Assessing Innovations in High-Speed Rail Infrastructure

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Abstract. Innovations in high-speed rail (HSR) have had substantial effects on different stakeholders within and outside the railway system. As part of the European Shift2Rail research programme, several innovative solutions are developed for, among others, improving the HSR infrastructure. The Joint Undertaking behind this research program has set objectives for these innovations in terms of punctuality, capacity, and life cycle costs. With a focus on infrastructure-related innovations for HSR, this paper aims at assessing their impacts in relation to these targets. We review the relevant research literature about the effects of HSR innovations and their assessment. The paper presents a hybrid assessment methodology combing different approaches to assess capacity, punctuality, and cost effects. This contributes to reducing the existing gap that is found in the research literature. Based on a reference scenario for HSR line and collected data from different stakeholders, the results indicate that infrastructure innovations in HSR, being developed within the European Shift2Rail research programme, can contribute to reaching the target set for punctuality. Further innovations in HSR infrastructure and/or other railway assets may be needed to reach additional targets and for more accurate improvement values giving more insights into their impacts.

Keywords: High-speed, Railway, Infrastructure, Innovation.

1 Introduction

In this section, we introduce the relevant background information of this study and briefly describe the context to which this paper is contributing. Thereafter, we present the aim of the work as well as a delimitation of the scope of the research. We conclude the section with an overview of the paper's structure.

1.1 Context

Early innovations in high-speed rail (HSR) and its infrastructure have substantially contributed to enhancing the railway system as an important means of passenger transport. With higher speed and thus shorter travel times, these innovations enabled HSR to, among others, withstand the competition from other modes such as air transport, respond to and attract more demand for train passenger traffic, and reduce the negative environmental effects from other more polluting means of transportation. Thus, to keep up with developments of other competing transport modes and to improve and further increase the modal shift to rail passenger transport, continuous research and innovations (R&I) in different assets of the rail system are needed.

In this context and as part of the Shift2Rail (S2R) research programme, the S2R Joint Undertaking (JU) defined different Innovation Programmes (IPs) focusing on several subsystems of the railway system, e.g., infrastructure (or IP3), see Fig. 1. Moreover, the JU defines various cross-cutting-activities (CCAs) including the long-term needs and socio-economic research of the different IPs, see the red box in Fig. 1.

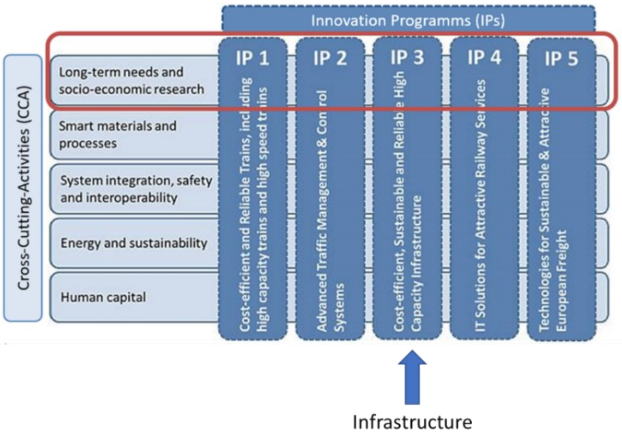

Fig. 1. Structure of the S2R IPs including infrastructure innovations [1].

As part of CCA and socio-economic research, the research project IMPACT-2 focuses on, among others, investigating the obtained and potential societal effects of R&Is within the S2R research programmes. For instance, specific key performance indicators (KPIs) are defined and monitored throughout the project, namely relating to punctuality, life cycle costs (LCC) as well as capacity.

1.2 Aim and Scope

With a focus on infrastructure-related innovations in HSR, this paper aims to quantitatively assess their effects using three different KPIs, namely capacity, punctuality, and LCC. Also, the study examines, through sensitivity analyses, how the assessed effects of such innovations in HSR infrastructure stand compared to the strategic targets set by the JU, i.e., doubling capacity (+100%), halving the life cycle costs (-50%) and increasing punctuality through improving reliability by 50% [1].

1.3 Structure of the Paper

The paper is structured as follows: Section 2 reviews the existing literature whereas the methodology and assessment model are described in section 3. The results of the study are presented in section 4. Section 5 concludes the paper.

2 Literature Review

In this section, we review the relevant literature of existing research. We first start with a historical background of R&Is in HSR and its infrastructure. Second, we present several studies on the various effects of different HSR innovations and their assessment. Finally, we identify the gap in the existing literature and present this work's contribution.

2.1 A Brief History of R&I in HSR Infrastructure

Earlier innovations in HSR took place in Japan when Shinkansen (also known as the bullet train) started operations in 1964 with train speeds reaching 210 kmph [2]. Thus, pioneering new technologies in designing and maintenance of infrastructure and rolling stocks, e.g., redesigned pantographs minimizing noise, rail welding reducing vibrations, and trains with a lower center of gravity and body weight [2].

After progressive but careful innovations, the French HSR (also known as TGV - *Train à Grande Vitesse*) started operations in 1981 with services between Paris and Lyon at 200 kmph [2]. The TGV project led to new HSR innovations such as in infrastructure (rails, bending radii, cants, switches at turnouts, catenary, pantograph, signaling system) and trains/vehicles (jointed trainsets, lower axle-load, distributed motorization, motors under engines' body, aerodynamics). Since the beginning of its operations, subsequent improvements helped achieve higher speeds, e.g., a record speed of 515 kmph in 1990. In a review of the development of HSR innovations, Walrave [2] presented the system approach, see Fig. 2, that was followed for R&Is in the French TGV project. Both estimations of the costs of infrastructure investments, rolling stock and their operations are considered alongside estimates of demand and revenues, see Fig. 2.

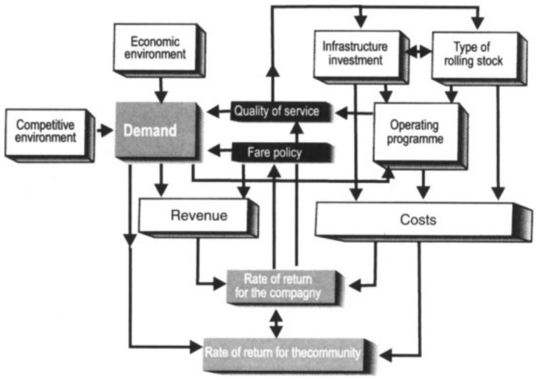

Fig. 2. System approach adopted for innovations in the TGV project [2].

During the last two decades alone, China has become a major innovation actor in HSR with a total network length of more than 19 000 km, i.e., around 60% of the world's HSR network [3]. While studying the innovation evolution of the Chinese HSR industry, Chen and Mei [3] state that, after years of indigenous R&Is with support from the central government, the first milestones were reached in 2010 with a service speed reaching 350 kmph. This came out of different science and technology research projects, including different stakeholders (e.g., research institutes and laboratories, universities, academicians) working on several core technologies (e.g., EMU system assembly, car body, bogie, train control network system, and brake system) and other complementary technologies (e.g., air-conditioning system, toilet, door, window, windshield, flow receiving device, auxiliary power supply system, interior decoration materials, and seat). All of this made China one of the most active patent-filing countries in HSR technologies and the leader in many HSR technological innovations [4].

2.2 Effects of HSR Infrastructure Innovations

The previously mentioned past innovations in, among others, infrastructure-related assets have led to increasing speeds on HSR lines, see Fig. 3. For speeds above 200 kmph, the infrastructure can be categorized as HSR as defined by the International Union of Railways UIC [5], also consistent with the definition by the European Commission EC [6]. These developments in operational speeds for such train services have various effects on different stakeholders in the railway market and society.

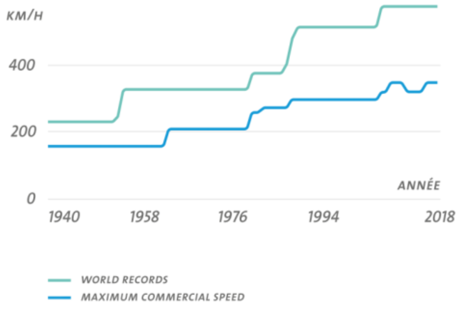

Fig. 3. Commercial and record speeds for HSR worldwide [5].

Higher speeds and shorter travel times have meant increased capacity utilization for the existing railway infrastructure capacity for both passenger and freight train services. Such infrastructure capacity can be defined as the maximum number of trains or passengers (for dedicated passenger lines) passing a specific section of the infrastructure under a given period [7]. Extensive studies show positive effects of HSR infrastructure on network capacity [8], e.g., increased infrastructure capacity [9], promotion of conventional passenger and freight rail [10], and induced travel demand [11].

Moreover, the development of HSR infrastructure worldwide has both socioeconomic and environmental effects [12]. For instance, in the case of a sustainable economy, the booming Chinese HSR has been shown to positively affect social welfare by significantly stimulating regional green innovation performance [13]. In Spain, it has been shown by Guirao, Campa [14] that the HSR has a direct positive linkage with the performance of tourism in certain regions. The authors recommend, however, further research by considering alternative explanatory indicators.

Additional effects have been associated with HSR infrastructures such as facilitating economic growth [15], reduced regional disparity [16], equity [17] and accessibility [18]. Moreover, Komikado, Morikawa [19] have recently found a positive influence of the existence of HSR on induced regional innovation.

2.3 Assessment of HSR Innovation Effects

To assess the effects of interest when studying HSR, different methods and approaches have been used such as optimization and simulation methods (for capacity assessments), econometric analysis, or monetary studies such as LCC and cost-benefit analysis (CBA), see Table 1 for an overview summary of some references.

When large sets of data exist such as empirical or historical data, econometric methods are commonly used, e.g., to analyze and compare differences (in one or several aspects) before and after the investments in HSR infrastructure. For instance, Multivariate Panel Data Analysis (MPDA) was used to analyze the significance of the HSR impacts on Spanish Tourism by Guirao, Campa [14]. Difference-in-differences (DD) is another econometric method which was used for example to study the effects of HSR infrastructure on social welfare in the case of a green economy [13].

When focusing on the monetary aspects of the effects, methodologies such as CBA and/or LCC analysis are often adopted to assess the impact of HSR infrastructure. CBA has been recently increasingly used as a decision support tool for assessing large infrastructure investment projects. Several examples of economic appraisal applications and methodology are summarized in the EU CBA guide, i.e., [20]. In a study attempting to assess the effectiveness of the HSR project Turin-Lyon, CBA was shown to fail to account for equity implications [17]. CBA has been therefore extended with strategic approaches to include the so-called wider economic impacts. Such extensions have been used, e.g., to measure the impacts of HSR in Europe [21].

LCC or life cycle costing is a monetary analysis that focuses more on the life cycle of one or more assets. It allows for estimating the costs of building, operating and maintenance, e.g., of HSR lines [22]. LCC can also be combined with a reliability assessment, for instance, to evaluate the optimal safety standards for HSR bridges [23]. By focusing on the environmental impacts, such analysis is also called life cycle assessment/analysis (LCA) and can, for instance, be used with LCC to assess both the economic and sustainability impacts of HSR over their life cycle [24].

Table 1. Examples of research on assessing the effects of HSR infrastructure innovations.

Reference	Studied effects of HSR	Assessment approach
[14]	The output of the tourist sector	Econometric analysis (MPDA)
[13]	Social welfare in the green economy	Econometric analysis (DD)
[9]	Infrastructure/network capacity	Analytical and optimization
[11].	Demand and social equity	Surveys and econometrics (logit)
[21].	Strategic impacts in Europe	CBA and wider economic impacts
[24]	Environmental and economic impacts	LCC and LCA
This paper	LCC, capacity and punctuality	Hybrid (LCC, CBA and analytical)

2.4 Research Gap

The literature review has revealed that most studies focus on isolating and assessing specific effects of HSR infrastructure, e.g., capacity, equity, economic growth, etc. Moreover, most of these studies adopt a single assessment approach, e.g., simulation, and econometric analysis. Table 1 gives an overview of some studies from the literature and the methods that are adopted to assess the HSR impacts.

In this paper, we present an assessment framework that adopts a hybrid approach combining different methods such as LCC, CBA and analytical analysis. Furthermore, several impacts of HSR infrastructure are assessed, namely punctuality, LCC and capacity effects.

Note that the presented studies include the effects of innovations in all HSR technologies. This paper focuses, however, on the infrastructural assets of HSR.

3 Assessment Methodology and Model

In this section, we present an overview of the methodology and describe the different sub-models that constitute the assessment model.

3.1 Overview of the Assessment Methodology

To quantitively assess the impact of innovations in HSR infrastructure, the S2R project IMPACT-2 focuses on three quantitative KPIs, namely capacity, punctuality and LCC [25]. The assessment is based on a reference scenario for HSR that could be found anywhere in Europe, also called “System Platform Demonstrator” (SPD) within S2R [26]. Thereby, the data of the SPD characteristics for HSR in the reference scenario is provided by different stakeholders in the railway market [27].

For assessing the potential impact of innovations in HSR infrastructure, various segments of the railway infrastructure system are analyzed in S2R and categorized into specific so-called "Technical Demonstrators" (TDs). Through the assessment methodology developed within IMPACT-2, it becomes possible to estimate the impacts of individual infrastructure-related innovations on the infrastructure system as well as on the whole railways. For these individual innovations in infrastructure, the relative improvements (in %) between the baseline and the future scenario are provided by the TDs [28]. See Fig. 4 for an overview of the assessment methodology that is adopted in this study.

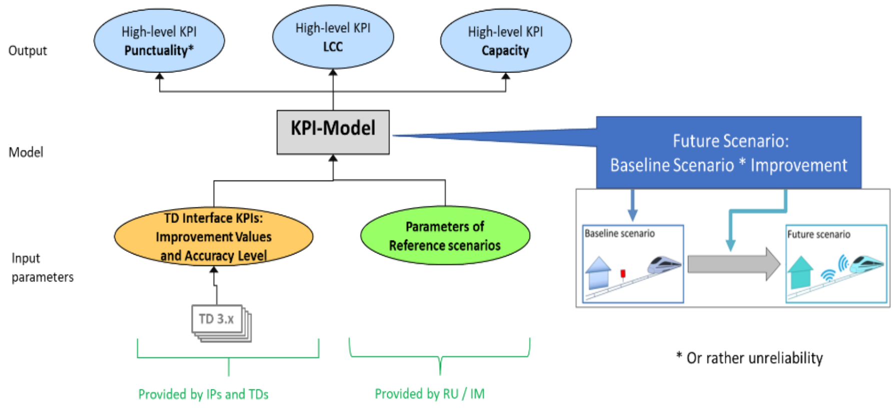

Fig. 4. Overview of the adopted methodology for assessing innovations in HSR infrastructure.

3.2 Assessment Model

In this subsection, we briefly describe each of the sub-models forming the assessment model, namely the LCC, punctuality and capacity sub-model for assessing different effects of S2R innovations in HSR infrastructure.

Life Cycle Cost (LCC)

Based on an assessment period of 30 years, the life cycle costs are calculated by summing up both the capital and maintenance costs of all the infrastructure-related assets, i.e., switches, track, bridges, tunnels, passenger stations, power supply, and infrastructure management.

To convert the total life cycle costs to an equivalent value in the present (also called Present Net Value or PNV), we use the discounting formula in (1) where LCC_y are the costs during year y and i is the discounting factor/rate, set to 3%.

$$PNV = \sum_{y=0}^{30} \frac{LCC_y}{(1+i)^y} \qquad (1)$$

Other parameters are also assumed in the sub-model such as the life service of certain assets (e.g., 20 years for switches & crossings, 100 years for bridges/tunnels). Moreover, the costs are also assumed to have a certain distribution among the different assets.

Punctuality

Some technical innovations in HSR infrastructure, e.g., improved predictive maintenance, can provide better service reliability and hence reduced downtime and delays. Such effects are captured in the punctuality sub-model using the methodology that is illustrated in Fig. 5.

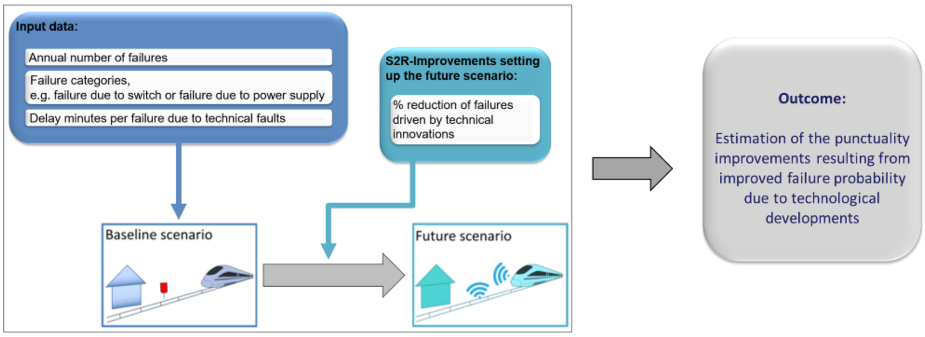

Fig. 5. Overview of the structure of the punctuality model [29].

Based on input data about historical infrastructure-related failures, it is possible to estimate future on-time performances using improvement values about technical failures in future HSR infrastructure assets.

Capacity

With a focus on peak hours where capacity is most needed, the calculation of the capacity for HSR is based on the definition given in the literature review, i.e., the number of passengers passing a specific section of the infrastructure under a given period [7]. The analytical expression in equation (2) is hence used to calculate the maximum capacity usage (in passengers per peak hour) during peak hours with/without the innovations in HSR infrastructure.

$$Cap\ [pax/h] = Line\ [trains/h] \times Train\ [pax/unit] \times Coupling\ [unit/train] \tag{2}$$

The line capacity (*Line*) is the number of trains per peak hour and day whereas the train capacity (*Train*) accounts for the maximum number of passengers that are transported during peak hours on a train unit of the line. The coupling ability (*Coupling*) captures the number of coupled units per train on the line during peak hours.

4 Assessment Results

In this section, we describe the data collection process and present the main KPI-assessment results of S2R innovations in HSR infrastructure. We conclude the section with sensitivity analyses and discussions on the accuracy levels of some parameters.

4.1 Data Collection

Various types of data were collected from the railway stakeholders and were used in several components of the model such as reference scenarios, innovation improvements, cost distributions and accuracy levels, see Table 2 for an overview.

To characterize the reference scenario of the studied HSR line, data was collected from railway undertakings (RUs) and infrastructure managers (IMs) actively involved in S2R as well as publicly available data, e.g., national transport ministries and data from European authorities such as the European Union Agency for Railways (ERA).

For assessing the potential impact of innovations in HSR infrastructure, various segments of infrastructure-related innovations are analyzed in S2R and categorized into specific so-called "Technical Demonstrators" (TDs). Through the assessment methodology developed in IMPACT-2, it is possible to estimate the impacts of individual infrastructure-related innovations. The overall relative improvements (in %) between the baseline and the future scenario are provided by the TDs.

Table 2. Data collection for assessing S2R innovations in HSR infrastructure.

	Baseline	Future
Collection process	Specification of the HSR reference scenario (infrastructure characteristics)	Periodic improvement values from different technical demonstrators
Example of parameters	Maintenance/capital costs of infrastructure assets, life span, delay (due to infrastructure failure)	(Updated) improvement values corresponding to, e.g., a reduction in maintenance costs of an asset
References	Industry (RUs, IMs), Research (S2R research projects)	Leaders of different TDs of the S2R innovations in infrastructure

Additional data were also collected. For instance, the distribution of costs is used for innovations where the KPIs cannot be captured at the level of details of the TDs. Accuracy levels (and their maximal value) are used to understand the precision of the provided improvement values. Such levels are further analyzed and discussed in the sensitivity analyses later in this section.

4.2 Results

Based on the collected data for both baseline and future scenarios, the assessment methodology allows calculating the impact of innovations in HSR infrastructure elements on the total railway system. Fig. 6 summarizes the assessment results (in blue) in comparison with EU targets (in red). The assessment results present the estimated percentage improvement in the KPIs (except for capacity which is lower than 1%) for the whole railway system when the different S2R innovations in HSR infrastructure are implemented.

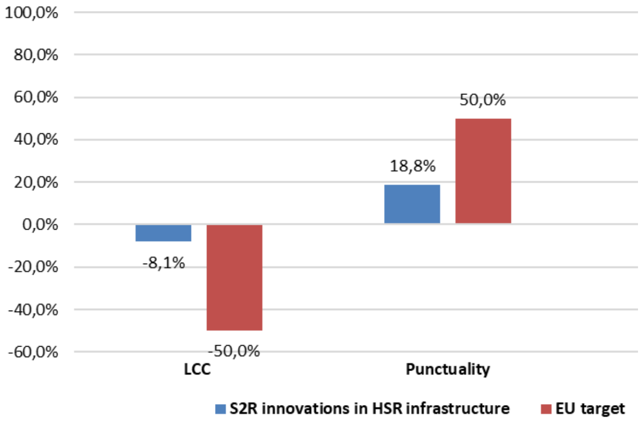

Fig. 6. KPI assessment results (in blue) of S2R innovations in HSR infrastructure (on the whole railway system) in comparison to the EU targets (in red).

The results in Fig. 6 indicate that innovations in HSR infrastructure have the highest impact on punctuality/unreliability, i.e., 19% which accounts for around 38% of the whole EU target of 50%. This is thanks to, among others, improved asset monitoring and condition-based maintenance which decreases the occurrences of infrastructure-related failures and delays.

However, although not presented in the figure, the impact of HSR infrastructure innovations in terms of capacity is negligible. In fact, the main gains in capacity (from infrastructure-related innovations) are thanks to the reduction in downtime time for planned maintenance. Such gains are negligible since the assessment of capacity effects is done during peak hours when the need for capacity is the highest. Innovations in other assets of HSR such as train design/capacity and/or signaling systems can be more important but are out of the scope of this paper.

Although below the EU target of -50% for LCCs, S2R innovations in HSR infrastructure allow for a reduction of around 8% in LCCs. This relative reduction in costs is mainly due to optimized maintenance, i.e., reduced costs for corrective maintenance activities.

4.3 Sensitivity Analyses and Accuracy Levels

To validate the assessment results, the leaders of the technical demonstrators (TDs) also provide so-called accuracy levels (AL), allowing to identify how the delivered improvement values were determined, see appendix B for detailed definitions of the ALs. The AL data are provided for two categories, namely technical and cost values, and can be assigned to one of four ALs, i.e., from highest (based on test results from laboratory/field) to lowest (e.g., expert knowledge). See Fig. 7 for the distribution of such AL for the different technical as well as cost improvements.

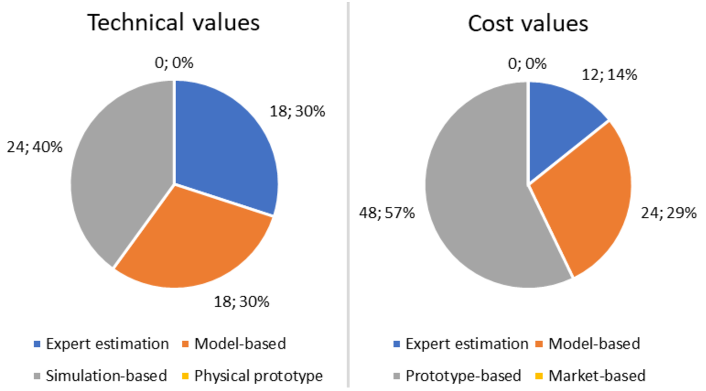

Fig. 7. Distribution of the accuracy levels of technical and cost improvement values for S2R infrastructure innovations in HSR.

Fig. 7 shows that most of the improvement values are based on simulation (if technical) or on a prototype (if monetary). Physical/market-based values are however absent since many of the innovations have not yet been used in the railway market. Note that, although not shown here, TD leaders may also indicate the maximum achievable AL from their demonstrators.

To further analyze the assessment results, we focus in this subsection on the improvements relative to the baseline infrastructure system, in contrast to the whole railway system as previously presented in Fig. 6. The assessment results (relative to the baseline infrastructure system) are as follows: -20,1% in LCCs and 55,2% in punctuality. The results for capacity remained as negligeable as for the whole system, i.e., 0,4%.

We perform sensitivity analyses on LCCs and punctuality. We therefore study two improvement values corresponding to different HSR infrastructure assets, namely bridge capital costs and power supply-related failures. The variations of the corresponding improvements in LCCs (for bridge capital costs) and unreliability (for power supply failure) are shown in Fig. 8 and Fig. 9, respectively.

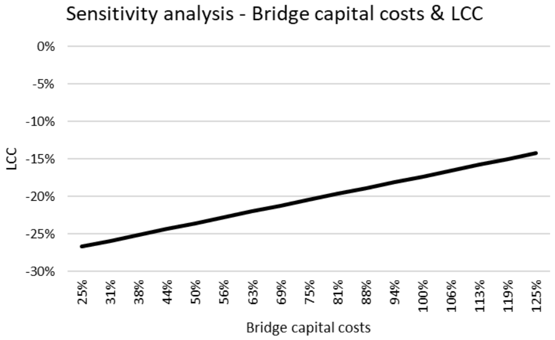

Fig. 8. Improvements in LCCs (relative to the baseline infrastructure system) when varying the capital costs of bridges.

With a focus on the effects of HSR bridge capital costs on the LCC, we these costs (on the horizontal axis in Fig. 8) around the reference value, i.e., 100 %. The corresponding improvements in LCCs (on the vertical axis) are decreasing (almost linearly) with decreasing the capital costs for the HSR bridges. However, the results are still robust since the variation in the resulting LCCs is substantially smaller (around 13%, from -27% to -14%) in relation to the variation in bridge capital costs (around 100%, from 25% to 125%).

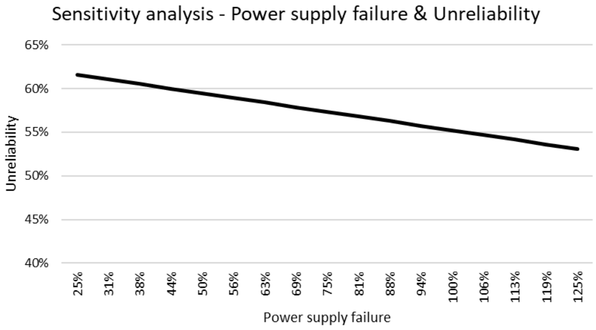

Fig. 9. Variation of the unreliability when varying the percentage improvement in power supply failures.

Another sensitivity analysis is performed on the effect of power supply failures on punctuality and unreliability. Like the LCC analysis in Fig. 8, the unreliability measure (on the vertical axis in Fig. 9) increases almost linearly with decreasing power supply failures. Both analyses (in Fig. 8 and Fig. 9) indicate that even with high variance in the improvement values (bridge capital costs and power supply failure, respectively), the measures are rather robust in terms of punctuality and LCCs (relative to the baseline infrastructure system).

5 Concluding Remarks

This section ends the paper with the main concluding remarks. We mention important conclusions as well as some of the limitations before briefly presenting some of the most relevant possible future works.

5.1 Highlights and Conclusions

In this paper, we have presented a methodology to assess innovations being developed within the Shift2Rail research programme for improving HSR infrastructures. The presented methodology combines different existing assessment approaches in the literature such as capacity analysis, life cycle costing and cost-benefit analysis.

Based on the baseline scenario of an HSR line and collected data from different railway stakeholders, we show that infrastructural innovations have the greatest effect on punctuality and can substantially contribute to the corresponding target that is set by the Joint Undertaking. Furthermore, we investigated the robustness of the assessment results using sensitivity analyses (and accuracy levels) and discussed them in relation to achieving the three different targets, namely punctuality, costs, and capacity.

5.2 Limitations and Future Works

During the development of the assessment methodology, we made a few assumptions. For instance, the case study has been parametrized based on the specifications within the Shift2Rail research programme. Therefore, the results can be considered tailored to the requirements of the programme. General conclusions as to the need for innovations in HSR infrastructure and their impacts can still be drawn.

Certain limitations are also relevant to mention in this context. In particular, the different effects (on capacity, life cycle costs and punctuality) are assessed separately, i.e., when one is assessed, the others are kept constant. Some assessed effects may, in reality, have additional contributions to another (separately) assessed effect. Moreover, several parameters, such as cost improvement values, are found to be difficult to accurately estimate as illustrated by the (maximum achievable) accuracy levels. Such limitation is beyond the scope of this work but is important to the assessment results.

The mentioned assumptions and limitations leave room for several possible future works. For instance, it is possible to continue the assessment of innovations in HSR infrastructure (and other railway assets) for future development of new ideas and innovative improvements under the European Rail Joint Undertaking. Furthermore, more market-based insights from the implementation of ongoing innovations (e.g., moving blocks, automatic/virtual train coupling, condition-based railway maintenance) would increase the accuracy of the assessment results.

Acknowledgement

This project has received funding from the Shift2Rail Joint Undertaking (JU) under grant agreement No 777513. The JU receives support from the European Union's Horizon 2020 research and innovation program and the Shift2Rail JU members other than the Union.

This preprint has not undergone peer review (when applicable) or any post-submission improvements or corrections. The Version of Records of this contribution is published in the conference proceedings of Socioeconomic Impacts of High-Speed Rail Systems (Springer Proceedings in Business and Economics) and is available online at https://doi.org/10.1007/978-3-031-26340-8_13.

Appendix A – Abbreviations and Acronyms

AL	Accuracy levels
CBA	Cost-benefit analysis
CCA	Cross-cutting-activities
DD	Difference-in-differences
EC	European Commission
EU	European Union
HSR	High-speed rail
IP	Innovation programmes
JU	Joint Undertaking
Kmph	Kilometer per hour
KPI	Key performance indicator
LCA	Life-cycle analysis
LCC	Life-cycle cost
MPDA	Multivariate Panel Data Analysis
PNV	Present Net Value
R&I	Research and innovation
SPD	System Platform Demonstrator
S2R	Shift2Rail
TD	Technical demonstrator
TGV	high-speed train (Train à grande vitesse)
UIC	International Union of Railways (Union internationale des chemins de fer)

Appendix B – Definitions of the Accuracy Levels

Accuracy levels	Cost value	Technical value
Based on the market (for costs), physical prototype (for technical)	Improvement values based on prototypes and estimation of scale effect for series production as well as acceptable market prices based on	Improvement values based on results of a test in field or laboratory conditions (foreseen to be similar in the field).

	first discussions among involved stakeholders.	
Based on a prototype (for costs), simulation/labs (for technical)	Improvement values are based on the evaluation of prototype cost without consideration of economies of scale.	Improvement values based on results of the test under laboratory conditions (requiring further testing in the field), or simulations of the technology.
Model-based	Improvement values are based on prototype drawings or based on calculations for similar technologies or comparable methods.	
Expert estimation	Improvement values based on knowledge of experts.	

References

1. JU, S.R. *Multi-annual Action Plan*. 2019 [cited 2022; Available from: https://rail-research.europa.eu/wp-content/uploads/2020/09/MAAP-Part-A-and-B.pdf.
2. Walrave, M., *THE DEVELOPMENT OF HIGH SPEED RAIL INNOVATION AND TRADITION. PROSPECTS FOR THE FUTURE.* Rivista Internazionale di Scienze Sociali, 1993. **101**(3): p. 375-397.
3. Chen, J. and L. Mei, *Innovation evolution of China's high-speed rail industry.* Frontiers of Engineering Management, 2018. **5**(4): p. 548-552.
4. Liu, X. and X. Yang. *Identifying Technological Innovation Capability of High-Speed Rail Industry Based on Patent Analysis*. in *2019 8th International Conference on Industrial Technology and Management (ICITM)*. 2019.
5. UIC, *High Speed Rail: Fast Track to Sustainable Mobility*. 2018.
6. EC, *96/48/EC on the interoperability of the trans-European high-speed rail system.* Commission of the European Communities, Brussels, 1996. **23**.
7. UIC, *UIC Code 406 - Capacity*, I.U.o. Railways, Editor. 2004.
8. Bracaglia, V., et al., *High-speed rail networks, capacity investments and social welfare.* Transportation Research Part A: Policy and Practice, 2020. **132**: p. 308-323.
9. Abril, M., et al., *An assessment of railway capacity.* Transportation Research Part E-Logistics and Transportation Review, 2008. **44**(5): p. 774-806.
10. Cheng, J. and Z. Chen, *Impact of high-speed rail on the operational capacity of conventional rail in China.* Transport Policy, 2021. **110**: p. 354-367.
11. Ren, X., et al., *Impact of high-speed rail on social equity in China: Evidence from a mode choice survey.* Transportation Research Part A: Policy and Practice, 2020. **138**: p. 422-441.
12. Momenitabar, M., et al., *Literature Review of Socioeconomic and Environmental Impacts of High-Speed Rail in the World.* Sustainability, 2021. **13**(21): p. 12231.
13. Zhu, Z., X. Lin, and H. Yang, *Booming with Speed: High-Speed Rail and Regional Green Innovation.* Journal of Advanced Transportation, 2021. **2021**: p. 9705982.
14. Guirao, B., J.L. Campa, and M.E. López-Lambas, *The Assessment of the HSR Impacts on Spanish Tourism: An Approach Based on Multivariate Panel Data Analysis.* Transportation Research Procedia, 2016. **18**: p. 197-204.

15. Chong, Z., Z. Chen, and C. Qin, *Estimating the economic benefits of high-speed rail in China*
A new perspective from the connectivity improvement. Journal of Transport and Land Use, 2019. **12**(1): p. 287-302.
16. Chen, Z. and K.E. Haynes, *Impact of high-speed rail on regional economic disparity in China.* Journal of Transport Geography, 2017. **65**: p. 80-91.
17. Bruzzone, F., F. Cavallaro, and S. Nocera, *The effects of high-speed rail on accessibility and equity: Evidence from the Turin-Lyon case-study.* Socio-Economic Planning Sciences, 2022: p. 101379.
18. Gutiérrez, J., A. Monzon, and J.M. Piñero, *Accessibility, network efficiency, and transport infrastructure planning.* Environment and planning A, 1998. **30**(8): p. 1337-1350.
19. Komikado, H., et al., *High-speed rail, inter-regional accessibility, and regional innovation: Evidence from Japan.* Technological Forecasting and Social Change, 2021. **167**: p. 120697.
20. Sartori, D., et al., *Guide to cost-benefit analysis of investment projects.* Economic appraisal tool for Cohesion Policy, 2014. **2020**.
21. Rothengatter, W., *Approaches to measure the wider economic impacts of high-speed rail and experiences from Europe.* 2019.
22. Maout, E.L. and H. Kato, *Life Cycle Cost-Estimation Model for Building, Operating, and Maintaining High-Speed Rail Systems.* Asian Transport Studies, 2016. **4**(1): p. 245-260.
23. Han, S.-H., *Optimal safety valuation of high-speed railway bridges based on reliability assessment and life-cycle cost concept.* International Journal of Steel Structures, 2017. **17**(1): p. 339-349.
24. Rungskunroch, P., Z.-J. Shen, and S. Kaewunruen, *Benchmarking environmental and economic impacts from the HSR networks considering life cycle perspectives.* Environmental Impact Assessment Review, 2021. **90**: p. 106608.
25. IMPACT-2, *D4.1 - Initial quantitative KPI model*. 2018, Shift2Rail.
26. IMPACT-2, *D4.4 - First SPD integrated assessment* 2020, Shift2Rail.
27. IMPACT-2, *D4.5 - Validated quantitative KPI model*. 2020, Shift2Rail.
28. IMPACT-2, *D4.2 - Initial estimation of the KPIs*. 2018, Shift2Rail.
29. Kurt, F., et al., *The KPI-Model – An integrated KPI assessment methodology to estimate the impact of different innovations in the railway sector*, in *SmartRaCon Workshop*. 2022.