay in defining a Shift2Rail graphical profile and document management platform. This was worsened by the delay from WP6 in delivering templates for In2Track. Naturally, this delay was also partly due to the lack of a Shift2Rail graphical profile. The situation was especially damaging since the first deliverable reports were due before any official Shift2Rail graphical profile, nor any official In2Track templates existed. To solve the situation, temporary templates had to be created and employed. In addition, since the document management platform was not established, these deliverables could not describe how this platform should be employed. Due to comments at the Shift2Rail review on the diversity in templates and lack of information regarding the cooperation tool, these deliverables then had to be rewritten and transferred to new templates. It is estimated that these issues costed several man-months in additional work.

Issues with the CooperationTool has complicated revision control. As an example, the CooperationTool renames uploaded documents, which breaks the In2Track naming scheme (see (In2Track D1.1) that was designed to steer revision control. Further, CooperationTool does not allow more than one level of folder or folder names of more than 6 characters(!). It also does not allow moving documents that have been uploaded to incorrect folders. It is also not possible to delete documents or folders, just to mark documents (but not folders as obsolete). This has resulted in incidents when documents have been uploaded to incorrect folders, when obsolete documents have remained on-line, when there have been risks that incorrect versions of documents have been used. In addition, uploading and finding documents have taken far more time than what should be needed. We estimate the productivity loss of these issues to be on the order of some man-months.

To mitigate these issues, we believe it is vital that templates, graphical profiles and document management solution are up and running at the start of the project. We further believe that the current document management solution has to be enhanced.

5.2 Drafting and quality assurance of deliverable reports

The use of templates has also had problems. Firstly, the experience of the partners of working with templates has been very varied. Some partners that are completely competent to use templates and follow instructions for formatting, referencing etc. These instructions were given on a separate page in the template. However, some partners seem to have very limited

experience of working with multiple-author documents. Issues such as hard-coding of crossreferences, inability to follow style guidelines etc has required large efforts in all stages of quality assurance. This has been exacerbated by the tendency of Word to break cross-references and redefine formatting styles when merging contributions from several authors. It is estimated that the additional work efforts due to these issues are also on the order of man-months.

To ease problems related to the use of Word templates, we believe that the most efficient way is to have more of the deliverable report material presented in annexes – this was a strive already for In2Track, but it must probably be much more strongly enforced. As a rule of thumb, the problems increase significantly when the document length exceeds around 100 pages. This holds for most technical deliverables of In2Track.

5.3 Internal reviewing of deliverable reports

The internal reviewing has in essence functioned well. The early drafting of the skeletons allowed the relevance of topics addressed to be ensured. Further, the definition of responsible partners allowed all review comments to be directly linked to the responsible project partner (and also the responsible person). Revisions have been delivered rather swiftly and generally with high quality.

A general issue is that much material has been delivered at the very end of the project. This is not surprising giving the limited length of the project, but it has caused complications with the quality assurance.

The first complication was the time required to provide a stringent quality assurance. Since most reports were not fully compiled until the end of the project, there was a need for review of eight major technical deliverables within some three months. Naturally this was not a sustainable situation. Instead of compromising quality, the decision was instead made to ask for a prolongation of the project with two months.

The second complication was that there was not time for section and deliverable leaders to enforce a detailed linguistic/stylistic review of the deliverables. This required the final review to focus more on linguistic/stylistic issues than what would have been desired.

5.4 Independent reviewing of deliverable reports

For independent review of the technical deliverables, project partners that have allocated time to WP5 were invited. Several partners did not respond with the requested review. After reminder, a discussion was made whether the existing review (all deliverables were subjected to a very detailed technical, linguistic and stylistic review of the projects scientific & technical coordinator) was sufficient, or if the submission should be delayed due to awaiting additional reviews from the non-responding partners.

The list of invited reviewers (in addition to Trafikverket who reviewed all deliverables in the role of scientific & technical coordinator) is presented below. Here "-" indicates that no review

comments were submitted, and "V" indicates that a review was submitted. The reviews by TRV included technical review, but also an assessment of linguistic and layout issues. As seen, the response rate from project partners was low.

D2.1:	TRV: √	SBB: –	ACC: –	
D2.2:	TRV: √	SZ: –	WL: -	ACC: √
D2.3:	TRV: √	ACC: √	SZ: –	PT: √
D3.1:	TRV: √	SZ: √	ACC: √	SBB: -
D3.2:	TRV: √	SZ: –	VAE: –	VCSA: -
D3.3:	TRV: √	SZ: √	NR: √	SNCF: –
D4.1:	TRV: √	SZ: –	SNCF: -	
D4.2:	TRV: √	TATA: √	WL: V	VAS: √
D4.3:	TRV: √			

Table 1Internal review of technical deliverable reports by project partners ('-': did
not provide review; '\': did provide review). I

5.5 Peer review in scientific publishing

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For a project that runs under such a limited time span as the In2Track project, it is very difficult to ensure a functioning quality assurance with only internal means. The reason is that reports presented in the In2Track project focus on the end result. They should therefore preferably be presented in a holistic context. For this reason, the majority of research reports are not written until at the end of the project. Consequently (as also discussed in other sections of this report), the review process will be very time restricted.

Even more cumbersome – from a quality assurance perspective – there is very limited possibilities to mitigate major flaws in the theoretical framework leading up to the end results. For this reason, the external peer reviewing in scientific publishing is crucial to provide confidence in that the science underlying the end results is sound. It also provides an additional confirmation that the research is relevant in the sense that the research duplicates previous research efforts. (In contrast, the industrial relevance is ensured through the willingness of the sector to fund the research and through the adoption of results.)

As seen from section 4.2, we have a large number of peer reviewed publication. The confidence in these reviews (together with the fact that TRV made very extensive reviews of all reports) was the main reason that the low review response rate seen in Table 1 could be accepted.

6 Coordination of input to technical demonstrators

As outlined in the Grant Agreement, one important part of the scientific & technical coordination was to compile the input to subsequent technical demonstrators from all technical deliverables. This compilation is provided here. For backgrounds and details on each specific item, please refer to the pertinent technical deliverable.

6.1 Identifying and understanding core S&C issues (D2.1)

Chapter 9 of the deliverable contains an "identification of prioritised areas for improvement". This chapter outlines the main directions for future work in Shift2Rail in eight pages. In addition to this, some of the main results and conclusions from the work in D2.1 are presented below.

It was found that the main areas for potential improvement of S&C relate to the elimination or minimisation of failures caused by rail deformation, wear and RCF; optimisation of switch rail profile; greater understanding of the effects of S&C support conditions; and enhancement of whole system monitoring, to reduce the requirement for visual and manual measurement to monitor and control remaining failure modes. It was considered that improvement in these areas offers the largest benefit in terms of improved RAMS performance and LCC.

The main cause of S&C failure was found to be a loss of function to support and guide trains due to plastic deformation, wear and crack initiation and growth due to RCF; the major damage mechanism involved in S&C failure being RCF. This causes safety and economical risks, resulting in spalling and potential rail breaks.

It has been shown that selection of higher-grade steels for use in S&C offers better wear resistance than standard R260 steel, leading to improved service life, although material and manufacturing costs are higher. In particular, analysis of the use of R350HT rail for switch blades has demonstrated twice the service life compared to equivalent use of R260 rail, although moderate RCF has been experienced.

The use of bainitic steel in S&C has demonstrated improved wear resistance when compared with R260 rail, with a corresponding reduction in RCF. However, during field trials, the use of B360 in a curved switch blade experienced a discrete flaking defect, which is further investigated in IN2TRACK deliverable D3.1.

It has been found that S&C failures are generally reported as superstructure faults. However, studies in IN2TRACK deliverable D2.1 suggest that poor support conditions may be an underlying cause. Further research is required to better understand the mechanics of S&C substructure interaction. Research into S&C bearer optimisation is included in IN2TRACK deliverable D2.2.

Measurement following eight years in service of two innovative turnouts installed in the INNOTRACK project found that the most heavily loaded turnout experienced several of the failure modes identified as critical in the existing S&C designs.

The most critical S&C failure modes were identified using a FMECA approach. If the FMECA is to be used for preventative or statistical analysis, it will need to be expanded to include individual

rail defects in line with those described in the UIC rail defect catalogue (UIC, 2018). Also, the developed S&C failure mode catalogue could be used as a standalone reference document but may then benefit from grouping failure modes by component (rather than criticality) and referencing the applicable UIC (UIC, 2018) defect codes.

A data analysis and modelling methodology is presented, which is used to establish failure or degradation time distributions for S&C components. Further research is required to validate that the methodology could be used to predict the remaining service life of S&C.

It was found that six of the most critical failure modes relied on detection using inspection by visual / manual measurement or ultrasonic means. A fault tree analysis was performed to understand the interconnected relationship of the failure modes identified in the FMEA. It was proposed that ALD power consumption could be used as a means of detecting switch blade and stock rail wear. This is further discussed in IN2TRACK deliverable D2.3.

6.2 Enhanced S&C whole system analysis, design and virtual validation (D2.2)

Chapter 5 of the deliverable contains "enhanced S&C system specifications and test plans". This chapter of thirty-five pages details the work going forward with the two planned S&C demonstrators. It also states necessary requirements of a new component to satisfy acceptance onto the railway infrastructure, including product acceptance, design for reliability, and common safety method assessment. In addition, some of the main conclusions and results from D2.2 are presented below.

Simulation of non-uniform settlements has concluded that the use of under sleeper pads, increasing sleeper width and the use of (soft) rail pads decreases the track stiffness gradient, which helps to prevent differential track settlement. This will be an important element for further simulation work.

Noise and vibration (N&V) is a known symptom of track degradation, both in the substructure and the overall superstructure. This leads to a decrease in track quality as a result of wheel and rail wear. Under sleeper pads, baseplate pads, ballast mats and rail pads should all be implemented into simulation tools (as mentioned above) with their nonlinear elastic or elastoplastic characteristics in doing so.

A number of failure modes of current simulation has been identified to require improvements, which can be resolved using modular simulation of sub-models, incorporating deterioration mechanisms such as wear, rolling contact fatigue and plastic deformation. Additionally, S&C specific models should consider dynamic stiffness across the bearer lengths, and discretised settlement modelling across the bearer. This will be the approach taken for further modelling.

Another suggestion included using real-world measurements to verify and validate existing simulations. To do this, wear and rolling contact fatigue prediction modelling needs to be improved, as well as the modelling capability of rail fastening system degradation. This work will be continued in In2Tack2.

Work on a whole system model approach and prototype, has been carried out and will be continued in In2Track2 where the influence of a wheel over the crossing in terms of apparent contact forces and degradation characteristics can be verified and validated against real-world examples.

Improved multibody dynamics simulation tools to investigate issues with current designs and results from preventive actions has been studied and will continue. This includes kinematic gauge optimization (KGO), optimisation of switch/stock rail and crossing overrunning conditions, use of modern actuation, locking and detection system sensors, clever implementation of under sleeper mats and under ballast mats.

Optimisation of bearers looked at continuous concrete bearers, a modular bearer jointed with a fixed metal shroud and a modular bearer jointed with an elastic sleeper coupling. Work with bearing systems will continue in In2Track2.

How optimisation of lubrication and grinding practises influenced rail performance was investigated. This included a modular continuous support system. This work will continue.

Proposals for enhanced S&C steel grades looked at currently utilised steels across Europe, and how these could be potentially optimised. Whilst the introduction of new steel grades to switch and crossing components would be beneficial, the study also highlighted how it would also introduce a requirement for a great deal of testing and analysis to be undertaken by manufacturers, particularly in areas such as welding to assess suitability of the new material with the pre-existing rail on the infrastructure. The work on the three new steel grades discussed in this report will be taken forward and developed further in future works within Shift2Rail.

The use of additive manufacturing as a novel solution was investigated. Laser cladding simulated testing was used to explore failure modes associated with additively manufactured crossings. Overall, there was good correlation between modelling and experiments regarding depth and extent of plastic damage in clad and substrate. Bending tests demonstrated that a good quality clad can meet or exceed fatigue requirements developed for welded rails. Poor clads (with inclusions for example) however, were shown to lead to defect growth. An additive demonstrator will be included in In2Track2.

The opportunity of using self-lubricating slide plates has been carried out, However, a friction coefficient at least twice as high as between metal–plastic plates occurs. This caused increased wear rather than reduced wear.

Implications of optimising steel grades in the crossing panel have been studied. Further work to identify future steel grades will be carried out in subsequent projects.

6.3 Enhanced monitoring, operation, control and maintenance of S&C (D2.3)

Conclusions and input to demonstrators from D2.3 is presented in chapter 7 of D2.3. A brief summary is given below with focus on demonstrator input.

A list of potential S&C communication and sensing technologies was presented. Identification of a suitable selection along with a specification for a plug and play system and architecture that can be demonstrated at TRL 4 followed.

The application of the electro-mechanical impedance technique for the detection of cracks and other defects in rails – primarily frogs/crossings was studied There were some limitations to the work due to large computational requirements leading to delays in producing meaningful modelled results.

The performed application of the whole-system model illustrated how a poor crossing geometry causes a higher local ballast settlement rate under the crossing transition compared to that in the surrounding crossing panel. The amount of crossing geometry degradation (and corresponding increase in impact angle) required to reach this point is dependent on the line speed and track resilience. For a nominal and well-maintained crossing, no significant amplification in settlement rate around the crossing transition compared to the surrounding track is to be expected. To correlate the calculation results to the situation in track and current crossing geometry maintenance limits, the following steps are proposed: If measurements of crossing geometries that are on the limit of current maintenance limits are taken, the impact angles for a range of wheel profiles can be obtained using computer simulations. This information can then be correlated to the impact angles used in the study presented in D2.3. In this way one can also observe what impact angles are currently tolerated and to what extent the stipulated maintenance limits on crossings correlate to the resulting impact angles in track.

Regarding S&C self-adjustment capability there are many robust technologies for adjustment of position. Actuation has a different scale of displacement, compared to detection and locking. The control of turnout actuation is dominated (technically and culturally) by the end positions, but further control of the tolerances will need measurement and modulation. The adjustments needed are not only in actuation, but also in detection and locking. Evaluation of technical difficulty and cost effectiveness will be important in future work towards demonstrators.

Opportunity exists to prevent a significant proportion of faults relating to switches by selfadjusting. The faults which remain, or are uneconomical to prevent, may be detected early using a range of sensing, which is mature in the railway industry. Automatic self-adjustment can be fitted to the majority of the actuation for ALD. A cost-benefit analysis of self-adjusting S&C infrastructure with built-in monitoring, considered over the life-cycle of the asset was performed. Statistical information for the possible failure modes, and the Pareto analysis is cited from a study. This case study described the cumulative net benefit with an 8% annual rate of return. The cost benefit is dependent on accurate figures for the new infrastructure, as well as the site of the turnout, and the timing of potential inspections and interventions, so each installation requires such details for a true assessment. As with any new investment, the selfadjusting S&C is likely to have the biggest benefit at busy locations.

6.4 Enhanced track structure – Status, key influencing parameters and prioritised areas of improvement (D3.1)

Studies have been carried out to investigate the formation and growth of squats and squat type defects. Squats were characterized using different destructive and non-destructive methods in order to gain an understanding of the processes for crack initiation experiments. Fatigue experiments evaluated the influence of initial thermal damage and crack face friction on crack initiation and crack growth. Although the effect of these, and more, conditions require further investigation, the results from these studies are expected to provide suitable data for crack initiation and crack face friction in upcoming experimental and numerical studies of RCF crack propagation.

The derivation and identification of appropriate quantities for measuring the Rolling Contact Fatigue (RCF) crack loading for elastoplasticity was investigated. Crack growth experiments from the literature with loading conditions similar to those under rolling/sliding contact were numerically simulated and criteria to predict crack growth directions were evaluated. Promising criteria that will be further studied in In2Track and subsequent projects were identified.

A pre-deformation technique was developed and described. This technique can be used to evaluate the ability of various rail steels to sustain large deformations under field like loading conditions related to rolling contact fatigue. Further investigations of the deformed state is carried out in In2Track and subsequent projects.

Resistance to head checking of bainitic rails was observed. The tracks observations also showed that welding conditions must be optimised. Potential demonstrators (curves in plain tracks) in In2Track2-3 with bainitic rails with an optimised chemical composition and optimised welding conditions were discussed together with the possibility to introduce these grades in future versions of guidelines on the use of different rail grades.

Rail failure catalogues were evaluated, and it was concluded that the failure catalogues from UIC (2002) and from Capacity4Rail (2014) shall be used for further application within In2Track.

Better use of premium steel and optimising rail grinding would tackle the issues with rail defects forming. Having that programme aligned with tonnage and curvature would promote efficiencies and assure a safer track overall (specific with local areas and regimes available). This is considered in later Shift2Rail projects.

Based on previous works from UIC, a general proposal for a new generation of databases oriented to *analytics* maintenance is proposed. The main goal is to ease and speed up the process of calculation for the optimization and cost-analysis of maintenance tasks. This structure represents a step forward in the development of an international standard which should be completely finished by the cooperation of UIC, the main railway infrastructure managers among others.

Starting from In2Track the work on optimization of rail steel and profile combinations will be extended. Special care will be given to squat defects since they are influenced by many factors, particularly the rail head profile shape

Investigations revealed that deep grinding marks and large grinding facets can initiate "flaking" RCF defects on high rails in curves. Hard rails are more prone to these defects. "Rough" grinding conditions with high energy input and deep grinding marks can initiate squat defects in curves, through the formation of a martensitic layer on the rail surface; hard rails are also more prone to these defects. Non-conformal grinding profiles can also facilitate the initiation of these defects. The recommendations to mitigate these defects are to grind the rails with a conformal profile, narrow grinding facets, shallow grinding marks and a low energy input. No limit values can be given at this stage and the definition of these limits should be the objective for further research. These results should be introduced in future versions of guidelines on the use of different rail grades.

It was demonstrated how cost data attributed to different asset failure types can be aggregated at a suitable level to provide a meaningful indication of the likely cost of different failures. This data should be further classified to account for the "criticality" of the track where the failure occurs, as this may have a significant impact on performance costs. The principles and methodology demonstrated here could be applied to different infrastructure operator's data to facilitate more accurate life cycle cost analyses and to establish a base level of the failure/cost relationship.

A bibliographic review of the existing slab track systems has been performed, assessing its suitability to various aspects including construction and assembly costs as well as maintenance and repair aptness. The maximum operating train speed has also been taken into account. As a result of this review, the modular prefabricated slab track is identified as a competitive system with maintenance and repair advantages.

The work in In2Rail on track forms and the conclusions drawn from the In2Rail research are summarized and it is concluded that In2Track has extended the work in In2Rail. Important contributions from In2Track is the definition of large number of Key Performance Indicators and in demonstrating a procedure of ranking track solutions, which showed the significant difficulties in such a task. Potential demonstrators in In2Track2–3 could be to refine the set of KPIs and to perform a track form evaluation for a specified scenario where several of the pitfalls with a general assessment could be resolved.

A finite element model is built for investigation of track vibration mitigation by the use of USPs. Impact hammer experiments are employed to calibrate/validate a half-track model. Model showed good agreement with measurements in terms of time domain results. Frequency domain analyses and update of the half-track model can give results for track vibrational behaviour that matches track experiments better.

Investigations show that the loading amplitude levels at a bituminous sub-ballast layer are very small compared to typical road pavement values. Taking into account these low load levels, the results also show that available common road base-course mixtures present adequate thermomechanical properties for them to be used as sub-ballast materials, even after moisture conditioning. Therefore, the use of common bituminous mixtures appears suitable for railway applications. This allows an important optimization since no sophisticated mixture design procedures or over-engineered components are needed. Good quality components (aggregates,

bitumen) and proper construction methods, especially compaction, are however required, as is the case for any other infrastructure project.

To further assess the performance of asphalt railway tracks, large scale laboratory tests of a railway subgrade transition zone were performed and presented in section 7.5. A 9.40MGT cyclic compression test of a conventional ballast track with and without asphalt layer was undertaken. The overall settlements were found to be larger in the ballasted track than in the ballast-asphalt track. It also resulted in a lower subgrade overall mean surface pressure.

The extent and value of maximum compressive residual stresses due to high intensity shot peening of rail welds was investigated. Shot peening was found to create good surface conditions with less defects and notches that could behave as crack initiation sites. An improved fatigue life of the peened samples was found. With additional parametric variations of peening and additional fatigue tests the knowledge of benefits of shot peening can be enhanced.

A comprehensive literature review of rail break detection technologies was carried out. The reactive broken rail detection systems are also discussed in terms of efficiency, reliability and compatibility. Proactive methods are discussed in terms of their reliability and detection speed. It is noted that some methods/systems are used together to detect different kinds of rail defects.

For track monitoring and inspection, there are tools that gather data, models that perform analysis and manual interpretation of that data. A central database, with enhanced frequency of recordings can potentially provide better information about the asset's degrading condition, which can be used to ultimately allow for more pro-active intervention. Network Rail is aiming to bring all the data together. This would enable e.g. degradation to be mapped, as well as providing validation of effectiveness of maintenance carried out.

6.5 Enhanced track design solutions through predictive analyses (D3.2)

An analysis of the different slab track systems in the market was carried out, identifying the advantages and drawbacks of each system, with the aim of identifying the requirements that the new modular track system should comply with in order to be competitive in the market.

A new modular track system based on the concept of multiple-level modularity is investigated with focus on maintenance requirements. Elastomer products have been considered for elastic support of concrete rail supporting blocks and the rail fastening system within the modular track system. The nonlinear elastomer characteristic has been considered in the track design calculations and in the vibration performance prognosis.

A new design of continuously supported precast concrete ballastless slab track was analysed. The comparison of its static behaviour with other ballastless track systems currently in use, especially for high speed trains, has been satisfactory. Regarding the increase in damping properties, the solutions tested so far on the basis of using waste rubber materials have not shown significant improvements. Therefore, additional alternative products must be considered and tested. The examination of non-heat-treated carbide free upper bainite bainitic rails welds (flash butt and aluminothermic welds) shows a modification of the metallurgical structure, with tempered bainite, ferritic and martensitic regions. The hardness profile has been correlated with the microstructure. This hardness profile explains the cupping and cracks found in track on some welds. From these observations it will be possible to design an optimised chemical composition and optimised welding conditions in order to reduce the formation of these modified metallurgical structures. These optimisations could be implemented in potential demonstrators (curves in plain tracks) in In2Track2-3, which will confirm the improvement of the behaviour of the welds in track.

It was shown that surface ballast gluing does not have any impact on the evolution of the track geometry. On the other hand, lateral resistance can be significantly increased by more than 60% by gluing the whole shoulder of the track to full depth and by more than 20% by gluing only the surface of the shoulder. This result is of practical interest to predict lateral resistance to counter long welded rail buckling during heat waves.

It was acknowledged that the limitations in predictive capabilities regarding rail crack formation and growth mainly relate to imprecise theories, simplifications and required assumptions. An overview of how these issues were tackled in the deliverable report and in the current project was given. The increased knowledge and awareness of limitations allow for demonstrations targeting both predictions, but also to improve calibration/validation of these predictions. The work on these topics will continue in In2Track2.

Track deterioration can be related to vertical and lateral geometric deterioration, to fatigue of components, to wear and to rolling contact fatigue of rails. Models simple enough to be included in a whole track system model were reviewed. Simple models describing geometric track deterioration take normal load / axle load, speed and unsprung mass into account and empirically relate these quantities to damage and costs. Fatigue of components is included in some of the models. It was acknowledged that the models need to be calibrated to the operating conditions at hand. Deterioration of the rail surface due to wear and rolling contact fatigue is similar to the mechanisms on the wheel. Thus, it can be expected that models applicable to rails can also be used for wheels. However, for squats on rails no simple models regarding initiation and growth exist, which makes it difficult to include squat damage explicitly based on key vehicle parameters in a cost model.

Improved FE computational procedures have been implemented, that can be applied to both welding and thermal damage. Needs for further development have been identified. Both experimental work and modelling will be taken further, and the predictive capability of the model will be demonstrated within In2Track2-3.

A methodology to quantify the equivalent temperature increase corresponding to a decreased resistance to track buckling was developed in In2Rail. The methodology has been employed for a number of common scenarios of decreased track resistance to quantify their effect. A structured approach to employ the equivalent temperatures in a decision support system that considers current and stress-free temperatures together with a decreased track resistance

(including uncertainties in these) has been outlined. The work will be taken further and be demonstrated in In2Track2–3.

An FE model for the simulation of white etching layers is combined with more advanced material models. The kinetics and the constitutive relations in the FE modelling are improved, with the purpose to increase the accuracy of the predicted residual stress fields that are obtained when the railway rail and wheel steels are subjected to repeated heating events (with potential formation of WELs). It is observed from the FE analyses that below the transformed martensite layer (WEL), high tensile residual stresses are generated. Since the tempered martensite material is rather brittle it is more susceptible to crack initiation.

A framework for numerical predictions of crack growth has been further refined. It is intended to be demonstrated in In2Track2–3 as a support tool for inspection and maintenance planning with respect to crack growth and the risk of rail breaks.

The effect of tensile thermal stresses in the vicinity of repair welds has been investigated. A significant decrease in tensile residual stresses at the highest stressed locations is found after some wheel passages. This implies that from a tensile stress point of view, repair welds will not have a major detrimental effect once some traffic has passed. The topic of repair welds was further discussed in In2Track Deliverable D3.3 and could be taken further for additional demonstration (in addition to demonstration made in In2Rail) in In2Track2–3. However, this relies on the interest from industrial partners and infrastructure managers, and on relevant safety approval from regulatory bodies.

Several methodologies for data analytics in railways have been identified, and subsequently classified in two different categories: nowcasting and forecasting. Complementary, a set of condition indicators for the main railway components has been defined together with a proposal for key performance indicators (KPI). In this regard, main failures modes for railway components have been associated to these KPI.

A recent method in the literature for prediction of rail corrugation using complex eigenvalue analysis has been adopted. The model is adopted using the input of wheelset-rail and track parameters from a corrugated section and the results show satisfactory similarity to actual rail corrugation frequency encountered in the chosen section.

Current standard for rail materials (EN 13674-1:2017) that lists a total of 9 steel grades was scrutinized. The standard covers a wide range of hardness levels and tensile properties but their link to known mechanisms of rail degradation is somewhat limited to increasing hardness being desirable for achieving greater resistance to both wear and RCF. A meaningful prediction of the rate of degradation and residual life of rail requires the determination of the link between material properties and the rate of degradation. The two key material properties that are closely linked to the in-service performance of rails are resistance to wear and rolling contact fatigue, but a direct measure of these properties is not mandated within EN13674-1:2017. There is a need to examine the multi-dimensional nature of the steel.

A preliminary investigation to understand the reason why the bainitic grades resist head check formation better than pearlitic grades was carried out. Several techniques have been developed and applied on a used rail: optical micrography, SEM, TEM, EBSD, XRD, micro hardness tests, in order to identify key parameters in bainitic steel damage mechanisms in railroad loading conditions. According to the obtained results, a scenario of crack formation has been proposed. Although additional observations are still missing in order to confirm the theoretical approach of the proposed mechanism, it was proved that the bainitic microstructure features at a very fine scale that can explain the good mechanical behaviour in use. In a further work in In2Track2, we propose a comparison of the sound microstructure and the wear affected zone in real parts after different times of use. Thanks to TEM analysis we propose also to verify the hypothesis of phase transformation $\gamma \rightarrow \alpha'$ under high strain rate.

The pre-deformation technique presented in the report can be used to evaluate the ability of various rail steels to sustain large deformations under field like loading conditions. Further investigations of the deformed state can lead to an improved understanding of the material behaviour in the highly deformed state. Then these observations can be used in material models to improve the current simulation capabilities on rail crack formation.

A a methodology is developed to evaluate the railway track long term dynamic behaviour due to soil degradation based on a 2.5D model that significantly reduces the computational effort and has the advantage of using sub-structured models. An empirical approach based on laboratory tests (cyclic triaxial tests) is used to model the soil degradation. The performance of three types of railway structures is analysed (ballasted, ballastless and a special ballastless track only constituted by the concrete slab) considering three irregularity profiles with different amplitudes and frequencies. This parametric study shows the main characteristics and advantages of the proposed methodology.

A study of under sleeper pad properties such as information material bedding non-linearity was carried out. Results are required to be able to calculate the superstructure response with under sleeper pad.

Work regarding track information model framework to aid building information modelling for railway inspection and maintenance was investigated. This should be a comprehensive inventory management system with the ability to process railway inspection and component information for use in inspection management, maintenance programming, budget development and strategic maintenance planning.

A guideline design chart for track bed design using asphaltic formation for different subgrade modulus (E) was developed using means of FEM. It is recommended that further research be undertaken to investigate the effect of asphalt on the long-term behaviour of railway track.

It was shown that continuous or discrete modelling assumption of the ballast layer has strong consequences on the model predictions capabilities. A new approach coupling a new paradigm for the ballast modelling to an efficient numerical scheme is developed. Over In2track2, results supported by experimental data are expected to confirm the potential and the performance of this approach.

The basic structure of the whole system model framework was shown. A subset of the whole system model framework was used for the prediction of squats and for the prediction of white etching layers. The prediction of white etching layers was based on wheel-rail contact

D5.2

temperature simulations. The simulations showed austenitisation temperature down to a depth approximately the thickness of white etching layers from full scale test rig experiments.

Possibilities and challenges of analysing rolling contact fatigue crack initiation and growth at different levels of detail and complexity were investigated. This charting provides a solid foundation e.g. for improving simulation-based product validation. The work needs to be continued at different levels: Product assessment focused simulations can adopt more sophisticated simulation approaches for vital features. More research-focused simulations can employ more in-depth simulations to (in combination with tests) enhance the general understanding of the phenomena. However, the main potential for demonstration lies in connecting simulations of different scope and level of detail to each other.

The development of a bespoke optimum track stiffness value for a railway network was pursued. This was achieved using means of numerical modelling to correlate the total strain energy of the train–track system with the global stiffness of the track system. Further research is required to investigate and test the sensitivity of the results found based on the assumptions made throughout the analysis and to carry out further validations.

Grooved rail track test will be continued in In2Track2 to collect sufficient load and degradation as input for the validation of the whole system model at urban conditions.

A tentative roadmap for monitoring of rail cracks was discussed based on the current state-ofthe art established in e.g. Capacity4Rail and other parts of In2Track. Here use of monitoring data coupled to numerical simulations and investigations into required monitoring precision are two aspects deemed to be of interest.

6.6 Enhanced inspection, maintenance and operation of track (D3.3)

The factors affecting grinding and different grinding practices were investigated including economical aspects. Determining the grinding interval is one of the most important points for optimising grinding. Another important point is the optimised grinding depth. The most important challenge about determining a standard optimum grinding strategy is that the "optimum" term differentiates according to conditions and requirements of different IMs. A group study (consist of different IMs like in INNOTRACK) would therefore be of use to be able to present a proposal of the optimal European grinding strategy. A workshop could be organized on this matter with the broad participation of IMs all around Europe in the future.

Plastic deformation is shown to significantly influence the hardening behaviour of rail steel. In particular, it was shown how a combination of shear and compression will lead to a severely anisotropic yield surface of the rail material. Criteria to predict crack growth direction under twin disc testing conditions have been developed from criteria in the literature and validated towards experimental data. The sensitivity of repair welds to RCF has been investigated and it is shown that the operational loading after repair welding significantly reduces the risk. Related topics to be investigated and demonstrated in later parts of Shift2Rail to optimize maintenance

include how restoration of plastic hardening (and related formation of damage) will progress for different materials and under different operational conditions. Prediction of crack growth under operational conditions will be further improved. If interest exists from the industry to commercialise the method, repair welding will be further investigated and demonstrated.

The overall market development of light rail systems as well as their future perspective are investigated. Furthermore, the technical and operational constraints for the application of rail grinding are assessed and underlined by the findings from a market survey conducted among network operators. Preventive rail grinding will increase the availability of the asset and reduces the impact of noise and vibration by delivering a good rail surface quality. Grinding for light rail infrastructure has to meet both operational as well as infrastructural constraints, such as narrow curve radii and of a high number of turnouts and crossings per track kilometre. These challenges have to be solved by future developments In2Track.

It was discussed how PLPR systems (or similar systems) bring significant benefits to the maintenance management of track assets. The PLPR information is digitised which removes subjectivity and previous manual or paper processes. The safety of staff is significantly enhanced by being isolated from a live railway, and the amount of track access can be significantly reduced.

Maintenance parameters that should be taken into account to assess the maintenance technical viability of new slab track systems were identified. Based on this, research on the modular slab track concept has been carried out with focus on optimal control of structural damage, and optimal track maintenance and innovative track renewal methods

With regards to the continuously supported modular track, it is being conceived for a fast placement, as well as for a fast replacement, in order to reduce rail traffic disturbances. To this end, the investigated use of cement-based mortars reinforced with steel and/or polypropylene fibres has two different goals: As a mortar reinforcement, fibres will increase the bonding durability and toughness, ensuring a more continuous support for the precast slab. Whereas, as a debonding precursor, fibres will only be activated to deteriorate the bonding interfaces when replacement is necessary. The preliminary results show that the microwave application is a promising technique but needs to be further developed.

The method of welding layers with desirable wear properties on critical sections of the track using a laser is proposed as an economical and time-saving maintenance measure. Initial wear tests on the layers applied on standard track materials showed good wear resistance and the fatigue tests showed the behaviour of crack formation. Different laser coatings will be developed, and the influence of process parameters on wear and fatigue behaviour will be tested in the follow-up project In2Track2

A very brief overview of the work in Capacity4Rail and In2Track regarding monitoring strategies for the track structure in general and of rail crack formation and growth in particular is presented. In In2Track-2 and In2Track-3 this work is intended to be taken further towards establishing monitoring strategies for rail cracks (and other parts of the railway track structure).

A new technology of sensor based on MEMS with the main advantage to be totally passive and reliable in another field of application (aeronautics) has been tested. It was shown that the

sensors are precise and reliable but not tough enough to sustain the harsh condition (vibration) experienced when fixed to the rail. Way of progress has been identified and already undertaken by the solution provider.

The technology of oscillating grinding is currently not established in tram networks. Due to developing of a corrugation degradation model and including the results in the so-called loop model, a benchmark for oscillating grinding has been made. As a result, oscillating grinding shows a lot of potential. Additional factors which have to be considered when designing a rail maintenance (grinding) machine have been listed and statistical analyses of near rail obstacles (which in contrast to main line tracks have to be considered) have been made.

6.7 Inspection and monitoring techniques for tunnels and bridges (D4.1)

The main aim has been to identify, develop and wherever possible test advanced techniques and methodologies for the gathering and interpretation of data pertaining the present and expectable health status of tunnels and bridges.

Said techniques and methods were selected for their ability to fulfil (within reasonable economic and operative constraints) one specific requirement: reduction in operational disturbance when compared with current practice, both during the actual inspection operations and as a consequence of the enhanced identification and prediction of health issues in the assets.

As a result of the work developed during In2Track, several steps forward were taken in the development of an autonomous image-based tunnel lining inspection system, by the name of DIFCAM. The DIFCAM system strives to replace long, risky and severely traffic-disturbing in situ inspections by recording high definition images of the tunnel lining paired with precise positioning, lidar scanning and an autonomous digital image correlation software capable of automatically detecting significant changes in the external aspect of the tunnel lining. Several test runs were performed during the project, and additional runs are planned as a part of In2Track2. Additionally, research is ongoing for the implementation of additional data gathering and interpretation systems with the capacity of detecting sub-surface damage.

Adopting the Tunnel Condition Marking Index (TCMI) currently in use by NR, steps have been taken to explore the deleterious effects of several contributory factors to the accelerated degradation of tunnels, such as the influence of geotechnical conditions, weather conditions and the position of the water table. TCMI continues its evolution striving to provide more accurate and objective evaluation of the current state of tunnels, implement prognostics and trend detection, and in general become as useful and complete a tool for tunnel health evaluation as possible. In particular, future work in the context of In2Track2 will take a closer look at the structural behaviour of shaft eyes.

The implementation of BIM methodology for the creation of so-called digital twins both ex-novo and already existing tunnels, along with a succinct study of irreducible data to be included, database structures and potential uses in the context of health assessment and maintenance planning has also been visited in this deliverable. The work performed will serve as starting point for future endeavours to fully digitalize the railroad network.

Several different work streams have been developed during the project related to the issue of bridge inspection, use of UAVs for visual inspection and optical measurement systems for structural assessment being the most significant. The aging bridge population will continue to be subject to higher and more frequent traffic as well as higher speeds. Visual inspections will become more challenging due to increasing access restrictions as we move towards a 24-hour railway. Currently, if a visual inspection highlights a concerning defect, a more detailed inspection is carried out and the associated risks are assessed. Mitigation measures may need to be introduced to reduce the risks which in some cases could be very costly and disruptive to the normal operation of the railway. Network Rail has carried out two trials exploring existing and emerging inspection and monitoring techniques for metallic and masonry bridges supporting railway traffic. The results from the UAV survey are promising in respect of possibility to undertake a visual inspection from a safe place of work with minimum disruption to the operational railway. The collected data is still to be evaluated but the trial demonstrated that the data is of improved quality compared to the traditional methods and provides sufficient information to the asset owners to assess the overall condition of the bridge. This type of survey also allows the efforts to undertake tactile inspections to be targeted only to critical defects which can lead to significant savings. The potential of using this technology to link multiple asset management processes, such as inspections and assessments, has been explored. This aspect can be beneficial in respect of addressing challenges such as introducing new rolling stock and higher speeds on existing structures. It is recommended to explore further the possibilities of developing real time capability assessment established at each structure examination. A separate trial has been carried out on a masonry arch with existing structural defects. This work is underway, and the benefits associated with it can be assessed once the monitoring period is complete in March 2019.

Optical measurement methods, both ground based and UAV mounted were applied by Trafikverket in several Swedish bridges in order to test the applicability of several image-based technologies in the creation of digital twins, the detection of damage and the identification and tracking of slow (but potentially fatal) changes in geometry and structural behaviour of bridges. Future work in this field will strive to prove that the aforementioned slow phenomena may be detected by comparing the results of subsequent inspections in the same bridges under comparable circumstances.

Several assessment methodologies have been developed. From a theoretical analytic perspective, a semi-empirical methodology to predict structural performance under augmented loads was developed. Its application would unlock the full potential of existing bridges vis a vis changes in speeds and axle loads of the lines they are located in. Validation of the developed methodology in real bridges undergoing or already having undergone such changes of use is pending and would represent the following step to be taken in future research endeavours.

In a similar way, a methodology for the assessment of current capacity and reliability of existing bridges based on fragility curves was developed, making use of already existing yet underused data streams coming from in-place monitoring and opening the path for enhanced use of future

monitoring deployments on the basis of radically improved cost/benefit ratios. Still, as before, the full potential of the developed methodology requires on site implementation for its validation.

Hybrid sensing deployment for the follow-up of fatigue capacity consumption, on the other hand, already presents a definite validation and demonstration plan that extends into future Shift2Rail projects, making use of the real bridge provided by Trafikverket and properly monitored as part of this project.

Finally, as pointed before with the implementation of BIM methodology in tunnels, it is to be expected that the work developed around the elaboration and full use of digital twins of bridges shall be the starting point for future developments in that area.

6.8 Improvement of tunnels and bridges (D4.2)

The main aim was to identify, develop and wherever possible test advanced techniques and methodologies for the enhancement of maintenance and capacity upgrading of bridges and tunnels. Additionally, research effort was also applied to broaden the understanding of recurrent degradation mechanisms, striving to develop knowledge-based strategies to prevent or delay their appearance.

The proposed techniques and methods were selected for their ability to fulfil (within reasonable economic and operative constraints) reduction in operational disturbance when compared with current practice in maintenance, repair and upgrading operations.

Finally, the first steps towards better comprehension of railway bridge design parameters were taken, thus facilitating the future development of more efficient design codes.

A hypothesis was put forward that the behavioural change in transition zone degradation relates to the accumulated vertical difference between bridge or tunnel transient rail level and that of open track. This difference triggers several concurring degradation acceleration mechanisms in the area located at one axle distance from the fixed point causing a localized damaged area that expands due to recurrent feedback loops. A modular, easily adjustable FE model of a track to bridge transition was developed for the diagnostics of faulty transitions and the elaboration of vertical stiffness fine-tuning mitigation strategies. The main conclusions of the research shall be further developed in the upcoming In2Track2 project, where transitions between floating geometries (ballast to S&C, ballast to slab, etc) shall be visited: in particular, transitions between plain track and switches, the use of under-sleeper pads for the optimization of vertical stiffness shift between fixed and floating geometries and the transition between plain track and a novel slab track system shall be studied.

An exhaustive study of calcite precipitation mechanisms in drainage pipes was performed. Information on railway tunnels affected by the calcification problems was collected together with drainage water data. A new method where the inside of existing concrete gutters is covered with an easily removable material was proposed. This aims to reduce the contact surface between calcite and concrete and decrease overall costs. The results obtained from laboratory suggest that the proposed method (using geotextile lining and acrylic) is feasible and should be tested in the field.

Literature study and preliminary tests have been carried out regarding properties of various thermoplastic pipe materials and various additives in order to enable the extension of its lifespan and to get an increased resistance to the cleaning processes. Small scale tests are under way using capacitive tomography technologies, acoustic analysis of the drainage pipe and detection of the amount of scale deposits by monitoring the changes of the pipe's mass moment of inertia.

Literature study and a first test have been carried out using cured-in-place pipes. It seems that all repair procedures are developed for sewage pipes only. Apparently, none of the methods is suitable for repairing broken drainages in tunnels so that they are fully functional again and have the full lifespan. Ongoing research on the subject shall continue during In2Track2.

In order to prolong the remaining life of old steel bridges, the possibility of applying carbon fibre reinforced polymer plates to stringer to floor beam connections was studied. These connections are known to be prone to fatigue, and present difficulties when reinforced by traditional means due to weldability issues. Given the promising results obtained in laboratory tests, on-track demonstration in an old steel bridge is planned for In2Track2

Optimization of reinforced concrete T-beam shear strengthening with carbon fibre reinforced polymer laminates was achieved by studying the interactions between inner rebar and laminates and quantifying the beneficial effect of laminate anchoring to the beam wings. Research shall continue in In2Track2, applying the gained knowledge to the development of a shear reinforcement methodology for trough beams with no access to the inner beam surface.

Finally, the use of CFRP laminates to grant structural capabilities to concrete elements past the failure due to fatigue of the steel reinforcement was studied. Extensive laboratory testing yielded promising results.

Novel techniques for the replacement of damaged or structurally insufficient elements in old bridges were tested. Specifically, old masonry arch bridges were enhanced by using concrete liners, cross ties and fibre reinforced polymer pattress plates. In addition, old steel bridges had single structural elements or whole deck sections replaced by statically equivalent fibre reinforced polymer elements.

A review of current State of the Art in component replacement methods was undertaken in the context of an old timber bridge pile replacement program. A novel jacking system designed to serve as alternate path for permanent loads, was developed. Research on enhanced methods for repair and replacement will continue in the upcoming projects.

In order to provide more realistic values of dynamic parameters that strongly influence high speed bridge design, an ad hoc bridge exciter with adjustable frequency was designed, built, tested and validated. Finite element models of two bridges were developed and calibrated using the frequency and amplitude dependant damping values obtained from the exciter tests. Measured and modelled bridge dynamic responses under real train loads were shown to match closely. Further research on the damping interaction between bridge and soil, and the

application of the exciter to optimize the design of external dampers will be performed in In2Track2.

Additionally, a statistical methodology to validate and adjust different bridge load models was performed using data from impact load detectors. Results from the application of this methodology could have impact in future revisions of national design parameters, favouring a more efficient design without jeopardizing safety.

6.9 Planning and design of tunnel and bridge demonstrators (D4.3)

The report identifies the following concepts in need of being tested/demonstrated

- On-board health monitoring systems for tunnel structures to create digital tunnel twins and to develop building information models (BIM) adapted for tunnel structures by using commercial trains as a carrier systems.
- Tunnel structural monitoring using fibre optics
- Replacement of damaged lining of tunnel drainage pipes. The work includes 3D scanning of existing tunnels for needed replacement parts, tailor manufacturing of spare parts, and installation at the scanned location.
- Fatigue capability utilization of railway bridges that includes the development of hybrid sensing systems.
- Classification capacity of railway bridges by describing bridge bearing capacity by a limited number of parameters that can be used for load effect analysis.
- Damping and resonance of railway bridges under rapid cyclic loading including enhanced understanding and description of uncertainties regarding bridge damping including surrounding soil and track itself.
- Passive dampers to improve damping of railway bridges not intentionally built for high speed train traffic.

For demonstration activities the following bridges and tunnel alternatives are investigated:

- A steel truss bridge with riveted connections between orthogonal elements foreseen to be sought within the Network Rail network.
- To make further research activities related to load bearing capacity and bridge dynamics, TRV will provide a set of bridge structures. The following bridges have been identified as potential demonstrators:
 - o 3500-2142-1, Abiskojokk.
 - o 3500-2050-1, Bensbyvägen, Concrete bridge with cracks
 - o 3500-2199-1, Skellefteå VP E4, a lot of cracks
 - o 3500-2118-1, Södra Rautasjokk, steel bridge
 - o 3500-2086-1, Spännajokk, small concrete bridge with cracks
 - 3500-2058-1, Svartbäcken, small concrete bridge with strengthened with steel beams

- o 3500-2204-1, Alderholmen, a lot of cracks in the bridge, ASR
- \circ $\,$ 3500-2046-1, Gammelstad, concrete bridge with cracks
- The Meyssiez Railway Tunnel in the SNCF network is identified as a potential suitable demo site for tests on drainage maintenance related to calcite precipitation.
- The Kaponig tunnel and the Sieberg tunnel within the railway network of ÖBB.

7 In2Track deliverable reports

Note that number of pages may differ from final versions due to revisions, style changes etc brought about by the Shift2Rail JU review.

- D1.1: Project management plans, 29 pp, 2018
- D2.1: Identifying and understanding core S&C Issues, 153 pp and 2 annexes (2+38 pp)
- D2.2: Enhanced S&C whole system analysis, design and virtual validation, 338 pp and 2 annexes (61+11 pp), 2019
- D2.3: Enhanced monitoring, operation, control and maintenance of S&C, 191 pp and 1 annex (7 pp), 2019
- D3.1: Enhanced track structure Status, key influencing parameters and prioritised areas of improvement, 268 pp and 15 annexes
 (59+17+14+9+6+7+47+25+49+7+8+10+9+11+29 pp)
- D3.2: Enhanced track design solutions through predictive analyses, 327 pp and 9 annexes (10+11+49+4+6+59+8+7+10 pp), 2019
- D3.3: Enhanced inspection, maintenance and operation of track, 118 pp and 7 annexes (8+7+42+8+7+54+16 pp), 2019
- D4.1: Inspection and monitoring techniques for tunnels and bridges, 135 pp and 6 annexes (23+20+60+66+1+1 pp), 2019
- D4.2: Improvement of tunnels and bridges, 134 pp and 4 annexes (19+42+18+14 pp), 2019
- D4.3: Planning and design of tunnel and bridge demonstrators, 18 pp, 2019
- D5.1: Quality assurance plan, 17 pp, 2017
- D5.2: Report on coordination and quality, 35 pp, 2019
- D6.1: Project identity, website, brochure and document repository, 32 pp and 2 annexes (8+3 pp)
- D6.2: Communication activites, 22 pp, 2019

3036 pp in total (29+193+410+410+575+491+260+306+227+18+17+35+43+22).

8 Conclusions

The review process of In2Track is summarized. In particular, it is emphasized how the internal review is complimented by independent peer-review of scientific and technical publications. It is discussed how this is a key requirement to ensure a high quality in such a short and fairly high-volume research project as In2Track.

Complications in the quality assessment process have been outline, and recommendations for mitigating actions have been proposed.

A summary of conclusions and input to subsequent research in Shift2Rail is outline. This relates to the summaries in the referenced deliverable reports, where also further details can be found.

The full documentation is provided in the 3036 pages of In2Track reports as listed in chapter 7.

9 References

In2Track D1.1 (2016) Project management plans.

- In2Track D5.1 (2016), Quality assurance plan.
- UIC (2018) IRS 70712, 'Rail defects', Paris, France, International Union of Railways. ISBN 978-2-7461-2699-2
- Maurice, M., Sellier, F. and Silvestre, J.-J. (1986) *The Social Foundations of Industrial Power: A Comparison of France and Germany*, Cambridge, MA, MIT Press.
- Schneiberg, M. (2005) 'What's on the Path? Path Dependence, Organizational Diversity and the Problem of Institutional Change in the US Economy, 1900–1950', Socio-Economic Review, **5**, 47–80.